Developing Resilience in Disaster Relief Operations Management through Lean Transformation

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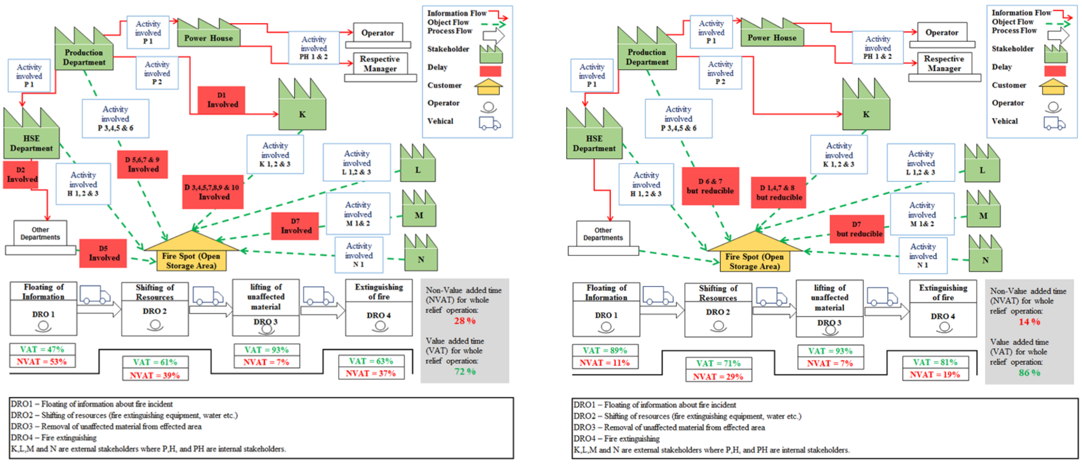

Highlights

- This research aims to investigate the use of lean transformation approach for achieving resilience in disaster relief operations (DROs).
- A systematic lean based method instigated through DROs' management initiative was developed.
- This was validated through an empirical industrial fire case study where selected lean concepts and tools like SIPOC-analysis, value stream maps (VSM), key performance indicators, fish-bone diagram, and plan-do-check-act were used to investigate DROs resilience in terms of their responsiveness.
- The VSMs were developed for 'as-is' and 'to-be' scenarios, and comparative analysis against standardized key performance indicators was carried out.
- The lean transformation approach was found effective in the studied case of industrial fire for developing resilience in DROs.
- Furthermore, lean tools could help in devising pragmatic strategies to prevent delays and achieve higher resilience through better coordination, communication, capacity building and awareness.
- This research contributes to the operations management and disaster management fields through lean transformation.

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Developing resilience in disaster relief operations management through lean transformation

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The impact of disasters in terms of the loss of human lives, infrastructure and economy has been increasing over time. Planning and management strategies for disaster relief operations (DROs) have got attention of the researchers and policymakers, particularly on how to achieve resilience in such operations. This research aims to investigate the use of lean transformation approach, which is the process of evaluating relief operations' performance in terms of responsiveness and road mapping interventions, for achieving resilience in DROs. A systematic lean based method instigated through DROs' management initiative was developed. This was validated through an empirical industrial fire case study where selected lean concepts and tools like SIPOC-analysis, value stream maps (VSM), key performance indicators, fish-bone diagram, and plan-do-check-act were used to investigate DROs resilience in terms of their responsiveness. The VSMs were developed for 'as-is' and 'to-be' scenarios, and comparative analysis against standardized key performance indicators was carried out. The lean transformation approach was found effective in the studied case of industrial fire for developing resilience in DROs. Furthermore, lean tools could help in devising pragmatic strategies to prevent delays and achieve higher resilience through better coordination, communication, capacity building and awareness. This research contributes to the operations management and disaster management fields through lean transformation.

Keywords: Operations management; Lean transformation; Value stream mapping; KPI; Responsiveness; Disaster resilience; Resilience; Disaster relief; Disaster management; Industrial fire; case study

1. Introduction

Disasters have been affecting social, ecological, financial, and physical infrastructures around the globe. According to the Centre for Research on Epidemiology of Disasters, Belgium (CRED), 315 natural disasters occurred in 2018 which affected 122 countries (based on the EM-DAT International Disaster Database). Moreover, these disasters have also caused economic damage worth US $131.7 billion, and 11,804 people lost their lives while affecting another 68.5 million people. Asia has been the most vulnerable continent as 45% of reported disaster incidents, 80% of reported deaths and 76% of the affected community belong to this region. Due to increased number of disasters, their severity, economic and social impact (CRED 2019; Weru 2015; Below and Wallemacq 2018), DROs have drawn the attention of professionals (Masood et al. 2017; Gupta et al. 2016) to develop better understanding of disaster resilience. Also it sheds light on designing relief activities to reduce human sufferings and damages (Gupta et al. 2016; Bosher 2014).

In this regard, Masood et al. (2017) proposed a disaster resilient supply chain operations (DROPS) framework as an outcome of an EPSRC Global Challenges Research Fund (GCRF) project of the University of Cambridge. As part of this project, the first international 5-day DROPS workshop was held at the University of Cambridge (2016) in which a mechanism for idea generation, review and control was formulated for conducting this research aiming at how resilience could be designed in disaster management operations (DMOs), particularly in South Asia. Three follow-on DROPS workshops were conducted during 2017-19. Several other follow-on projects were completed focussing on various countries. For example, a collaboration-resilience (COLRES) framework was proposed for Philippines, which was an adopted version of the DROPS framework for the Philippines (Medel et al. 2020). In addition, 46 collaboration-resilience activities were also identified in this case study of Philippines (Medel, Kousar, and Masood 2020).

Effective and timely execution of DROs is extremely important for saving human lives and damages to infrastructure and the economy. There is a need to develop and improve upon DROs management strategies preferably based on the real data to strategize practices for controlling the damage (Gupta et al. 2016). DROs usually include locating wounded persons, moving victims to safe places e.g., refugees camps, hospitals, uninterrupted provision of medicine, medical services as these operations are different and critical (Masood et al. 2017). The phenomenon of DROs' management is challenging because of the involvement of multiple stakeholders and managing activities in the minimum possible time. It is important to consider resilience in the context of DROs management as damages due to increase in number of disasters. The resilience in disasters' context deals with adaptive capacity building of resources, active involvement, and coordination of all stakeholders at each level of relief processes and collaborative exchange of innovative ideas among the stakeholders and social community.

This research aims to investigate the possibility of using the lean transformation approach as a strategy to achieve resilience in DROs' management. Therefore, the overall aim of the research is to explore the overarching question of ***"how can resilience be designed in DROs using lean tools?"***. The goal is to formulate a strategized roadmap which helps in enhancing the efficiency of DRO and to induce resilience in the system. We propose a systematic lean transformation approach for DROs management, which includes the use of selected lean tools, like SIPOC Analysis, Key Performance Indicators (KPIs), Value Stream Mapping (VSM) and Fish-Bone Diagram, for investigating the role of key stakeholders, main causes of delays in DROs, analysing value-added and non-value-added activities, developing action planned for improvement and then their impact by developing 'to-be' scenarios through an industrial fire case study. The scope of this work is limited to this case study; however, the approach could also be used for understanding and managing other disaster scenarios.

The rest of the article is organised as following. Analysis of related literature is presented in section 2. The section 3 provides a brief overview of the research method being used; Section 4 describes a detailed industrial disaster case study. Sections 5 and 6 present results and analysis, and discussion respectively. Finally, section 7 frames conclusions and future research directions.

2. Literature Review

Due to increase in population and urbanization, the effects of disasters are also increasing all over the world (Masood et al. 2017; Habib and Sarkar 2017). The single disaster event could cause the loss of thousands of human lives and billions of dollars to the national and global economy as observed during the Tsunami and earthquake in Japan (2011) (Masood et al. 2017; Habib et al. 2019). Such events attracted the attention of the DMOs community to research and develop approaches addressing challenges related to such events. 'DROs' are classified as a subset of disaster operations that are performed after the occurrence of a disaster for controlling the impact. (Gupta et al. 2016) presented a comprehensive review of disaster operations in Production and Operations Management (POM) perspective and recommended the development of case studies with real data.

On similar terms, DROs management is about managing relief activities throughout mitigation, preparedness, response, and recovery to reduce the impact of the disaster through better planning and strategies. Humanitarian operations are mostly divided into two main categories: disaster response and development programs that are performed by government organizations and humanitarian organizations jointly. The response phase provides relief supplies effectively that includes food, drinking water, medicine etc. to the victims, where constraints like resource scarcity, lack of visibility and uncertainty are real challenges (İvgin 2013; Dubey, Gunasekaran et al. 2019; Habib et al. 2016; Masood et al. 2017). However, on the other hand, lean concepts and their applications have been extensively reported in the literature (Castañeda et al. 2021; Hussain et al. 2016; Miller at al. 2011; Wahid et al. 2008). The summary of the literature is shown in Table 1.

Table 1: Summary of related works

Reference	Lines of research	Academic contributions	Solution Approach
(Masood et al. 2017)	Supply chain mapping to big data analytics for disaster resilient supply chain operations	The study proposes a novel Disaster Resilient Operations (DROPS) framework with key elements of supply chain mapping, resilience criteria/ factors and big data analytics of DMOs.	DROPS Framework integrating resilience, supply chain integration and big data analytics
(Medel et al. 2020)	Collaboration-resilience framework for disaster management supply networks	The model also provides practitioners the lens to improve processes with the perspective on collaboration to complement government and NGO efforts and expertise with those of the private sector.	Collaboration-Resilience (COLRES) Analysis Framework for disaster management supply networks

Reference	Lines of research	Academic contributions	Solution Approach
(Castañeda et al. 2021)	Analysing response process flow of humanitarian organization through Lean Six Sigma tools for disastrous situations	The study mandates to ensure that disasters are responded to or mitigated through timely supply of relief aid. Lean Six Sigma tools are deployed to make Zimbabwe's organizations resilient for managing the disaster relief operations.	DMAIC methodology (integration of Lean and Six Sigma), SIPOC Diagram, Fishbone Diagram, Swim Lane Diagram
(Miller et al. 2011)	Improving performance in service organizations through lean transformation	The lean philosophy (key performance indicators, value stream mapping, fishbone analysis) could potentially improve operational efficiency in relief operations and emergency response.	Value Stream Mapping (VSM), Fishbone Diagram,
(Ghaffari et al. 2020)	Emergency scheduling in disaster relief operations	Efficient (part of lean philosophy) utilization of resources helps in managing disaster relief activities.	Metaheuristic Approach
(Ivanov 2021)	Lean resilience: AURA (Active Usage of Resilience Assets)	A framework AURA is developed to support operations management in pandemics (sub type of disasters (Farooq et al. 2021)) through lean and agile approaches. AURA is based on the integration of Viable Supply Chain (VSC), Reconfigurable Supply Chain (RSC) and Low-Certainty-Need Supply Chain (LCNSC)	Active Usage of Resilience Assets (AURA)
(Upadhyay et al. 2020)	Lean and agile management in the pre-disaster and post-disaster phases for humanitarian supply chains	The study tries to provide support for achieving operational resilience by strategizing effective sourcing and speedy deployment of resources, with minimum wastage; in each disaster life-cycle phase through a systematic literature review.	The study concludes that lean and agile paradigms are beneficial in all disaster phases (mitigation, preparedness, response and recovery)
(S. M. H. Mojtahedi and Oo 2012)	Possibility of applying lean in post disaster reconstruction	The study uses lean philosophies of quick mobility, just-in-time, pull scheduling for achieving smooth workflow, eliminating wastes, and	Just-In-Time (JIT), Pull Scheduling, Six Sigma

Reference	Lines of research	Academic contributions	Solution Approach
		performance enhancement.	
(Masood et al. 2021)	Characteristics of changeable systems across value chains	This research presented a value chain approach to engineering change assessment.	Value chains; engineering change assessment
(Taylor and Pettit 2009)	Lean supply chain concepts for humanitarian aid provision	This study employs Lean Logistics technique; Value Chain Analysis (VCA) in humanitarian aid supply chain to enhance the efficiency and effectiveness of disaster relief operations.	Value Chain Analysis (VCA)
This study	Disaster relief operations management through lean transformation	Evaluation of possibility of lean tools for developing resilience in disaster relief operations management is carried out. The lean tools improve operational efficiency and effectiveness aiming for sustainable practices in activities.	SIPOC Analysis, Value Stream Mapping (VSM), Root Cause Analysis, Key Performance Indicators (KPIs), Plan-Do-Check-Act (PDCA)

Multiple organizations are involved in relief activities; therefore, an efficient collaboration among the stakeholders is necessary to move relief items optimally from supplier's locations to disaster demand locations (Medel et al. 2020). Moreover, coordination, communication, and involvement of humanitarian organizations in the preparedness and response phase are also of great significance in decision-making process (Galindo and Batta 2013; Kaynak and Tuğer 2014; Cozzolino 2012). Furthermore, participation of multiple stakeholders under proactive state leadership is important in the management of humanitarian relief activities. Masood et al. (2017) presented a disaster supply network operation map for earthquakes and floods and presented top five urgent needs in case of such disasters: evacuation machinery, communication devices, bottled water, food / energy biscuits, and medicines (and medical care). The role of multiple stakeholders from commercial and humanitarian organizations in disaster relief supply activities makes it complex process.

According to varying severity and impact of disasters, different strategies are required to reduce the impact through efficient supply of relief supply items (Kaynak and Tuğer 2014; Waters 2011; Papadopoulos, Gunasekaran et al. 2017). Consequently, transportation is the most important element of humanitarian supply chains and DROs that significantly depend. Delivery delays, market instabilities, loss of shipments, goods decay, inadequate capacity, lack of information and ethical anxieties considered to be the most important transportation risks in humanitarian supply chains (Jahre et al. 2007; Cozzolino 2012).

2.1 Disaster resilience

The concept of resilience has been discussed in different domains like engineering, psychology, management and social sciences where broader meanings of the concept are similar however values vary from application to application and context to context (Paton and Johnston 2006; Cutter et al. 2008; Lee et al. 2013; Martin-Breen and Anderies 2011; Paton 2006; Masood et al. 2016). For understanding the meanings of resilience in a given context, it is highly important to define resilience by whom and resilience to what. The concept of resilience is defined as interventions goal towards reducing and mitigating the risk of displacement and increasing the ability of a system to resist relief operations causalities, accommodate fluctuations, adapt to changing requirements, and facilitate affected ones in a timely and efficient manner, incorporating the preservation activities of the system.

The literature has reported on resilience in the contexts of organizations, systems, economics, and communities. In recent years, organizational and community resilience to disasters has been discussed in the literature. Organizations and communities are linked in a system where resilient organizations help in improving preparedness of communities to disaster response and maintaining business continuity in a better way (McManus et al. 2008; Moore and Lakha 2006; Sawalha 2015). Importantly, the Sendai Framework for Disaster Risk Reduction (SFDRR) 2015-2030 emphasises the need for joint efforts for reducing disaster risks and improving resilience capability at all levels from both public and private organizations (Aitsi-Selmi et al. 2015).

Resilience in disaster operations management can be achieved by adaptive capacity building of resources, involvement and coordination of all the stakeholders at each level of relief processes and a collaborative exchange of innovative ideas between respective organizations and social community jointly (Brown et al. 2017; Ye 2011; Craighead et al. 2007). Disaster operations management in the context of managing relief activities covers a wide range of stakeholders from public and private sector organizations along with humanitarian organizations. Resilience in disaster relief activities need considerations in different areas like supply networks, healthcare organizations especially emergency departments, availability of resources like evacuation machinery, humanitarian organizations, community etc. at mitigation, preparedness, response, and recovery stages.

For example, Barroso et al. (2010) and Carvalho et al. (2012) discussed the involvement and then actions taken by multiple stakeholders in the context of supply networks during natural and man-made incidents (intentionally or accidentally). This highlights the need to understand the apparent and underlying causes of interruptions so that appropriate actions could be taken for enhancing the resilience capability of DROs. The need for investigating the causes of delays and then developing action plans to eliminate undesirable effects for achieving supply network resilience in disaster operations has been emphasized. It has been concluded that the implementation of appropriate measures against delays could help supply chains to rapidly return to their original state or even in the improved state (Tofighi et al. 2016; Ransikarbum and Mason 2016a; Ransikarbum and Mason 2016b). Traditional risk management strategies cannot effectively respond to unforeseen events like disasters, but resilient supply chains can address the issues by developing strategic plans that are viable in changing circumstances and can respond effectively (Keating and Hanger-Kopp 2020; Prasad et al. 2019; Rajesh 2018; Rajesh 2020; Tiernan et al. 2019). Appropriate design and implementation of mitigation and contingency plans could help in reducing the negative impacts caused due to unwanted delays in supply networks as mitigation deals with the preparedness at the pre-disaster phase and contingency techniques put focus on supply chain readiness at the post-disaster phase. Both these help in enhancing the capacity of resources to respond efficiently against disturbances (Chowdhury and Quaddus 2017; Sharma and Srivastava 2016; Dubey et al. 2021).

Similarly, the need for achieving better response prior to, during and after the disasters through improved robust communication and coordination mechanisms among the stakeholders has been emphasized (Dubey et al. 2020; Timperio et al. 2016; Sharma and Srivastava 2016; Chen et al. 2019). Hence, the development of a resilient environment against disasters for responding to identified and unidentified risks during multiple stages is linked with the capacity building, appropriate training of the stakeholders involved, effective communication and coordination with clearly defined roles and missions among the stakeholders like donors, rescue organizations, government agencies, suppliers of relief goods and local community (Rajesh 2020; Tiernan et al. 2019; Altay et al. 2018; Chen et al. 2019; Papadopoulos et al. 2017).

Mohamed (2008) defined technological disaster as an occurrence of emission, fire or explosion resultant of uncontrolled developments in industrial settings which leads to serious danger to mankind, environment, and structures. Technological disaster management scenarios usually deal with dynamic environments and varying requirements for relief operations. During one of the categories of disasters, urban and industrial fires cause serious challenges in terms of relief operations for smoke detection and tracking of persons (Capitan et al. 2007). The situation causes harmful conditions such as loss of the visibility which requires superior degree of relief team cooperation, coordination and communication. Skarbek (2014) examined bottom-up strategies for coordination during relief activities. In this strategy, individuals from the location where fire accident happened enforce and govern disaster relief for their own community. However, this also affects the hospital's disaster resilience capability to plan effectively for medical services as healthcare resilience directly reduces the impact of disasters and helps in achieving community resilience (Aitsi-Selmi et al. 2015; Chen et al. 2019; Bentley et al. 2008). Similarly, hospital disaster resilience concluded by Zhong et al. are related to mainly related to emergency critical care capabilities that include urgent medical treatment, surge capacity, on-site rescue operations, referring of the patients with complex needs and ability to manage emergency medical treatment at mass scale. Moreover, hospital resilience capability can be improved through developing flexible plans, co-operation, and coordination with other facilities, prioritizing and maintaining critical healthcare functions and strategies to meet resources, medications, and skilled staff (Zhong et al. 2015).

2.2 Lean Transformation in DROs

The concept of Lean Manufacturing was developed to meet global competitiveness challenges, especially when considering cost and quality in combination with customer satisfaction, operations sustainability, and responsiveness by reducing wastes. Lean production philosophy helps in achieving higher organizational competitiveness through reducing inventories and lead times (Upadhyay et al. 2020; Ivanov 2021). It has been proposed that practitioners could take benefit by transforming their organizational performance through well-integrated and sustainable lean practices (Keating and Hanger-Kopp 2020).

The objective is to achieve resilience in DROs in attached with multiple factors like community, stakeholders, supply networks, financing, capacity planning, contingency plans, communication and coordination, healthcare organizations etc. Lean transformation of different operations helps in achieving resilience of DROs by using different lean tools and techniques. Upadhyay et al. (2020) recommended that operations management scholars should pay attention to explore the possibility of the use of operational excellence techniques such as Lean, Six Sigma and Value-Stream Maps (VSM) for making DROs more cost-effective and responsive. For example, mapping of supply chain operations in enterprise settings is common as these improve the coordination and collaboration among different stakeholders and the same can be used against the stakeholders involved in different phases of DROs (Jahre et al. 2007; Upadhyay et al. 2020).

It has been observed that a significant portion of relief resources are not efficiently used due to the replication of efforts, improper system analysis and lack of the use of operational excellence drivers in humanitarian operations (Jahre et al. 2007; Tiernan et al. 2019; Dubey et al. 2020). Logistics aspects of disasters have been discussed in the literature in the perspective of effective delivery of relief goods to the victims (Luis et al. 2012). Lean, six sigma and value stream mapping, cause and effect diagram etc. are among those techniques that have been frequently used for organizational supply chain performance evaluation. These help in achieving improvements by eliminating non-value-added activities and variations in quality while improving effectiveness of the system at operational level (Farooq et al. 2021; Fernández Campos et al. 2019).

Regarding the response time of disaster relief activities, it has been found that non-value-added times including traffic blocking, inappropriate ambulance base locations, inefficient routings, and unavailability of ambulances for attending emergency calls can increase the response time. Whereas exclusion of waste or any kind of non-value-added activities that can affect the performance of a system is considered as an essential aspect of a lean system. For example, supply chain mapping helps in decision making by identifying key bottlenecks and taking decisions for eliminating non-value-added activities (Tofighi et al. 2016; Keating and Hanger-Kopp 2020; Rajesh 2018; Luis et al. 2012). Similarly, the resilience capability of healthcare organizations can be improved by using lean methodologies, where two waste elimination frameworks have been proposed by (Bentley et al. 2008).

Paramedic distribution location has been identified as an important aspect for emergency medical relief operations where emerging lean transportation approach for improving the performance of emergency medical services through identifying wastes at the system level has been found useful. Enterprise modelling and simulation methodologies have been popular in support of methods based engineering, particularly lean implementation (Zhen et al. 2009; Wahid et al. 2008). Recently, Garza-Reyes et al. (2019) proposed and validated the Lean-TOC (Theory of Constraint) approach and found that it's an effective alternative to simulation, mathematical modelling and operations research methods to improve emergency medical services. Conclusively, resilience capability of the system can be enhanced through lean transformation; however, the use of lean tools and techniques for enhancing disaster relief operations' resilience has not been explored yet.

2.3 Research Gap and Research Highlights

The objective of achieving resilience in DROs is quite challenging because of the complexities caused due to many uncertainties. DROPS resilience capability is linked with many critical factors like cooperation and communication among the stakeholders, community awareness, optimal utilization of resources, capacity building and preparedness, efficient and timely delivery of relief goods to the victims, contingency plans, healthcare resilience financing etc. Previously attempts have been made to improve the performance of DROs through mathematical modelling, operations research, and simulation methods. It is evident from the literature that transformation of operations by using different lean tools and techniques is an effective way to identify different kinds of wastes, non-value-added activities that cause delays, and devising strategies to achieve responsiveness of the system, which is ultimately linked with resilience capability of the system. However, its evidence for achieving resilience of DROs context is missing in the literature. There is a need to explore the possibility of using different lean tools and techniques for achieving DROs resilience.

The overall aim of the initiative is to explore the overarching question of ***"how can resilience be designed in DROs using lean tools?"***. In this context, the following research objectives (RO) have been set so that the concept of resilience by using different lean tools and techniques could be understood in a better way:

RO_1 Identify key DROs,
RO_2 Develop Value Steam Maps for exiting DROs,
RO_3 Investigate key causes of disruptions during relief activities, and
RO_4 Develop 'to be' scenarios by using lean tools and quantify the impact of suggested interventions.

The above-mentioned objectives will help in identifying existing DROs practices, causes of disruptions and delays negatively affecting the resilience of the operations by using appropriate lean tools and finally how these tools could help in improving the resilience capability by eliminating delays and winning responsiveness. Previously lean tools and techniques have been used for enterprise settings and their evidence in DROs' management perspective is missing because of the uncertain and dynamic nature of disaster scenarios. Whereas this work provides a well-structured and systematic lean based approach to investigate the performance of existing relief operations' and this can be improved for achieving resilience.

3. Research Methodology

As mentioned earlier, the research presented in this article was motivated by the EPSRC GCRF funded DROPS project of the University of Cambridge (Masood, So, and McFarlane 2017). Four annual DROPS workshops were conducted during 2016-2019. As part of the DROPS programme, the first 5-day international DROPS workshop was held at the University of Cambridge (2016) in which a mechanism for idea generation, review and control was formulated. The DROPS-2016 workshop included operations and disaster management experts from all over the world who discussed challenges and possible reforms across disasters portfolio concerning resilience for DMOs, with a particular focus on South Asia. Especially, experts from Pakistan, India, Bangladesh, and Sri Lanka with diverse expertise broadly in operations management, humanitarian logistics, big data analytics and financial management of DROs were invited. Key findings of DROPS-1 are reported in terms of operations map, DROPS framework, and requirements of big data in the face of disasters (Masood et al. 2017).

One of the key contributions from the workshop was the development of the DROPS framework - a systematic approach to resilience for supply networks in DMOs. The proposed DROPS framework identifies five key considerations for achieving resilient supply networks for DMOs across the disaster management cycle (response-recovery-mitigation-preparedness). These are: analyse requirements, analyse current disaster relief practices, analyse DROPS considerations, analyse DROPS strategies and finally contextualizing DROPS model (Masood et al. 2017). Another key contribution from the workshop was to develop a mechanism for idea generation, control, and review for conducting research aiming at how resilience can be designed in disaster management operations so that the impact of disasters could be minimized.

In continuation of the DROPS initiative, a one-day workshop was conducted at Lahore, Pakistan (2017) where local stakeholders like RESCUE 1122 of Punjab province, National Disaster Management Authority of Pakistan (NDMA), management of local hospitals and researchers from the universities were engaged. The focus of this DROPS-2017 workshop was to develop case studies to understand DROs' phenomenon through empirical evidence by involving key stakeholders. One of the major research areas selected for this purpose was to conduct some case studies on the lean transformation of DROs in the context of resilience. Similarly, research progress was reviewed during DROPS-2018 and DROPS-2019 workshops organized at the University of Cambridge in 2018 and 2019 respectively. Moreover, during this time, engagement with other stakeholders like local hospitals, donor agencies and volunteer organizations has been established. Figure 1 presents the methodology of this particular research including its relationship with DROPS framework, where a five-step approach has been used to achieve the desired objectives.

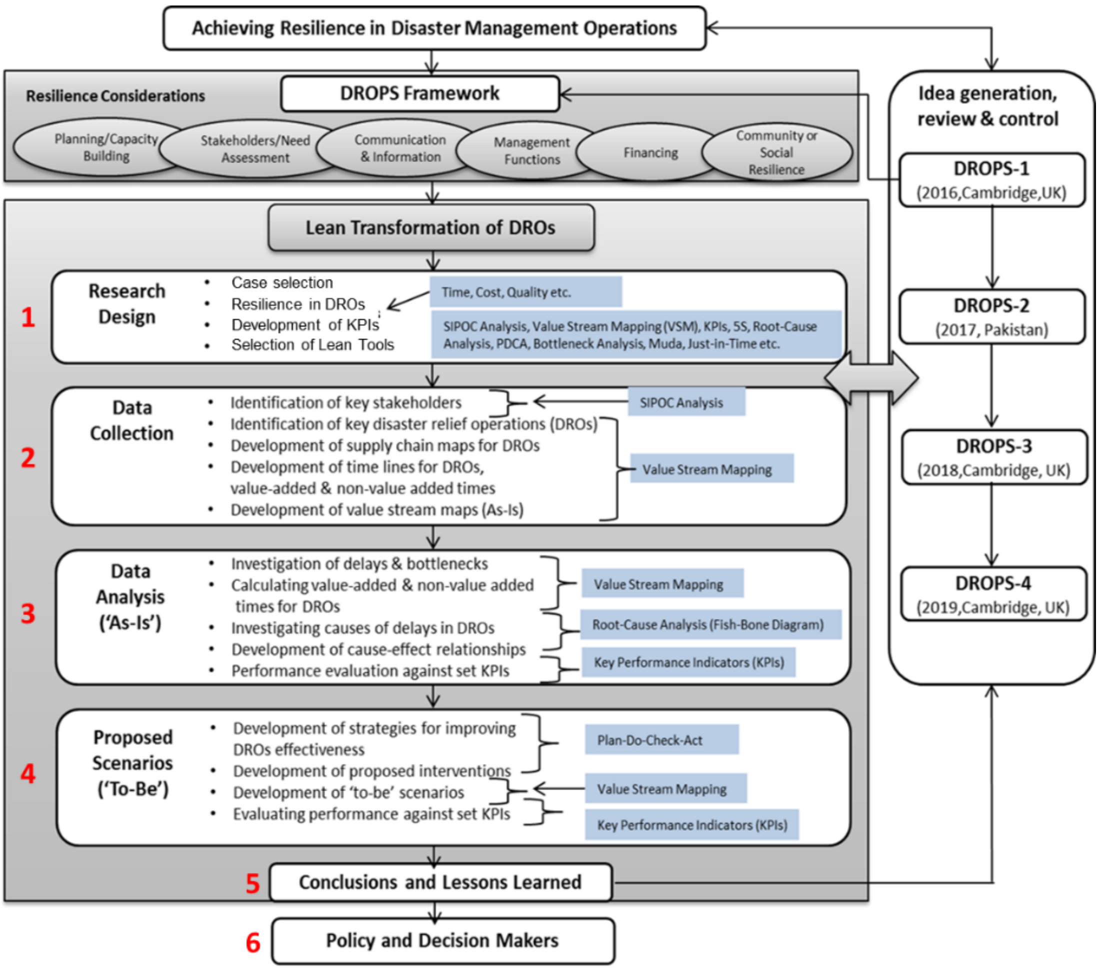

Figure 1: Research Methodology.

3.1 Research Design

Research design is discussed in the following, and presented in Figure 1.

3.1.1 Case Selection

Because of the complexity of the problem caused due to a variety of disaster scenarios, varying needs, diverse stakeholders and uncertainties, the case study method has been adopted so that case-based assessments could be carried out. However, one of the gaps identified in the literature is the lack of empirical evidence of real disaster situations (Gupta et al. 2016). In this way, case-based investigations of real disaster situations help in getting deeper insights into dynamics present in single settings. Therefore, in this research, case-based method was employed for evidence collection (quantitative and qualitative).

As per guidelines by (Childe 2011; Eisenhardt 1989), case selection should be made carefully so that the challenges faced in achieving DROs' resilience could be emphasized. For example, one of the challenges being highlighted is the involvement of multiple stakeholders where effective coordination and communication is required to make relief operations resilient. One of the key criteria for case selection might be the involvement of multiple stakeholders (Fernández Campos et al. 2019). Similarly, another important aspect linked with the resilience capability of relief operations is community resilience, which covers victims of the disaster, rescue workers, personnel of volunteer organizations; in general, any type of human resource involved directly or indirectly. In this respect, the case should have the role of community (personnel). Similarly, other important aspects like capacity planning, the impact of the disaster, communication, involvement of healthcare organizations etc. could be the deciding factors for case selection.

3.1.2 Resilience in DROs

The conventional understanding of DROs management has been around design-for-service, and responsiveness against absorptive, adaptive, and restorative strategies. The resilience in DROs is an outcome as well as a process. As an outcome, practices tend to adopt reactive approach to support operations during chaotic environment of the disaster. However, as a process it focuses to support capacity building of organizations, and communities to minimize non-value-added practices. It further builds absorptive capacity (ability of a system to adsorb disruptive event), adaptive capacity (ability to adapt event), and restorative capacity (ability of a system to recover) (Zhong et al. 2015; Ivanov 2021; Hosseini et al. 2019; Ye 2011). The focus on restorative capacity is focused herein to support relief operations to restore system. However, the efficient relief operations are governed by lean and agile principles. The prime goal behind these agile and lean operations is to improve relief activities at possibly superior degree to avoid delays and casualties, and maximize service (Garza-Reyes et al. 2019). Nevertheless, resilience in DROs, undertakes the resilient operations' chain, is formulated to strategize relief operations for unanticipated, severe disturbances caused by natural disasters, strikes or epidemic outbreaks, and fires at facilities. Recently, (Kusiak 2020) anticipated the design-for-resilience perspective for the mitigation of disaster impacts through redundant resources (capacity buffers, back-up systems and inventories).

Operational resilience is mainly dominated by following resilience capabilities to recover affected system to a stable or better state. These capabilities include (i) redundancies (high buffer inventories to reduce risk, backup supplies, and transportation infrastructure); (ii) real-time data-driven efficient systems; (iii) flexible and contingency strategies. Introducing buffer capacities, high-level of inventory pre-positioning or multiple sourcing incurs huge costs which directly conflicts the goal of lean (cost efficiency) (Ivanov 2021). However, current study attempts to develop resilience in DROs following points (ii and iii) as described earlier. The research fosters resilient DROs through lean transformation tools and techniques.

It is established from literature, responsiveness is a typical measure to analyse both business and humanitarian supply chains although it could also be considered as a resilience measure (Chowdhury and Quaddus 2017; Hosseini et al. 2019). The resilience is introduced through improving the efficiency of the system in terms of responsiveness, and strategizing response plans by identifying system's failure root causes. This is because, in conventional approach to disaster management, the disaster relief teams (at least in the reported literature) failed to realize the survivors' needs or they were far from reality after reaching the affected areas in time (Sebatli et al. 2017; Papadopoulos et al. 2017; Upadhyay et al. 2020). Therefore, lean transformation helps to remove redundant activities, thus results into minimal casualties and reducing the impact of disaster. Consequently, the resilience of the system improves through enhanced effectiveness of relief operations.

Lean transformation could help to understand different stakeholders, their roles, and services so that efficient and robust mechanisms, strategies, and procedures could be developed. Also, its systematic approach, identifies causes of delays encountered due to disruptions. As a result, it could help in devising strategies for the smooth and uninterrupted of relief activities. Like in enterprise systems, lean could enhance relief operations' resilience by eliminating non-value-added activities.

3.1.3 Development of KPIs

The key performance indicators are the measurable values that show the effectiveness of systems' performance against the business goals. Every defined KPI should be linked with the outcomes so that its achievement could be linked with the performance. Very commonly used KPIs like time, cost, quality, cycle time, employees' turnover, profit, production, lead time, customer satisfaction, availability etc. However, for measuring the performance of disaster relief activities, 'time' is the most critical performance indicator that is directly linked with resilience. Financing has been discussed as an important aspect so 'cost' might also be considered. Moreover, as the risk of the loss of human lives is there so the quality of relief services could be an area of interest. In the case described below, 'Time' has been taken as KPI to measure the performance of DROs. Besides, the utilitarian policy is incorporated in DROs ensuring the facilitation of aids on the principle of equality for all affected people (Luis et al. 2012; Ransikarbum and Mason 2016b). The selection of 'Time' as a key performance indicator is as a discrete measurement to monitor and evaluate coordination, and efficiency of DROs. Moreover, the metric helps to enhance responsiveness and to update relief strategies without compromising on the wellbeing of people (Luis et al. 2012; Ransikarbum and Mason 2016a; Tofighi et al. 2016).

3.1.4 Selection of Lean Tools

Analysing the situation at different stages of the DROs is important. As this work intended to use lean tools for the said purpose, so it was important to investigate the scope of different available lean tools. Many researchers conclude the most frequently used lean tools and techniques sometimes also called quality management tools (Negrão et al. 2017; Curry and Kadasah 2002; Antony et al. 2005; Ivanov 2021), include Pareto Histograms, Fishbone diagrams, Process flow charts, SIPOC analysis, Plan-Do-Check-Act (PDCA), VSM, failure mode and effect analysis (FMEA), Gantt Charts, quality function deployment (QFD), statistical process control, trend analysis, and brainstorming. Keeping in view the objectives of this study in the light of the suitability of tools, following lean tools were selected for this study: SIPOC Analysis, Fishbone Diagram, PDCA, KPIs and VSM. Table 2 provides characteristics of these lean tools and their relevance to developing resilience in DROs. Table 2 also explains in detail how selected lean tools could help in investigating causes of delays, identification of important stakeholders, the relationship among the causes and effects and how to design, implement and evaluate the effectiveness of interventions, regarding the promotion of DROs' resilience. Implementation of lean philosophy has been concluded as a useful technique for performance improvement (Negrão et al. 2017). Figure 1 (research methodology) further explains the relationship of the selected lean tools with the expected outcomes of this research.

Table 2: Selected lean tools - Characteristics and relevance to DRO resilience.

Lean Tools	Characteristics of the Lean Tools	Relevance of the Lean Tools to DRO Resilience
SIPOC Analysis	It states that all organizations are built by five interactive components i.e., Suppliers, Inputs, Processes, Outputs, and Customers. It outlines an organization's business processes; identifies the constraints between upstream and downstream sectors; balances the information and material flow (Mishra and Sharma 2014).	• Multiple stakeholders are involved in performing disaster relief activities where they provide diverse kinds of products and services to the affected community. • It is important to understand different stakeholders, their roles, and services so that efficient and robust mechanisms, strategies, and procedures could be developed. • In this respect, for achieving resilience, SIPOC analysis could be a basic tool that could help in designing resilient communication and coordination mechanisms among the stakeholders. This could help by answering the following questions: o Who were the key disaster relief suppliers? o What kind of relief inputs were supplied by different stakeholders? o Which activities were carried out during the DRO? o What was the output of relief activities? o Who was the customer?
Fishbone Diagram	It identifies the different types of possible causes that have led to a specific problem or effect. Fishbone Diagram visualizes relationships between causes and effects and visualizes dependent relationships (Radej et al. 2017).	• Fishbone Diagram could help in developing a relationship among the causes of delays and disruptions and their possible causes during relief operations. • Right assessment of delays caused due to disruptions could help in devising strategies for the removal of causes; this will lead towards the execution of smooth and uninterrupted relief activities.
PDCA	Plan-Do-Check-Act is an iterative process that allows pursuing	• PDCA is a continuous improvement based iterative process that could be used to monitor

Lean Tools	Characteristics of the Lean Tools	Relevance of the Lean Tools to DRO Resilience
	continuous improvements while achieving end goals. It's widely applied in diverse nature of areas (Radej et al. 2017).	performance achievement against set KPIs continuously. • The cyclic process could help in monitoring the performance of relief activities and the effectiveness of implemented interventions, designed for achieving resilience.
KPIs (Performance Measurement)	KPIs could be used for performance evaluation and monitoring against given criteria (Herron and Hicks 2008). These are critical for improving the efficiency and effectiveness of existing processes and methods (Gunasekaran et al. 2004; Beamon 1999).	• Time, cost, and quality are important KPIs for benchmarking the performance of disaster relief activities. The resilience capacity of existing systems could be evaluated and monitored through well-defined KPIs. • In case of a disaster, timely response (response time) of humanitarian, public and private organizations could be one of the resilience criteria used to measure and monitor the resilience capability of related organizations.
Value Stream Mapping (VSM)	VSMs visualize productive resources, their use and inherent wastes (non-value added activities) (Tapping 2002). These quantify production time and identify opportunities for improvement. These are visual and allow quick assessment of processes.	• Like enterprise systems, DROs' resilience capability could be enhanced by eliminating non-value-added activities. • VSMs of relief activities could help in finding the total time of the activities and how much time is being wasted, which stakeholder is involved in that and how overall activity time could be reduced to a minimum. As these are visual so these could allow visualizing the impact of proposed interventions.

3.2 Data Collection

Data collection was done through interviews with the stakeholders, datasheets, records, and physical observations. Industrial representatives of respective departments for example HSE, production, inventory, and rescue operators (in-house and external) were accessed for this purpose. Data collection was done for the identification of key stakeholders involved in relief activities, determination of key DROs and development of VSMs for visualizing the timelines of DROs and finally identification of value-added and non-value-added activities. Importantly there is a need to understand which lean tool is being deployed and what important information is required for the analysis purpose. In this respect, the above-mentioned information is linked with the use of SIPOC analysis and VSMs.

3.3 Data Analysis ('As-Is')

The role of multiple stakeholders in different relief activities in terms of information flow, coordination, providing relief goods and services could be visualized on VSMs. Non-value-added times help in identifying bottlenecks and causes of delays and their effects, respectively. Performance measurement in terms of time, cost and quality of relief services could be benchmarked. Different lean tools like VSMs, Fish-Bone Diagrams and KPIs would help in developing 'As-Is' scenarios. The analysis, with the help of these tools, would help in devising strategies and methods to eliminate causes of delays throughout the cycle.

3.4 Proposed Scenarios ('To-Be')

The proposed 'To-Be' scenarios could be developed by incorporating the impact of suggested interventions. These will help in visualizing the impact in terms of reduction in time loss and quality of relief services. Comparative analysis between existing practices and proposed interventions could be made visible through these lean tools. Making improvements is a cyclic process based on the 'Plan-Do-Check-Act' cycle where goals for further improvements could be set for the next cycle.

3.5 Conclusions and Lessons Learned

Findings in terms of the causes of delays in relief activities, roles, and activities of performed by different stakeholders, communication and coordination mechanisms, capacity building, training requirements of rescue workers, community resilience etc. would help in developing knowledge in the form of lessons learned in each case. Varying types of disasters might be bringing up entirely different challenges and strategies to achieve resilience of relief activities.

3.6 Policy and Decision Makers

Conclusions and key lessons learned from the set of case studies are linked with an idea generation, control, and review mechanism where practitioners, researchers, planners and policymakers would be engaged through workshops, seminars and conferences. This would help in developing ideas to meet upcoming challenges, devising strategies to overcome those and sharing key findings with others through publishing the work. Section 4 describes an industrial fire case study where investigations have been made on how the above-explained methodology help in achieving DROs' resilience by deploying different lean tools.

4. DRO Case Study – A Factory Fire in Pakistan

The technological disaster is categorized as man-made disaster caused because of malfunction of technological system/structure or human errors in managing the technology. In this category, an empirical study was developed where disaster response to a factory fire was studied. 'XYZ' is a well-reputed export-based tyres and tubes manufacturing company located near Lahore, Pakistan. XYZ also deals with oil lubricants, rubbers, and automobile spare parts. It operates in Asia, Middle East, Africa, and Europe. It has more than 3,000 employees.

Case study incident: In January 2017; the company planned to build the inventory stock of finished goods and hence raw materials were purchased and stored as per the requirement. Due to the shortage of space, finished goods and raw materials were stacked in an open area. The main storage area was under an 11KV electric supply line and accidentally spark was generated due to a short circuit and the materials underneath caught fire. Raw materials including butyl rubber and finished products like tyres caught fire very quickly.

Different stakeholders like in-house workers, rescue professionals and rescue teams of nearby industries got involved in the DRO very quickly. The affected area was almost 800-metre away from the main entrance/exit gate and there was no other direct access to the affected area. Due to the improper layout design of the area, accessibility became a real challenge for firefighting teams, especially for those who were approaching from outside the factory. The orientation of the affected area with reference to rescue teams A, B, C and D is as 6, 3, 1 and 0.5 km away respectively. Three rescue teams approached the location from the other side of the road which was quite busy as it was the link between two main cities, Lahore (11.13 million population) and City X (more than 3 million population).

5. Results and Analysis

This section describes the results of the case study in detail. This contains SIPOC analysis of the case with details of involved suppliers, inputs, processes, outputs, and customers; causes of delays in relief operations and effects of the delays, VSMSs of relief operations, proposed scenarios, and the impact of interventions in the form of a reduction in overall relief operations' time.

5.1 Key DROs and SIPOC Analysis

The following DROs were undertaken for the case study incident:

DRO1 – Sharing information about the fire incident.

DRO2 – Shifting of resources (fire extinguishing equipment, water etc.)

DRO3 – Removal of unaffected material from the affected area

DRO4 – Fire extinguishing

Table 3 shows the results of SIPOC analysis where we can see that there two types of suppliers: in-house and external (K, L, M and N). Relief operations' inputs, processes, outputs, and customers are shown.

Table 3: Case study results: SIPOC analysis

Suppliers	Inputs	Processes	Outputs	Customer
1. In-house i) Production Team ii) HSE Department iii) Powerhouse **2. Supplier K** **3. Supplier L** **4. Supplier M** **5. Supplier N**	Water carrying vehicles, Fire extinguishers, Sand, Drinking water, Firefighters, Personnel from other departments like production, HSE & Powerhouse.	1. Flow of information 2. Shifting of resources 3. Shifting of unaffected material towards a safe area 4. Extinguishing fire	Relief services resulting in personnel rescue, fire stoppage and material savage	Fire spot (storage area)

Rescue activities performed by different stakeholders were identified along with their time durations (percentage of total time), as presented in Table 4. Symbols P, H, PH, K, L, M and N show relief activities being performed by the Production Team, HSE, Powerhouse, and by the rescue teams provided by external stakeholders A, B, C and D respectively.

Table 4: DROs performed by internal and external stakeholders.

Stakeholders		Designated Activity Symbol	Relief Operations (RO)	Duration (% age of total time)
In-house	Production Team	P1	Information flow to HSE & Powerhouse (through telephone, internal) about the occurrence of the fire accident.	0.51%
		P2	Informing of fire incident to stakeholder K (external).	0.41%
		P3	The arrival of workers at the affected area (from the production floor)	0.41%
		P4	Moving unaffected material (not exposed to fire) to the safe area	15.27%
		P5	Shifting of water, sand & fire extinguishers (present within the department) at the fire spot by workers	1.02%
		P6	Extinguishing the fire	18.84%
	Health, Safety & Environmental Department	H1	Transformation of information about fire incident to top management and other departments through telephone.	0.81%
		H2	Bringing workers out of their working areas	1.53%
		H3	Shifting of fire quenching instruments at the fire spot	2.04%
	Powerhouse	PH1	Shutting down power supplies	0.20%
		PH2	Informing senior staff through telephone about the fire incident	0.51%
External	**K**	K1	The arrival of the Rescue1122 team	0.51%
		K2	Showering of water through showers which were connected with water carrying vehicles.	17.31%
		K3	Spraying of CO_2	2.55%
	L	L1	The arrival of stakeholder L's team	0.51%
		L2	Quenching fire	1.93%
		L3	Providing guidelines to workers on how to remove unaffected material	1.53%
	M	M1	Providing high-pressure water supply	12.73%
		M2	Providing water carrying vehicles for quenching fire	10.69%
	N	N1	Providing drinking water to the workers	10.69%

5.2 Delays during relief operations

To find disruptions causing a delay in relief operations, stakeholder's records were explored, and professionals involved in relief operations were interviewed. Stakeholder 'A' (a government rescue organization) was found responsible for performing rescue operations throughout the province. It was found that during rescue activity (K1), there was a delay in response due to role ambiguity caused due to miscommunication and lack of coordination among the stakeholders. During interviews, it was found that the major reason for the delay was the confusion about whether the location (affected area) would be dealt with by the team that was called upon or another team. As mentioned, that 'A' operates throughout the province but with different regional remits. Furthermore, the arrival of team 'A' at the affected area also took some extra time because of traffic disruptions on the road. XYZ's layout was not properly designed to counter such emergencies, which also created problems during rescue operations. The burning of volatile compounds and petrochemicals raised surrounding temperature very high that interrupted the operations and exhausted workers. Another reason for the delay in rescue operations was the unavailability of water due to the lack of capacity and planning as the water brought at the first instance was insufficient.

Table 5: Disruptions during DROs

Sr. No.	Designated symbol	Causes of Disruptions	Description	Time (% of total disruption time)
1	D1	Lack of coordination	Delay in response by ‘A’ because of role clarity and lack of communication	14.13%
2	D2	Unavailability of emergency alarms	Delay in information sharing with other departments within the factory	5.43%
3	D3	Hurdles on roads	Unclear roads (A’s Vehicles)	5.43%
4	D4	Lack of preparedness	Preparedness issue (making ready for the relief operation)	5.43%
5	D5	Lack of mitigation strategy	Shortage of water	16.30%
6	D6	Exposure to heat & smoke	Fire exposure caused smoke; temperature rise etc.	9.78%
7	D7	Exertion of workers due to heat	Reduced performance of workers due to D6	10.87%
8	D8	Inaccessibility	Inaccessibility to the affected area	5.43%
9	D9	Unavailability of resources	Unavailability of required resources like water pipes etc.	16.30%
10	D10	Insufficient resources	Insufficient resources (mismatch between the demand and supply)	10.87%

5.3 Performance Evaluation of DROs through Value Stream Mapping (VSM- ‘As-Is’)

A Value-stream map (Figure 2) of DROs has been developed, showing key stakeholders involved in the relief operations and disruptions involved. This demonstrates the flow of information, objects’ flow and processes flow. Green arrows in the map show the direction of relief supplies from different stakeholders towards the affected area. Disruptions (D) involved during relief supplies have been highlighted with red coloured boxes. DRO represents DRO; D shows Disruptions involved in relief operations; R is the relief activity performed by the stakeholder A; P is the relief activity performed by production team; H is the relief activity performed by Health Safety and Environment Department; PH demonstrates the relief activity performed by powerhouse; K1-3 are the Relief activities performed by stakeholder K; L1-3 are the relief activities performed by stakeholder L and similarly by M and N.

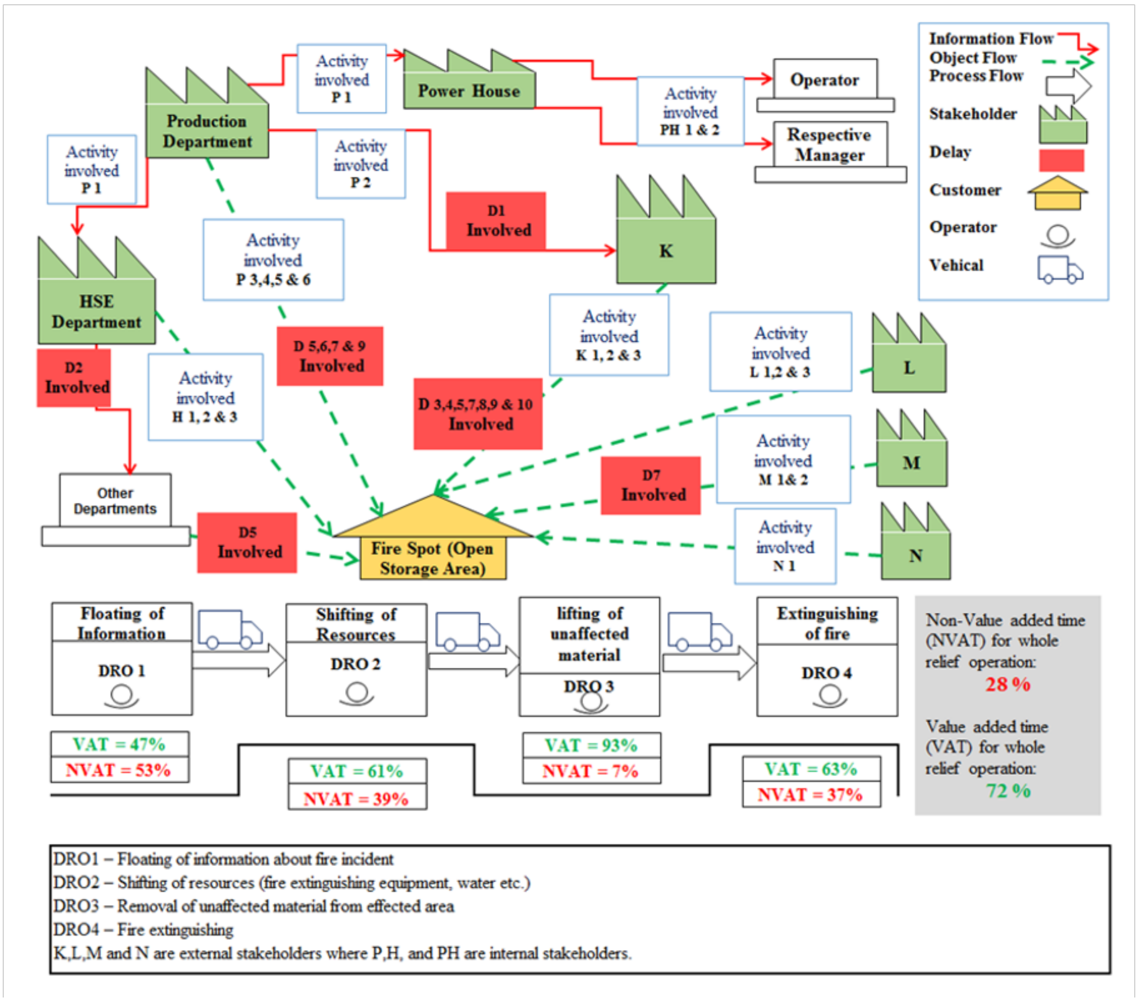

Figure 2: Value Stream Map of DROs showing detailed activities and disruptions (as-is)

As shown in Figure 2, at the first instance, information about the incident was shared from the production department with the HSE department and powerhouse (activity P1) and external stakeholder 'K' (Rescue 1122) (activity P2). Immediately, the HSE department shared the information with other departments (activity H1), started taking the workers out of the building (H2) and shifted fire extinguishing material at the affected area (H3). As long as the information shared with the powerhouse, they responded by shutting down the power supplies (activity PH1 and PH2). It was noticed that because of the inadequate level of training, operators took a lot of time to plan and then start the activity. After some time, team K arrived and started working in coordination with local teams. However, external stakeholders L, M and N noticed the smoke when the incident was telecasted on a local news channel. All other details of the activities are shown in Figure 2.

Total value-added time has been found as 72% whereas 28% of the total time has been noted as the non-value-added time that has been wasted because of several reasons. It is clear from Figures 1 and 2 that there are several reasons for disruptions during relief operations. Details of relief operations and respective disruptions and their percentage contributions in the total non-value-added time are shown in Table 5. This is visible from the data shown in Figures 1 and 2 that a significant amount of time is wasted because of the lack of coordination, communication, mitigation strategy, planning and training of the workers. In this respect, the resilience capability of relief operations is mainly compromised because of these factors; whereas communication and coordination among the stakeholders might be considered as very important aspect (bottleneck activity) as all other relief activities start after this.

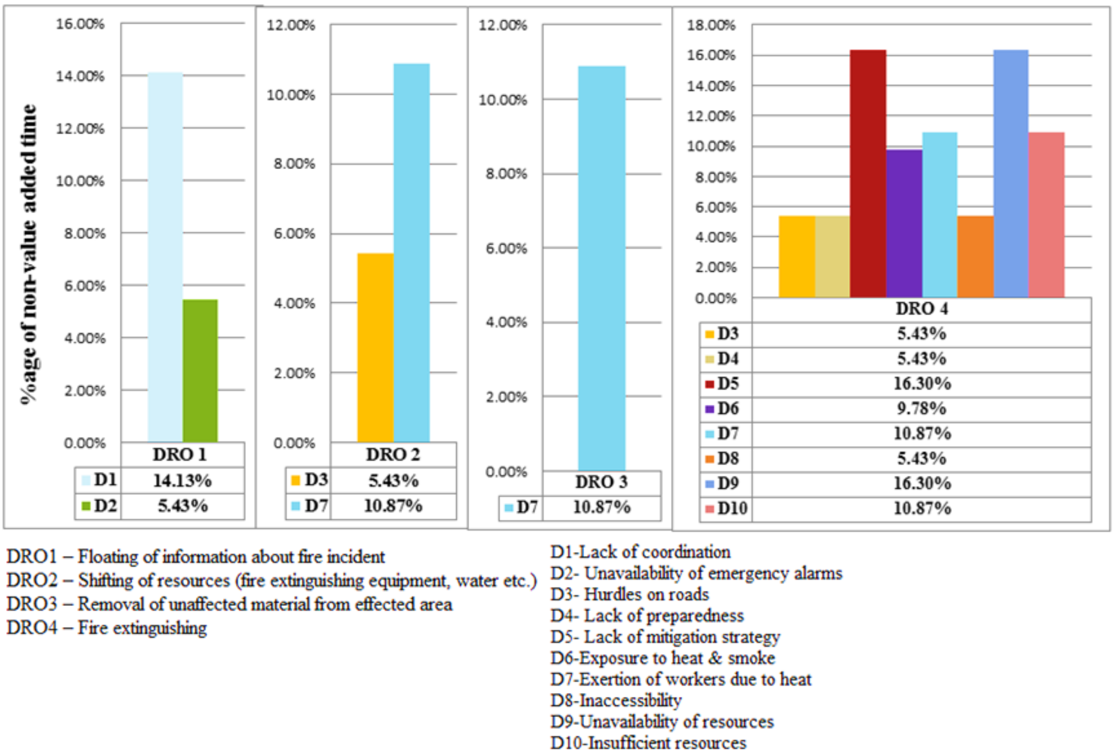

Figure 3: Percentage of non-value-added times during DROs.

5.4 Cause and Effect Relationship

Causes of disruptions in relief operations in combination with their respective effects could be developed through the fish-bone diagram. This systematic incident investigation approach provides opportunities to capture a deeper insight into the processes, possible causes of issues and their impacts on performance indicators. The potential primary causes resulting in the delay in DROs are categorized through brainstorming session of experts and stake-holder representatives. It helps to probe the problem iteratively to explore multiple "whys" until the root cause is found. Previously, this tool has been successfully used against several industrial applications especially in production-related applications where the main objective has been to reduce cost, improve product quality, reduce lead time, and achieve a higher level of customer satisfaction. Figure 3 presents major causes of delays identified through the case study, which are related to the lack of communication and coordination among the stakeholders, lack of preparedness and lack of mitigation. Other important considerations are employees' training and community awareness so that they could play positive roles in emergencies. All these considerations concluded through the use of lean tools could help in developing strategies to improve relief operations' performance and hence achieve resilience.

5.5 Proposed Scenario and Performance Evaluation through VSM-'To-Be'.

Total financial loss because of this disaster was estimated to be approx. 150 million PKR (GBP 0.65 million as of 20th September 2021). Keeping in view the investigations carried out by using lean tools like SIPOC Analysis, VSM, and Fish Bone Diagram, underlying causes of delays and role of stakeholders could be better understood. The prominent causes of delays in relief operations are related to role clarity, communication and coordination among the stakeholders, community awareness and preparedness through better planning.

To develop 'to-be' scenarios, some organizational level (specific industry in this case) interventions have been proposed. Disruptions like D2, D3, D5, D9 & D10 are caused due to inappropriate planning in terms of unavailability of resources like water, water pipes etc. and lack of communication and coordination among the departments within the industry. Table 6 below highlights these proposed interventions and their link with associated disruptions.

Table 6: Proposed interventions for the development of 'to-be' scenarios.

Proposed Intervention	Details	Disruption Involved
Communication and Coordination	Development of communication and coordination mechanisms among the stakeholders (for example different departments within the industry).	D2
Capacity building	Providing adequate resources to handle disaster situations like firefighting equipment, water supply, pipes etc.	D5, D9, D10
Planning	Development of contingency plans in case of a fire incident, awareness of employees, and layout design.	D3

How would the proposed interventions influence the delays caused due to disruptions are shown in Table 7? This shows if proposed interventions are implemented the time delays caused due to disruptions like D2, D3, D5, D9 & D10 will be minimized (assumed zero in this case). Based on these interventions, future (to-be) scenarios were developed and a respective VSM (to-be) is shown in Figure 4. If the suggestions are implemented, it is expected that approx. 100 million PKR (GBP 0.43 million as of 20th September 2021) could be saved.

Value Stream Map (VSM-'to be') helps in calculating relief operations' completion time and indicates that the percentage of non-value added time has been reduced significantly (from 28% in 'as-is' to 14% in 'to-be' scenario of total relief operations' time). Similarly, overall relief operations' time has also reduced by 15.6%. In Figure 4, it is visible that the number of disruptions causing delays in relief operations have been reduced (shown in red colour boxes). In DRO_1, DRO_2, and DRO_3, there is only one disruption per operation; these are D1, D7 and D7 respectively. Whereas DRO4 is still affected by many disruptions like D4, D6, D7, D8, shown in Figure 5.

Table 7: Proposed interventions and their impact on delays

Delay in relief operation	**Designated Symbol**	**Actual delay time (% age of total delay time)**	**Proposed intervention**	**Improved delay time (%age of total delay time)**
Delay in response by 'K' because of role clarity and lack of communication	D1	14.13%	Improving communication and coordination among all the stakeholders with clarity of role	6.45%
Delay in information sharing with other departments within the factory	D2	5.43%	Capacity building through providing alerts/emergency alarms	0%
Unclear roads (K's Vehicles)	D3	5.43%	Appropriate planning and scheduling along with community awareness	0%
Preparedness issue (making ready for the relief operation)	D4	5.43%	Effective training and learning best practices in real-time scenarios (Preparedness)	16.13%
Shortage of water	D5	16.30%	Capacity building (alternative water sources)	0%
Fire exposure caused smoke; temperature rise etc.	D6	9.78%	Appropriate design of the building	29.03%
Reduced performance of workers due to D6	D7	10.87%	Facilitating workers with personal protective equipment along with awareness and training	32.26%
Inaccessibility to the affected area	D8	5.43%	Contingency plans, proper planning	16.13%
Unavailability of required resources like water pipes etc.	D9	16.30%	Availability of freshwater points as per planning	0%
Insufficient resources (mismatch between the demand and supply)	D10	10.87%	Better planning and inventory management	0%

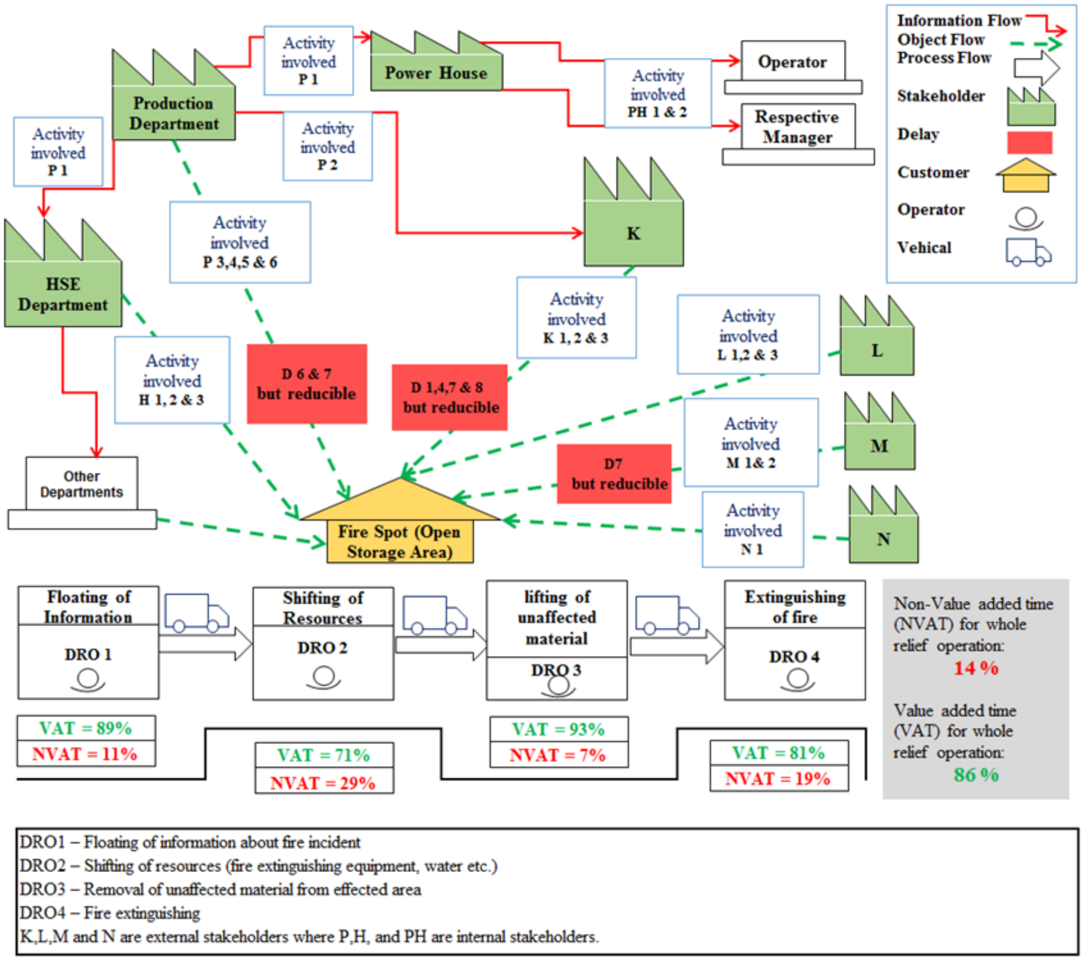

Figure 4: Value Stream Map (VSM) for proposed relief operations (to-be).

If we compare the percentage of non-value-added times between 'as-is' and 'to-be' scenarios against DROs, this can be concluded that the percentages of NVATs have been reduced significantly (79.24%, 34.48% and 69.84% for DRO1, DRO2 & DRO4 respectively), shown in Figure 6.

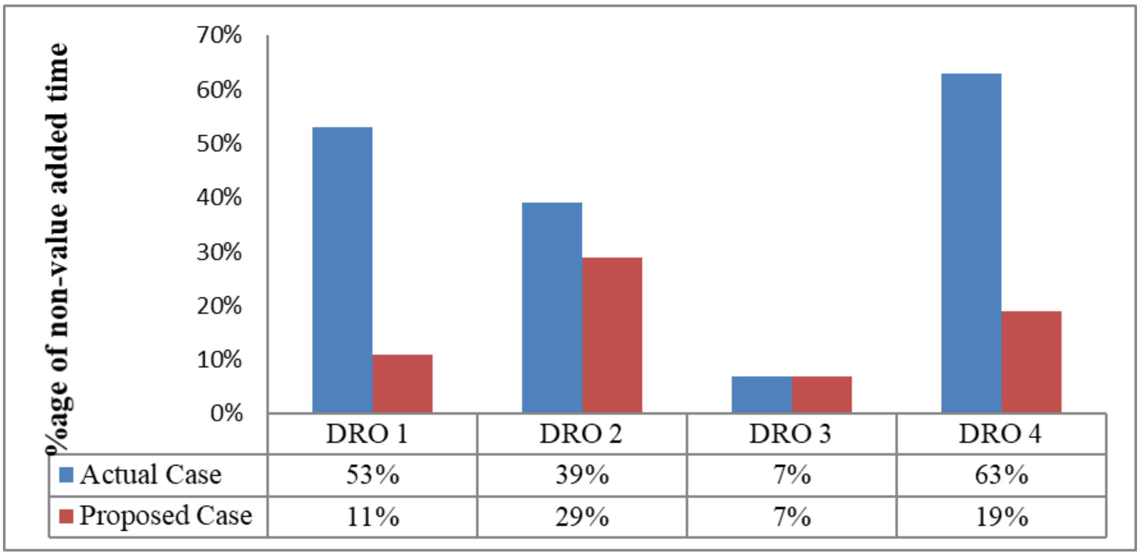

Figure 5: Percentage of non-value-added times (NVAT) during relief operations (to-be scenario)

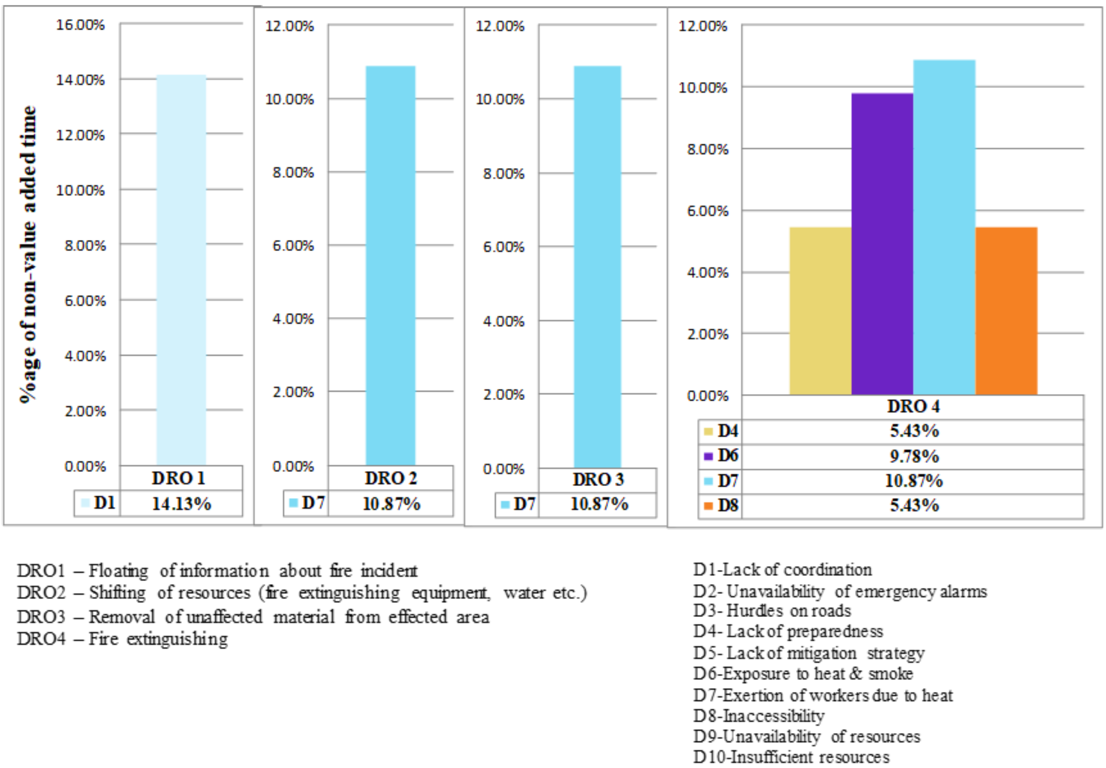

Figure 6: Comparison of non-value-added times between ‘as-is’ and ‘to-be’ scenarios.

6. Discussion

6.1 Achieving DROs resilience through lean transformation

Disasters causing major accidents and hazard installations are categorized as technological disasters. Mohamed (2008) classified technological disasters’ phases as mitigation, preparedness, response and recovery. The research mainly targets response phase in which emergency operations are carried out to save lives, minimize property damages, enhancement of recovery activities, and relief operations. This research aims to investigate the possibility of using a lean based approach as a strategy to achieve operational resilience in DRO management in disaster response phase where responsiveness is the most critical factor.

This research contributes to the existing body of knowledge through an industrial fire case study where all investigations have been made from operations management perspective. Moreover, this work validates the recommendations from the literature (Sebatli et al. 2017; Oloruntoba and Gray 2006; Maghsoudi and Pazirandeh 2016) to use lean tools for making DROs more cost-effective and responsive so that operational resilience could be achieved.

Different lean tools like SIPOC analysis, VSMs, fish-bone diagram and KPIs have been used successfully to identify key stakeholders involved in relief operations, the effectiveness of collaboration and communication among them and identification of key causes of disruptions and their potential impacts in case of disasters' scenarios. Similarly, VSMs and fish-bone diagrams are the techniques that have been frequently used for supply chain performance evaluation and help in improving by eliminating non-value-added activities (Gupta et al. 2016; Maghsoudi and Pazirandeh 2016).

The lean tools used in DROs' scenario were found useful for eliminating redundant activities and designing useful interventions for achieving operational resilience through better responsiveness.

For achieving the desired aim, a systematic five-step approach has been applied against an industrial fire case study. Research objectives helped in identifying key relief operations and causes of disruptions that directly affect resilience of the operations. In the given fire incident case, the following key relief operations have been concluded: (i) floating of incident information among the stakeholders (internal and external), (ii) shifting of rescue resources at the affected area, (iii) removal of unaffected material to the safe area, and (iv) fire extinguishing.

Moreover, disruptions causing delays in relief operations were because of the following reasons: (i) lack of coordination and communication among the stakeholders (internal and external), (ii) unavailability of resources, (iii) lack of preparedness, mitigation strategy and contingency plans, (iv) exposure to heat and smoke (lack of protective equipment), and (v) inaccessibility (road blocking, layout design and community awareness).

This research also found that a significant amount of time is wasted because of these disruptions where VSMs could help in identifying key interactions among the stakeholders and how disruptions affect the performance in terms of time. As shown in 'As-Is' VSM that 28% of time is lost because of the identified disruptions and it can be easily reduced to 14% (shown in VSM – 'To-Be') by implementing small scale interventions related to capacity building through better planning and proper coordination and communication. The resilience is introduced through improving the efficiency of the system in terms of responsiveness, and strategizing response plans by identifying system's failure root causes. The SIPOC analysis is important to understand different stakeholders, their roles, and services so that efficient and robust mechanisms, strategies, and procedures could be developed. As per insights drawn from this analysis, communication and coordination among teams and stakeholders has been found as a prime concern for achieving resilience which should be addressed at planning phase. Moreover, the analysis identifies weak links in DROs which can potentially be evaluated to further improve the effectiveness of the operations.

Also, its systematic approach identifies delays caused through Fish Bone Diagram lean approach could help in devising strategies for the removal of causes which will lead toward the execution of smooth and uninterrupted relief activities. The PDCA-based cyclic process could help in monitoring the performance of relief activities and the effectiveness of implemented interventions, designed for achieving resilience. This is important to mention that all these critical aspects have been determined by using lean tool KPIs. In case of a disaster, timely response (response time) is considered as the most important KPI. Public and private organizations both could use the aforementioned criteria to measure and monitor the resilience capability of the organizations. In similar context, DROs' resilience capability could be enhanced by eliminating non-value-added activities. Conclusively, these lean tools help in investigating the factors that could potentially impact operations' resilience and develop strategies for effective disaster response.

6.2 Research implications (academic, industry, government, and society)

This research contributes to the knowledge areas like disaster operations management, lean transformation, and resilience. The findings of the research help in identifying existing DROs practices, causes of disruptions and delays that negatively affecting the resilience of the operations by using appropriate lean tools and finally how these tools could help in improving the resilience capability by eliminating delays and winning responsiveness.

This research also contributes towards assessing the possibility of using lean tools while implementing the DROPS framework presented in (Masood et al. 2017). This framework proposed systematic considerations for achieving resilience in supply networks throughout the response-recovery-mitigation-preparedness cycle. The considerations of the DROPS framework are: analyse requirements, analyse current disaster relief practices, analyse DROPS key considerations, then strategies and finally contextualizing the model. This case study concludes the usefulness of lean tools deployed in this case as relevant to almost all steps presented in the framework. For example, 'analysing current disaster relief practices' is the same thing that has been done in this case by using lean tools like VSM and KPIs. In this way, this study further extends the understanding of the use of this framework for achieving relief operations' resilience.

Conclusively, this research contributes to knowledge in different areas like a real-time case study on disasters relief operations' management, achieving resilience through a well-structured systematic use of lean approach and effective use of different tools and techniques like SIPOC analysis, VSM, KPIs, PDCA and Fish-Bone Diagram for investigating operations' performance and developing strategies for making DROs more resilient.

In addition to academic contributions, this research is beneficial for practitioners, policymakers, government agencies, humanitarian organizations, and society at large. The conclusions of the work provide a deeper insight into the disaster operations management phenomenon, criticality of capacity planning, information sharing and community awareness for achieving resilience. The findings could be used to devise system-level strategies to prevent or eliminate the causes of disruptions so that more reliable, robust, cost-effective and time-efficient relief operations could be designed. This study also emphasizes the need for developing a resilient culture at all levels; individual, organizational, and societal level through proactive involvement of stakeholders in the decision-making process. The findings of this research could help in the decision-making process where human sufferings along with the loss to infrastructure and economy could be reduced at the local and global level.

Previously it has been emphasized that for developing a resilient environment against disasters for responding to identified and unidentified risks, the factors like capacity building, training of the stakeholders involved, role clarity and missions, robust communication and coordination, pro-activeness in information sharing, supplies of relief goods and role of the local community are important (Bosher 2014; Brown et al. 2017; Benadusi 2013; M. Mojtahedi and Oo 2017). In addition, various lean tools and techniques are used to achieve operations' resilience in emergency/disaster environment for humanitarian activities or rescue operations. This research also found similar kind of factors causing a delay in relief operations, so the elimination of these through appropriate interventions would help in attaining higher resilience. However, the findings of this research have been extracted from a real-time case study. (Keating and Hanger-Kopp 2020) evaluated the practitioners' perspectives and resulted that operationalizing resilience in disaster resilience operations is complex. Similarly, (Prasad et al. 2019) applied a project management framework to reduce the delay caused during operations. Besides, (Rajesh 2020) incorporated the network design policies to achieve resilient disaster management operations. However, our study tries to achieve resilience through the application of lean tools.

6.3 Impact of this Research on Practice

As per the data shared by the RESCUE 1122; government organization deals with emergencies like road accidents, medical emergencies, fire incidents, structural collapse etc. The organization has dealt with 177.5M emergency calls of different nature from 14th October 2004 to 24th July 2021 from the whole province Punjab (details are shown in Table 8); where 168,035 fire incidents have been reported only in Lahore (Capital city of the Punjab province). We can see from the list of cases reported by an emergency relief organization RESCUE-1122 (is one of the stakeholders participated in relief activities of the given case) that a significant number of cases has been reported as direct 'fire incidents' whereas many others like structural collapse, road accidents and medical emergencies also involve fire handling operations. This further emphasises the value of the findings of this research.

Table 8: Detail summary of emergency calls and rescue operations in Punjab from 14/10/2004 to 24/07/2021

Total No. of Cases Reported	
Total calls	177,588,197
Total Emergency Calls	8,616,426
Patient Rescued	9,554,550
Road Accidents	2,894,205
Medical Emergencies	4,423,606
Fire Incidents	168,035
Structure Collapse	9,901
Crime Incidents	275,222

As mentioned earlier, an outcome of the DROPS initiative was the development of collaboration among the local stakeholders e.g., RESCUE 1122, NDMA, Provincial Disaster Management Authority (PDMA), and local hospitals. Key findings of this research have been shared with the key stakeholders especially RESCUE 1122, which is an emergency relief services public sector organization operating in the whole province of Punjab in Pakistan. In this respect, relief operations carried out by RESCUE-1122 could be improved to control the damage to human lives, infrastructure, and economy. Even though the case presented in this work has a localized context; however, findings could be equally helpful for promoting the resilience capability of multiple disaster relief scenarios.

The usefulness of lean tools like SIPOC Analysis, fishbone diagram and value-stream maps for investigating the performance of DROs, will encourage the practitioners and planners to use these for achieving a higher level of performance of DROs. As mentioned earlier the effectiveness of the usefulness of lean tools for achieving performance excellence of industrial operations especially in the production environment is well-established; however, the use of the same tools for gauging and improving the performance of DROs is not established yet.

7. Conclusion and future works

This research work was inspired by the initiative taken by the University of Cambridge titled ‘Resilient Supply Chains for Disaster Relief Operations in South Asia (DROPS). Effective and timely execution of DROs can save human lives and damages too. Recently, DROs management strategies have caught the attention of researchers; however, the literature on systematic approaches for resilient disaster operations management is missing. Moreover, the need for the development of real data-based case studies has also been emphasized. This study concludes literature on the following three knowledge areas: disaster operations management; resilience and lean transformation. It has been found that like enterprise settings, the lean approach could help the resilient transformation of DROs by using appropriate lean tools throughout the relief operations cycle. In this respect, this study investigates the possibility of using different lean tools for investigating the responsiveness of DROs in terms of their timely execution through a well-structured lean based approach.

This research concludes that lean based operations management strategies are useful for investigating and improving resilience in DROs, similar to their usefulness in other industrial applications. In the reported case study of a response to an industrial fire, lean tools greatly helped in investigating the situation and developing possible strategies to achieve resilience in DROs. The existing body of knowledge emphasized that for developing a resilient environment against disasters for responding to identified and unidentified risks, the factors like capacity building, training of the stakeholders involved, role clarity and missions, robust communication and coordination, pro-activeness in information sharing, supplies of relief goods and role of the local community are important. While using appropriate lean tools, this study concludes that the factors mentioned earlier affects the responsiveness of DROs. For example, robust communication and coordination among the stakeholders, capacity building, planning, training, and awareness of the local community, along with infrastructure and resources are the key areas of focus for enhancing resilience. Furthermore, it was found that VSM could be used for quantifying the impact of suggested interventions in terms of decrease in non-value-added activities (time lost) by comparing 'as-is' and 'to-be' scenarios (e.g., 14% decrease in the time lost due to non-value-added activities in the reported case study). Finally, it was found that the proposed well-defined lean based approach was a useful technique to capture a deeper insight of DROs. It could help to develop strategies for overcoming challenges of achieving resilience in DROs through better responsiveness by eliminating redundant non-value-added activities.

Future work will include the development of further empirical cases around various disaster types in various countries. Additionally, initiatives on 'Social/Community Resilience' and 'Health Care Supply Chain in Emergency Situations' are underway. Collaboration with local and global agencies will be developed further so that the findings of the research could help in the decision-making process. Currently, research collaborations with three major medical institutions, i.e., Shaukat Khanum Memorial Cancer Hospital (SKMCH), King Edward Medical University (KE) and Allama Iqbal Medical College (all based in Lahore) have been established in which case studies will be developed on how emergency departments work during DROs.

Certainly, this study roadmap is a new research direction of using lean tools in DROs. It has some limitations e.g., using only one case study that represents a specific type of disaster and only one KPI that is 'relief activities time' has been used for the investigation purpose. Similarly, the work presented in this case has a specific reference to culture as well. Multiple case studies by using different lean tools (as per suitability of disaster cases) and other KPIs like cost, quality etc. might be used for further investigations. Cultural and community perspectives concerning the resilience of disaster operations could be used for further investigations. Research on this topic is still preliminary; hence further research is needed where more detailed empirical studies around various disaster types are required to further strengthen the concept. The use of different lean tools for analysing DMOs throughout relief operations' cycle in enabling DROPS context could be further investigated.

References

Aitsi-Selmi, Amina, Shinichi Egawa, Hiroyuki Sasaki, Chadia Wannous, and Virginia Murray. 2015. "The Sendai Framework for Disaster Risk Reduction: Renewing the Global Commitment to People's Resilience, Health, and Well-Being." *International Journal of Disaster Risk Science* 6 (2). Springer: 164–176.

Altay, Nezih, Angappa Gunasekaran, Rameshwar Dubey, and Stephen J. Childe. 2018. "Agility and Resilience as Antecedents of Supply Chain Performance under Moderating Effects of Organizational Culture within the Humanitarian Setting: A Dynamic Capability View." *Production Planning & Control* 29 (14). Taylor & Francis: 1158–1174.

Antony, Jiju, Maneesh Kumar, and Christian N. Madu. 2005. "Six Sigma in Small-and Medium-Sized UK Manufacturing Enterprises." *International Journal of Quality & Reliability Management*. Emerald Group Publishing Limited.
Barroso, A. P., V. H. Machado, A. R. Barros, and V. Cruz Machado. 2010. "Toward a Resilient Supply Chain with Supply Disturbances." In *2010 IEEE International Conference on Industrial Engineering and Engineering Management*, 245–249. IEEE.
Beamon, Benita M. 1999. "Measuring Supply Chain Performance." *International Journal of Operations & Production Management*. MCB UP Ltd.
Below, R., and P. Wallemacq. 2018. "Annual Disaster Statistical Review 2017." *Centre for Research on the Epidemiology of Disasters (CRED)*.
Benadusi, Mara. 2013. "The Two-Faced Janus of Disaster Management: Still Vulnerable, YetAlready Resilient." *South East Asia Research* 21 (3). Taylor & Francis: 419–438.
Bentley, Tanya GK, Rachel M. Effros, Kartika Palar, and Emmett B. Keeler. 2008. "Waste in the US Health Care System: A Conceptual Framework." *The Milbank Quarterly* 86 (4). Wiley Online Library: 629–659.
Bosher, Lee. 2014. "Built-in Resilience through Disaster Risk Reduction: Operational Issues." *Building Research & Information* 42 (2). Taylor & Francis: 240–254.
Brown, Nancy A., Jane E. Rovins, Shirley Feldmann-Jensen, Caroline Orchiston, and David Johnston. 2017. "Exploring Disaster Resilience within the Hotel Sector: A Systematic Review of Literature." *International Journal of Disaster Risk Reduction* 22. Elsevier: 362–370.
Capitan, J., D. Mantecon, P. Soriano, and A. Ollero. 2007. "Autonomous Perception Techniques for Urban and Industrial Fire Scenarios." In *2007 IEEE International Workshop on Safety, Security and Rescue Robotics*, 1–6. IEEE.
Carvalho, Helena, Ana P. Barroso, Virgínia H. Machado, Susana Azevedo, and Virgilio Cruz-Machado. 2012. "Supply Chain Redesign for Resilience Using Simulation." *Computers & Industrial Engineering* 62 (1). Elsevier: 329–341.
Castañeda, Jaime Andrés, Annel Zodzi, Paulo Gonçalves, and Liliana Rivera. 2021. "An Analysis of CARE Zimbabwe's Emergency Response Process Flow in the Masvingo Province through Lean Six Sigma Tools." *Production Planning & Control*. Taylor & Francis. DOI: https://doi.org/10.1080/09537287.2020.1834131.
Chen, Hsi Yueh, Ajay Das, and Dmitry Ivanov. 2019. "Building Resilience and Managing Post-Disruption Supply Chain Recovery: Lessons from the Information and Communication Technology Industry." *International Journal of Information Management* 49. Elsevier: 330–342.
Childe, Stephen J. 2011. *Case Studies in Operations Management*. Taylor & Francis.
Chowdhury, Md Maruf H., and Mohammed Quaddus. 2017. "Supply Chain Resilience: Conceptualization and Scale Development Using Dynamic Capability Theory." *International Journal of Production Economics* 188. Elsevier: 185–204.
Cozzolino, Alessandra. 2012. "Humanitarian Logistics and Supply Chain Management." In *Humanitarian Logistics*, 5–16. Springer.
Craighead, Christopher W., Jennifer Blackhurst, M. Johnny Rungtusanatham, and Robert B. Handfield. 2007. "The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities." *Decision Sciences* 38 (1). Wiley Online Library: 131–156.
CRED. 2019. "201EM- DAT International Disaster Database, Centre for Research on the Epidemiology of Disasters (CRED)." Accessed August 18. www.cred.be.

Curry, Adrienne, and Nasser Kadasah. 2002. "Focusing on Key Elements of TQM–Evaluation for Sustainability." *The TQM Magazine*. MCB UP Ltd.
Cutter, Susan L., Lindsey Barnes, Melissa Berry, Christopher Burton, Elijah Evans, Eric Tate, and Jennifer Webb. 2008. "A Place-Based Model for Understanding Community Resilience to Natural Disasters." *Global Environmental Change* 18 (4). Elsevier: 598–606.
Dubey, Rameshwar, Angappa Gunasekaran, David J. Bryde, Yogesh K. Dwivedi, and Thanos Papadopoulos. 2020. "Blockchain Technology for Enhancing Swift-Trust, Collaboration and Resilience within a Humanitarian Supply Chain Setting." *International Journal of Production Research*. Taylor & Francis, 1–18.
Dubey, Rameshwar, Angappa Gunasekaran, Stephen J. Childe, Samuel Fosso Wamba, David Roubaud, and Cyril Foropon. 2021. "Empirical Investigation of Data Analytics Capability and Organizational Flexibility as Complements to Supply Chain Resilience." *International Journal of Production Research* 59 (1). Taylor & Francis: 110–128.
Dubey, Rameshwar, Angappa Gunasekaran, and Thanos Papadopoulos. 2019. "Disaster Relief Operations: Past, Present and Future." *Annals of Operations Research* 283 (1). Springer: 1–8.
Eisenhardt, Kathleen M. 1989. "Building Theories from Case Study Research." *Academy of Management Review* 14 (4). Academy of management Briarcliff Manor, NY 10510: 532–550.
Farooq, Muhammad Umar, Amjad Hussain, Tariq Masood, and Muhammad Salman Habib. 2021. "Supply Chain Operations Management in Pandemics: A State-of-the-Art Review Inspired by COVID-19" 13 (5). MDPI: 2504.
Fernández Campos, Pablo, Paolo Trucco, and Luisa Huaccho Huatuco. 2019. "Managing Structural and Dynamic Complexity in Supply Chains: Insights from Four Case Studies." *Production Planning & Control* 30 (8). Taylor & Francis: 611–623.
Galindo, Gina, and Rajan Batta. 2013. "Review of Recent Developments in OR/MS Research in Disaster Operations Management." *European Journal of Operational Research* 230 (2). Elsevier: 201–211.
Garza-Reyes, Jose Arturo, Bernardo Villarreal, Vikas Kumar, and Jenny Diaz-Ramirez. 2019. "A Lean-TOC Approach for Improving Emergency Medical Services (EMS) Transport and Logistics Operations." *International Journal of Logistics Research and Applications* 22 (3). Taylor & Francis: 253–272.
Ghaffari, Zahra, Mohammad Mahdi Nasiri, Ali Bozorgi-Amiri, and Ali Rahbari. 2020. "Emergency Supply Chain Scheduling Problem with Multiple Resources in Disaster Relief Operations." *Transportmetrica A: Transport Science* 16 (3). Taylor & Francis: 930–956. doi:10.1080/23249935.2020.1720858.
Gunasekaran, Angappa, Christopher Patel, and Ronald E. McGaughey. 2004. "A Framework for Supply Chain Performance Measurement." *International Journal of Production Economics* 87 (3). Elsevier: 333–347.
Gupta, Sushil, Martin K. Starr, Reza Zanjirani Farahani, and Niki Matinrad. 2016. "Disaster Management from a POM Perspective: Mapping a New Domain." *Production and Operations Management* 25 (10). Wiley Online Library: 1611–1637.
Habib, Muhammad Salman, Young Hae Lee, and Muhammad Saad Memon.2016. "Mathematical models in humanitarian supply chain management: A systematic iterature review." *Mathematical Problems in Engineering.* Hindawi: 2016

Habib, Muhammad Salman, and Biswajit Sarkar. 2017. "An integrated location-allocation model for temporary disaster debris management under an uncertain environment." *Sustainability* 9(5). MDPI: 716.

Habib, Muhammad Salman, Biswajit Sarkar, Muhammad Tayyab, Muhammad Wajid Saleem, Amjad Hussain, Mehran Ullah, Muhammad Omair, and Muhammad Waqas Iqbal. 2019. "Large-scale disaster waste management under uncertain environment." *Journal of Cleaner Production*, 212. Elsevier: 200-222.

Herron, Colin, and Christian Hicks. 2008. "The Transfer of Selected Lean Manufacturing Techniques from Japanese Automotive Manufacturing into General Manufacturing (UK) through Change Agents." *Robotics and Computer-Integrated Manufacturing* 24 (4). Elsevier: 524–531.

Hosseini, Seyedmohsen, Dmitry Ivanov, and Alexandre Dolgui. 2019. "Review of Quantitative Methods for Supply Chain Resilience Analysis." *Transportation Research Part E: Logistics and Transportation Review* 125. Elsevier: 285–307.

Hussain, Amjad, Ata Ur Rehaman, Keith Case, Tariq Masood, and Muhammad Salman Habib. 2016. "Lean manufacturing culture: The role of human perceptions in standardized work", In P. Thorvald & K. Case (Eds), Advances in Manufacturing Technology XXXII, Volume 8 of Advances in Transdisciplinary Engineering (pp. 523-528). Amsterdam, The Netherlands: IOS Press. Proceedings of the Sixteenth International Conference on Manufacturing Research, 11-13 September 2016, University of Skövde, Skövde, Sweden.

Ivanov, Dmitry. 2021. "Lean Resilience: AURA (Active Usage of Resilience Assets) Framework for Post-COVID-19 Supply Chain Management." *The International Journal of Logistics Management*. Emerald Publishing Limited.

İvgin, Mehmet. 2013. "The Decision-Making Models for Relief Asset Management and Interaction with Disaster Mitigation." *International Journal of Disaster Risk Reduction* 5. Elsevier: 107–116.

Jahre, Marianne, Gøran Persson, Gyöngyi Kovács, and Karen M. Spens. 2007. "Humanitarian Logistics in Disaster Relief Operations." *International Journal of Physical Distribution & Logistics Management*. Emerald Group Publishing Limited.

Kaynak, Ramazan, and Ahmet Tuğrul Tuğer. 2014. "Coordination and Collaboration Functions of Disaster Coordination Centers for Humanitarian Logistics." *Procedia-Social and Behavioral Sciences* 109. Elsevier: 432–437.

Keating, Adriana, and Susanne Hanger-Kopp. 2020. "Practitioner Perspectives of Disaster Resilience in International Development." *International Journal of Disaster Risk Reduction* 42. Elsevier: 101355.

Kusiak, Andrew. 2020. "Open Manufacturing: A Design-for-Resilience Approach" 58 (15): 4647–4658. doi:https://doi.org/10.1080/00207543.2020.1770894.

Lee, Amy V., John Vargo, and Erica Seville. 2013. "Developing a Tool to Measure and Compare Organizations' Resilience." *Natural Hazards Review* 14 (1). American Society of Civil Engineers: 29–41.

Luis, E., Irina S. Dolinskaya, and Karen R. Smilowitz. 2012. "Disaster Relief Routing: Integrating Research and Practice." *Socio-Economic Planning Sciences* 46 (1). Elsevier: 88–97.

Maghsoudi, Amin, and Ala Pazirandeh. 2016. "Visibility, Resource Sharing and Performance in Supply Chain Relationships: Insights from Humanitarian Practitioners." *Supply Chain Management: An International Journal*. Emerald Group Publishing Limited.

Martin-Breen, Patrick, and J. Marty Anderies. 2011. “Resilience: A Literature Review.” IDS.
Masood, Tariq, Duncan McFarlane, Ajith Kumar Parlikad, John Dora, Andrew Ellis, and Jennifer Schooling. 2016. “Towards the Future-Proofing of UK Infrastructure.” *Infrastructure Asset Management* 3 (1). Thomas Telford Ltd: 28–41.
Masood, Tariq, Emily So, and Duncan McFarlane. 2017. “Disaster Management Operations–Big Data Analytics to Resilient Supply Networks.” In *Proceedings of the 24th EurOMA Conference*.
Masood, Tariq, Maximilian Kern & P. John Clarkson. 2021. "Characteristics of changeable systems across value chains". *International Journal of Production Research* 59 (6). 1626-1648, DOI: https://doi.org/10.1080/00207543.2020.1791997.
McManus, Sonia, Erica Seville, John Vargo, and David Brunsdon. 2008. “Facilitated Process for Improving Organizational Resilience.” *Natural Hazards Review* 9 (2). American Society of Civil Engineers: 81–90.
Medel, Krichelle, Rehana Kousar, and Tariq Masood. 2020. “A Collaboration–Resilience Framework for Disaster Management Supply Networks: A Case Study of the Philippines.” *Journal of Humanitarian Logistics and Supply Chain Management*. Emerald Publishing Limited.
Miller, Joyce Ann, Tatiana Bogatova, and Bruce Carnohan. 2011. *Improving Performance in Service Organizations: How to Implement a Lean Transformation*. Oxford University Press.
Mishra, Pratima, and Rajiv Kumar Sharma. 2014. “A Hybrid Framework Based on SIPOC and Six Sigma DMAIC for Improving Process Dimensions in Supply Chain Network.” *International Journal of Quality & Reliability Management*. Emerald Group Publishing Limited.
Mohamed, Shaluf Ibrahim. 2008. “Technological Disaster Stages and Management.” *Disaster Prevention and Management: An International Journal* 17 (1). Emerald Group Publishing Limited: 114–126. doi:10.1108/09653560810855928.
Mojtahedi, Mohammad, and Bee Lan Oo. 2017. “Critical Attributes for Proactive Engagement of Stakeholders in Disaster Risk Management.” *International Journal of Disaster Risk Reduction* 21. Elsevier: 35–43.
Mojtahedi, S. Mohammad H., and Bee Lan Oo. 2012. “Possibility of Applying Lean in Post-Disaster Reconstruction: An Evaluation Study.” In *Proc., 20th Annual Conf. of the Int. Group for Lean Construction: Challenging Lean Construction Thinking: Are We near a Tipping Point*, 1:411–420.
Moore, Tony, and Raj Lakha, eds. 2006. *Tolley’s Handbook of Disaster and Emergency Management*. 3rd ed. Amsterdam ; Boston: Elsevier.
Negrão, Léony Luis Lopes, Moacir Godinho Filho, and Giuliano Marodin. 2017. “Lean Practices and Their Effect on Performance: A Literature Review.” *Production Planning & Control* 28 (1). Taylor & Francis: 33–56.
Oloruntoba, Richard, and Richard Gray. 2006. “Humanitarian Aid: An Agile Supply Chain?” *Supply Chain Management: An International Journal*. Emerald Group Publishing Limited.
Papadopoulos, Thanos, Angappa Gunasekaran, Rameshwar Dubey, Nezih Altay, Stephen J. Childe, and Samuel Fosso-Wamba. 2017. “The Role of Big Data in Explaining Disaster Resilience in Supply Chains for Sustainability.” *Journal of Cleaner Production* 142. Elsevier: 1108–1118.

Papadopoulos, Thanos, Angappa Gunasekaran, Rameshwar Dubey, and Samuel Fosso Wamba. 2017. “Big Data and Analytics in Operations and Supply Chain Management: Managerial Aspects and Practical Challenges.” *Production Planning & Control* 28 (11–12). Taylor & Francis: 873–876.

Paton, Douglas. 2006. “Disaster Resilience: Building Capacity to Co-Exist with Natural Hazards and Their Consequences.” *Disaster Resilience: An Integrated Approach*. Charles Thomas Springfield, IL, 3–10.

Paton, Douglas, and D. M Johnston. 2006. *Disaster Resilience: An Integrated Approach*. Springfield, Ill.: Charles C Thomas. http://public.ebookcentral.proquest.com/choice/publicfullrecord.aspx?p=564163.

Prasad, Sameer, Jason Woldt, Jasmine Tata, and Nezih Altay. 2019. “Application of Project Management to Disaster Resilience.” *Annals of Operations Research* 283 (1). Springer: 561–590.

Radej, B., J. Drnovšek, and G. Begeš. 2017. “An Overview and Evaluation of Quality-Improvement Methods from the Manufacturing and Supply-Chain Perspective.” *Advances in Production Engineering & Management* 12 (4). University of Maribor, Faculty of Mechanical Engineering, Production …: 388–400.

Rajesh, R. 2018. “Pseudo Resilient Supply Chains: Concept, Traits, and Practices.” *Journal of Risk Research* 21 (10). Taylor & Francis: 1264–1286.

Rajesh, R. 2020. “Network Design for Resilience in Supply Chains Using Novel Crazy Elitist TLBO.” *Neural Computing and Applications* 32 (11). Springer: 7421–7437.

Ransikarbum, Kasin, and Scott J. Mason. 2016a. “Multiple-Objective Analysis of Integrated Relief Supply and Network Restoration in Humanitarian Logistics Operations.” *International Journal of Production Research* 54 (1). Taylor & Francis: 49–68.

Ransikarbum, Kasin, and Scott J. Mason. 2016b. “Goal Programming-Based Post-Disaster Decision Making for Integrated Relief Distribution and Early-Stage Network Restoration.” *International Journal of Production Economics* 182. Elsevier: 324–341.

Sawalha, Ihab Hanna Salman. 2015. “Managing Adversity: Understanding Some Dimensions of Organizational Resilience.” *Management Research Review*. Emerald Group Publishing Limited.

Sebatli, Asli, Fatih Cavdur, and Merve Kose-Kucuk. 2017. “Determination of Relief Supplies Demands and Allocation of Temporary Disaster Response Facilities.” *Transportation Research Procedia* 22. Elsevier: 245–254.

Sharma, Mohita Gangwar, and Samir K. Srivastava. 2016. “Leveraging the Social Welfare Chain to Provide Resilience during Disaster.” *International Journal of Logistics Research and Applications* 19 (6). Taylor & Francis: 509–519.

Skarbek, Emily C. 2014. “The Chicago Fire of 1871: A Bottom-up Approach to Disaster Relief.” *Public Choice* 160 (1–2). Springer: 155–180.

Tapping, Don. 2002. *Value Stream Management: Eight Steps to Planning, Mapping, and Sustaining Lean Improvements*. CRC Press.

Taylor, David, and Stephen Pettit. 2009. “A Consideration of the Relevance of Lean Supply Chain Concepts for Humanitarian Aid Provision.” *International Journal of Services Technology and Management* 12 (4). Inderscience Publishers: 430–444. doi:10.1504/IJSTM.2009.025817.

Tiernan, Anne, Lex Drennan, Johanna Nalau, Esther Onyango, Lochlan Morrissey, and Brendan Mackey. 2019. “A Review of Themes in Disaster Resilience Literature

and International Practice since 2012.” *Policy Design and Practice* 2 (1). Taylor & Francis: 53–74.
Timperio, G., G. B. Panchal, R. De Souza, M. Goh, and A. Samvedi. 2016. “Decision Making Framework for Emergency Response Preparedness: A Supply Chain Resilience Approach.” In *2016 IEEE International Conference on Management of Innovation and Technology (ICMIT)*, 78–82. IEEE.
Tofighi, S., S. Ali Torabi, and S. Afshin Mansouri. 2016. “Humanitarian Logistics Network Design under Mixed Uncertainty.” *European Journal of Operational Research* 250 (1). Elsevier: 239–250.
Upadhyay, Arvind, Sumona Mukhuty, Sushma Kumari, Jose Arturo Garza-Reyes, and Vinaya Shukla. 2020. “A Review of Lean and Agile Management in Humanitarian Supply Chains: Analysing the Pre-Disaster and Post-Disaster Phases and Future Directions.” *Production Planning & Control*. Taylor & Francis, 1–14.
Wahid B.M., C. Ding, J.O. Ajaefobi , K. Agyapong-Kodua, T. Masood, and R.H. Weston. 2008. "Enterprise modelling in support of methods based engineering: lean implementation in an SME bearing manufacturer." *International Conference on Manufacturing Research (ICMR)*, September 9-11, London, Brunel University.
Waters, Donald. 2011. *Supply Chain Risk Management: Vulnerability and Resilience in Logistics*. Kogan Page Publishers.
Weru, A. 2015. “United Nations Office for Disaster Risk Reduction.” *Hyogo Liaison Office (UNISDR Hyogo)*.
Ye, Zi. 2011. *Supply Chain Risk Management on Natural Disaster: A Study of Global Supply Chain Influence By2011Tohoku Earthquake*.
Zhen, Min, Tariq Masood, Aysin Rahimifard, and Richard Weston. 2009. "A structured modelling approach to simulating dynamic behaviours in complex organisations." *Production Planning & Control* 20(6). Taylor & Francis: 496-509, DOI: https://doi.org/10.1080/09537280902938597.
Zhong, Shuang, Michele Clark, Xiang-Yu Hou, Yuli Zang, and Gerard FitzGerald. 2015. “Development of Key Indicators of Hospital Resilience: A Modified Delphi Study.” *Journal of Health Services Research & Policy* 20 (2). SAGE Publications Sage UK: London, England: 74–82.

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