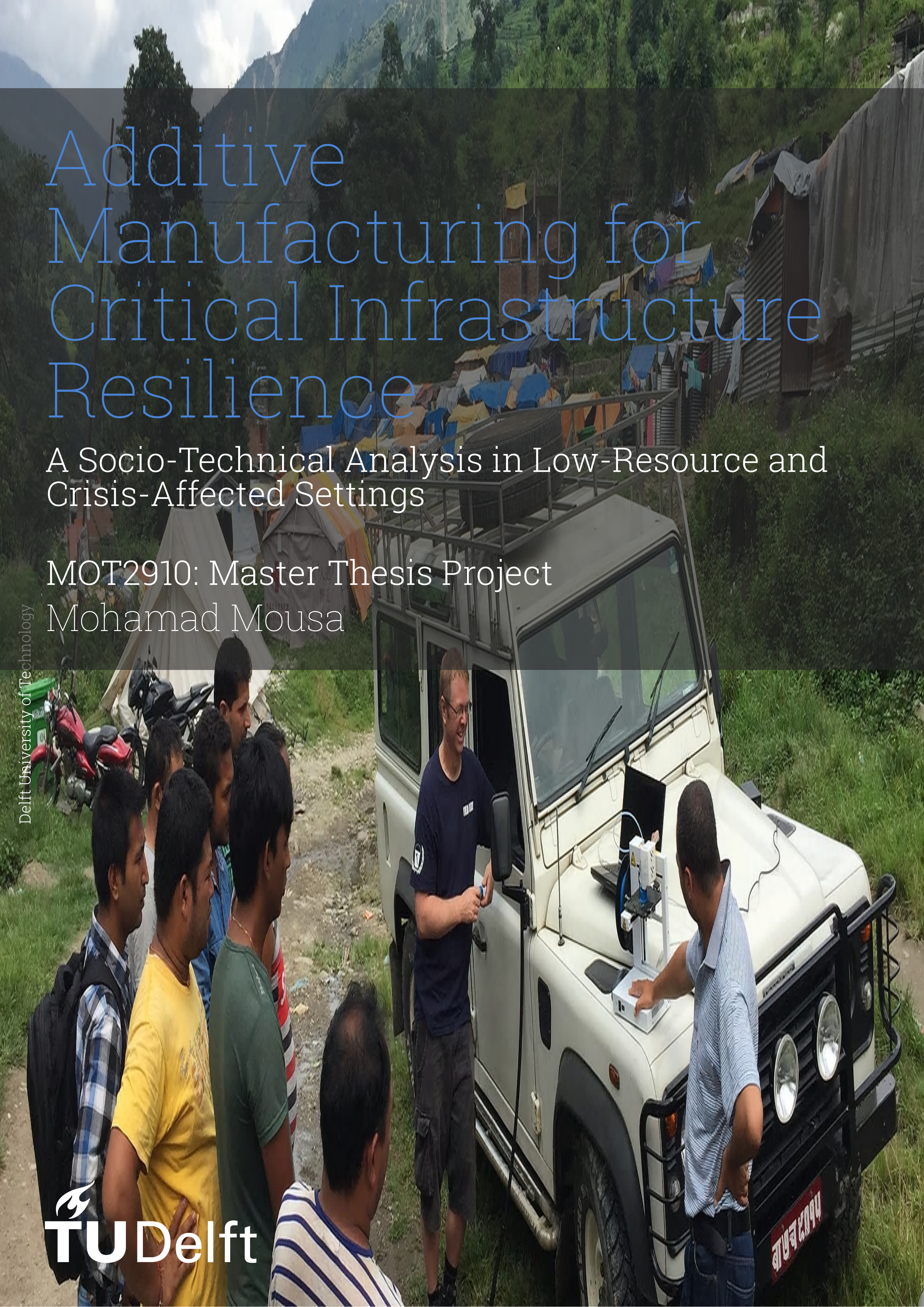

Additive Manufacturing for Critical Infrastructure Resilience

A Socio-Technical Analysis in Low-Resource and Crisis-Affected Settings

MOT2910: Master Thesis Project

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by

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List of Abbreviations

AM:	Additive Manufacturing
CAD:	Computer-Aided Design
CI(s):	Critical Infrastructure
CIR:	Critical Infrastructure Resilience
IDP:	Internally Displaced Persons
NGO(s):	Non-Governmental Organization(s)
PPE:	Personal Protective Equipment
QCA:	Qualitative Content Analysis
SC(s):	Supply Chain(s)
SCDs:	Supply Chain Disruptions
SCR:	Supply Chain Resilience
STS:	Socio-Technical System(s)
WASH:	Water, Sanitation, and Hygiene

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Abstract

Critical infrastructure in low-resource and crisis-affected settings faces compounding threats from supply chain disruptions, geopolitical conflict, and natural disasters. When essential systems such as healthcare facilities, water networks, and energy grids are damaged or cut off from global supply chains, the absence of spare parts and local manufacturing capacity prolongs service failure and deepens humanitarian impact. Existing scholarship on additive manufacturing (AM) and supply chain resilience has largely examined these issues from a technical standpoint, leaving the socio-technical conditions of implementation in crisis-affected settings underexplored. This study contributes to the intersecting fields of critical infrastructure resilience, humanitarian logistics, and socio-technical systems research by examining AM not as a standalone technology, but as an intervention shaped by the social, institutional, and material conditions in which it operates.

The study investigates how additive manufacturing functions as a socio-technical intervention to enhance the resilience of critical infrastructure during supply chain disruption in low-resource and crisis-affected settings, with a focus on Gaza and Syria. A qualitative research design was adopted, combining a literature review with eight semi-structured interviews conducted with practitioners drawn from three distinct stakeholder groups: community-level actors, NGO and humanitarian practitioners, and technology providers. The study examines which infrastructure sectors benefit most from AM, what technical and social factors enable or constrain its deployment, and how it relates to established resilience dimensions, interpreted through the Socio-Technical Systems (STS) framework and the 4Rs resilience lens (Robustness, Redundancy, Resourcefulness, Rapidity).

The findings reveal that AM offers its strongest contributions in healthcare and water, sanitation, and hygiene (WASH) sectors, where small but essential components can halt entire service systems when unavailable. AM contributes most clearly to rapidity, by shortening response times through local production and digital file transfer, and to resourcefulness, by enabling iterative, context-specific problem-solving. Its contributions to redundancy and robustness are more conditional, depending on material quality, maintenance capacity, and sustained user trust. Across all sectors, implementation depends on the alignment of technical resources with social conditions including skills, coordination, and institutional support.

The findings offer practical guidance for humanitarian organizations and policymakers seeking to integrate AM into crisis preparedness and infrastructure recovery strategies, particularly in settings where conventional supply chains are fragile or restricted.

Keywords: Additive Manufacturing, Critical Infrastructure Resilience, Supply Chain Disruption, Low-Resource Settings, Socio-Technical Systems, Humanitarian Logistics

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Introduction

1.1. Background

The modern globalized world is characterized by highly complex and interconnected systems, making them increasingly vulnerable to shocks and disturbances (Bouchenine and Abdel-Aal, 2023; Singh et al., 2024a). The reliance on traditional supply chains (SCs) for the procurement, production, and distribution of goods means that any disruption can have severe consequences (Ivanov and Sokolov, 2020; Singh et al., 2024a). Geopolitical conflicts, natural disasters (such as hurricanes, earthquakes, and floods), cyberattacks, and industrial accidents regularly expose the vulnerabilities inherent in contemporary supply networks (Rahman et al., 2025; Raja Santhi and Muthuswamy, 2022; Ivanov and Sokolov, 2020).

The implications of global supply chain disruptions (SCDs) extend into the function of essential societal systems, known as Critical Infrastructures (CIs). CIs, defined as the assets and systems vital for maintaining societal functions and providing key services such as electricity, healthcare, water, telecommunication, and transportation, are the very foundation of modern economies and daily life (Saurin et al., 2024; Saha et al., 2024; Gordan et al., 2024). Supply chains effectively function as the backbone of functioning CI. Their paralysis may trigger a corresponding slowdown in the whole essential services (Olivares-Aguila and Vital-Soto, 2021; Ivanov and Sokolov, 2020). Disruptions in the supply chain, whether affecting raw materials, components, or logistics, directly threaten the continuity of vital public services. For example, a severe supply disruption can lead to shortages in inventory and increased transportation expenses, severely affecting the overall performance of the supply network (Bai et al., 2024; Saurin et al., 2024; Singh et al., 2024a).

A critical characteristic of modern CIs is their interdependency, meaning a failure in one sector rapidly cascades across others, amplifying the overall disaster impact. These interdependencies create systemic system-of-system vulnerabilities (Månefjord and Johansson, 2024; Almoghathawi, 2024; Gordan et al., 2024). Recently, the complexities of cascading failures were seen when power outages caused by disasters, such as hurricanes, subsequently led to cell site outages, disrupting communication, emergency response, and restoration logistics. Ensuring the rapid restoration of these interdependent networks, such as power and wireless cellular systems, is thus imperative for post-disaster recovery (Moglen et al., 2025).

The increasing frequency and complexity of disruptive events necessitate a fundamental shift in focus from mere efficiency to resilience. Resilience, in this context, refers to a system's ability to anticipate, absorb, adapt to, and rapidly recover from a potentially disruptive event within an acceptable timeframe and at an acceptable cost (Deelstra and Bristow, 2023; Moglen et al., 2025; Naghshineh and Carvalho, 2022). For critical infrastructure, resilience involves maintaining a minimum acceptable level of service and quickly recovering essential functions following a disruptive event (Guo et al., 2021).

Supply Chain Resilience (SCR) involves the prevention, response, and management of risks at multiple stages of the supply chain process (Abdulrahman et al., 2023). Resilience strategies generally fall into two broad areas: increasing supply chain capabilities (such as inventory and capacity) and redesigning networks to reduce vulnerability (Belhadi et al., 2024; Chowdhury et al., 2021). These capabilities include proactive elements like redundancy, flexibility, integration, and disaster readiness, along with reactive capabilities focusing on quick response and recovery (Ivanov and Sokolov, 2020).

The advent of digital transformation and Industry 4.0 has introduced new paradigms for managing supply chain uncertainties and building resilience . Industry 4.0 is underpinned by concepts such as Cyber-Physical Systems (CPS), Big Data Analytics, Artificial Intelligence (AI), and the Internet of Things (IoT) (Ullah et al., 2024; Reza et al., 2022; Spieske and Birkel, 2021). These technologies offer the potential to drive efficiencies, boost innovation, and ensure flawless operation, thereby increasing the resilience of production networks (Raja Santhi and Muthuswamy, 2022; Fernando et al., 2024). Digital technologies can contribute to resilience by enabling firms to predict threats and by supporting pre-disruption resilience measures, thereby allowing for more effective proactive risk management (Saurin et al., 2024; Spieske and Birkel, 2021).

Within the spectrum of emerging technologies, Additive Manufacturing (AM), also known as 3D printing, presents a disruptive solution uniquely positioned to enhance supply chain resilience (Naghshineh and Carvalho, 2022; Ullah et al., 2024). AM involves the layer-by-layer deposition of material to create objects directly from a digital file, contrasting sharply with traditional subtractive manufacturing (Muthukumarasamy et al., 2018; Ullah et al., 2024). This technology facilitates localized, on-demand manufacturing of complex and customized parts, drastically reducing reliance on long, complex global supply chains and decreasing inventory needs by allowing the storage of digital inventory (Muthukumarasamy et al., 2018; Kamble et al., 2023).

The capabilities afforded by AM directly strengthen supply chain resilience by enhancing flexibility, responsiveness, and speed of recovery (Singh et al., 2024a; Ivanov and Sokolov, 2020). AM is characterized by design freedom and tool-less manufacturing, allowing for distributed ways of manufacturing, supporting a decentralized supply chain structure where production can occur on-site and on-demand, even in hard-to-reach locations. During crises, AM has proven its effectiveness, notably during the COVID-19 pandemic, for the immediate production of essential medical equipment like PPE and valves (Priyadarshini et al., 2025; Ivanov and Sokolov, 2020; Naghshineh and Carvalho, 2022). Beyond the medical sector, AM has shown potential in humanitarian logistics for repairing critical assets like water piping systems and is being explored for the rapid construction of critical civilian structures and shelters in disaster areas (Rodríguez-Espíndola et al., 2020; Priyadarshini et al., 2025). AM is recognized as having high potential in CIs, specifically in energy, transport, and water supply, offering solutions for spare parts production and mobile repair systems (Budzik et al., 2022).

The challenges of SCDs, CI fragility, and resilience are particularly pronounced in low, and middle-income countries, where resources are scarce and infrastructure is often less robust (Nguyen et al., 2025; Campoli et al., 2024). In the Middle East and surrounding regions, critical infrastructure faces systemic threats ranging from wars and conflicts to the increasing frequency of natural disasters and climate change effects (Belhadi et al., 2024; Priyadarshini et al., 2025).

Natural disasters, such as the Turkey-Syria earthquakes (2023), lead to massive destruction of buildings and displacement of populations, severely compromising access to essential services (Nguyen et al., 2025). In complex humanitarian settings, infrastructure inadequacy, coupled with security threats, makes effective relief operations challenging. Furthermore, geopolitical tensions in the region can cause significant supply chain disruptions, for instance, affecting food supply chains that rely on Black Sea imports, leading to acute food insecurity (Rahman et al., 2025).

Countries characterized by low resources, much like Nepal, rely heavily on external aid and imports for basic necessities. When disasters strike these low-resource environments, the destruction of existing infrastructure (roads, power, water) leads to logistical bottlenecks, hindering the timely delivery of aid and reconstruction materials (Nguyen et al., 2025; Rahman et al., 2025). Hospitals, as critical infrastructure, also confront challenges during crises, demanding rapid recovery strategies (Bai et al., 2024). This continued dependence on complicated global supply chains, combined with the political instability and disaster risks in the Middle East, highlights the urgent need for local and resilient solutions.

Given the increasing severity and frequency of multi-hazard events and the critical interdependencies between supply chains and infrastructure, particularly in vulnerable geopolitical and low-resource settings like the Middle East, this research seeks to address the gap in developing adaptive and resilient strategies. Specifically, the integration of emerging technologies like additive manufacturing into local systems to enhance immediate post-disruption recovery capacity remains under-explored in this crucial geographical and socio-economic context. This study aims to explore how new digital technologies, especially additive manufacturing, can strengthen the resilience of critical infrastructure supply chains in low-resource Middle Eastern countries after major disruptions.

1.2. Problem Definition

Critical infrastructure disruption in crisis-affected settings is often understood through the most visible signs of destruction: bombed hospitals, damaged water systems, demolished homes, and blocked roads. Yet in places such as Gaza and Syria, the deeper problem is not destruction alone, but the inability to maintain, repair, replace, and restore essential systems once disruption occurs. In these settings, infrastructure failure becomes prolonged because the supporting conditions that keep services running (materials, spare parts, skilled personnel,logistics), are fragile or disrupted. What we see is not just a sudden breakdown, but a long-term struggle to keep services running. Essential services may still exist in some form, but they become weaker, less reliable, and more difficult to repair or bring back properly. (Smith, 2015; Alhaffar and Janos, 2021; Sikder et al., 2018). This crisis is particularly severe in Gaza, where the geography of a densely populated, enclosed, and resource-scarce territory intersects with blockade and repeated military escalation. Smith (2015) argues that siege in Gaza undermines healthcare through two intertwined processes: withholding materials and resources, and weakening healthcare at a systems level. His analysis shows that the problem is not limited to emergency shortages after an attack. Rather, the siege produces a long-term condition in which hospitals and clinics struggle to access medicines, disposables, fuel, raw materials, and spare parts, while planning, coordination, and institutional autonomy are steadily weakened. In this sense, Gaza's infrastructure crisis is fundamentally political and geographical: service provision is shaped by restricted mobility, dependence on external approval for goods and inputs. Smith (2015) also show how hospitals in Gaza have been unable to maintain laboratories, x-ray departments, emergency units, intensive care units, nurseries, and renal dialysis services because spare parts are delayed or blocked. Hassoun et al. (2025) reinforces this argument by showing that the blockade imposed since 2007 has restricted access to essential goods such as medical supplies, clean water, fuel, and food, contributing to prolonged socio-economic decline and worsening instability. Their analysis also emphasizes that critical infrastructure in Gaza is highly interconnected: damage to hospitals, water systems, sanitation networks, and energy supply creates cascading effects across health, education, and daily life. In such a setting, infrastructure breakdown is rarely isolated to one sector, it spreads across the wider system that sustains survival.

Syria presents a related pattern of infrastructural fragility. Alhaffar and Janos (2021) describes the Syrian war as a devastating humanitarian crisis that has produced enormous destruction in infrastructure and the collapse of much of the healthcare system. They report that up to 50% of health facilities were destroyed and up to 70% of healthcare providers fled the country, leaving the remaining system under severe strain. They note that while efforts have been made to establish basic healthcare structures in vulnerable areas, these remain fragile and unsustainable. Here too, the central problem is not only that facilities were attacked, but that the systems needed to operate them (Ekzayez et al., 2021). The problem extends to broader humanitarian service delivery. Aburas et al. (2018) show that even when local clinics and humanitarian initiatives emerge to fill critical gaps, they face persistent logistical difficulties in securing medical equipment, materials, staffing, and sustainable funding.

In WASH systems, Sikder et al. (2018) note that before the conflict, more than 90% of Syrians had access to drinking water, but the infrastructure gradually became less functional because there was not enough power supply, insecurity, displacement of trained professionals, lack of preventive maintenance, and the unavailability of spare parts and consumables.

In this context, AM has gained increasing attention. The appeal of AM in such places lies in its apparent ability to reduce dependence on long, fragile, and politically exposed supply chains by enabling localized production from digital designs. This appears especially relevant where one missing component can disable a much larger system, as in medical devices or WASH infrastructure. However, its contribution should not be assumed. Corsini et al. (2022) argue that 3D printing does not necessarily shorten or simplify the humanitarian supply chain. Instead, it often introduces a new one, with its own dependencies on printers, filament, maintenance, digital coordination, and quality control. This means that AM is not a simple technical fix for disrupted geographies. Its value depends on whether it can be embedded within already fragile socio-technical environments where the need for local production is high, but the conditions for implementing it are often weak

In both Gaza and Syria, the challenge is not simply how to rebuild after destruction, but how to sustain essential service systems when the logistical and institutional foundations of continuity are repeatedly undermined. The question here is how AM can make a meaningful contribution to critical infrastructure resilience during supply chain disruption in low-resource, crisis-affected settings.

1.3. Research Objective

This study aims to connect what technology could possibly do with the reality of trying to survive in some of the world's most restricted places. The primary aim is to investigate how additive manufacturing functions as a socio-technical intervention to enhance the resilience of Critical Infrastructure in low-resource settings, with a specific focus on Gaza and Syria. By moving away from a purely mechanical view of 3D printing, this research sees the technology as something shaped by society and everyday life and in order to it to be effective, it needs to fit local needs, political limits, and the skills and creativity that people already have. To address the Main Research Question, the study is structured around three specific objectives that correspond directly to the research sub-questions:

- **Identifying Sectoral Relevance**

  The first objective is to identify and map the specific critical infrastructure sectors where AM can most effectively intervene during supply chain disruptions.

- **Analyzing the Socio-Technical Landscape**

  The second objective is to uncover the technical and social factors that either enable or neutralize the impact of digital fabrication. By examining the roles of NGOs, local community, and technology providers.

- **Evaluating Resilience through resilience dimensions**

  The final objective is to evaluate how the unique characteristics of AM translate into observable resilience contributions.

1.4. Research Questions

To reach the different objectives, a main research question has been set up to fulfil the main objective of the research and fill up the research gaps.

1.4.1. Main Research Question

How does additive manufacturing contribute to the resilience of critical infrastructure during supply chain disruption in low-resource and crisis-affected settings?

1.4.2. Sub-Questions

- In which critical infrastructure sectors can additive manufacturing support resilience during supply chain disruption?
- What technical and social factors enable or constrain the contribution of additive manufacturing to infrastructure resilience?
- In what ways does additive manufacturing relate to different dimensions of critical infrastructure resilience during supply chain disruption?

1.5. Thesis Structure

This thesis is organized into seven chapters. **Chapter 1** introduces the research context, problem definition, and the research questions that guide the study. **Chapter 2** develops the conceptual foundation through a review of critical infrastructure resilience, additive manufacturing, and the socio-technical systems perspective combined with the 4Rs framework. **Chapter 3** outlines the qualitative research design, covering the literature review, semi-structured interview methodology, and qualitative content analysis approach. **Chapter 4** presents the empirical findings by sector, technical conditions, social conditions, and resilience-related results as described by participants. **Chapter 5** interprets those findings through the STS framework and the 4Rs resilience lens to answer the three research sub-questions. **Chapter 6** discusses the findings in relation to existing literature, identifying what the study confirms, extends, and adds. **Chapter 7** concludes with theoretical contributions, practical implications, limitations, and directions for future research. Figure 1.1 provides an overview of this structure.

Figure 1.1: Overview of the thesis structure

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Literature Review

This chapter builds the conceptual and analytical foundation of the study. Rather than surveying each topic in sequence, it develops a structured argument: beginning with how critical infrastructure fails under supply chain disruption, particularly in low-resource and crisis-affected settings; examining additive manufacturing as a technology whose properties could address some of these vulnerabilities; and reviewing what existing evidence from sectoral applications actually shows. From this review, the chapter identifies the central gaps in existing knowledge, above all the disconnect between AM's technical potential and the socio-technical realities of implementation under crisis conditions. These gaps give rise to the three research sub-questions and justify the adoption of the socio-technical systems (STS) perspective combined with the 4Rs resilience framework as the most appropriate analytical tools for this study.

2.1. Critical Infrastructure

2.1.1. Definition

Although there is no single universally accepted definition of critical infrastructure (CI), most definitions converge on its role in sustaining societal functioning. Critical infrastructure can be understood as the systems, assets, and services essential to public well-being, economic stability, and effective crisis response, particularly where disruption would have severe consequences for daily life and recovery efforts (Perera et al., 2024). For this study, CI is understood through a disaster risk reduction lens as the infrastructure that supports societal stability, and the provision of essential services during crises and disasters (Bektaş and Yildiz, 2025). Critical infrastructure does not operate as a set of isolated sectors but rather as a highly interconnected system of systems (Bakhtiari et al., 2025). The functioning of one infrastructure often depends on the services, materials, or operational continuity of others. This interdependence means that disruption in one sector can quickly affect other sectors, transforming a localized failure into a broader systemic crisis. As a result, critical infrastructure resilience cannot be understood only at the level of individual sectors, it must also account for the relationships and dependencies between them (Månefjord and Johansson, 2024; Almoghathawi, 2024).

In this study, particular attention is given to infrastructure sectors that are especially important for sustaining life and basic services during crises, including healthcare, water and sanitation, shelter, and, where relevant, energy and transport-related support systems. Healthcare infrastructure is essential for emergency treatment and the protection of life (Bai et al., 2024). Water and sanitation systems are fundamental for hygiene, disease prevention, and public health (Bhandari et al., 2023). Shelter provides the physical basis for safety, survival, and continuity of daily life during displacement or disruption (Zezulova et al., 2023). These sectors are significant because their failure directly affects human security, public health, and the capacity of communities to cope with and recover from crises. Their resilience plays a central role in maintaining essential services under disrupted conditions (Bakhtiari et al., 2025).

2.1.2. Supply Chains and Critical Infrastructures

Supply chains are essential to the functioning and resilience of critical infrastructure because they ensure the continuous flow of materials, equipment, and services required to maintain daily operations and support rapid recovery during crises. The availability of these essential resources depends heavily on efficient supply chain management and robust logistics networks. In this sense, a critical infrastructure system's ability to absorb shocks is closely tied to the reliability of its supply chains (Rathnayaka et al., 2024). Supply chains and critical infrastructure are highly interdependent, meaning that disruptions within a supply chain can quickly generate ripple effects across multiple sectors. Because modern critical infrastructure often relies on global supply chains, disruption in one region can trigger wider cascading failures, as seen during the COVID-19 pandemic, when lockdowns and halted production caused shortages of materials and components that affected transportation and energy networks (Månefjord and Johansson, 2024). These disruptions directly affect the continuity of essential services. Critical infrastructure sectors such as healthcare, water, and energy depend on the timely delivery of specialized equipment, spare parts, fuel, treatment materials, and technical support. When supply chains are interrupted, hospitals may face shortages of medicines, medical devices, or personal protective equipment, while water and energy systems may struggle to access the components needed for operation and repair (Chowdhury et al., 2021; Månefjord and Johansson, 2024). In this sense, infrastructure failure is not caused only by direct physical damage, but also by the inability to obtain the resources required to keep systems running or restore them after disruption.

The consequences of supply chain disruption are often more severe in low-resource and crisis-affected settings. Many such contexts rely heavily on imported goods, external technical support, and international humanitarian assistance for essential supplies, which increases their exposure to disruption originating beyond the local level. This dependence becomes harder when conflict, disaster, border restrictions, damaged transport infrastructure, or market instability interrupt the flow of goods and services. At the same time, limited financial resources, weak local production capacity, and shortages of trained personnel reduce the ability of affected communities and institutions to respond proactively. In many cases, there are few domestic alternatives available when imported supplies are delayed or unavailable, which means that even minor disruptions can have disproportionate effects on infrastructure performance (Kumar et al., 2025; Bektaş and Yildiz, 2025; Besenyő, 2024). Recovery is further constrained by reduced purchasing power, institutional weakness, insecurity, and competing humanitarian demands, all of which slow the restoration of critical services. In such settings, supply chain disruption does not only create temporary inconvenience, it can prolong infrastructure failure, increase social vulnerability, and undermine the capacity of communities to cope with and recover from crisis (Saha et al., 2024).

These vulnerabilities have contributed to a broader shift in critical infrastructure thinking from protection alone toward resilience. While earlier approaches focused primarily on preventing failure through risk reduction and asset protection, more recent perspectives recognize that not all disruptions can be anticipated or avoided (Knodt et al., 2022; Kozine et al., 2018). In this context, resilience includes not only the robustness of infrastructure assets but also the capacity to maintain, adapt, and restore the supply relationships that support essential services (Rathnayaka et al., 2024). Understanding critical infrastructure resilience requires attention to supply chain continuity as a central condition for operational stability and recovery (Månefjord and Johansson, 2024).

2.1.3. Vulnerability and Cascading Effect

Critical infrastructure vulnerability is frequently presented as the opposite of resilience, emphasizing how exposed and prone to disruptions infrastructures are. In its broadest sense, vulnerability is defined as an infrastructure system's performance declining under stress, which affects the extent of service interruption as well as the amount of time and resources needed to recover (Irankunda et al., 2024). Because determining resilience levels is crucial to defining suitable technical, organizational, and security measures, measuring vulnerability thus necessitates not just hazard exposure but also an evaluation of current resilience capacities (Rehak et al., 2024).

Cascade effects are an important focus of resilience research because they increase the impact of disruptions in critical infrastructures. In general, cascading failures result from interdependencies between various types of hazards and CI sectors, creating intricate patterns of disruption that are especially noticeable in urban locations with highly connected infrastructure. According to Gordan et al.

(2024), evaluating and managing cascading effects is still very difficult, particularly at the city scale, where a coordinated multi-sector response requires deep public–private cooperation. The systemic nature of these cascades is demonstrated by examples from various domains. Energy failures stop food production, transportation breakdowns delay distribution, and cyberattacks or disruptions in transportation can paralyze processing, logistics, and safety monitoring in the food and agriculture industries (Zheng et al., 2025). Interruption in the health sector causes cascade impacts by interfering with medical services, which compromise community resilience, public health, and economic stability (Mani et al., 2024).

2.1.4. Resilience

In the context of critical infrastructure, resilience generally refers to the capacity of systems to anticipate, prepare for, absorb, adapt to, and recover from disruptive events while maintaining essential services (Moglen et al., 2025). Resilience recognizes that not all hazards are predictable or avoidable, in contrast to traditional approaches that prioritize protection and prevention (Mentges et al., 2023). It focuses on reducing vulnerabilities, limiting the scale and duration of disruption, and enabling infrastructure systems to continue functioning under stress. In this sense, resilience is not simply about avoiding failure but about ensuring that essential services can be sustained and restored under challenging conditions (Ewa et al., 2024; Almaleh, 2023).

A widely cited definition, originating from the field of disaster risk reduction, comes from the United Nations Office for Disaster Risk Reduction (UNISDR). UNISDR defines resilience as the "ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management"(United Nations Office for Disaster Risk Reduction, 2017). This definition, applied to critical infrastructure systems, emphasizes a broad range of capacities, not only resisting and absorbing shocks but also adapting and even transforming under stress, all while maintaining or quickly regaining essential functions (Engler et al., 2019).

Earlier infrastructure management mainly focused on protecting physical assets by predicting threats and trying to prevent damage. However, this view is now seen as too limited because modern infrastructure systems operate in uncertain and complex environments where disruptions cannot always be avoided(Toroghi and Thomas, 2020). Because of this, resilience is now understood more broadly. It is not only about being strong enough to resist damage or recover after failure, but also about being flexible, adapting to new conditions, and reorganizing when situations change (Kim et al., 2025; Guo et al., 2021). Therefore, resilience is no longer seen as only a technical issue. It also depends on institutions, people's decisions, cooperation, and the ability of the whole system to continue providing essential services during and after crises (Rathnayaka et al., 2024; Arabadzhiyski et al., 2025).

2.1.5. Resilience Dimensions

In the early 2000s, researchers like Bruneau et al. (2003) introduced a novel framework that transformed how we understand and assess the resilience of critical infrastructures, the 4Rs of resilience which is Robustness, Redundancy, Resourcefulness and Rapidity. This framework has been expanded by many scholars such as Knodt et al. (2022); Kozine et al. (2018) , emphasizing that true resilience does not lie only on the physical strength of infrastructure but also in the social and organizational dimensions. According to Bruneau et al. (2003): Robustness illustrates the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without losing function. Redundancy is the extent to which elements, systems, or other units of analysis exist that are substitutable. Resourcefulness is the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis. Lastly, rapidity refers to the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

While the preceding definition provides a useful foundation, recent studies have introduced broader and more detailed interpretations of resilience. These definitions reflect the multidimensional nature of critical infrastructure resilience and highlight key components such as robustness, redundancy, resourcefulness, and rapidity. Table 2.1 summarizes these definitions as presented in recent literature.

Table 2.1: Definitions of the 4Rs of Critical Infrastructure Resilience

Resilience Component	Definitions from the Literature
Robustness	The ability of a system to prevent the dissemination of damage during a hazardous incident (Toroghi and Thomas, 2020). The capacity to absorb disturbances and continue delivering stable service (Toroghi and Thomas, 2020). The ability to withstand disastrous events without significant damage and the ability to sustain strain or demand without losing functionality (Sathurshan et al., 2022).
Redundancy	The ability to maintain service using alternative resources during an incident (Toroghi and Thomas, 2020). The presence of backup components that maintain functionality if parts are damaged (Kim et al., 2025). The extent to which a system can be replaced or continue to meet functional requirements after breakdown or loss (Sambowo and Hidayatno, 2021).
Resourcefulness	The capability to respond to a hazardous incident and mobilize required resources (Toroghi and Thomas, 2020). The ability to prioritize and allocate resources effectively during recovery (Sambowo and Hidayatno, 2021). The capacity to manage and utilize available materials and human resources (Guo et al., 2021).
Rapidity	The speed at which a system returns to its original or functional state (Sambowo and Hidayatno, 2021). The speed of restoring full functionality after a disaster (Kim et al., 2025). The capability of recovery (Sathurshan et al., 2022).

Together, these four dimensions offer a structured way of understanding what resilience requires in practice. Robustness concerns whether a system can withstand stress; redundancy, whether alternatives exist when primary pathways fail; resourcefulness, whether actors can mobilize and adapt under constraint; and rapidity, whether response is fast enough to limit cascading harm. In low-resource and crisis-affected settings, all four of these capacities are typically under pressure simultaneously. Supply chains are disrupted, alternatives are scarce, adaptive capacity is constrained by weak institutions and limited resources, and slow response has immediate consequences for life and service continuity. This raises a practical question that runs through the rest of this review: what kind of production capability could support these resilience dimensions when conventional supply chains can no longer be relied upon? The following sections examine additive manufacturing as a candidate answer, exploring both its potential and the conditions that determine whether that potential is realised in practice.

2.2. Additive Manufacturing

Additive Manufacturing (AM), or 3D Printing (3DP), serves as a specific and highly effective technology for enhancing resilience. AM embodies the core principles of Industry 4.0 by using digital 3D models to build physical objects layer by layer. It stands out because it directly addresses a critical weakness of traditional CI supply chains: their centralized vulnerability to disruption, as it introduces on-demand, on-site manufacturing with digital inventory, making it a powerful tool for rapid response during disruptions (Priyadarshini et al., 2025).

Additive manufacturing offers several strengths that support the goal of building more resilient and adaptable production systems. It allows for customization and design flexibility, enabling the creation of complex, tailor-made components directly from digital designs without the need for specialized tooling. This makes it easier to produce parts suited to specific repair or maintenance needs in critical infrastructure. Additive manufacturing supports decentralized production, allowing items to be made closer to where they are needed. By reducing dependence on lengthy and fragile supply chains, this approach makes it possible to manufacture on-site and on-demand, an essential capability in remote, resource-limited, or disrupted environments.

2.2.1. Additive Manufacturing and Resilience

AM is commonly defined in the literature as the process of producing objects directly from digital design data by adding material layer by layer rather than cutting away material or relying on dedicated tooling. In resilience terms, the key issue is not how AM works technically but what it means for organisations. Since AM uses digital files and can move from one design to another without the need to change tools in many traditional methods, it is often seen as a flexible and local way to make certain products when conditions are uncertain (Kleer and Piller, 2019; Attaran, 2017).

The first point linked to resilience is local production. The literature consistently shows that AM can make it possible to produce parts closer to where they are needed, such as in hospitals, repair centres or local workshops. During disruptions this is significant because supply problems are often caused by distance, such as transport delays, import issues, border problems, or suppliers being unable to deliver on time (Nazir et al., 2021; Tareq et al., 2021). By producing closer to the user, AM can reduce reliance on long and complex supply chains and help keep things running when centralized production cannot respond quickly enough. Kleer and Piller (2019) shows that the main trade-off is that local AM can provide faster access and products that better match local needs, while traditional centralized manufacturing is still usually better for producing large quantities efficiently. A second consideration is design flexibility. AM can move quickly from one design to another, test and improve prototypes, and make complex or customized parts without needing expensive special tools. In disrupted situations the need is often not for large amounts of the same standard product. Instead, people may need something specific, such as a changed medical fitting, an old spare part, a temporary repair piece, or a design adjusted to the materials available locally. In these cases, being able to adapt quickly can be just as important as producing efficiently (Delic and Eyers, 2020; Attaran, 2017). Nazir et al. (2021); Tareq et al. (2021) show this through the pandemic experience, where shared CAD files and quick design changes helped local groups respond when normal supply routes were not working. A third dimension concerns on-demand production. Instead of predicting demand in advance and storing many finished products, AM can make an item only when it is needed. The literature connects this to lower storage needs, less risk of parts becoming outdated, and quicker response when demand suddenly rises for specific items (He et al., 2021; Keskin et al., 2025). For CI this is very useful, where some spare parts may be rarely needed but become essential when something breaks. Muvunzi et al. (2022); Dzogbwu et al. (2023) show this in rail and industrial settings. In these cases, AM is not mainly used to replace normal mass production, but to help restore operations when a missing part could otherwise cause a long delay. In order to make on-demand manufacturing feasible, a digital inventory must be established to be as a complementary feature to AM, by design repositories that can be transmitted electronically and manufactured near the point of use (Nazir et al., 2021).

2.2.2. Additive Manufacturing vs Conventional Manufacturing

AM and conventional manufacturing differ when disruption occurs. Conventional manufacturing is usually built around large-scale production, standardisation, and low unit costs across high volumes. It depends on centralised factories, established supplier networks, specialised equipment, and inventory planning based on expected demand. In stable conditions, these features make production efficient and reliable. During disruption, the same features can create problems. Long supply routes, high setup costs, and fixed production schedules can make it difficult to respond quickly when demand changes or supply chains are interrupted (Alogla et al., 2021; Kleer and Piller, 2019). AM is less tied to specialized equipment, easier to distribute across different locations, and more suitable for small batches or special parts. It can also shift between designs more quickly than many conventional processes. Its strength is not in replacing mass production where large volumes are needed at the lowest cost. Instead, its value lies in situations where speed, local access, design adjustment, and small-scale production are more important.

Table 2.2 shows the key differences between conventional manufacturing and additive manufacturing under conditions of supply chain disruption. The comparison shows that the two models are organized around different production logics. Conventional manufacturing usually works better when large-scale production, high output, and standardized products are needed. In contrast AM may be more useful where disruption creates urgent, localised, low-volume, uncertain, or highly customized demand. In order to analyze resilience, we should make this distinction as the literature presents AM as a complementary capability that can support supply chain flexibility, local production, digital inventories, and emergency response, while also recognizing its limits in relation to material availability, process reliability, certification, and cost (Alogla et al., 2021; Kleer and Piller, 2019; Manero et al., 2020; Naghshineh and Carvalho, 2022; Tareq et al., 2021).

Table 2.2: Comparison of conventional manufacturing and additive manufacturing under disruption

Dimension	**Conventional manufacturing under disruption**	**AM under disruption**	**Implication for resilience**	**Authors / source support**
Production geography	Typically centralised and supplier-dependent, especially where production relies on economies of scale and distant suppliers.	More easily distributed and localised, particularly when AM capacity is available near the point of need.	AM can reduce transport vulnerability and support production closer to the point of need.	(Kleer and Piller, 2019; Manero et al., 2020; Tareq et al., 2021).
Inventory	Physical stock and forecast-driven restocking, with disruption risk when demand exceeds available inventory.	Potential for digital inventory plus local print-on-demand.	Useful for rare and uncertain-demand items.	(Alogla et al., 2021; Manero et al., 2020; Naghshineh and Carvalho, 2022).
Scale economics	Strong for large, standardised production volumes because fixed tooling and setup costs are spread across many units.	Stronger for low-volume, high-variety, customised output because AM does not rely on dedicated tooling in the same way.	AM helps where flexibility matters more than scale efficiency.	(Alogla et al., 2021; Kleer and Piller, 2019).
Lead times	Long when tooling, shipping, supplier coordination, or production ramp-up is needed.	Shorter when validated designs, feedstock, machines, and operators are available locally.	AM can act as a bridging capability while conventional supply chains recover.	(Manero et al., 2020; Naghshineh and Carvalho, 2022; Tareq et al., 2021).
Customisation	Often costly and slow because it may require new tooling, setup, or process changes.	Comparatively easy because production can be modified through digital design files.	Valuable for emergent or user-specific needs.	(Alogla et al., 2021; Kleer and Piller, 2019; Tareq et al., 2021).
Resilience role	A reliable main support system during normal, predictable, and high-volume operations.	Agile supplement during volatility, scarcity, demand uncertainty, or localised disruption.	Complementarity rather than substitution.	(Alogla et al., 2021; Manero et al., 2020; Naghshineh and Carvalho, 2022).

2.2.3. Additive Manufacturing in Crisis and Humanitarian Settings

In crises, AM is valuable because it can shorten the time between identifying a need and producing a usable item. In emergencies, the situation is often unclear, demand can change quickly, and normal purchasing or delivery routes may not work properly. AM can help in these moments by allowing people to test designs quickly, improve them as needed, and produce them locally or across different sites once a workable design is ready (Marchetta-Cruz et al., 2025; Manero et al., 2020; Nazir et al., 2021). This was clear during the pandemic, when hospitals, universities, companies, and maker groups used AM to produce items such as protective equipment, testing accessories, ventilator parts, and other medical supplies.

AM can also be useful beyond healthcare. It can support decentralized aid, improve access to medical services in remote areas, help produce parts for temporary shelters, and allow mobile production in emergency settings (Marchetta-Cruz et al., 2025). Even though some of these uses are still developing, AM can bring part of the production process closer to the crisis area. This can reduce the time between recognizing a need and producing something that can actually be used. In emergencies, its value also depends on how well available printers, materials, designs, and people are coordinated across different locations and needs (He et al., 2021). There are also some limitations of AM. One major issue is materials. Not every material can be printed locally, and even when printing is possible, the final part may not always have the strength, durability, heat resistance, or medical safety needed for real infrastructure or healthcare use (Tofail et al., 2018; Kalkanis et al., 2023). Moreover Printers need to be maintained, calibrated, and repaired, and this can be difficult in low-resource settings where technical support, replacement printer parts, or trained operators may be limited (Tofail et al., 2018; Marchetta-Cruz et al., 2025). Also, AM is often not the best option for making large quantities over a long period because many processes are slower and more expensive than conventional manufacturing. This is why traditional manufacturing is still essential when demand is stable and large volumes are needed (Keskin et al., 2025; Kleer and Piller, 2019).

AM also depends on basic support systems, especially electricity and technical skills. A digital design file is not very useful if the power supply is unreliable, if people do not have the software skills to prepare the file, or if operators cannot check the right printing settings and finishing steps. This becomes even more important in crisis settings, where the systems needed to support AM may be just as fragile as the supply chains it is supposed to help with (Manero et al., 2020; Marchetta-Cruz et al., 2025). There are also concerns around rules, responsibility, and safety, especially in medical emergencies. In urgent situations, parts may be produced faster than formal approval systems can respond. This raises concerns about testing, legal responsibility, and how much risk is acceptable when time is limited (Kalkanis et al., 2023; Manero et al., 2020).

The challenges are not only technical. AM also needs good organisation to work well. If there is poor coordination, no trusted database of approved designs, weak procurement systems, limited connection with emergency responders, or unclear decision-making, then AM may not be used effectively, even when the printers and materials are available (Manero et al., 2020; Naghshineh and Carvalho, 2022; Keskin et al., 2025; Singh et al., 2024b).

2.3. Applications of Additive Manufacturing

2.3.1. Recasting the Supply Chain

AM should not be treated as a direct replacement for conventional humanitarian logistics. It is more useful to understand it as a change in where production capacity is placed. In humanitarian settings, 3D printing does not automatically make the supply chain shorter. Instead, it changes the type of things that need to move through it. Finished products may need to travel less from distant factories, but other inputs still have to be available, such as raw materials, printers, digital files, spare parts, software, and technical expertise. The four models of humanitarian AM, which include production through a local hub, production by the implementing organisation, production in a mobile facility, and production through distributed local hubs, show that the shift is not only about moving production from far away to nearby places. It is more about moving from the transport of finished goods to the transport of the ability to produce them. Each model also has different effects on speed, governance, last-mile delivery, and local ownership (Corsini et al., 2022).

A similar argument is made in relation to military and humanitarian mission logistics. AM can improve responsiveness because parts can be produced closer to teams working in the field. This can reduce waiting times, lower the need for large stocks, and decrease the risk of spare parts becoming outdated. However, this does not mean that dependency disappears. It only changes shape. Instead of depending on finished spare parts arriving from outside, organisations may become dependent on electricity, feedstock, digital designs, data security, machine maintenance, and people with technical skills (Den Boer et al., 2020). From a crisis-management point of view, AM can also make storage and transport easier, since some reserves can be kept as raw materials rather than finished products. Still, portable printing is not always reliable in difficult field conditions. Unstable electricity supplies, damaged infrastructure, or harsh operating environments can interrupt production or stop it completely. Because of this, the printer alone is not enough. What matters is the wider system around it, since this system decides whether AM can actually work during a crisis (Wysoczański et al., 2021).

2.3.2. Health

Health is the area where the evidence is clearest and most developed. Even before COVID-19, many humanitarian uses of AM were already focused on medical and assistive devices, such as prosthetics, suction pump repairs, microscopes, tourniquets, and spare parts. In the twelve cases examined by (Corsini et al., 2022) several examples come from healthcare settings, including prosthetic arms in East Africa, South Sudan, Nepal, Jordan, and Cambodia, a suction pump spare part in Nepal, a complete suction pump machine in Kenya, and medical optics in Kenya and Tanzania. These examples do not suggest that AM is mainly about producing medical goods in large quantities. Instead, they show its value in situations where local fit, quick redesign, patient needs, or equipment downtime are more urgent than mass production.

This point is also clear in several health-related cases. In Nepal, a spare connector for a suction pump was produced for a rural health post within a few hours, and the printed part was estimated to cost around 90% less than replacing the whole machine.However, the case also showed some limits, since the health post still depended on outside support for design, maintenance, and technical knowledge (Corsini and Moultrie, 2019). In Kenya, a suction pump machine was developed through a wider process that included designers, engineers, hospital staff, procurement officers, and local manufacturers. The design was adapted to local conditions, such as rough floors, nursing practices, easier repair, modular parts, and lower costs. This made the printer part of a broader local production system, not only an emergency tool (Corsini and Moultrie, 2019).

COVID-19 expanded the role of AM much further. During the early pandemic, many projects focused on personal protective equipment, with PPE forming 60% of the reviewed projects and face shields making up 62% of those PPE-related efforts. Online platforms such as GitHub, GitLab, and the NIH 3D Print Exchange also became important for sharing designs and organising collaboration. This showed the strength of distributed manufacturing, but also its difficulties. Designs could spread very quickly, while validation was often slower, and the many different versions sometimes created confusion for healthcare workers and makers(Novak and Loy, 2023).

The pandemic also showed that successful AM responses depend on networks, not only on printers.

Effective face-shield production, for example, needed hospitals, municipalities, makers, universities, companies, and regulators to work together. Companies helped source non-printed parts, coalition leaders managed liability and distribution, and trusted organisations helped review suitable designs. This suggests that short-run custom manufacturing capacity, trusted design repositories, and community manufacturing networks should be prepared before a crisis, rather than built only after the emergency begins (Manero et al., 2020). Other pandemic uses also included masks, ventilator parts, tissue models, door openers, and isolation facilities, but these raised further issues around safety, certification, design quality, manufacturing standards, and legal responsibility (Wang et al., 2021).

Another issue was coordination and cooperation between different actors. When there are many manufacturers, many requests, and several disaster sites, printing capacity cannot be used randomly. It needs to be organised so that the right products are made in the right places and at the right time (He et al., 2021).

2.3.3. Water, Sanitation, and Hygiene (WASH)

In WASH applications, AM is mainly useful for quick repair and adaptation rather than for producing whole water or sanitation systems. Its value is clearer when normal supply routes are slow, blocked, or not available. After the 2015 earthquake in Nepal a remote camp lost access to clean water because a plastic pipe fitting broke. A normal replacement was difficult to get, and the nearby available fittings were made from the wrong material. The broken part was measured and a replacement was printed in less than a day, which allowed the water supply to be restored locally instead of waiting for the usual relief supply chain (Lipsky et al., 2019). This kind of example shows how fused deposition modelling can help produce small repair parts for water, sanitation, and hygiene equipment directly on site (Rodríguez-Espíndola et al., 2020). AM has also been used for hygiene products, not only infrastructure repair. One example is a hand-washing device used in a conflict setting in Lebanon. In this case, ideas were crowd-sourced, prototypes were produced quickly, and the designs were tested in the camp environment. The aim was not to replace the full WASH supply chain. Instead, AM helped make the design process faster, so products could be tested, adjusted, and later prepared for wider production through more conventional methods (Corsini et al., 2022; Lipsky et al., 2019). At the same time, AM has clear limits in WASH. Many water and sanitation systems depend on large pieces of equipment, which are not suitable for 3D printing. Because of this, AM is better suited to smaller parts, such as fittings, connectors, adapters, customised attachments, and repair components, rather than complete sanitation systems or large-scale water infrastructure (Corsini et al., 2022). A similar point can be seen in water filtration. Filter housings may be printed locally, but the more specialised filter materials would still need to be transported. This may reduce transport volume, but it does not mean the whole purification system can be produced on site (Wysoczański et al., 2021).

2.3.4. Shelter

In shelter-related work, AM is often discussed as a possible way to respond to urgent housing needs after disasters. The main idea is that large-scale printing could be useful where labour, materials or access are limited. This does not mean the technology is already ready for wide use in every disaster setting. Rather, its potential comes from automation, custom design, and the possibility of using some materials that are available locally. In this way, AM could help produce emergency shelters or more tailored longer-term housing when normal construction is too slow or difficult to organise (Camacho et al., 2018).

Still, the discussion around 3D-printed shelter should not be too optimistic. AM may help shorten supply chains, reduce the need for formwork, lower labour demand, and make better use of local materials. However, these benefits only become realistic when several practical issues are solved. These include material quality, printability, construction logistics, labour skills, structural safety, environmental impact, and whether the printed building can actually work well in its local setting. So, AM is only suitable when local materials can meet technical standards and when printing on site is more practical than conventional construction (Bazli et al., 2023).

2.3.5. Collaboration

Collaboration is a major factor in how AM works, and there could be many forms of collaboration. Digital collaboration is one important form where designs can be shared through online repositories, websites, maker platforms, and cloud-based systems (Corsini et al., 2022; Novak and Loy, 2023). This model enables geographically dispersed actors to design, adapt, print, and troubleshoot together. Corsini et al. (2022) describe how distributed design can support local manufacture, while Novak and Loy (2023) show how websites, GitHub, GitLab, and the NIH 3D Print Exchange helped coordinate pandemic production. Moreover Rodríguez-Espíndola et al. (2020) explore how blockchain and AI could make these information flows more transparent and accountable.

Collaboration also works better when production happens close to the people who will use the final product. This can include hospitals, clinics, makerspaces, local hubs, or community facilities. Being nearby helps users give feedback faster, and it also makes the product more visible and trusted. In health-related cases, printing close to users helped clinicians and patients understand and accept prosthetics and medical devices more easily. Similar examples can be seen in health facilities, community settings, and fab-labs, where AM was connected not only to production, but also to training, livelihoods, and self-help (Corsini et al., 2022; Lipsky et al., 2019). Formal forms of collaborations like institutional collaboration is also important, especially when many actors are involved. This can include stakeholder mapping, framework agreements, and public-private partnerships (Manero et al., 2020; Kolade et al., 2022).

Taken together, the literature establishes a consistent picture of AM's potential across CI sectors, but one that remains partial and under-evidenced when it comes to the conditions that make this potential realisable in practice. Healthcare offers the most developed evidence base, with concrete examples of AM being integrated into care pathways and repair workflows. WASH applications demonstrate clear value in spare-part production and localised repair, though the evidence is limited to specific cases rather than systemic use. Shelter applications are the least mature, with most examples confined to prototypes or single-event responses rather than sustained field implementation. Across all sectors, a shared pattern emerges: AM tends to work best when the production task is specific, bounded, and closely connected to an existing social and organisational infrastructure. Where these conditions are absent, technical capability alone has not been sufficient to drive implementation. Equally important, the literature has tended to examine AM primarily through a technical lens, focusing on what the technology can produce, while paying far less attention to the wider socio-technical conditions that determine whether production capacity actually translates into resilience. This gap between technical potential and implementation reality is the central concern that the following research gap section seeks to formulate.

2.4. Research Gap

The review above points to a genuine and growing interest in AM as a tool for CI resilience during supply chain disruption, but it also reveals three interconnected gaps that existing literature has not resolved.

The first gap concerns sectoral specificity. The literature identifies healthcare, WASH, and shelter as relevant domains, but the evidence is uneven and context-dependent. Healthcare is the most developed, with real examples of AM being used for prosthetics, medical-device repair, and customised components in humanitarian settings. WASH and shelter applications are far less established, with most examples confined to pilots or single-event responses that have not demonstrated sustained integration into infrastructure systems. More importantly, the literature does not explain why some sectors offer more viable pathways for AM than others, or what it is about the technical and social characteristics of a sector that determines whether AM can be meaningfully integrated. Without this, it is impossible to understand where AM genuinely strengthens CI resilience as opposed to where it remains a promising but unrealised possibility. This motivates the first research sub-question:

In which critical infrastructure sectors can additive manufacturing support resilience during supply chain disruption?

The second gap concerns the conditions of implementation. The literature acknowledges that AM faces both technical and social barriers, such as material constraints, machine quality, skills gaps, coordination challenges, and weak institutional support, but these tend to be discussed in isolation or listed as separate limitations rather than examined as an interconnected set of conditions. This matters particularly in low-resource and crisis-affected settings such as Gaza, the West Bank, and northwestern Syria, where disrupted supply chains, limited technical capacity, fragmented governance, and competing humanitarian priorities are not background constraints but the primary determinants of whether a technology like AM can function at all. The existing literature does not offer a coherent account of how technical and social factors combine in such settings to enable or prevent implementation. Understanding this combination, rather than merely cataloguing individual barriers, is essential for any realistic assessment of AM's contribution. This leads to the second sub-question:

What technical and social factors enable or constrain the contribution of additive manufacturing to infrastructure resilience?

The third gap concerns how AM's contribution to resilience is framed and examined. Most studies treat resilience as a single, undifferentiated outcome: AM is described as useful for crisis response or supply chain flexibility without distinguishing between different dimensions of what resilience actually involves. The 4Rs framework draws a meaningful distinction between robustness, redundancy, resourcefulness, and rapidity, but this framework has not been systematically applied to empirical research on AM in crisis-affected settings. As a result, it remains unclear whether AM supports all resilience dimensions equally, or whether its contribution is concentrated in some dimensions and limited in others. This has practical consequences: a technology that primarily supports rapidity but not robustness demands different investments and institutional arrangements than one that strengthens redundancy or resourcefulness. Without a differentiated analysis, policy and practice cannot be well-informed. This motivates the third sub-question:

In what ways does additive manufacturing relate to different dimensions of critical infrastructure resilience during supply chain disruption?

Together, these three gaps converge on a single overarching concern and give rise to the main research question that this study sets out to answer:

How does additive manufacturing contribute to the resilience of critical infrastructure during supply chain disruption in low-resource and crisis-affected settings?

Answering this question requires an empirically grounded study that examines AM not as a technical capability in isolation, but as a socio-technical intervention whose contribution to CI resilience depends on the interplay between people, organisations, institutions, and technology in specific crisis contexts. It also requires a theoretical framework that can hold technical and social dimensions together and provide a structured way of examining resilience outcomes across the three sub-questions identified above. The following section introduces the two frameworks that together meet this need.

2.5. Theoretical and Conceptual Framework

The gaps identified in the preceding section share a common feature: none of them can be addressed by treating AM as a purely technical tool. Whether AM supports CI resilience in a given sector depends not only on what the technology can produce, but on whether the surrounding social, organisational, and institutional conditions make production meaningful, trusted, and sustained. Understanding the factors that enable or constrain implementation requires a framework that treats technology and its social context as inseparable. And analysing resilience in a differentiated way requires a lens that specifies what different resilience dimensions look like in practice and how they can be distinguished empirically. Two frameworks address these needs directly. The socio-technical systems (STS) perspective provides the theoretical foundation for examining how technical capabilities and social conditions interact to produce, or prevent, resilience-supporting outcomes. The 4Rs framework provides the analytical vocabulary for distinguishing between robustness, redundancy, resourcefulness, and rapidity as different dimensions of resilience. Together, they form the conceptual basis of this study and constitute the most appropriate response to the gaps identified above.

2.5.1. Socio-Technical Systems

Socio-technical theory emerged as a response to technological determinism, which assumes that technological implementation produces direct and inevitable effects on organizational and social outcomes. In contrast, STS argues that outcomes can only be understood by considering social, psychological, environmental, and technological systems together rather than in isolation. Therefore, STS functions both as a normative perspective, concerned with designing systems that support organizational and human goals and suggesting that people should be involved in designing the relationships between technology and work, and as a theoretical perspective for analyzing the relationship between people, technology, and organizational performance (Emery and Trist, 1960; Griffith and Dougherty, 2001). At the core of STS is the idea that organizations consist of interdependent social and technical subsystems. The effectiveness of the system depends on how these subsystems are designed in relation to one another and in relation to the demands of their environment (Cirik and Mendonça, 2009; Griffith and Dougherty, 2001). STS therefore rejects the view of technology as a standalone or monolithic force. Instead, technology is understood as a system of physical, social, and cognitive elements that are built, used, and reshaped in practice, and that interact continuously with interpersonal relations, task allocation, design, engineering, and manufacturing processes (Kahlen et al., 2017). Several principles defines the STS perspective. First, joint optimization means that system performance depends on the alignment of the technical and social subsystems, privileging one at the expense of the other is likely to weaken performance and utility. Second, STS treats organizations as open systems, meaning that they are shaped by ongoing interaction with their wider environment. Third, STS adopts a position of anti-technological determinism, recognizing that people do not simply adapt to technology in a fixed or automatic way, but actively shape and respond to it within broader organizational and social contexts (Frei et al., 2016; Cirik and Mendonça, 2009). For these reasons, STS has become increasingly relevant in research on complexity and resilience, particularly in relation to critical infrastructure, where socio-technical resilience has been described as the capacity of a complex adaptive system to sustain essential services under disruption and ongoing change (Amir and Kant, 2018).

2.5.2. Relevance of STS to This Study

The STS perspective is particularly relevant to this study because the use of AM in disruption-affected settings cannot be understood as a purely technical issue. Existing work already suggests that the sustained use of localized AM solutions for CI resilience is limited not only by material or engineering constraints, but also by organizational fragmentation, insufficient local technical capacity, and the absence of effective models for cross-sector collaboration and community involvement (Petrenj et al., 2023; Mohd Zahari et al., 2025; Priyadarshini et al., 2025; Bazli et al., 2023). These challenges point directly to the need for an approach that can analyze technology together with the social and institutional conditions in which it is deployed. In the context of this study, the technical system includes the material and operational elements required for AM to function in practice, such as hardware, raw materials, CAD files, and data-sharing infrastructures. At the same time, the social system includes the actors and the relationships between them that shape how the technology is accepted, coordinated, and used. These include NGOs, technology providers, community actors, local skills and knowledge. The key STS insight for this study is that resilience-supporting outcomes do not arise from technical capability alone, but from the interaction between these two systems. For this reason, STS offers a more suitable theoretical foundation for the present research than a purely technical perspective. It makes it possible to examine AM as a socio-technical intervention whose contribution to CIR depends on the alignment between material capacity, institutional support, stakeholder coordination, and local capability. Low-resource and crisis-affected settings create distinct conditions for technological intervention, shaped by scarcity, disrupted infrastructure, fragmented governance, and uneven access to knowledge and resources.

It is important to note that STS theory was originally developed in the context of stable organizational environments where the design of work could proceed through deliberate socio-technical alignment (Pasmore et al., 2019). Crisis conditions fundamentally disrupt these assumptions. In conflict zones and disaster-affected settings, the social system is fragmenting in real time: organizations lose staff, funding becomes unpredictable, institutional authority is contested, and community structures are under stress. The technical system is equally unstable: equipment breaks down, supply chains collapse, and infrastructure that AM depends on, such as electricity, internet connectivity, logistics, may be intermittently or permanently unavailable. Applying STS in this context therefore requires treating joint optimization not as a design ideal to be achieved, but as a dynamic and contested process that must be actively maintained against constant disruption.

2.5.3. Resilience Dimensions 4Rs

While the socio-technical systems perspective provides the main theoretical foundation for this study, resilience itself remains a broad concept that requires further specification in order to be analyzed. This study adopts the 4Rs framework as a resilience lens. Originally developed in infrastructure resilience research, the 4Rs conceptualize resilience through four dimensions: robustness, redundancy, resourcefulness, and rapidity. These dimensions offer a practical way to interpret how systems respond to disruption and how their capacity to maintain or restore CI can be understood. The 4Rs are not used as a separate theoretical framework, instead, they are used as an analytical lens that supports the wider socio-technical perspective. The socio-technical framework helps explain how resilience is shaped through the relationship between technical systems and social conditions. The 4Rs help make resilience more specific and easier to examine in practice.

2.5.4. Conceptual Framework

Building on the socio-technical systems perspective and the 4Rs resilience lens, this study develops an integrated conceptual framework for understanding how additive manufacturing may support critical infrastructure resilience during supply chain disruption. The framework is based on the assumption that additive manufacturing does not contribute to resilience through technical capacity alone. Rather, its role depends on the interaction between technical resources, social conditions, and the ways in which these together shape resilience outcomes in practice.

The first component of the framework is the technical system. In the context of this study, this includes the material and operational elements required for additive manufacturing to function, such as printers, feedstock materials and digital designs. These elements determine the technical feasibility of using AM in a given setting. However, technical feasibility alone is not sufficient to generate resilience. The contribution of AM also depends on whether these technical resources are available, accessible, adaptable, and usable under the conditions created by crisis, disruption, and resource scarcity.

The second component is the social system, which includes the actors and the relationships between them that shape how AM is implemented and governed. This includes NGOs, technology providers, local communities, and other stakeholders involved in response, recovery, or service continuity. It also includes forms of Trust, collaboration and community participation. From a socio-technical perspective, these social elements are not secondary to the technology but central to whether AM can be meaningfully mobilized in practice. The use of AM in crisis-affected settings, depends not only on whether the technology exists but also on whether the social system can support its deployment, coordination, and long-term use.

At the center of the framework is the interaction between these two systems, understood through the principle of joint optimization (Frei et al., 2016; Griffith and Dougherty, 2001). This means that resilience-supporting outcomes are most likely to emerge when technical and social systems are aligned rather than treated separately.

These socio-technical interactions are interpreted through the 4Rs, which serve as the resilience outcome dimensions within the framework. In this way, the 4Rs unpack resilience into more specific forms of contribution, making it possible to examine not only whether AM appears useful but also how that usefulness is understood in resilience terms.

This framework serves as a guide for answering the research questions. The framework links the socio-technical systems perspective with the 4Rs resilience lens to structure how additive manufacturing is examined across sectors, resilience dimensions, and implementation conditions. In this way, it provides a foundation for both the empirical findings and the interpretation of findings and it is directly linked to the three sub-questions of the study.

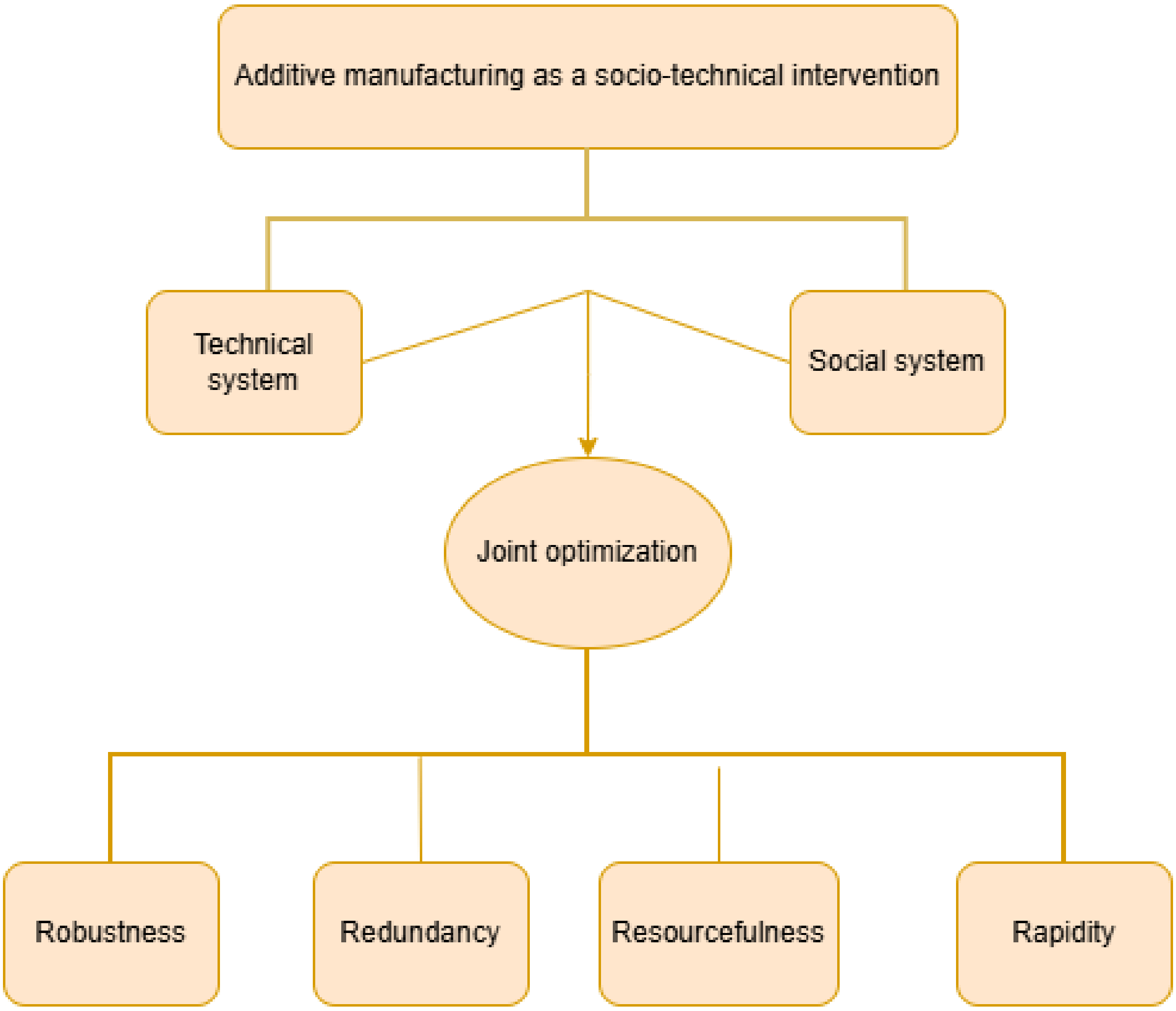

Figure 2.1: Conceptual framework: additive manufacturing as a socio-technical intervention linking the technical system and social system to resilience outcomes interpreted through the 4Rs dimensions

3

Methodology

This chapter outlines the methodological approach adopted in this study. It explains the research design, the data collection strategy, and the analytical approach used to examine the role of additive manufacturing in supporting critical infrastructure resilience during supply chain disruption. This study uses a qualitative, socio-technical research design supported by a literature review, with resilience interpreted through the 4Rs lens.

3.1. Research Design

This study adopts a qualitative exploratory research design grounded in a socio-technical systems perspective to examine how AM supports the resilience of critical infrastructure during supply chain disruption in low-resource and crisis-affected settings. A qualitative approach is appropriate because the study seeks to understand the relationships between technology and social actors. To formulate and address the research questions, a combination of a literature review and semi-structured interviews with eight participants drawn from three distinct stakeholder groups (community-level actors, NGO and humanitarian practitioners, and technology providers) was employed. A literature review was conducted to understand the under-explored domain of AM in certain places in the Middle East where supply chains are disrupted due to disasters. In order to explore the gaps identified in the literature, the interviews helped build upon existing knowledge and provided flexibility and in-depth insight into the practical realities of using AM in these contexts. By engaging with participants who had direct experience or relevant expertise, the interviews aimed to capture perspectives that may not be fully represented in academic publications. This approach allowed for a deeper understanding of the challenges, opportunities, and contextual factors influencing the adoption of AM during supply chain disruptions.

Researcher positionality

The researcher's background is relevant to this study and warrants explicit acknowledgement. As someone with personal and cultural connections to the Middle East, and with prior awareness of the humanitarian situation in Gaza and Syria, the choice of this research context was not neutral. This proximity carried potential advantages, familiarity with the regional context, ease of communication with Arabic-speaking participants, and sensitivity to the political dimensions of the research problem. At the same time, this created a risk that the focus might be too much on findings that matched what I already expected while giving less attention to evidence that challenged those expectations. To manage this, the analysis was conducted using a structured coding process, with deductive codes derived from the theoretical framework and inductive codes grounded closely in participant language rather than the researcher's own framing.

3.2. Literature Review

A literature review was conducted to provide the conceptual foundation for this study and to situate it within existing academic and practical discussions on critical infrastructure resilience, additive manufacturing, and disrupted settings. The review was structured and purposive in its approach: it was guided by a defined set of search terms and inclusion criteria, and it drew on the researcher's critical judgment to identify, evaluate, and connect relevant sources across multiple overlapping fields. The purpose was to identify key concepts, debates, and areas of fragmentation relevant to the research problem, and to provide the conceptual grounding needed to develop the study's theoretical framework and research questions.

The review served as a methodological support for the study in several ways. It helped shape the research focus, refine the research questions, and identify the main conceptual and empirical gaps addressed in the thesis. More specifically, it provided the conceptual grounding needed to frame critical infrastructure resilience as a socio-technical issue, clarified how additive manufacturing has been discussed in relation to localised production and disruption response, and helped identify the central gap that this thesis addresses.

The search process was designed to identify literature directly relevant to the study's scope. Initial searches were conducted in Scopus, ScienceDirect, and Google Scholar, as these databases provide broad coverage across engineering, social science, and disaster studies relevant to the topic. Search terms were developed around the core concepts of the study and included individual keywords and combinations such as *critical infrastructure resilience*, *additive manufacturing*, *3D printing*, *supply chain disruption*, *disaster response*, *humanitarian settings*, and *stakeholder collaboration*. These terms were used both individually and in combination using (AND/OR), for example *additive manufacturing AND supply chain disruption*, *3D printing AND humanitarian settings*, or *critical infrastructure AND resilience AND low-resource settings*. Sources that used the terms but had no substantive relevance to the study's core themes were excluded. Different combinations were tested across the databases to capture literature from multiple disciplinary angles. Following the initial database search, a snowballing strategy was used to identify additional relevant sources by reviewing the reference lists of key articles and tracing frequently cited or conceptually related studies. This was particularly useful because the research problem spans several overlapping fields, and relevant contributions were not always captured through keyword searches alone.

The selection of sources was guided by relevance to the research focus. Priority was given to publications addressing critical infrastructure resilience, additive manufacturing in disrupted or resource-constrained settings, supply chain resilience, and the social or collaborative dimensions of implementation. Peer-reviewed journal articles formed the main body of the review, although selected books, conference papers, and technical reports were included where they made a clear conceptual or contextual contribution. Sources focused exclusively on additive manufacturing in purely industrial or commercial settings without relevance to resilience, or addressing infrastructure without connection to the study's central themes, were excluded. Table 3.1 summarises the full inclusion and exclusion criteria applied during source selection.

Category	Inclusion criteria	Exclusion criteria
Language	English-language publications	Publications in languages other than English
Publication period	Publications from 2015 onward	Publications before 2015, except where included as foundational sources
Source type	Peer-reviewed journal articles, academic books and book chapters.	Informal blogs, news articles, non-academic websites, unpublished student theses, and sources lacking clear scholarly or practical relevance
Search terms	Combinations of keywords including critical infrastructure resilience, additive manufacturing, 3D printing, supply chain disruption, supply chain resilience, disaster response, humanitarian settings, low-resource settings, crisis-affected settings, and stakeholder collaboration.	
Topical relevance	Studies addressing one or more of the following: critical infrastructure resilience, additive manufacturing in disrupted, crisis-affected, or resource-constrained settings, supply chain resilience, disaster or humanitarian response, and technical, social, organizational, or collaborative dimensions of implementation	Studies focused exclusively on narrow technical performance without relevance to resilience or implementation, studies on infrastructure without connection to additive manufacturing, studies on additive manufacturing without relevance to disruption, crisis, or resilience

Table 3.1: Inclusion and exclusion criteria for source selection

3.3. Data Collection

This study draws on two main sources of data, a literature-based review of existing scholarship and semi-structured interviews with relevant stakeholders. Combining these sources allows the research to connect conceptual insights from prior work with first-hand perspectives from practice, thereby supporting a more grounded and context-sensitive understanding of additive manufacturing in disruption-affected settings. The literature review helped identify the main themes, debates, and knowledge gaps surrounding critical infrastructure resilience, additive manufacturing, and stakeholder collaboration, while the interviews introduced an empirical dimension by capturing the experiences, expectations, and constraints described by participants directly engaged with these issues. In this way, the data collection strategy was designed to produce both conceptual depth and practical insight, while ensuring that the study remained closely aligned with the research questions.

3.3.1. Semi-Structured Interviews

Semi-structured interviews were used as the primary method for generating empirical data in this study. This method was considered appropriate because it provides a balance between structure and openness: the researcher works with a predefined set of themes while retaining the flexibility to ask follow-up questions, adjust the order of questions, and explore issues that emerge during the conversation. In this sense, semi-structured interviews occupy a middle position between structured interviews, which follow a fixed sequence of questions, and unstructured interviews, which are more open ended and conversational (DeJonckheere and Vaughn, 2019; Kallio et al., 2016). The development of the interview guide followed the logic of rigorous semi-structured interview design. Kallio et al. (2016) emphasizes that a strong interview guide should be grounded in previous knowledge, aligned with the research questions, and developed through a transparent process. The choice of semi-structured interviews also aligned with the multi-stakeholder character of the study. Participants engaged with additive manufacturing from different positions, including technical, organizational, humanitarian and community-based. This format enabled the study to maintain consistency across interviews while still allowing each participant to emphasize the issues most relevant to their experience and role. The questions were open-ended, clear, neutral, and non-leading.

3.3.2. Participant Selection and Sampling

A total of eight participants were recruited for this study. This sample size was considered appropriate for an exploratory qualitative study of this scope. In qualitative research, sample adequacy is assessed not by statistical representativeness but by the concept of information power: a sample is sufficient when it provides enough richness and variation to answer the research questions with credibility (Malterud et al., 2016). Given the specificity of the research problem " practitioners with direct experience of AM in crisis-affected or low-resource settings " the population of eligible participants was inherently limited. Eight participants drawn from three distinct stakeholder groups, spanning the same regional contexts and covering all three infrastructure sectors of interest, provided sufficient variation to identify cross-cutting patterns while remaining manageable for in-depth qualitative analysis.

Participants were selected through purposive sampling, as the study required perspectives from individuals with relevant knowledge or experience related to additive manufacturing, resilience, and implementation in disruption-affected settings. Purposive sampling was applied because the aim of the study was not to obtain a statistically representative sample but to engage with stakeholders who could provide informed and experience-based insights into the research problem (Rai and Thapa, 2015). In qualitative research, such a strategy is particularly suitable when the objective is to explore a phenomenon in depth and from multiple relevant viewpoints. The sampling approach was guided by the socio-technical orientation of the study. To capture both technical and social dimensions of additive manufacturing in practice, the eight participants were drawn from three distinct stakeholder groups: (1) community-level actors, who represented the perspective of people directly affected by infrastructure disruption; (2) NGO and humanitarian practitioners, including field implementation actors and innovation lab practitioners; and (3) technology providers, including digital fabrication specialists, AM technical service providers, and construction printing professionals. These three groups were selected because they represent different forms of involvement in the design, distribution, implementation, or local use of additive manufacturing in disruption-affected contexts. Bringing these perspectives together made it possible to explore how resilience is shaped not only by technological capability but also by collaboration, institutional arrangements, local knowledge, and practical constraints.

Participants were identified through professional networks and targeted outreach via LinkedIn. The researcher used LinkedIn to locate practitioners and professionals with demonstrable experience in additive manufacturing, humanitarian response, local production, or related fields in relevant regional contexts. Direct contact was made with a brief description of the study and an invitation to participate. In several cases, initial participants suggested further contacts, incorporating a limited element of snowball sampling within the purposive framework. A participant was included only if they had direct professional experience or substantive knowledge relevant to the research questions; their stakeholder group and regional context were considered alongside this criterion to ensure the sample reflected the variation required by the socio-technical orientation of the study.

3.3.3. Interview Procedure

The interviews were conducted using a semi-structured format guided by a flexible interview protocol. The interview guide was developed on the basis of the research questions and the socio-technical orientation of the study. Each interview began with a brief introduction to the study. The researcher explained the purpose of the research, the general structure of the interview, the expected duration, and the voluntary nature of participation. Participants were also given the opportunity to ask questions before the interview began. Participants needed to understand what participation involved, how their data would be used, and that they could decline to answer any question or withdraw from the study. the introduction helped establish rapport and create a conversational environment in which participants could speak openly. The opening questions invited participants to introduce themselves, describe their role, and explain their connection to additive manufacturing, humanitarian response, local production, or disruption-affected contexts. The interview then moved gradually toward the central themes of the study. Participants were asked to reflect on where additive manufacturing might be useful, what kinds of disruptions it could respond to, and which sectors or needs it might address. During the interview, the researcher used probing questions for clarification and more elaboration. The interviews were conducted online via Microsoft Teams due to practical considerations, including participants' availability, geographical location, and scheduling constraints. Online interviewing was appropriate for this study because it allowed participants from different locations to take part

Each interview lasted approximately 45 minutes. This duration provided sufficient time to cover the main themes of the interview guide while allowing participants to elaborate on issues they considered significant. The length also reflected a balance between depth and participant burden. The interviews were conducted in either English or Arabic, depending on the participant's preference. Allowing participants to choose the language of the interview helped support clarity, comfort, and more accurate expression of experience. Interviews conducted in Arabic were transcribed verbatim in Arabic by the researcher, who is a native Arabic speaker, and subsequently translated into English for analysis. To maintain accuracy, translated segments were cross-checked against the original Arabic transcripts during the coding process, and any ambiguities in meaning were resolved by returning to the original phrasing rather than relying on the translation alone. With participants' consent, the interviews were recorded to support accurate analysis. Recording allowed the researcher to focus on listening and facilitating the conversation rather than relying solely on note-taking. It also enabled the interviews to be transcribed and revisited during analysis, preserving participants' wording and reducing the risk of misrepresentation. The recordings were stored securely on TU Delft OneDrive to ensure protected access and appropriate data handling.

3.3.4. Overview of the Participants

This study draws on eight semi-structured interviews with participants selected through purposive sampling to reflect the main actor groups relevant to AM in crisis-affected and low-resource settings. The interview sample was designed to capture variation across the socio-technical system rather than to represent a single organization or sector. Accordingly, the participants include community-level actors, humanitarian practitioners, innovation and fabrication practitioners, and technology providers. Geographically, the interviews span contexts directly affected by war, displacement, or infrastructural disruption, including the West Bank, North Gaza, Jordan, and Syria, as well as a technology provider working internationally. This broadens the analysis beyond a single case while still keeping the focus on crisis-affected and resource-constrained settings. It also supports cross-case comparison between different types of additive manufacturing applications, including prosthetics, hearing devices, spare parts, WASH-related components, shelter-related prototyping, and large-scale construction printing.

To protect confidentiality, all participants are anonymized and identified using the labels P1 to P8. Where relevant, participants are described by role, sector, and regional context rather than by personal identifiers.

Table 3.2: Overview of interview participants

Participant	**Stakeholder group**	**Role / affiliation**	**Context / location**
P1	Local Community actor	Community actor / engineer	West Bank
P2	LocalCommunity actor	Community / engineer	North Gaza
P3	NGO	CEO Humanity Link / prior UN and World Vision experience	International / multi-country humanitarian experience
P4	Humanitarian field implementation actor	Director, Field Ready	MENA / Syria-related experience
P5	Humanitarian actor	Humanitarian fab lab / innovation lab practitioner	Northwest Syria
P6	Refugee-led innovation actor	Refugee Openware	Jordan / Syrian refugee camp context
P7	AM technical service provider	3D technician, 3DP4ME	Jordan, with work linked to Gaza and Syria
P8	Technology provider	Co-founder, COBOD	International / construction technology context

3.4. Data Analysis

The empirical material in this study was analyzed using qualitative content analysis. This method was chosen because it offers a clear and systematic way to work through interview data while still paying attention to context, meaning, and differences between participants. Qualitative content analysis is useful for organizing large amounts of text into meaningful categories. Its value lies in helping the researcher understand what participants are saying, how they make sense of an issue, and what patterns appear across their accounts (Hsieh and Shannon, 2005; Elo and Kyngäs, 2008). This approach is suitable for the study because the aim was to understand how AM is perceived, used, and limited in relation to critical infrastructure resilience. The method made it possible to identify common ideas across the interviews without putting participants' experiences into simple descriptions. It also helped connect practical stakeholder views to broader questions about resilience and implementation. The analysis combined deductive and inductive reasoning. The deductive part was guided by the socio-technical framework and the 4Rs lens of resilience. At the same time, the analysis remained open to ideas that came directly from the findings. This approach was useful because participants often discussed practical concerns, real examples, and tensions that were not fully expected before the interviews. The study therefore did not treat theory as a fixed framework to be applied to the data. Rather, theory offered a starting point for the analysis, while the interview findings helped shape the final categories and interpretations. This created a balance between existing theoretical ideas and the patterns emerging from the data, which fits well with qualitative research that moves between deductive and inductive analysis to develop, revise, or question existing concepts.

In practice, the analysis was guided by a combination of deductive and inductive logic. A deductive orientation provided an initial analytical structure based on the socio-technical framework and the 4Rs lens of resilience. The socio-technical framework directed attention to the relationship between technical factors, such as AM capabilities, materials, infrastructure readiness, and logistical conditions, and social or organizational factors, such as governance, coordination, stakeholder roles, skills, and community participation. The 4Rs lens added a resilience-oriented structure by framing potential contributions of additive manufacturing in terms of robustness, redundancy, resourcefulness, and rapidity. Together, these perspectives provided a conceptually informed starting point for the analysis and ensured that the empirical material was interpreted in relation to the central themes of the study.

At the same time, the analysis was not limited to these predefined categories. An inductive element was incorporated to capture themes and concerns that emerged directly from the interview data. The realities of implementation in disruption-affected settings could not be fully anticipated in advance, and practical barriers, stakeholder-specific experiences, and context-dependent issues often extended beyond the initial analytical structure.

Throughout the analysis, reflexivity was maintained as a deliberate practice. The researcher's familiarity with the regional context, while valuable for understanding participant accounts, also created the risk of reading expected narratives into the data. To counter this, analytical decisions were documented through brief memos attached to coded segments, unusual or disconfirming evidence was flagged and examined rather than set aside, and the deductive coding structure was treated as a starting point rather than a fixed interpretive grid. This reflexive orientation helped ensure that the analysis remained responsive to what participants actually said rather than what theory predicted they would say.

3.4.1. Coding Process

The coding process was developed in direct relation to the empirical material described in the preceding sections. The analysis drew on eight semi-structured interviews, each lasting approximately 45 minutes, conducted online via Microsoft Teams with participants selected through purposive sampling. Participants were chosen because they had direct experience with or substantive knowledge of additive manufacturing, critical infrastructure resilience, or implementation in disruption-affected settings. Selection was guided by the socio-technical orientation of the study: to capture both technical and social dimensions of AM in practice, participants were drawn from three distinct stakeholder groups, namely community-level actors (P1, P2), NGO and humanitarian field implementation actor (P3, P4), innovation and fabrication practitioners (P5, P6, P7), and a technology provider (P8). No claim to statistical representativeness is made; the aim was to obtain informed, experience-based accounts from actors positioned differently within the socio-technical system of AM implementation. This sampling structure ensured that the coding process remained attentive to variation across roles, sectors, and institutional settings rather than treating all accounts as equivalent.

Coding proceeded in two complementary stages: a deductive stage guided by the study's conceptual framework, and an inductive stage that remained open to themes emerging directly from the data.

Deductive coding

Deductive content analysis was used where the analysis was guided by existing concepts from the literature. In contrast to the inductive approach, deductive analysis begins with a framework, model, or set of concepts that helps structure the reading of the data. This approach is useful when the goal is to apply an existing theory or framework to a new setting, or examine whether it helps explain the material being studied (Kyngäs et al., 2020).

Deductive codes were developed prior to analysis on the basis of the socio-technical systems perspective and the 4Rs resilience lens. These codes provided an initial analytical structure by directing attention toward the dimensions most relevant to the research questions. Rather than functioning as a fixed checklist, they served as a starting point for reading the transcripts: the researcher identified segments of text corresponding to each predefined category and assigned a code capturing the main idea of that segment.

The deductive coding process followed a structured sequence. In the first step, each transcript was read in full before any coding began, in order to gain an overall sense of the participant's account and the context of their experience. In the second step, each transcript was re-read with the codebook open alongside it; text segments judged relevant to the research questions were marked and tagged with the corresponding code. A single segment could receive more than one code where it simultaneously addressed multiple analytical dimensions. In the third step, all segments assigned to each code were reviewed across transcripts to assess consistency and identify recurring patterns. Where a segment did not map clearly onto any predefined code, it was flagged and set aside for the inductive stage rather than being assigned to an ill-fitting category. Throughout this process, the researcher maintained brief annotations explaining each coding decision, supporting reflexivity and transparency in the analytical process.

Table 3.3 presents the full set of deductive codes used in this study, organized by their theoretical origin. The codes are grouped into four clusters: the technical system and social system components drawn from STS theory, the four resilience dimensions drawn from the 4Rs framework, and a set of infrastructure sector codes used to address the first research sub-question.

Table 3.3: Deductive codes derived from the STS framework and 4Rs resilience lens

Origin	**Code**	**What it captures**	**Linked RQ**
Technical system (STS)			
STS-T	AM hardware availability	Whether printers and production equipment are accessible and operational in the setting	RQ2
STS-T	Material and feedstock access	Whether printing materials are obtainable locally or require import through disrupted supply chains	RQ2
STS-T	Digital design infrastructure	Availability and accessibility of CAD files, design repositories, and shared digital knowledge	RQ2
STS-T	Power and infrastructure dependency	Extent to which AM relies on stable electricity and other physical support systems	RQ2
STS-T	Technical fit and quality standards	Whether AM outputs meet the required performance, safety, or durability standards for the intended use case	RQ2
Social system (STS)			
STS-S	Local skills and technical capacity	Availability of trained operators, designers, and technicians in the implementation setting	RQ2
STS-S	Stakeholder coordination	How different actors such as NGOs, technology providers, and communities organize implementation across roles	RQ2
STS-S	Institutional and governance support	Role of organizational structures, procurement systems, and formal decision-making in enabling or blocking AM	RQ2
STS-S	Community participation and ownership	Extent to which end-users are involved in needs identification, design, testing, or governance of AM solutions	RQ2
STS-S	Trust and legitimacy	Whether AM-produced items and processes are accepted and trusted by users and institutions	RQ2
Resilience dimensions (4Rs)			
4Rs	Robustness	AM contributions to preventing service loss, maintaining infrastructure function, or ensuring durability under stress	RQ3
4Rs	Redundancy	AM as an alternative production pathway when conventional supply chains are disrupted or unavailable	RQ3
4Rs	Resourcefulness	Adaptive use of AM to identify problems, mobilize resources, and innovate under constraint	RQ3
4Rs	Rapidity	Speed of AM response in producing items during or after disruption, thereby reducing downtime	RQ3
Infrastructure sectors			
Sector	Healthcare applications	AM use in medical devices, spare parts, prosthetics, hearing aids, and health equipment repair	RQ1
Sector	WASH applications	AM use in water, sanitation, and hygiene infrastructure repair and component production	RQ1
Sector	Shelter and construction	AM use in temporary shelter improvement and large-scale construction printing	RQ1

Inductive coding

While the deductive codes provided an initial analytical structure, many participants described experiences, conditions, and tensions that did not map straightforwardly onto the predefined categories. Inductive coding was therefore incorporated alongside the deductive stage to ensure that data-driven themes were not overlooked or forced into categories that did not genuinely fit.

Inductive content analysis was used to capture ideas that emerged directly from the interview material. This approach is especially useful when existing knowledge about a topic is limited, fragmented, or does not fully explain what is happening in practice. Instead of starting with a fixed list of categories, it implies reading the data closely and allows codes and categories to develop from what participants actually say (Vears and Gillam, 2022).

The inductive coding process proceeded through several clearly defined stages. In the first stage, each transcript was read without the codebook, and any passage that appeared meaningful, recurrent, or analytically notable was highlighted and assigned a provisional first-order code using terminology close to the participant's own phrasing rather than theoretical vocabulary. In the second stage, these first-order codes were reviewed across all eight transcripts; codes addressing the same underlying concern from different angles were grouped together and assigned a more analytical second-order label that captured their common theme without erasing participant-specific nuance. In the third stage, the resulting categories were evaluated for frequency and relevance: codes recurring across multiple participants and connected to the research questions were retained as standalone inductive categories, while those appearing only in isolated accounts were recorded as contextual detail rather than analytical codes. In the fourth and final stage, the inductive categories were assessed in relation to the deductive framework to determine whether they extended, nuanced, or overlapped with existing codes, and were integrated accordingly.

In practice, inductive coding began with a second, more open reading of each transcript after the deductive pass. Segments that appeared meaningful but fell outside the existing framework categories were flagged and assigned provisional codes that stayed close to the language and framing used by participants themselves. This approach resembles what Hsieh and Shannon (Hsieh and Shannon, 2005) describe as open coding: the researcher resists imposing a theoretical label and instead allows the participant's own terminology and emphasis to suggest the category. As all eight transcripts were read and compared, provisional codes were grouped where they addressed similar concerns. Codes that recurred across multiple participants were retained as distinct analytical categories; those too specific to a single account or too peripheral to the research questions were treated as contextual detail rather than standalone codes.

Several inductive codes emerged through this process. Participants repeatedly described a meaningful distinction between using AM for prototyping and using it for full-scale production, a process-level concern that the deductive framework did not fully anticipate. References to dignity, social inclusion, and emotional recovery, particularly in prosthetics and hearing-device accounts, pointed to a social dimension of resilience outcomes that extended beyond technical service restoration and the narrower vocabulary of the 4Rs. Design iteration and user feedback were described as central to how solutions were developed and refined in practice, suggesting an adaptive dimension of AM use not captured by any single 4Rs category. The concept of hybrid manufacturing, in which AM functions as one stage within a broader production process rather than a standalone method, also appeared consistently across participants in different sectors and scales.

These inductive codes were not treated as competing theoretical claims. Rather, they were used to extend and nuance the deductive structure by capturing the practical logic through which participants experienced and understood AM implementation. Some inductive codes were eventually merged with existing deductive categories after it became clear they addressed the same underlying concern from a different angle; others remained as supplementary codes that added specificity to the analysis without replacing the framework categories. The final coding framework, incorporating both deductive and inductive codes, provided the basis for structuring the findings chapter and interpreting results in relation to all three research questions.

The coding process was iterative throughout. Transcripts were read repeatedly, codes were revised, and categories were refined where necessary. Some codes were merged or expanded to better reflect recurring patterns across the sample, while others were added to capture issues that participants emphasized but had not been anticipated in the initial framework. This iterative movement between concept-driven and data-driven coding made it possible to develop an analytical structure that reflected both the theoretical concerns of the study and the lived realities described by participants, and that remained directly linked to the research questions guiding the investigation.

3.4.2. Comparative interview analysis

In addition to the deductive and inductive coding described above, a comparative interview analysis was carried out as a supplementary analytical step. This involved systematically comparing the coded interview material across all eight participants to identify patterns of emphasis, convergence, and divergence between stakeholder groups. The purpose was to make visible which themes were consistently shared across the dataset and which were more specific to particular participants, roles, or sectors. This comparison was conducted using structured matrices that mapped each participant's engagement with the main analytical categories, including sectoral applications, technical conditions, social and collaborative conditions, and resilience contributions across the 4Rs. The matrices did not replace the qualitative interpretation but complemented it by providing a transparent cross-case overview. The full comparative matrices are presented in subsection 5.3.5 of the analysis chapter.

3.4.3. Trustworthiness and Quality

In qualitative research, conventional criteria of reliability and validity do not apply in the same way as in quantitative studies. Instead, Lincoln (1985) framework of trustworthiness provides a more appropriate set of quality criteria, organized around four dimensions: credibility, transferability, dependability, and confirmability.

Credibility refers to the confidence that the findings accurately reflect the participants' perspectives. In this study, credibility was supported through prolonged engagement with the data (repeated readings of all eight transcripts during coding), the use of a structured deductive-inductive framework that required each code to be grounded in specific text segments, and the triangulation of perspectives across three stakeholder groups.

Transferability refers to the degree to which findings may be relevant to other contexts. Rather than claiming generalizability, this study provides thick description of the participants, settings, and conditions, enabling readers to assess whether the findings may transfer to comparable contexts, other low-resource crisis-affected settings where AM is being considered as an implementation tool.

Dependability refers to the consistency of the analytical process. The coding process was documented step by step, with deductive codes derived transparently from the theoretical framework and inductive codes grounded in participant language. The iterative nature of the analysis, and the process of revising categories across multiple readings, is described in the coding section above.

Confirmability refers to the extent to which findings reflect the participants' experiences rather than the researcher's preferences. In this study, confirmability was ensured through an audit trail linking codes to participant text, an explicit deductive framework grounded in STS and 4Rs theory, open acknowledgement of researcher positionality, and active attention to disconfirming evidence, ensuring conclusions remain traceable to the empirical material.

3.5. Ethical Considerations

Ethical considerations were an important part of the research process, particularly because the study involved human participants reflecting on professional experiences and implementation challenges in disruption-affected settings. Although the topic of the research did not involve highly personal or medical data, it still required careful attention to issues of consent, confidentiality, data security, and the responsible representation of participants' views. Ethical care was therefore integrated throughout the design, collection, storage, and analysis of the empirical material.

Participation in the interviews was voluntary. Potential participants were approached with information about the purpose of the study, the general themes of the interview, and the intended use of the data. Before each interview took place, participants were informed that their involvement was voluntary and that they could choose not to answer particular questions or withdraw from the interview if they wished. This helped ensure that participation was based on informed consent and that respondents were able to engage with the study on clear and transparent terms. Confidentiality was also treated as a key consideration. Because some participants discussed institutional practices, implementation barriers, and operational challenges, care was taken not to present findings in a way that could unnecessarily expose individuals or organizations. Interview data were therefore handled with attention to anonymity, particularly when reporting statements that might be sensitive in professional or organizational contexts. In the presentation of findings, the emphasis was placed on analytical themes and stakeholder perspectives rather than on identifying individual participants. Data security was an element of the ethical approach. With participants' consent, interviews were recorded to support accurate analysis. These recordings were stored securely on TU Delft OneDrive, ensuring protected access and appropriate handling of the material. The interviews were conducted in English or Arabic, depending on participants' preferences, and the resulting material was treated as confidential research data throughout the process of transcription, coding, and interpretation. The data management plan and informed consent form were approved by TU Delft's Human Research Ethics Committee (HREC) on 2 December 2025.

4

Findings

4.1. Healthcare

Across the interviews, participants described both direct clinical applications and indirect support functions, including prosthetics, hearing devices, medical tools, surgical guides, and the repair of damaged or incomplete medical equipment.

At one level, healthcare was described in terms of urgent and basic medical need, both P1 and P4 pointed to situations in which local production could respond to severe shortages.

I can see 3D printing helping with urgent medical needs in Gaza. For example, people could print syringes, birthing kits, or even tourniquets for bleeding wounds. Women are giving birth without proper supplies, so even simple medical items could make a serious difference.

P1

Under siege, when medical supplies were blocked, we could still send filament and digital designs online. Local teams could then print items such as surgical tools, obstetric tools, splints for fractures, and other small medical parts that were urgently needed.

P4

A second point of agreement concerned repair and spare-part production in health facilities, P3 and P4 described medical infrastructure as highly vulnerable to interruption when a small but important component failed or could not be replaced.

In health facilities, we repaired more than 400 critical medical devices, and around half of those repairs involved manufacturing spare parts through 3D printing, CNC, or laser cutting.

P4

Many humanitarian agencies buy low-cost products because they are seen as the best value, but those products are often imported and not always easy to maintain. Spare parts then become a constant problem, and solving that problem can have an enormous impact on long-term infrastructure resilience

P3

Prosthetics and hearing aids were discussed in more detailed and practical way. Here, P7 described workflows that went beyond one-off fabrication and included scanning, design, fitting, and follow-up care. In their view, the printed item formed part of a wider rehabilitation or support process.

"Our first goal was hearing aids for patients suffering from hearing loss. We use 3D printing to produce the molds for patients, but the device itself is only one part of the service. The patient also needs training, speech support, psychological support, and help integrating into society"

P7

For prosthetics, we scan the patient's residual limb, manufacture the socket using 3D printing, and then combine it with the other components so the patient receives a full prosthetic and can walk again. For us, the goal is not only to manufacture a device, but to help the person return to daily life.

P7

Participants also linked these health-related applications to dignity, emotional support, and social participation, especially in the case of children.

> *"We focused especially on children because children are victims of war and have nothing to do with what happened. Whether through hearing aids or prosthetics, we try to support them physically and emotionally so they can go to school, see their friends, and not feel broken inside."*
>
> *P7*

At the same time, not all healthcare applications were described as equally straightforward, P4 and P6 pointed to the complexity of prosthetics in particular, stressing that printing a form is not the same as delivering a well-functioning device.

> *We also worked on prosthetics, but prosthetics are not simple. It is easy to print something that looks like a prosthetic, but it is much harder to produce something that truly benefits the user, because the body changes and the device needs continuous adjustment.*
>
> *P4*

> *In my own case, I needed a replacement part for my prosthetic. If I ordered it through the usual medical route, I might wait weeks. But because I had learned 3D printing, I could design it, make prototypes, test them, and solve my problem much faster.*
>
> *P6*

While participants repeatedly identified it as the most mature field of application, they also described major constraints related to printer quality, material limitations, expertise, and quality assurance. P6 recalled that early prosthetic printing efforts were affected by weak printer performance and frequent breakage. He also emphasized that these technical difficulties were reinforced by material limitations, especially in the earlier stages of implementation.

4.1.1. Water, Sanitation, and Hygiene (WASH)

Across the interviews, participants referred to water access, sanitation, drainage, water treatment, and replacement parts for water-related systems as areas where additive manufacturing could either directly restore functionality or indirectly reduce the effects of service disruption. Compared with healthcare, WASH applications appeared less mature and less standardized, but they were repeatedly framed as relevant, especially in settings where imported components were unavailable and local infrastructure had partially or completely broken down. For community-level participants, WASH was often described first in terms of urgent need rather than technology. P1 and P2 described water, sanitation, sewage, and drainage not as secondary humanitarian issues, but as core infrastructure needs that directly shape health, safety, and daily living conditions in displacement settings.

> *The biggest issue is displacement. People have left their homes and now live in tents that lack even the most basic infrastructure. There are no proper water systems and no proper sewage systems, so people are forced to manage waste in very primitive ways and depend on water tanks whenever they arrive.*
>
> *P1*

> *The most urgent need is clean drinking water. That comes before everything else. After that, people need sanitation, bathrooms, sewage networks, hygiene infrastructure, and rainwater drainage, because without these systems the whole living environment becomes unsafe.*
>
> *P2*

The community participants described the practical consequences of failing WASH systems, the issue was not only the absence of infrastructure itself, but the way that absence affected survival, hygiene, and dignity.

> *When rain falls, water gathers around the tents, and this creates serious danger. Children have died from the cold and from drowning. That is why even a basic drainage system, or raising and insulating the tents, can make a real difference in people's survival.*
>
> *P2*

Participants with more direct experience described the same sector from a different angle. While P1 and P2 emphasized need and urgency, P3, P4, and P5 more often referred to the kinds of technical interventions that additive manufacturing could support within WASH systems, especially where maintenance and repair were difficult.

> *Replacement parts are a very big issue in humanitarian work. Often there is money to build something, like a well, but there is no money or system to maintain it afterwards. So when a small part breaks, the whole infrastructure can stop working.*
> *P3*

> *In WASH and healthcare, these projects were especially useful because we manufactured critical parts that simply did not exist anywhere in Syria. Bringing them from outside was extremely expensive and could take months, so local fabrication saved time, money, logistics, and waiting.*
> *P5*

> *We worked on more than one WASH-related product. Sometimes the need was very specific, like a connector or fitting with a certain shape that could not be found in the market. In those cases, 3D printing allowed us to produce the missing part and keep the water-related system functioning.*
> *P4*

4.1.2. Shelter

Compared with health and WASH, the examples here were more varied and less consolidated. Participants referred both to small-scale shelter improvements and to large-scale construction printing, suggesting that shelter-related additive manufacturing was understood across very different scales.

At the smaller and more immediate end of the spectrum, P1 and P5 both described additive manufacturing in relation to improving temporary shelter conditions rather than replacing full shelter systems.

> *For shelters, 3D printing might not directly save lives in the same way as a medical item, but it could still improve living conditions. For example, printed plastic sheets or shelter-related parts could help improve tent roofs and protect people from harsh weather.*
> *P1*

> *One project I am proud of was insulating flooring for tents made from 100% recycled plastic. We printed the first prototype with a 3D printer and tested it for thermal insulation, pressure, shear force, and other conditions before moving toward a better version.*
> *P5*

These accounts view shelter through tent improvement, insulation, protection, and physical conditions inside temporary structures. In this sense, the emphasis was on adaptation within displacement settings rather than on complete rebuilding.

Other participants referred to shelter more broadly as a possible area for local manufacturing, but with less direct implementation experience. P6 and P7 both suggested that shelter could be a field of application.

> *3D printing can enter any field that involves manufacturing, including shelter or construction. If instead of plastic you use a cement mixture, then in principle you can print layer by layer and build a small structure.*
> *P7*

The most developed construction perspective came from P8, whose account referred to a very different scale of additive manufacturing from the desktop and medium-scale examples described elsewhere.

> *Our work is different from small desktop 3D printing because we produce large-scale concrete printers that build houses. These machines can print around 300 square meters of house in one go, so this is a very different scale of additive manufacturing.*
> *P8*

> *For emergency situations, I think concrete 3D printing is a very good use case. Smaller housing units can be built in only a couple of days, and row housing can be printed quickly, although the roof, water system, and other parts still need to be completed separately.*
> *P8*

4.2. Technical Conditions Shaping Implementation

Participants described additive manufacturing as dependent on a wider technical setup rather than on the printer alone. Its implementation was shaped by how designs were developed, whether suitable materials were available, how reliable the machines were, and whether the wider production workflow could be sustained over time. In this sense, the technical side of implementation was presented not as one isolated tool, but as a combination of inputs, processes, and production choices that had to work together in practice.

4.2.1. Design, Prototyping and Production

The interviews show that AM was especially valuable in early-stage design, prototyping, and proof-of-concept work, but much less often described as the sole method for large-scale production. Participants distinguished between using digital fabrication to develop and test a solution, and using it to manufacture at volume. In this sense, additive manufacturing was often presented as technically strong at the front end of a production process, while scale-up usually depended on other actors, machines, or manufacturing methods.

This distinction was most clearly described by P5, who explained that digital fabrication entered after the problem had already been identified and framed, mainly as a way of creating and testing possible solutions.

> *Digital fabrication mainly enters at the prototype stage, just before testing. First, we study the need, define the problem, generate ideas, and then use tools like 3D printers, CNC machines, or other fabrication methods to create and test a prototype.*
>
> *P5*

The technical value of AM lay in iteration, the ability to move back and forth between design, printing, testing, and modification. At the same time, he made it clear that this should not be confused with full production. Once a design had been validated, the workflow often shifted to other methods that were better suited to larger quantities.

> *Prototyping is one stage, but manufacturing is another. A 3D printer can help prove the concept and improve the design, but when you want larger production, you usually need suppliers, factories, molds, or industrial manufacturing.*
>
> *P5*

From the construction side, P8 described the issue in terms of wider adoption. He sees that technical viability alone was not enough. Construction firms still needed evidence that the method could work reliably at scale.

> *For mass adoption, the bigger issue is proof at scale. Construction companies are conservative, so they want to see successful large projects, clear return on investment, and hard numbers before they widely adopt a new technology*
>
> *P8*

Participants also repeatedly noted that additive manufacturing was most useful when used selectively, rather than treated as a universal manufacturing answer. Both P3 and P4 emphasized that it was better suited to specific parts, tools, or local needs than to mass, repetitive production across all cases.

> *Sometimes the design and printing process takes a lot of effort for one single part. That can still be worth it if the supply chain is broken, but it also shows why 3D printing should be used selectively, not as a universal solution.*
>
> *P4*

> *In a place like Gaza, I would not imagine additive manufacturing as a giant warehouse with thousands of printers making the same thing repeatedly. I would imagine it more as smaller, distributed production for tools, spare parts, and specific local needs.*
>
> *P3*

This selective norm was also reflected in hybrid workflows. Participants often described additive manufacturing as one part of a wider technical arrangement, rather than as a complete replacement for other methods. Construction accounts illustrated this most directly.

In construction printing, we do not print the whole building. What we address is the wall system, the raw construction. The roof, water system, utilities, and other building systems still have to be completed separately.
P8

4.2.2. Materials, Machine Quality, and Technical Fit

Material and machine conditions required for production to work reliably. From the interviews, participants emphasized that AM depends not only on having a printer, but also on having the right inputs, the right machine quality, and a good fit between the technical setup and the intended use. These conditions were especially visible in healthcare and prosthetics, where comfort, durability, fit, and repeated use mattered, but they also appeared in construction and general fabrication work. A strong point of agreement across P3, P5, P6, and P7 was that material availability could become a major technical bottleneck. Even where local production was possible in principle, printing still depended on feedstock, filament, or other technical inputs that were often difficult to source locally.

For 3D printing, one of the technical challenges is not only having the right printer, but also having the right feedstock available consistently. If the materials are not available in the country, they have to be imported, which adds cost and complexity
P3

Material availability is a major condition. If the materials are not available locally, the price increases, and implementation may become impossible. We also tried to use materials that were environmentally friendly, because humanitarian solutions should not create new problems
P5

The filament was all from outside. The local market did not have it, so we had to order it, wait for customs, pay fees, and sometimes wait weeks. That means even local 3D printing still depends on another supply chain
P6

We work with a full package system: materials, printer, scanner, and other components. If we do not plan storage properly and the material finishes, it is almost impossible to find the same type of filament in the whole Middle East
P7

These show that participants did not describe material supply as a minor technical detail. On the contrary, it was treated as one of the main conditions that could enable or block implementation. In some cases, the technical promise of local production remained limited by dependence on imported and specialized inputs. At the same time, P8 described a contrasting strategy in construction printing, where the system had been designed from the beginning around local materials. He believes that technical viability depends on avoiding full dependence on proprietary material packages.

Our approach allows around 99% of the material to be local, with only a small additive needed. This keeps the system economically realistic because the client can use local sand, aggregates, cement, or ready-mix concrete instead of importing everything.
P8

A second point of convergence concerned quality. Several participants made clear that the presence of a printer alone did not guarantee that the output would be strong enough, safe enough, or suitable enough for the intended use. Health-related accounts brought this into sharpest focus.

A key issue is having the right printers to produce the right quality. It is not enough to have a printer, the printer, the materials, and the final product all have to meet the standard required for the use case.
p3

The second issue was materials. At that time, we mostly had basic plastic. Stronger materials, like carbon-fiber reinforced options, came later, but in the early stage the available material limited what we could safely and reliably make.
p6

There are limitations in the process. It is not because 3D printing is bad, but because each method specializes in certain materials and certain applications. You have to know what the technology can and cannot do
p7

Participants also described technical fit in relation to different climates, bodies, and user conditions. This was clear in prosthetic applications, where the same technical design could not simply be transferred across settings without modification.

Cases in the Middle East are not exactly the same as cases in Europe or America. Every environment has its own conditions, and even the climate can affect what materials patients accept and what designs actually work.
P7

In Gaza, patients refused the silicone soft liner because of the high humidity and heat. They told us it caused skin problems, so we moved toward a foam liner that could better fit their local conditions.
P7

4.2.3. Digital design & transferring data

Participants described the digital elements as part of the technical infrastructure of implementation. In these accounts, the usefulness of AM did not stop at the moment of printing. It also depended on whether designs could be accessed, modified, stored, and reused later. P5, P6, and P3, all of whom referred to the importance of open or shareable design knowledge. In their view, access to existing files reduced the need to start from zero and made it easier for designs to circulate between actors and settings.

We had an open-source policy for many of these products because we wanted the solution to remain open. If someone else reached the design, they could improve it, adapt it, and build on it rather than starting from zero.
P5

For prosthetics, we used open-source communities to access designs. The idea was that you could download a file, modify it, and manufacture locally without needing to buy a commercial design from a company.
P6

Some of the replacement-part designs were open-sourced, especially in contexts like Nepal where Field Ready worked on water-well components and hand-pump parts. That allowed designs to circulate beyond one organization.
P3

They also mention the process of storing digital files as technically useful because they could be reused for modification, reprinting, or follow-up support. This was helpful in prosthetics and other cases where the user's condition changes over time or where repeated travel is difficult.

When you design a part, you should store the file. If tomorrow you need the same part again, you can produce it directly or share it with another person or another organization. This creates a kind of digital stock.
P5

Digital storage removes barriers for patients who live far away. If a patient cannot travel seven hours to reach us, the stored file still allows us to adjust the design and continue supporting them.
P7

4.3. Social Conditions Shaping Implementation

The implementation of AM does not depend only on the technical part. Its implementation also depended on people: those who could learn the tools, define needs, build trust, coordinate across institutions, and support use over time. In this sense, the social side of implementation was not described as secondary to the technology. It was presented as part of what made the technology workable, accepted, and useful in practice. Participants referred repeatedly to skills, training, communication, institutional roles, community participation, and trust as conditions that shaped whether additive manufacturing could move beyond a promising idea and become a functioning intervention.

4.3.1. Skills, Training, and Local Capability

A strong pattern was that AM depended heavily on skills and learning. Participants repeatedly described a shortage of local technical expertise, especially in areas such as design, scanning, advanced fabrication, and product adaptation. At the same time, they did not treat this only as a permanent limitation.

Many of them also spoke about training, education, and local capability-building as necessary parts of implementation.

P1 emphasized that the technology itself is not unreachable for ordinary people if the right support exists, while P6 and P7 pointed to the real scarcity of specialized expertise in practice.

Even something like a 3D printer, which may sound high-tech, is relatively easy to use if you have the design file. A regular person can operate it without being a programmer.
P1

There was also the issue of professional expertise. In Jordan, it was early. Our team had one Jordanian, and the rest were internationals. . . There was a big gap in specialized staff
P6

There is also a scarcity of expertise. . . this field itself is not widely available in our region.
P7

These opinions show that participants saw knowledge as unevenly distributed. On the one hand, there was a sense that the technology could become accessible. On the other hand, implementation often remained dependent on a small number of trained actors, especially where design and fitting had to be done carefully. This is why training appeared so frequently in the interviews. P4, P5, and P6 all described learning spaces, maker spaces, or training-oriented visions in which local people would not only receive products, but also gain the ability to work with the technology themselves.

We have offered training in digital manufacturing, in digital fabrication software such as Fusion 360, in the manufacturing process itself, and in design thinking.
P4

If you mean training people on digital fabrication itself, that is another level, and yes, that also happened. This was part of our policy around community empowerment and community resilience. The idea was to make local people part of the solution, not just recipients of it.
P5

The dream was to have a hub where someone could come with a problem and we help solve it, or where someone from the camp community could learn the technology as a profession and source of income.
P6

Training was described as part of what makes implementation possible in the first place. Without local capability, the technology remained dependent on outside expertise. With training, the possibility emerged for longer-term local use, follow-up, and adaptation.

In terms of education, participants also described how they offered courses designed to develop design and fabrication skills among community members, fostering technical capacity as part of a wider empowerment approach.

We provided courses, study tours for school and university students, and practical training, so people could learn basic design, fabrication, and prototyping rather than only receive finished products.
P5

The most underestimated area is education. People often focus on the object being printed, but when children design and print something, they learn complex ideas in geometry, technology, and even chemistry in a way that stays with them.
P6

4.3.2. Collaboration and Coordination

Another pattern that appeared was the importance of collaboration across different actors. Participants rarely described additive manufacturing as something one organization or one group could do effectively alone. Instead, implementation was often presented as depending on coordination between NGOs, hospitals, communities, local specialists, private firms, technology providers, and users themselves.

The accounts of P3, P4, P7, and P8 captured this most concretely, each describing models in which different actors handled different parts of the process rather than one organisation controlling everything from beginning to end.

> *Very rarely is the NGO itself directly providing the manufacturing service. Usually, the work is about finding local capacity and then augmenting it with technical support, expertise, or additional assistance*
> *P3*

> *Field Ready is not a donor organization. We are an implementing organization, so our work depends on partnerships with other organizations, donors, and local actors.*
> *P4*

> *In our model, the local specialist can examine the patient, take the scan, and send it to us. We design and manufacture the device in Jordan, then the remaining challenge is logistics and delivery back to the patient.*
> *P7*

> *We are a technology provider. We sell the technology to clients, support them, teach them how to install and operate the equipment, and then they carry out the project themselves*
> *P8*

At the same time, participants also pointed to communication as a recurring weakness. P2 and P3 were especially clear that there is often a gap between affected communities and aid organizations, particularly in emergency settings where speed and standard packages dominate.

> *There is always misalignment between what people actually need and what humanitarian actors deliver. In the first phase after a disaster, organizations move very quickly, so they often bring standard packages like hygiene kits, water, shelter, and other basic items.*
> *P3*

> *Usually, NGOs write a project proposal, secure funding, and then implement it. They do not typically consult the community first.*
> *P2*

This concern with communication also appeared in more constructive terms. P3 described communication not only as a problem, but as a form of infrastructure that needed to be built so organizations could listen as well as deliver.

> *They need to communicate with people in need. They did not only need to send information, they also needed to listen and receive feedback.*
> *P3*

4.3.3. Trust and Social Limits

Trust and the credibility of both organizations and technologies was an important theme across the interviews.

Participants described different kinds of trust: trust in NGOs, trust in new technologies, trust in products, and trust that institutions would support rather than block useful initiatives.

On the institutional side, P1 and P2 both described trust as complicated rather than straightforward. P1 spoke about the importance of NGOs and engineers in crisis settings, but also about the way contacts, corruption, or weak institutional relationships can limit participation. P2 described NGOs as constrained by their funders and therefore not always able to respond independently.

> *There can be mistrust because some systems depend on contacts, corruption, or personal connections. When people feel that institutions are not fair, they are less likely to participate.*
> *P1*

> *They try to manage the crisis with the resources they have, but they cannot always challenge the bigger picture or make bold decisions.*
> *P2*

This institutional uncertainty was reflected in the interviews not only as a political issue, but also as a practical one. Several participants described strong ideas or useful initiatives that remained unrealized because they lacked support, permissions, business development, or an institutional pathway.

Trust also appeared at the level of the technology itself. P6, P7, and P8 all described user acceptance as something that could not be assumed automatically. Some people were excited by the technology, while others were hesitant, cautious, or reassured only when long-term support was visible.

Some people did not believe in the technology. When they saw something new, they became afraid of it. Others were excited, and many were willing to try, but acceptance was not automatic
P6

Patients become more reassured when they understand that the digital impression is stored and can be modified later. If something feels tight or uncomfortable, they know we can adjust it, and that builds more trust in the technology
P7

Technology alone is not enough. The client needs training, operators need daily maintenance skills, and service support may be needed over time.
P8

This shows that trust is shaped by fairness, institutional credibility, communication, follow-up, and the wider support system around the technology.

4.4. Resilience-Related Results

Participants did not typically use formal resilience terminology when describing their work. However, when asked about the value of additive manufacturing in disrupted or resource-constrained settings, their accounts consistently pointed to four recurring types of contribution: faster response times, adaptive and iterative problem-solving, access to alternative production routes when normal supply chains were unavailable, and the maintenance of continued function through repair and modification. This section reports how these contributions appeared in the interview data, structured according to the four dimensions of the 4Rs resilience framework.

4.4.1. Speed and Shortened Response Times

A recurring theme across the interviews was that AM could substantially shorten the time between identifying a need and producing a usable response. This was described most concretely in prosthetics and medical-device repair, where participants contrasted AM timelines with the delays associated with conventional procurement, importation, or specialist referral.

The full prosthetic process takes from one week to ten days, depending on the case. With 3D printing, in one day we can make a prosthetic. So the patient can come today, we take the scan, manufacture the prosthetic, and tomorrow they can come and receive it.
P7

If I order it and wait for the doctor to give it to me, it can take weeks. But in one or two hours I can design it, make ten prototypes, change density, test it, and walk with it.
P6

Participants also highlighted that speed could be maintained even when physical movement of goods was blocked, because digital design files could be transmitted online and then printed locally.

What digital manufacturing contributes in disaster settings is mainly two things. Speed, going from design to a functional prototype can take hours instead of weeks or months. Flexibility, you can redesign quickly based on repeated user feedback.
P5

4.4.2. Adaptive Problem-Solving and Local Improvisation

Participants frequently described AM as enabling flexible, iterative responses in disrupted settings where standard solutions were unavailable. Rather than waiting for a complete answer, local actors could prototype, test, and redesign to fit specific material, environmental, or user constraints.

Innovation for us is like the bridge between lack of resources and the solution. So most of our work was about innovation: using the best of the tools and resources available to create at least an initial or partial solution to a problem, and usually it worked.

> *P5*

This pattern appeared across sectors. In northwest Syria, multiple rounds of tent-flooring prototyping were required before a usable design was reached. In prosthetics, P6 described an independent process of designing and testing a replacement part without depending on an external supply chain. In both cases, the contribution was not the immediate production of a finished solution, but the capacity to work through the problem iteratively using available tools and materials.

4.4.3. Alternative Production Pathways When Supply Chains Were Disrupted

In several accounts, AM served as an alternative route to accessing critical components when primary supply channels were blocked, delayed, or unavailable.

> *AM was definitely a solution because the supply chain was disrupted and there was often no way to bring things in. It is a solution for situations where there is no other solution.*
>
> *P4*

Participants described spare-part production as the clearest form of this contribution. When a single missing component could halt a much wider system (an incubator door, a water-system connector, a prosthetic component, or a well fitting), local fabrication through stored files, reverse engineering, or scanning provided an alternative route that did not depend on international logistics.

4.4.4. Maintaining Continued Function Through Repair and Modification

Participants also described AM as contributing to long-term continuity of service by enabling ongoing repair, replacement, and adjustment of devices and infrastructure components rather than requiring full replacement.

> *Since 2020, we have repaired more than 400 critical medical devices. Around half of those repairs involved manufacturing spare parts through 3D printing, CNC, or laser cutting.*
>
> *P4*

In prosthetics and hearing-device accounts, continuity appeared not only as repair but also as ongoing adaptation over time. P7 described how stored digital files enabled devices to be adjusted as a patient's condition or environment changed, while P6 noted that the same file could be used to produce replacement parts without requiring the patient to travel.

5

Analysis

This chapter interprets the findings through the socio-technical systems (STS) framework and the 4Rs resilience lens, explaining how the patterns identified in the findings chapter answer the research questions. It is organized into three parts: first examining sectoral patterns across healthcare, WASH, and shelter-related applications, then analyzing the socio-technical conditions of implementation across the technical and social subsystems and their alignment, and finally interpreting the findings in relation to the four resilience dimensions of robustness, redundancy, resourcefulness, and rapidity.

5.1. Cross-Case Patterns in Sectoral Applications

Across the cases, additive manufacturing was not seen as equally useful in every infrastructure sector. Participants mentioned several possible uses, but the findings showed clear differences in how realistic, developed, and practical these uses actually were. Healthcare stood out as the most established area, with more concrete examples and clearer links between design, production, and final use. WASH was also seen as a relevant area, especially when it came to repairs, spare parts, and keeping systems working, rather than providing whole systems from scratch. Shelter and construction were discussed in a more mixed way, from small adaptable solutions to larger ideas like concrete printing, but there were fewer examples showing long-term use in practice.

This difference shows that additive manufacturing was shaped not only by the needs of each sector, but also by the kind of problem being addressed. In the interviews, it seemed to work best when the task was more specific and easier to manage technically. Examples included prosthetics, hearing-aid molds, medical-device parts, connectors, or small improvements linked to shelter. Its role became less clear when the sector required large systems, many connected parts, or high-volume construction and service delivery.

5.1.1. Healthcare

The interviews suggest that healthcare is the sector where AM has reached the strongest level of sociotechnical maturity. In this context, AM does not appear only as a promising technical idea or an experimental tool. Instead, it has been taken into everyday healthcare practices and fitted into existing ways of working. Its success is not only about having advanced machines or materials. It is also about how well the technology fits with the social setting in which it is used. A key reason for this maturity is the close match between what healthcare needs and what AM can offer. From a sociotechnical perspective, the main task of healthcare is to provide care that responds to the needs of individual patients. AM supports this task because it is especially useful for producing customised items in small volumes. Products such as prosthetics, hearing-aid, and other patient-specific devices are not mass-produced objects. They are made for particular bodies and particular needs. This makes AM well suited to healthcare, where variation between users is expected rather than treated as a problem. Another important feature is the possibility for quick adjustment and iteration. AM allows clinicians and technical specialists to test, modify, and improve designs based on feedback from the patient. This creates a close relationship between the technical object and the social actors involved in its use. A device can be changed if it does not fit well, feels uncomfortable, or does not support the patient's daily activities. In this sense, the technology becomes useful not because it works in isolation, but because it supports an ongoing process of interaction between patient, clinician, and artefact. This social infrastructure helps explain why AM has clearer pathways to implementation in healthcare than in some other sectors. The route from design to use is more visible because there are professionals who can assess the product, adapt it, and guide the patient through its use. However, the interviews also suggest that healthcare should not be seen as a simple sector that could be embedded within AM. In fact, it is a sector where the relationship between the social and technical sides of the system becomes especially clear. AM works best when its role is focused and when it is supported by ongoing professional care. A printed prosthetic component, for example, may be technically successful, but still fail in practice if it is uncomfortable, difficult to use, or not accepted by the patient.

5.1.2. Water, Sanitation, and Hygiene (WASH)

While healthcare shows how AM can support more personalised forms of production, the WASH sector shows a different kind of value. Here, AM is less about making new customised products and more about keeping important systems working. The interviews suggest that in WASH, AM is not really seen as a complete solution on its own. Instead, it works more like a repair tool, or a way of helping fragile systems continue functioning when something small breaks down. From a sociotechnical perspective, WASH systems depend on many technical parts working together. Access to clean water is a large social need, but sometimes the whole service can depend on one small component. Participants described situations where a missing connector, fitting, or spare part could stop an entire water system from working. In these cases, the AM part becomes much more than just a printed object. It becomes the small technical link that allows the wider system to keep running. This distinction sets AM in WASH apart from AM in healthcare. In healthcare, AM is often used to produce something new for a specific person, such as a prosthetic socket or hearing-aid mould. In WASH, the role of AM is more about maintenance. It helps repair or replace parts so that existing infrastructure does not fail. The value of the technology comes from its ability to produce the right part at the right moment, especially when normal supply chains are slow, expensive, or not available. So AM is useful not because it transforms the whole water system, but because it can stop the system from breaking down completely. The interviews also show that many of the problems in WASH are not only technical. There are also weaknesses in the social and organisational side of the system. Participants pointed out that funding is often available for building or installing water infrastructure, but much less attention is given to long-term repair and upkeep. This creates a maintenance gap. The system may be built, but the resources, routines, and responsibilities needed to keep it working are not always there. Therefore, the application in WASH seems to be used mostly for small local adjustments rather than for changing the whole system. It helps replace a missing part, repair a component, or keep a service going. This is still valuable, but it means the technology is working mostly at the level of immediate problem-solving. The interviews suggest that AM has potential, but that potential depends on whether it becomes connected to stronger organisational practices.

5.1.3. Shelter

Compared with healthcare and WASH, where AM has found more clear and practical roles, shelter seems much more fragmented. It does not appear as one stable field where the technology can be easily placed. Instead, the sector is divided into very different uses, from small shelter components to large-scale construction. Because of this, the social and technical sides of the system do not always fit well together. Shelter is consequently a more difficult sector to understand. The technology is not failing because it has no value. In fact, participants recognised that AM could be useful in situations where shelter is urgently needed. But the problem is that the technical requirements change a lot depending on the scale of use. Printing a small connector for a tent is very different from printing parts of a building. These two examples almost belong to different systems, even though they are both placed under the wider Shelter sector. At the smaller scale, AM seems more practical and easier to integrate. For example, using AM for tent connectors, flooring pieces, or small repair parts allows the technology to respond to immediate needs. In these cases, the social system can stay fairly local and flexible. People can test a part, adjust it, and print again if needed. This is closer to the way AM works where the technology supports quick problem-solving without needing to change the whole system around it. However, when AM is used for larger shelter applications, such as concrete printing or printed housing, the situation becomes much more complicated. The technology is no longer just a small tool that helps with adaptation. It becomes part of a heavy construction process. This requires large machines, trained operators, suitable materials, reliable sites, and strong planning. Many humanitarian organisations are not yet set up to manage this kind of technical process. So the technical ambition is much bigger than the social system around it. A printed house may be technically possible, but it still needs regulations, funding, safety checks, and planning to work in real shelter contexts. Since this support system is still weak, AM is better seen as part of construction, not a full replacement.

Looking across healthcare, WASH, and shelter, as table 5.1 shows, it becomes clear that AM does not develop in the same way in every sector. Its success depends not only on what the technology can do, but also on how well it fits with the people, organisations, rules, and everyday practices around it.

Healthcare appears to be the most mature sector. AM fits well because healthcare already works with individual needs, professional care, and customised solutions. The technology supports existing clinical work, rather than disrupting it. This makes AM in healthcare feel more settled and easier to use in practice. WASH shows a different kind of value. Here, AM is mainly useful for repair and maintenance. It can help replace missing or broken parts and keep water systems working, especially when supply chains are weak. However, this also shows that AM is often used to patch problems rather than solve the deeper issue of poor long-term maintenance planning.

Shelter is the least settled sector. AM can be useful for small parts, such as tent connectors or repair pieces, but large-scale construction is much more difficult. Printed buildings need regulations, safety checks, funding, skilled workers, and links to existing infrastructure. Because these systems are not fully in place, AM in Shelter remains more experimental.

Table 5.1: Cross-case patterns in sectoral applications of additive manufacturing

Sector	Main applications	Intervention model	Maturity	Main limitations
Healthcare	Prosthetics, hearing-aid molds, medical tools, splints, and repair of medical devices	Customized, bounded, user-specific production; repair and restoration of functionality	High	Requires fitting, follow-up, technical expertise, and quality assurance
WASH	Connectors, fittings, drainage-related parts, and replacement components for water systems	Maintenance, repair, and continuity of service through localized component production	Medium	Mostly limited to parts rather than whole systems; dependent on materials and technical availability
Shelter and construction	Tent flooring, shelter-related parts, and large-scale concrete printing	Prototyping, localized improvement, and partial construction intervention	Low	Scale, regulation, logistics, and dependence on complementary systems such as roofing and utilities

5.2. Socio-Technical Conditions of Implementation

The sector patterns discussed above show that AM was not equally relevant across all areas of critical infrastructure. Still, looking only at the sector does not fully explain why some uses became more practical than others. The interviews also show that implementation depended on a wider mix of technical and social factors. This is where the socio-technical systems perspective becomes useful. Instead of seeing AM as a neutral tool that creates the same results wherever it is used, the STS perspective helps show how technical abilities, social relationships, and institutional settings all shape what the technology can actually do in real practice.

Across the cases, AM did not appear as something that works on its own. Its use depended on printers, materials, design files, and production processes, but also on skills, trust, cooperation, follow-up, and the ability of different actors to work around a specific need. In this way, the findings suggest that the main question is not only whether AM is technically possible. It is also whether the technical side and the social side fit together well enough for implementation to happen. This section looks at the findings through three steps: the technical subsystem, the social subsystem, and the connection between the two.

5.2.1. The Technical Subsystem

AM does not operate as an isolated machine that automatically turns digital designs into usable products; the findings show that AM depends on a wider technical chain. This chain includes the printer, but also materials, design files, scanning tools, software, power supply, machine maintenance, file sharing, and the skills needed to connect these parts together. Through an STS lens, the printer is only one part of the system. AM only works well when all these technical elements are available and able to function together. A clear finding from the interviews is that AM was rarely limited by just one technical issue. More often, its use depended on whether several technical parts could be aligned at the same time. For example, a printer may be available, but production can still fail if the right filament is missing, if the design file is not suitable, if the machine needs maintenance, or if the material does not meet the required standard. This shows the technical interdependence of AM. The different parts of the system depend on each other, and weakness in one part can affect the whole production process. This also explains why AM appeared more feasible in some applications than others. AM worked best when the technical task was clearly bounded, meaning it was easier to use AM when the product was small, specific, needed in limited numbers, and could be produced with the available machines and materials. This helps explain why prosthetic sockets, hearing-aid molds, medical-device parts, connectors, and fittings appeared more often in the findings. These objects have a more manageable technical scope. They do not require AM to replace a whole production system, but only to perform a specific and clearly defined task. At the same time, the findings challenge the assumption that AM automatically creates technical independence. Local production does not mean that all dependency disappears. Instead, the dependency often changes form. Rather than relying on imported finished products, actors may still depend on imported filament, feedstock, scanners, software, spare parts, and external technical support, a vulnerability made concrete by practitioners who described situations in which proprietary printing material ran out, making it "almost impossible" to source the exact filament locally in the region. This means that AM can make production more local in one sense, but it still remains connected to wider supply chains and technical systems. From an STS perspective, this can be understood as a relocation of dependency. The dependence shifts from the final product to the infrastructure needed to produce it. Crucially, however, this relocation is asymmetric: unlike physical goods, digital design files can cross borders that are closed to imported products. In severely disrupted contexts, once raw materials reach a local printer, fabrication can resume simply by transmitting "the designs online", bypassing the physical constraints that block conventional supply chains. AM is therefore not fully autonomous. Even when printing happens locally, the local printer is still part of a wider technological system. It depends on many factors, therefore, AM should not be understood as complete independence from global systems. It is more accurate to see it as a form of distributed production that still relies on external technical networks. Technical suitability depends strongly on the context of use, because the same machine or material does not work equally well in every setting. In prosthetics, printed parts still need to fit the body, climate, comfort, and daily use, while in Shelter, printing a tent connector is very different from printing part of a house. This contrast is especially pronounced at the construction scale, where shipping heavy proprietary feedstock over long distances is economically prohibitive; practitioners working at this scale emphasised that viability requires that "99% of the material can be local". AM should therefore be seen as comprising fundamentally different technical setups depending on sector and scale, not as one single solution. The interviews also show that AM works best when combined with other production methods, where its value comes from supporting existing systems rather than replacing them fully.

5.2.2. The Social Subsystem

The findings show that the social subsystem played a central role in whether AM could actually be implemented. AM did not become useful simply because the machines were available. It became useful when people had the skills to operate it, trusted the process, adapted it to local needs, and connected it to real service problems. From an STS perspective, the social subsystem is therefore not just the background around the technology. It is part of the system that makes the technology work.

Participants often pointed to a lack of local expertise, especially in areas such as design, scanning, fitting, machine operation, and more advanced fabrication. The significance of this gap grew with the complexity of the application, because complex uses required more specialised knowledge. For example, producing a simple connector is very different from designing a prosthetic socket or a medical device that has to fit a person's body and meet safety expectations. In these cases, AM depends not only on the printer, but also on the tacit knowledge of trained people. This kind of knowledge is built through practice, experience, and problem-solving, not only through manuals or instructions. The interviews did not, however, present this knowledge gap as permanent. Participants also discussed training, maker spaces, local education, and learning-by-doing as ways to build capacity over time. This shows that the social subsystem is not fixed. It can develop as people gain skills and as new roles are created around the technology. User acceptance was another central part of the social subsystem. Even when a product is technically successful, it may still fail if people do not trust it, understand it, or feel that it matches their needs. Prosthetics offered the most instructive example of this dynamic. A printed prosthetic part cannot be judged only by whether it is functional. It also has to be comfortable, dignified, adjustable, and accepted by the person who uses it. The success of the product therefore depends on the relationship between the user, the technician, the clinician, and the object itself. Trust is a practical condition for implementation: if users do not trust the product, the organisation, or the people providing the service, they may not use the technology or give the feedback needed to improve it. In prosthetics a follow-up care and adjustment are part of what makes the printed object usable. The technology has to be socially shaped around the user's body, needs, and expectations. AM implementation further depended on collaboration between different actors. It was rarely described as something that one person or one organisation could carry out alone. NGOs, hospitals, community actors, local specialists, private companies, designers, and technology providers all appeared in different parts of the process. Outcomes were stronger when these roles were clearly connected. For example, the people who understand community needs must be linked to the people who design and produce the object. The people who print the object must also be linked to those who test it, fit it, maintain it, and support the user afterwards. These connecting roles can be understood as boundary spanners. They are the people who move between the technical and social sides of the system, translating user needs into technical choices and technical limits into practical decisions. Without these roles, the system can easily become fragmented. Governance and security structures added a further layer of constraint that the interviews made explicit. Even where technical capacity was available, innovators in crisis zones sometimes found that institutional security narratives stalled their work: one practitioner described being required repeatedly to justify that he was not "designing a weapon", a form of bureaucratic friction that directly undermined the rapidity AM is meant to provide. Several participants also described a persistent "communication gap" between organisations and communities, especially when projects were planned from the top down or when urgent aid delivery left little space for consultation. This shows that social barriers are not only about missing skills. They are also about whose knowledge is included, how problems are defined, and whether communities are treated as partners or only as recipients of aid. Because of this, the social subsystem cannot be seen only as "human factors" around the technology. Skills, training, participation, collaboration, and trust were part of the actual conditions that made AM useful in practice, not something extra added after the technical work was done.

5.2.3. Socio-Technical Alignment and Joint Optimization

The clearest finding from the interviews is that AM implementation did not depend only on the technology, and it also did not depend only on people or organisations. What mattered most was the fit between these two parts. Through an STS lens, AM worked best when the technical subsystem was connected properly with the social subsystem. This is where joint optimization becomes useful. It shows that AM becomes valuable when the technical and social parts support each other around a clear problem. AM was not used as a separate or isolated tool. It was woven into an existing social and organisational setting. Healthcare provided the clearest illustration of this, with the printed object embedded in a wider care pathway. For example, scanning, fitting, specialist knowledge, patient feedback, and follow-up care all helped the technology become usable. The system was not just the printer or the printed part. The system included the patient, the clinician, the technician, and the steps needed to make the object actually work in daily life and this shows a strong case of joint optimization. In WASH, AM supported the continuity of water systems by helping to replace missing or broken parts. Its value came from connecting a technical ability, which is printing a specific component, with a social need, which is keeping water services running. In this case, joint optimization happened when actors could identify the problem, produce or access the needed part, and use it to bring the wider system back into function. AM was useful because it became a bridge between a technical gap and a social need. The weaker cases show the opposite problem. Some applications looked promising but did not move far beyond pilots because the technical idea was stronger than the social structure around it. Shelter offered the starkest example of this. Large-scale construction printing may be technically possible, but it needs regulations, planning systems, funding, local ownership, skilled workers, and clear responsibility after the project is finished. Without these social and institutional supports, the technology cannot become routine practice. So the issue was not that the technology had no potential. The issue was that the wider system was not ready enough to receive and sustain it. This gap between technical promise and social readiness can be understood as a socio-technical misalignment. A project may have a strong technical design, but still fail because it does not match local needs, user expectations, or institutional capacity. The findings also suggest that joint optimization was easier in bounded applications. These are cases where the problem was clear, the product was specific, the production process was shorter, and fewer actors were involved. Prosthetic sockets, hearing-aid molds, connectors, and fittings are examples of this. They are still complex, but the task is more manageable. It is easier to connect the user need, the design process, the printer, and the final use. Joint optimization therefore helps explain why AM implementation was uneven across the cases. AM should not be judged only by asking whether it can technically produce something. It also has to be asked whether the surrounding social system can use it, trust it, support it, and keep it working over time. The value of AM depends on the strength of the connection between the technical setup and the social setting. When this connection is strong, AM can become part of real practice. When it is weak, the technology often remains stuck as a pilot, an experiment, or a promising idea that does not fully settle into use.

Table 5.2: Socio-technical conditions shaping the implementation of additive manufacturing

Socio-technical domain	Key enabling conditions	Key constraining conditions	Analytical implication
Technical subsystem	Suitable printers, available materials, usable digital files, scanning systems, maintenance routines, and appropriate production pathways	Weak printer quality, imported feedstock dependence, maintenance burdens, poor fit between machine and application, and limited scale capacity	Implementation depends on a wider technical ecosystem rather than on hardware alone
Social subsystem	Skills, training, trust, user involvement, follow-up support, and local capability	Expertise gaps, weak acceptance, unrealistic expectations, poor consultation, and limited local technical confidence	Social capability and legitimacy shape whether technical output becomes usable in practice
Coordination and actor roles	NGO support, hospital collaboration, maker spaces, distributed roles, and local partnerships	Fragmented responsibilities, communication gaps, top-down delivery, and unclear implementation pathways	Implementation depends on organized coordination across different actors rather than on isolated action
Socio-technical alignment	Technical and social systems aligned around a clearly defined need, with workable feedback loops between design, production, and use	Mismatch between design and use, pilot-only interventions, lack of scaling pathways, and weak institutional embedding	Joint optimization is the main condition through which AM becomes implementable in practice

5.3. Resilience Contributions Across the 4Rs

After looking at the sector patterns and the socio-technical conditions behind implementation, the next step is to look more directly at how AM supported critical infrastructure resilience. This section focuses on the second sub-question by reading the findings through the 4Rs framework: rapidity, resourcefulness, redundancy, and robustness. Participants did not usually use these formal resilience terms when describing their experiences. Still, their accounts often pointed to four repeated contributions: responding faster, solving problems in more adaptive ways, creating alternative options, and helping systems keep functioning during disruption. These patterns show that AM did contribute to resilience, although its contribution was not the same across all four dimensions.

5.3.1. Rapidity

Among the four resilience dimensions, rapidity was the one that appeared most clearly in the findings. Across different sectors and participant groups, AM was consistently associated with shortening the time between identifying a need and producing a usable response. This was achieved not only through the speed of printing itself, but also through shorter waiting times, quicker prototyping, reduced dependence on procurement systems, and the possibility of transmitting designs digitally when physical movement of goods was constrained.

As reported in the findings, prosthetics participants contrasted AM workflows, where scanning, designing, and producing a usable part could happen within a single day, with conventional procurement timelines of a week or more. In medical-device repair, locally fabricating a missing component could determine whether critical equipment was restored quickly or remained out of service while awaiting external supply. In disrupted settings, this matters because delay itself is a form of harm: waiting affects mobility, rehabilitation, and continuity of care in ways that extend far beyond the immediate technical gap.

What the findings also make clear, however, is that rapidity should not be understood as an inherent property of the technology. AM produced rapid responses only when the wider setup was already in place: digital files, scanning tools, trained people, available materials, and a reliable production process. A printer without materials, or a design task without people who could scan, measure, or recreate the part, did not produce rapidity in practice. From an STS perspective, rapidity is therefore best understood as a systemic outcome, one that requires the technical and social subsystems to be coordinated and ready, rather than a capacity that the machine provides on its own.

This distinction is sharpest when comparing small-scale and large-scale applications. In prosthetics, medical-device repair, and component production, AM often shortened response times directly because the task was bounded and the production chain was manageable. In construction, rapidity was more limited: concrete printing could accelerate wall production, but it could not remove the need for roofing, utilities, finishing, and integration with wider infrastructure. The contribution was real but partial: it accelerated one stage of rebuilding without replacing the full delivery and recovery process.

5.3.2. Resourcefulness

When rapidity is about how quickly AM can support a response, resourcefulness is about how flexibly it can help people solve problems when options are limited. As described in the findings, this emerged as one of the strongest resilience contributions across the interviews. Participants did not describe AM as replacing normal systems with a standard alternative. Rather, they described it as enabling improvisation: the capacity to redesign, test different approaches, and create workable responses when established routes were not available.

This connects directly to the socio-technical perspective adopted in the study. Resourcefulness was not a property of the printer. It arose from the way local problems, people's creativity, available materials, design skill, and collaborative practice came together. In the tent-flooring case described in the findings, the value of AM was not that it immediately produced the right solution. It was that it created the conditions for working through the problem iteratively, through multiple rounds of prototyping, material changes, and structural adjustments, until something usable was reached. From a 4Rs perspective, this represents resilience as adaptive problem-solving rather than as a return to a fixed prior state.

Resourcefulness also manifested through significant cost compression. By locally adapting a search-and-rescue concept using available fabrication tools, practitioners were able to reduce the cost of a rescue airbag from approximately $5,000 to around $400. This economic dimension is not peripheral to resilience: it determines whether local civil defence teams can access life-critical equipment that global procurement would place far beyond their means. The contribution of AM here is not merely to substitute a finished product, but to render accessible, through local redesign, what was previously unaffordable.

A similar logic appeared in the prosthetics accounts, where user-led adaptation was central. The move from silicone liners to foam liners, driven by heat, humidity, and patient feedback, illustrates how AM supported resourcefulness by allowing local adjustment to real conditions rather than enforcing a standardised design. This also shows how some problem-solving capacity can shift closer to users and local technicians who are able to work with digital fabrication tools, rather than remaining solely with specialist organisations or supply chains.

At the same time, the findings are clear that AM did not create resourcefulness where none existed. Communities living through crisis were already adapting, using whatever materials and skills were available. AM's deepest contribution to resourcefulness came when it shifted communities from passive recipients of aid to active participants who were "part of the solution", a shift that participants framed consistently in terms of capacity-building rather than service delivery. As one practitioner put it, the goal was to teach communities "how to fish": to embed durable problem-solving skills that outlast the immediate crisis rather than deliver finished solutions that leave no lasting local capability behind. Resourcefulness therefore remained primarily a human and organisational capacity, with AM acting as a tool that could amplify but not substitute for it.

5.3.3. Redundancy

Compared with rapidity and resourcefulness, redundancy appeared in the findings in a more selective but still meaningful way. As the interview data makes clear, participants did not suggest that AM could replicate whole infrastructure systems or create full backup pathways in the conventional sense. Instead, its role was to provide an alternative route for obtaining parts, restoring functions, or maintaining production when the primary route was blocked. In this sense, AM supported redundancy by creating fallback options at specific failure points rather than by duplicating entire systems.

Spare-part and component production accounts offered the clearest evidence of this contribution. The central problem described was not the absence of whole infrastructure systems, but the way a single missing or broken component could bring a wider service to a halt: a broken incubator door, an unavailable connector, a missing well fitting, a failed prosthetic component. In these cases, AM created redundancy by offering a local or near-local fabrication pathway through stored designs, scanning, or reverse engineering, thereby replacing dependence on the original manufacturer or an international supply chain with a more distributed and locally accessible production route.

This also reframes what redundancy means in low-resource and crisis-affected settings. The standard resilience definition assumes that redundant systems involve full duplication of capacity. In practice, the cases in this study show that redundancy operated at a much smaller scale: an alternative route to a part, a module, or a workflow rather than an alternative to the whole system. This is consistent with what the STS perspective suggests about technical interdependence: a single weak point can cascade into a system-level failure, and addressing that point locally, even at small scale, meaningfully reduces overall fragility.

Distributed workflows reinforced this contribution. As noted in the findings, prosthetics workflows showed that scanning, design, fabrication, and fitting did not need to happen in the same place. A patient could be scanned in one location, the file sent elsewhere, the part manufactured at a third site, and delivery arranged through an institutional partner. Digital storage compounded this: once a file existed, the part could be reproduced or shared with another actor capable of printing it. Redundancy in this study therefore had both a physical and a digital dimension.

Still, this contribution remained selective. Most applications still depended on wider systems for materials, transport, regulation, and complementary components. AM therefore supported redundancy most reliably at the level of specific parts, modules, and workflows, rather than at the level of whole infrastructure systems.

5.3.4. Robustness

Robustness was the resilience dimension where AM's contribution was most conditional and indirect. In the resilience literature, robustness refers to the ability of a system to absorb disruption while maintaining function without significant decline. In the cases reported in the findings, AM did not typically build this strength from the outset. Its contribution appeared more through repair, continuity, and the maintenance of function over time, helping systems keep running after damage, shortage, or breakdown had already occurred.

As the findings show, AM was rarely described as the primary reason a hospital, water system, or care pathway was robust in the first place. Instead, it was used to manage existing weakness or interruption. When a missing or broken component threatened a wider clinical function, local fabrication could restore the device and return it to service. The repair of incubators and other medical equipment is the clearest example: one missing part could stop a piece of equipment from being used; making that part locally kept it inside the service system. The same logic applied to water connectors, well components, and other small but critical elements. From a resilience perspective, robustness here is not only about physical strength; it is also about whether the system can continue to provide its intended service after something has failed.

In prosthetics and hearing-device accounts, robustness took a more adaptive form. The device's usefulness was not determined only at the moment of production. It depended on whether it could be adjusted, repaired, or reproduced as the user's condition or environment changed over time. This was most evident in environments where standard materials could not function reliably: intense local "humidity and heat" led patients to reject standard silicone prosthetic liners, prompting practitioners to iterate toward 3D-printed foam alternatives suited to the local climate. Robustness in this sense is not about maintaining a fixed design, but about sustaining usefulness through contextual adaptation. AM supported this kind of adaptive durability, not through permanence, but through the capacity to keep the object usable across changing circumstances.

The findings also show, however, that this contribution depended on demanding conditions. A printed object did not support robustness simply because it could be produced quickly. It also needed to work reliably, fit the setting, and be trusted by the users and institutions involved. Managing "people's expectations" proved to be an active part of sustaining this trust: a prosthetic that is technically functional but understood by the user as a "temporary fix" may fail socially if the user anticipates a permanent solution. Preventing the overhype of 3D printing is therefore as necessary as ensuring material quality, since robustness has a communicative and psychological dimension alongside its physical one. Poor material quality, unstable printer performance, or inadequate maintenance could each reduce durability significantly. Robustness therefore placed the strongest demands on the socio-technical system as a whole: it required not only that a part could be made, but that the part met the quality and trust standards needed for continued use over time.

Table 5.3 illustrates the different levels of contribution among the 4Rs.

Table 5.3: Resilience contributions of additive manufacturing across the 4Rs

Resilience dimension	How it appeared in the data	Examples	Relative strength	Main condition
Rapidity	Faster response, shorter lead times, quicker repair, and accelerated prototyping	Prosthetic production, medical-device repair, and remote file transfer	Strong	Requires files, materials, skills, and operational readiness
Resourcefulness	Adaptation, redesign, iterative problem-solving, and local experimentation	Tent flooring, prosthetic adjustment, and siege-time medical solutions	Strong	Depends on creativity, local agency, and technical access
Redundancy	Alternative production routes, distributed workflows, digital stock, and backup fabrication pathways	Spare parts, remote scanning workflows, and stored digital files	Moderate	Most visible at the level of parts, modules, and workflows rather than whole systems
Robustness	Maintained functionality through repair, continuity, and ongoing use	Incubator repair, prosthetic reuse, and long-term modification of devices	Partial / conditional	Depends on durability, quality, maintenance, and continued support

5.3.5. Comparative interview analysis

To strengthen the cross-case interpretation of the interview data, a comparative interview analysis was carried out across all eight participants. The purpose of this step is to make visible where emphasis was strongest, where views converged, and where important differences appeared between stakeholder groups. The matrices below compare the interview material across four analytical areas: sectoral applications, technical conditions, social and collaborative conditions, and resilience contributions across the 4Rs. Using this comparison makes it easier to see which themes were widely shared across the dataset and which ones were more specific to certain participants, sectors, or roles.

Tables 5.4 and 5.5 compare how strongly each participant referred to the main application areas discussed in the study.

Tables 5.6 and 5.7 compare the main technical conditions that shaped implementation across the interviews.

Tables 5.8 and 5.9 compare the social and collaborative conditions discussed by participants, including skills, training, trust, participation, institutional support, and coordination. And table 5.10 compares how the four resilience dimensions appeared across the interviews.

Table 5.4: Comparative matrix of sectoral applications by participant (P1–P4)

Sector / application area	**P1**	**P2**	**P3**	**P4**
Healthcare / medical tools	M	L	L	H
Prosthetics / assistive devices	L	–	–	M
Hearing aids	–	–	–	–
Medical device repair	L	–	M	H
WASH / water / sanitation	H	H	M	H
Drainage / sewage / hygiene	H	H	–	L
Shelter / tent improvement	M	M	–	–
Construction printing / buildings	–	L	–	–
Education / training / learning	M	M	–	H
Communication / digital delivery	–	H	H	–
Repair / spare parts across sectors	M	–	H	H

Note: H = strong / central emphasis, M = clear but secondary, L = brief / indirect mention, – = not discussed. Continued in Table 5.5.

Table 5.5: Comparative matrix of sectoral applications by participant (P5–P8)

Sector / application area	**P5**	**P6**	**P7**	**P8**
Healthcare / medical tools	M	H	H	–
Prosthetics / assistive devices	–	H	H	–
Hearing aids	–	–	H	–
Medical device repair	M	M	L	–
WASH / water / sanitation	H	–	–	–
Drainage / sewage / hygiene	L	–	–	–
Shelter / tent improvement	H	M	L	–
Construction printing / buildings	–	L	L	H
Education / training / learning	H	H	L	–
Communication / digital delivery	–	–	–	–
Repair / spare parts across sectors	H	H	M	–

Note: H = strong / central emphasis, M = clear but secondary, L = brief / indirect mention, – = not discussed. Continued from Table 5.4.

Table 5.6: Comparative matrix of technical conditions by participant (P1–P4)

Technical condition	**P1**	**P2**	**P3**	**P4**
Printer / machine quality	–	–	M	M
Material availability	L	L	H	M
Design files / CAD access	L	–	M	M
Scanning / digital capture	–	–	L	L
Maintenance of machines / tools	–	–	M	M
Fit between machine and application	–	L	M	M
Scale-up beyond prototype	–	M	L	M
Open-source design use	–	–	M	L
Digital storage / reusable files	–	–	M	L
Hybrid production methods	–	M	L	M
Local material strategy	–	L	L	L

Note: H = strong / central emphasis, M = clear but secondary, L = brief / indirect mention, – = not discussed. Continued in Table 5.7.

Table 5.7: Comparative matrix of technical conditions by participant (P5–P8)

Technical condition	**P5**	**P6**	**P7**	**P8**
Printer / machine quality	M	H	M	H
Material availability	H	H	H	H
Design files / CAD access	H	H	H	M
Scanning / digital capture	M	L	H	–
Maintenance of machines / tools	M	L	M	H
Fit between machine and application	H	H	H	H
Scale-up beyond prototype	H	L	L	H
Open-source design use	H	H	L	–
Digital storage / reusable files	H	M	H	–
Hybrid production methods	H	L	L	H
Local material strategy	M	–	–	H

Note: H = strong / central emphasis, M = clear but secondary, L = brief / indirect mention, – = not discussed. Continued from Table 5.6.

Table 5.8: Comparative matrix of social and collaborative conditions by participant (P1–P4)

Social / collaborative condition	P1	P2	P3	P4
Skills / expertise	M	L	M	H
Training / capacity building	M	M	L	H
Community participation	H	H	M	M
Trust / mistrust	H	H	M	L
User acceptance	L	–	–	M
Institutional support	H	M	H	H
NGO / humanitarian actor role	H	H	H	H
Private sector role	M	L	M	H
Actor coordination	M	M	H	H
Communication / consultation	M	H	H	M
Stakeholder mapping / permissions	L	L	M	M
Political-logistical barriers	H	H	M	H

Note: H = strong / central emphasis, M = clear but secondary, L = brief / indirect mention, – = not discussed. Continued in Table 5.9.

Table 5.9: Comparative matrix of social and collaborative conditions by participant (P5–P8)

Social / collaborative condition	P5	P6	P7	P8
Skills / expertise	H	H	H	M
Training / capacity building	H	H	L	M
Community participation	H	M	L	–
Trust / mistrust	L	H	H	M
User acceptance	L	H	H	M
Institutional support	H	M	H	H
NGO / humanitarian actor role	M	M	L	L
Private sector role	M	M	–	H
Actor coordination	H	L	M	H
Communication / consultation	M	L	L	–
Stakeholder mapping / permissions	H	M	L	H
Political-logistical barriers	M	H	H	H

Note: H = strong / central emphasis, M = clear but secondary, L = brief / indirect mention, – = not discussed. Continued from Table 5.8.

Table 5.10: Comparative matrix of resilience contributions across the 4Rs by participant

Resilience dimension	P1	P2	P3	P4	P5	P6	P7	P8
Rapidity	L	L	M	H	H	H	H	M
Resourcefulness	H	H	M	H	H	H	M	L
Redundancy	L	L	H	M	M	M	H	L
Robustness	L	L	M	H	M	M	M	M

Note: H = strong / central emphasis, M = clear but secondary, L = brief / indirect mention, – = not discussed.

5.4. Refined Conceptual Framework

The analysis shows that the original conceptual framework remains valid, but five adjustments are needed to reflect the findings more accurately. The original framework was useful because it treated AM as a socio-technical intervention rather than a purely technical tool, and because it positioned the 4Rs as resilience outcomes shaped by the interaction between technical and social systems. However, the findings show that this relationship was more uneven, selective, and context-dependent than the original framework anticipated.

The first adjustment concerns the sectoral dimension. The original framework presented AM as potentially relevant across all areas of critical infrastructure, with sectors as an undifferentiated background. The empirical evidence, most clearly the contrast between the operational maturity of healthcare applications, the maintenance-and-repair role of AM in WASH, and the fragmented and scale-dependent situation in shelter, shows that sectors are not equally permeable to AM. Healthcare provided clearer socio-technical pathways because its work already centred on individual variation and iterative adjustment; WASH's value was concentrated at specific component-level failure points; shelter remained divided between small modular uses and large-scale construction that exceeded the current socio-technical readiness of humanitarian actors.

The second adjustment reframes AM as a targeted and selective capability rather than a general production model. Across the findings, AM contributed most reliably when the problem was bounded: a missing connector, a specific prosthetic socket, a defined repair component. Its role weakened when the need was systemic, large-scale, or required sustained high-volume output. The prototype-to-production gap that participants consistently reported captures this limitation. AM excels at the front end of a production process (design, iteration, proof of concept) but typically requires other methods for scale-up. This selectivity is not a failure of the technology; it is a property that shapes where AM can be most effectively deployed.

The third adjustment places conditional alignment at the centre of the framework. The original model showed technical and social systems interacting, but the findings suggest this interaction is better understood as conditional; the strongest resilience contributions emerged only when printers, materials, design files, and operational workflows were simultaneously matched with skills, trust, institutional support, and clear implementation pathways. The absence of any single element frequently blocked outcomes that seemed technically viable. This conditionality means that socio-technical alignment is not the background of AM implementation; it is the primary determinant of whether AM generates resilience value at all.

The fourth adjustment differentiates the 4Rs outcomes. The original framework treated the 4Rs as four parallel resilience dimensions that AM might support. The findings show a clear hierarchy; rapidity and resourcefulness were the strongest and most consistently reported contributions, supported across sectors and participant groups. Redundancy emerged more selectively, primarily through alternative production routes at the component and workflow level rather than at the system level. Robustness was the most conditional contribution, dependent on quality, maintenance, user trust, and expectation management, and most often achieved indirectly through repair and continuity rather than enhanced structural strength. This differentiation should inform how AM deployment is prioritised and evaluated in practice.

The fifth adjustment makes the outer environment an explicit structural element of the framework. The original model included the political and logistical environment implicitly through the open-systems principle of STS, but the findings showed that border closures, customs delays, security-framing constraints, donor priorities, and weak institutional pathways actively shaped both the technical and social subsystems rather than simply surrounding them. Importantly, the findings also revealed an asymmetry within this environment; while physical goods were blocked by the same political conditions that restricted access to materials and equipment, digital design files could move across closed borders. This digital asymmetry "the ability of AM to decouple production capability from physical supply chains at the design stage" is a theoretically significant property that distinguishes AM from other crisis-response technologies and explains why it retained value even in siege conditions where conventional logistics had collapsed entirely. The refined framework makes both the constraining outer environment and this asymmetric opening for digital transfer visible as structural features of the socio-technical system.

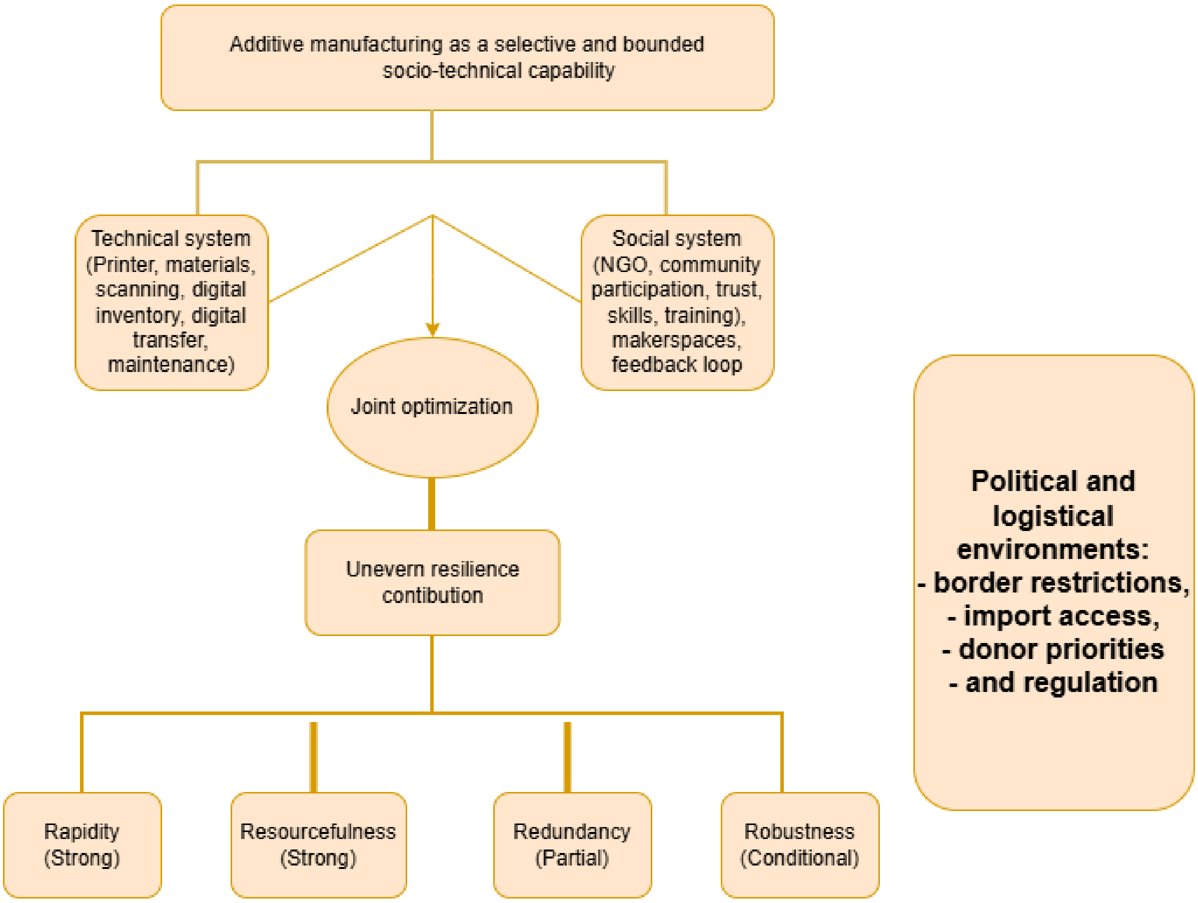

Figure 5.1: Refined conceptual framework: AM as a targeted socio-technical intervention, with conditional alignment at the centre, differentiated 4Rs outcomes, and political-logistical constraints as an explicit outer layer

6

Discussion

This chapter discusses the findings in relation to the research questions, the literature review, and the conceptual framework. The analysis showed that additive manufacturing can support critical infrastructure resilience during supply chain disruption, but that this contribution is selective, uneven, and highly dependent on context. Its strongest effects appeared where the problem was modular, urgent, and compatible with localized or digitally distributed production, while its weaker effects appeared where implementation depended on large-scale reconstruction, stable institutional support, or unrestricted access to materials and equipment. The discussion proceeds by answering the sub-questions on sectoral applications, enabling and constraining factors, and resilience contributions across the 4Rs before returning to the main research question.

6.1. Research Insights

6.1.1. Sectoral Applications of Additive Manufacturing, SQ1

The first sub-question asked which critical infrastructure sectors AM can support during supply chain disruption. The findings show that AM is most useful in healthcare and WASH, while shelter and construction are still less developed. In Gaza and Syria, AM works best when the need is urgent, specific, and suitable for small-scale local production. Healthcare is the strongest sector because AM can produce customised and specialised items such as prosthetics, hearing-related devices, surgical tools, obstetric equipment, and parts for damaged medical equipment. These uses go beyond the general examples in literature, such as PPE, because they directly support patient care when medical supplies are blocked, delayed, or unavailable. In WASH, AM is mainly used to make connectors, fittings, and spare parts that help keep water and sanitation systems working. In fragile contexts, one missing part can stop a whole system, so AM helps repair and extend the life of existing infrastructure. Shelter and construction show potential, but they are not yet as mature. Instead of printing full houses, AM is currently more useful for smaller modular improvements, such as tent connectors or insulating flooring. This shows that AM can support shelter needs, but only in targeted ways, not by replacing the wider construction system.

6.1.2. Technical and Social Factors That Enable or Constrain Resilience Contributions, SQ2

The findings show that AM only works well when the technology and the social setting fit together. On the technical side, printers, materials, design files, scanning tools, software, spare parts, and machine maintenance all mattered. A printer alone was not enough. In some cases, AM reduced dependence on long supply chains, but it also created new dependence on imported filament, feedstock, machine parts, or specific supplier systems. So, the vulnerability was not fully removed, it was often shifted to another part of the system. The social side was just as essential. Skills, training, trust, coordination, and institutional support shaped whether AM could actually be used in practice. In Gaza and Syria, trust was not only about whether a printed part was technically safe or reliable. It was also about whether local clinics, technicians, and fabrication hubs had enough autonomy to work under siege and restricted conditions. This was especially clear in healthcare and prosthetics, where the printed object needed fitting, follow-up, and user acceptance. The main constraint was the political and logistical environment. Border restrictions, war conditions, donor priorities, and weak institutions could limit AM even when local skills and technical capacity existed. This means AM's role in resilience depends on more than machines or local motivation. It depends on the connection between technical capacity, human expertise, user trust, organisational support, and the real conditions on the ground.

6.1.3. Resilience Contributions Across the 4Rs, SQ3

The findings show that AM supports all four dimensions of resilience, but in uneven way. Its strongest contribution is rapidity and resourcefulness. AM can make responses faster by reducing waiting times, supporting quicker repairs, and allowing digital design files to move even when people or products cannot cross borders. This was clear in prosthetics, medical equipment repair, and small infrastructure parts. It also supports resourcefulness because it gives local actors more ability to redesign, test, and adapt solutions when normal supply chains are blocked. Redundancy is more limited. AM does not usually create a full backup system, but it can provide alternative ways to make missing parts or restore specific functions. This means its backup role is mostly at the level of components, design files, and local workflows. Robustness is the weakest contribution. AM can help systems keep working after something breaks, but it does not automatically make infrastructure stronger from the beginning. Its value still depends on material quality, skilled users, maintenance, and follow-up support.

So, AM is not a universal fix in crisis settings. It works more as a selective sociotechnical capability that helps infrastructure continue functioning by solving specific, modular problems during long disruptions.

6.2. Findings in Relation to the Literature

This section addresses the question of how the study's findings relate to the existing body of scholarship: where they confirm what was already known, where they extend or deepen it, and where they introduce perspectives that the literature had not adequately developed.

6.2.1. What the Findings Confirm

Several findings align closely with established claims in the literature. The core argument that AM is a strategic supplement rather than a substitute for disrupted supply chains is confirmed across all sectors and participant groups. This is consistent with Kleer and Piller (2019), Corsini et al. (2022), and Manero et al. (2020), who show that AM does not replace conventional logistics but instead shifts where production capability sits. The study also confirms the observation by (Corsini et al., 2022) and (Den Boer et al., 2020) that dependency does not disappear with AM: organisations that stop relying on imported finished products still depend on imported filament, feedstock, machine parts, and technical expertise. This finding was consistently reported across the interviews and reinforces the literature's warning against treating AM as a path to full supply chain independence.

Healthcare as the most developed application area is also confirmed. Corsini et al. (2022) documented prosthetics, suction pump repairs, and medical optics as the clearest humanitarian cases; the present study found the same pattern, with prosthetics, hearing-aid molds, and medical-device repair accounting for the most concrete and operationally mature examples. The finding that WASH applications centre on spare-part production and component repair, rather than whole-system construction, is consistent with Lipsky et al. (2019) and Rodríguez-Espíndola et al. (2020), who describe how a single printed fitting can restore an entire water supply. Shelter's lower maturity and the large gap between small modular improvements and large-scale construction printing aligns with the cautious assessment offered by (Bazli et al., 2023).

The importance of multi-actor collaboration was also confirmed. Manero et al. (2020) and He et al. (2021) argue that AM implementation depends not only on printers but on networks of actors that can share designs, coordinate logistics, and connect production to real user needs. The interviews showed this clearly: no participant described AM as something an individual or single organisation could implement alone. The literature's characterisation of AM as a complementary production method that works alongside conventional manufacturing, rather than replacing it, was similarly confirmed across all sectors and scales (Alogla et al., 2021; Keskin et al., 2025).

6.2.2. What the Findings Extend

While the literature established that AM shifts rather than eliminates supply chain dependency, the present study adds a dimension that the literature had not fully articulated. The shift is asymmetric: digital design files can cross borders and blockades that are closed to physical goods, whereas raw materials cannot. This asymmetry is not a minor technical detail. In the siege conditions described by participants, it was the precise mechanism that allowed AM to function at all. The literature describes a relocation of dependency in general terms (Corsini et al., 2022), but does not examine the implications of that relocation in access-restricted conflict settings, where this asymmetry becomes the operational basis for using the technology.

The study also extends the literature's sectoral analysis by providing an explanation, not only a description, of why the sectors differ in maturity. The literature identifies healthcare as the most developed area and shelter as the least, but does not account for why this is so. The findings explain it through socio-technical alignment: healthcare already operates around individual variation, professional oversight, iterative adjustment, and close user-technology interaction, which match AM's properties precisely. Shelter, by contrast, involves radically different technical requirements at small and large scales, and lacks the organisational infrastructure needed to absorb construction-scale AM. This explanatory account moves beyond what the literature had previously offered.

The differentiation of the 4Rs is a further extension. The literature consistently presents resilience as a unified positive outcome of AM deployment (Naghshineh and Carvalho, 2022; Priyadarshini et al., 2025), without distinguishing between its dimensions. The findings show that rapidity and resourcefulness are strongly and consistently supported, redundancy is selective and operates mainly at the component level rather than the system level, and robustness is the most conditional contribution, depending on quality, maintenance, user trust, and expectation management. This more nuanced understanding helps practitioners identify where AM offers real value and where further investment is needed for it to become effective, a practical distinction that has not been clearly developed in the literature.

6.2.3. What the Findings Add That Was Largely Absent

It should be noted that this study did not conduct a fully systematic literature review; the review was purposive and conceptually oriented rather than exhaustive. Some of the patterns described below therefore reflect what seems to be absent or underexplored based on the sources engaged, rather than a verified gap established through comprehensive mapping. Future research should undertake a fully systematic literature review to establish a more complete picture of the field.

With that caveat, the study indicates that some of its findings have little parallel in the literature engaged. The role of political and security barriers appears to have received little attention in the scholarship reviewed, which addresses implementation challenges primarily in technical and logistical terms. The interviews suggest that bureaucratic friction rooted in security narratives, such as the repeated requirement to justify that fabrication tools are not being used for weapons production, can directly undermine the rapidity that AM is intended to provide. This seems to be a context-specific constraint that did not appear prominently in the literature reviewed, and was not anticipated by the conceptual framework.

The top-down communication gap between humanitarian organisations and affected communities is acknowledged in general terms in the literature on collaboration (Manero et al., 2020), but the interviews seem to describe it as a structural feature of how aid is designed and delivered, not merely an operational challenge. When organisations write project proposals without community consultation, the resulting interventions may be technically sound but socially misaligned. This gap appears to affect whether AM solutions address actual needs or reproduce the same disconnection that characterises broader humanitarian practice. The study indicates that this dynamic has not been closely examined in relation to AM specifically in the literature reviewed.

The environmental and climatic dimension of AM deployment also appears to have limited representation in the literature reviewed, which draws primarily on cases from Sub-Saharan Africa, Nepal, and high-income pandemic settings. The findings document how heat and humidity in Gaza and Jordan led patients to reject standard prosthetic components and prompted practitioners to develop locally appropriate alternatives. This suggests that global design standards may not transfer unchanged into

Middle Eastern contexts, and that AM's value in these settings seems to depend partly on its capacity for contextual redesign, a dimension that the literature, written largely from other geographic vantage points, appears not to have closely examined.

Finally, the psychological dimension of robustness, specifically the challenge of managing user expectations about what a printed device can and cannot offer, seems to be absent from the literature's predominantly technical framing of durability and quality. The findings suggest that a technically functional prosthetic can fail as a resilience intervention if the user expected something more permanent. This communicative and social dimension of whether an intervention succeeds indicates that the literature's understanding of what robustness requires in practice may need to be extended.

7

Conclusion

7.1. Theoretical Contribution

This study makes two related theoretical contributions. First, it repositions AM in relation to CI resilience: rather than a technical capability that generates resilience by default, AM is shown to be a socio-technical intervention whose contribution depends on the alignment between technical resources, social conditions, and institutional support. The value of AM in crisis-affected settings emerges not from hardware alone, but from the connection between printers, materials, and design files on one side, and skills, trust, coordination, and organisational capacity on the other. Second, the study contributes to the literature by bringing the STS perspective and the 4Rs resilience framework into direct analytical combination. Existing AM literature tends to foreground technical capacity and supply chain flexibility without adequately explaining how social systems shape whether that capacity is realised in practice. Resilience literature applies the 4Rs to infrastructure performance, but has rarely connected these dimensions to AM in crisis-affected settings. By combining both frameworks, this study offers an approach that is empirically grounded, theoretically integrative, and attentive to the conditions that determine whether AM's potential translates into actual resilience.

7.1.1. Practical Implications

For humanitarian organisations and policymakers, the central practical implication is that AM should be deployed selectively rather than broadly. Its strongest value lies in targeted, modular applications, particularly in healthcare and WASH, where a single missing or damaged component can bring a wider service system to a halt. In these sectors, AM can produce medical spare parts, surgical tools, prosthetic components, and water-system connectors when normal supply chains are blocked or too slow. Prioritising these bounded, high-impact uses is more likely to generate meaningful resilience than pursuing large-scale reconstruction applications for which AM is not yet ready.

Equally important, the study shows that successful AM deployment depends on investing in the social infrastructure around the technology, not only in hardware. This includes training local technicians, supporting maker spaces and fabrication hubs, strengthening coordination between organisations, and building feedback mechanisms between designers and end-users, including clinicians, patients, and community members. Without these human and organisational foundations, technical capability alone will not translate into sustained resilience in practice.

7.1.2. Limitations

This study has several limitations that should be acknowledged when interpreting its findings. These limitations do not undermine the value of the research, but they do shape the scope of the conclusions that can be drawn.

A first limitation concerns the scope and size of the empirical sample. The study is based on a relatively small number of semi-structured interviews with participants from different professional positions and geographic contexts. This diversity was valuable because it brought together perspectives from humanitarian practitioners, community actors, technology providers, and digital fabrication specialists. At the same time, the sample does not allow broad generalization across all low-resource and crisis-affected settings. The cases discussed in the interviews reflect particular experiences, especially from the Middle East and related humanitarian contexts, and these experiences may not fully represent conditions in other regions or infrastructure systems.

A second limitation relates to the uneven maturity of the cases discussed. Some interview examples referred to well-developed and repeated applications, such as prosthetics, hearing-related devices, and medical repairs, while others referred to prototypes, pilot projects, or future possibilities. As a result, the evidence base is stronger for certain sectors than for others. Healthcare, for example, was discussed through multiple concrete and operational cases, whereas shelter and construction often involved a mix of implemented examples and more speculative or emerging applications. This means that the thesis can speak more confidently about some sectoral contributions than others.

Another limitation of this study is that it did not examine the different types of 3D printing technologies in detail. The research focused on the general role of AM in supporting infrastructure resilience, rather than comparing specific processes such as FDM, SLA, or SLS. This means the findings do not explain how each type of 3D printing may differ in terms of cost, material availability, durability, technical skill, or suitability for different CI sectors.

A further consideration concerns the policy and regulatory environment. This study does not claim that AM is universally applicable across all critical infrastructure domains or geographic contexts. In some sectors and jurisdictions, stringent regulatory frameworks, certification requirements, quality standards, and import controls present significant barriers that may limit or prevent implementation regardless of technical capability. For example, the production of medical devices, structural components, or public infrastructure parts is subject to approval regimes that AM-produced items may not meet without formal certification. In areas where such regulatory frameworks are strictly enforced, the practical contribution of AM may be substantially constrained. This is an important qualification: the findings of this study reflect specific crisis-affected and low-resource contexts where formal regulatory oversight was often weak or absent, and these findings should not be generalised to settings where the policy environment is more restrictive.

7.1.3. Recommendations for Future Research

Future research should study each sector separately, as AM works differently in healthcare, WASH, and shelter. More work is needed on the long-term durability, maintenance, and real use of printed parts. More comparison between different crisis contexts is needed, such as conflict areas, disaster zones, and low-resource settings, to understand more barriers. Future studies should also examine material dependency, especially how AM still relies on filament, printer parts, software, and supply chains.

7.1.4. Conclusion

This thesis set out to answer the following main research question: How does additive manufacturing contribute to the resilience of critical infrastructure during supply chain disruption in low-resource and crisis-affected settings? The central answer is that additive manufacturing is best understood as a **strategic supplement rather than a complete substitute**. It does not replace disrupted infrastructure systems or global supply chains. Rather, its contribution to resilience is selective and socio-technical: it strengthens systems by addressing specific points of failure through localized production, digital design transfer, repair, customization, and adaptive problem-solving.

The study showed that AM is most useful where critical infrastructure depends on small but essential components that become unavailable during crisis. The ability to reproduce a missing part, adapt a design locally, or store and reuse digital files can prevent a larger system from failing altogether. This was most clearly visible in healthcare and WASH, where a single unavailable connector, a broken incubator component, or a delayed prosthetic element could interrupt a much wider service function, while localised fabrication provided a direct and proportionate response to that specific vulnerability.

These resilience effects are not automatic. The contribution of AM depends on the alignment of technical and social conditions: access to suitable printers, compatible materials, usable digital files, and maintenance capacity on the technical side; and skills, institutional support, user trust, and collaborative pathways connecting design to real infrastructure needs on the social side. Its value emerges only when embedded in a broader socio-technical arrangement that allows it to move from technical possibility to practical use.

Across the 4Rs, AM contributes most strongly to rapidity and resourcefulness. It shortens lead times, reduces dependence on slow procurement, and enables adaptive local problem-solving through iterative prototyping and context-specific redesign. Its contribution to redundancy and robustness is more partial and conditional: it can create backup production pathways and support continuity through repair, but these contributions remain modular rather than systemic. What this differentiation reveals is that AM's value in crisis settings is not evenly distributed across all resilience dimensions, and that understanding where it contributes most, and where its limits lie, is essential for deploying it effectively as part of a broader infrastructure resilience strategy.

Statement on the Use of AI

During the preparation of this thesis, I used ChatGPT as an AI-based tools during the writing process to assist with paraphrasing, improving sentence structure, and clarifying academic expression. This tool was used as a writing support aid only. In the later stages of the thesis, I also used Consensus AI to support and strengthen the literature review by helping identify and engage with relevant academic sources. These tools did not contribute to the design of the research, the collection or analysis of data, or the development of the study’s findings and conclusions. I reviewed and revised all AI-assisted outputs to ensure accuracy, consistency with my argument, and alignment with academic standards.

8

Appendix

8.1. Interview Questions

8.1.1. Appendix A: NGO Stakeholders

1. In which infrastructure areas have you seen the greatest need for rapid replacement parts or equipment during crises?
2. How do you evaluate whether a technology like 3D printing is appropriate for a specific sectoral need (e.g., medical devices, water systems)?
3. What challenges have you faced in accessing or deploying new technologies such as 3D printing during disaster response?
4. In your experience, what types of support (training, funding, logistics) would make 3D printing more feasible for restoring infrastructure quickly?
5. What has been your experience in coordinating with private sector actors or local groups when introducing new technologies in crises?
6. What mechanisms would help you collaborate more effectively with technology providers and communities for infrastructure recovery?
7. How do you currently engage communities in designing or implementing infrastructure recovery solutions?
8. What benefits or risks do you see in increasing community participation in additive manufacturing projects?

8.1.2. Technology Provider

1. Which critical infrastructure sectors do you believe 3D printing has the most potential to support, and why?
2. How do you adapt or design products for different sector-specific requirements?
3. From your perspective, what technical or design limitations restrict the use of 3D printing for emergency infrastructure repairs?
4. What technological innovations or adaptations could make 3D printing more effective in fragile or disaster-affected settings?
5. What challenges do you face when collaborating with NGOs or communities to deploy 3D printing solutions in disaster settings?
6. How can partnerships with humanitarian actors improve the scalability and reliability of your solutions?
7. How do you integrate feedback from end-users or communities when designing printable parts for infrastructure?

8. What role you play in sustaining or scaling digital manufacturing initiatives over time?

8.1.3. Community Stakeholders

1. Which everyday infrastructure failures (water, energy, transport, shelter) most affect your community during disasters?
2. How do you see 3D printing helping in these specific areas, compared to traditional supply methods?
3. What difficulties do you anticipate in operating or maintaining 3D printers locally during disasters (e.g., power, materials, skills)?
4. What forms of local training or resources would help you use 3D printing to repair essential infrastructure more effectively?
5. How have you been involved (if at all) in partnerships with NGOs or technology providers to solve local infrastructure problems?
6. What would make collaboration with external actors (NGOs, private companies) more useful and sustainable for your community?
7. What motivates you to take part in additive manufacturing initiatives aimed at fixing local infrastructure?
8. How do you think community-led use of 3D printing could strengthen your ability to cope with future risks?

8.1.4. Interview Protocol

Each interview followed a semi-structured format built around a flexible guide developed directly from the study's research questions and its socio-technical framing. Rather than following a fixed script, the guide functioned as a structured but adaptable resource, allowing the conversation to stay anchored to the study's central themes while remaining responsive to what each participant raised.

At the start of every interview, the researcher introduced the study to the participant. This included a brief explanation of the research purpose, an outline of how the session would be structured, an indication of the expected time commitment, and a clear statement that participation was entirely voluntary. Participants were also invited to raise any questions before the session began. This opening moment served two functions: it ensured that each participant was adequately informed about their role in the research, and it helped establish a relaxed conversational tone from which the interview could develop more naturally.

The session opened with questions inviting participants to describe their background, their professional role, and the nature of their engagement with additive manufacturing, local production, or humanitarian and crisis-affected settings. From there, the conversation moved progressively toward the substantive themes of the study. Participants were asked to consider where AM might offer practical value, what kinds of disruptions it could help respond to, and which sectors or unmet needs might benefit most from local production capacities. Where responses called for clarification or invited elaboration, the researcher used follow-up probes to draw out more detailed reflection.

All interviews were conducted online through Microsoft Teams. This was the most practical arrangement given the geographical spread of participants, differences in availability, and the logistical constraints of coordinating across multiple time zones and contexts. The online format did not limit the quality of the conversations; in practice, it made participation feasible for individuals who could not have taken part under in-person arrangements.

Sessions lasted approximately 45 minutes each. Interviews were carried out in either English or Arabic depending on each participant's preference. Giving participants this choice was a deliberate methodological decision: it supported clarity and self-expression, particularly when describing nuanced or context-specific experiences. Interviews conducted in Arabic were first transcribed verbatim in Arabic by the researcher, who speaks the language natively, and then translated into English for the purposes of analysis. During the coding process, translated excerpts were cross-checked against the original Arabic transcripts, and any uncertainties in meaning were resolved by returning to the source text rather than relying on the translation in isolation.

With each participant's prior agreement, interviews were audio-recorded. Recording allowed the researcher to remain fully attentive during the session rather than dividing focus between listening and note-taking. The recordings were subsequently transcribed in full, providing a stable textual basis for analysis and preserving the participants' own phrasing throughout. All recordings were stored on TU Delft OneDrive in line with institutional data management requirements.

8.2. Coding

This section explains how the deductive and inductive coding process described in Section 3.4 was applied in practice. It shows how participant accounts were translated into the findings and analysis presented in Chapters 4 and 5.

Deductive Coding in Practice

Deductive coding began with 17 pre-defined categories drawn from two theoretical frameworks: the socio-technical systems (STS) perspective and the 4Rs resilience lens. These codes are listed in Table 3.3 in the Methodology chapter and are organised into four clusters: technical system factors (STS-T), social system factors (STS-S), resilience dimensions (4Rs), and infrastructure sectors.

In practice, each of the eight transcripts was read in full before any coding began. During a second reading, the researcher identified text segments relevant to a pre-defined code and assigned a label. A single segment could receive more than one code if it addressed several analytical dimensions at the same time. Any segment that did not clearly fit a pre-defined code was flagged and set aside for the inductive stage.

The following examples illustrate how deductive codes were applied to the transcripts:

- A participant describing difficulty obtaining printer filament locally was tagged with *STS-T: Material and feedstock access*.
- A participant describing unclear responsibilities between an NGO and a local fabrication team was tagged with *STS-S: Stakeholder coordination*.
- A participant describing how a printed spare part kept a medical device running was tagged with *4Rs: Robustness*.
- A participant describing AM use in hearing-aid production was tagged with *Sector: Healthcare applications*.

Inductive Coding in Practice

After the deductive pass, each transcript was read again without the codebook. The aim was to identify passages that were analytically meaningful or recurring but did not fit any pre-defined category.

First-order codes were assigned to these passages using language close to the participant's own words rather than theoretical terms. For example, a participant describing multiple rounds of design testing was coded as *design iteration and material testing*. A participant describing AM as part of a larger fabrication chain was coded as *AM as one stage, not a standalone solution*.

Once all transcripts had been read, first-order codes were compared across participants. Codes addressing the same underlying concern from different angles were grouped and given a **second-order label**: a more analytical description of the shared theme. For example, first-order codes about testing, adjusting, and user feedback were grouped under the second-order theme *adaptive design and user-driven iteration*. First-order codes about dignity, emotional recovery, and social return were grouped under *restoration of social function as a resilience outcome*.

Finally, each second-order theme was assessed against the deductive framework. Some were merged with existing STS or 4Rs categories because they addressed the same concern from a different angle. Others remained as standalone inductive categories that extended the analysis beyond what the framework had anticipated.

The main inductive themes that emerged and shaped interpretation in Chapters 4 and 5 are listed below. Some extended existing deductive categories; others introduced concerns not anticipated at the start of the analysis:

- **Prototyping versus full-scale production** — participants consistently distinguished using AM to develop and test a design from using it for routine production at scale. The deductive framework did not capture this boundary, which proved important for understanding scope and limits across all three sectors.

- **Hybrid manufacturing** — AM was consistently described as one component of a wider production or repair process, not a standalone method. This shaped how technical contributions in Chapters 4 and 5 were framed across all sectors.
- **Digital files as crisis-crossing infrastructure** — the ability to transmit design files electronically across closed borders, store them for reuse, and draw on open-source repositories emerged as a distinct resilience property extending the deductive STS-T codes.
- **Context-specific material and design adaptation** — participants described how local climate, body conditions, and user environments required material and design changes that were not anticipated by the deductive framework (e.g. foam liners replacing silicone in high-heat settings).
- **Restoration of dignity and social participation** — in prosthetics and hearing-device accounts, resilience outcomes extended beyond service restoration to emotional recovery and social reintegration. This extended the 4Rs framework, which focuses on system-level function.
- **Community empowerment over one-off delivery** — participants described a consistent orientation toward building local problem-solving capacity rather than delivering finished products, extending the STS-S community participation code with a normative dimension.
- **Institutional friction and bureaucratic obstruction** — governance and security barriers, including security-framing scrutiny and funder constraints, actively blocked or slowed implementation. These were not captured by the deductive STS-S codes.
- **Maintenance gap as structural vulnerability** — the finding that infrastructure is routinely built without mechanisms for ongoing spare-part supply or repair emerged as a recurring structural condition that shapes AM's role in both WASH and healthcare, and was not anticipated by the deductive framework.

Codebook

The codebook below presents all codes used in this study. The deductive codes (Table 3.3 in the Methodology chapter) are reproduced here for reference alongside the inductive codes, so the full analytical structure is visible in one place.

Deductive codes were derived prior to data collection from the STS framework and the 4Rs resilience lens. They are organised into four clusters and are described fully in Table 3.3. A summary is provided here:

- *STS-T codes (technical system):* AM hardware availability; Material and feedstock access; Digital design infrastructure; Power and infrastructure dependency; Technical fit and quality standards.
- *STS-S codes (social system):* Local skills and technical capacity; Stakeholder coordination; Institutional and governance support; Community participation and ownership; Trust and legitimacy.
- *4Rs codes:* Robustness; Redundancy; Resourcefulness; Rapidity.
- *Sector codes:* Healthcare applications; WASH applications; Shelter and construction.

Inductive codes emerged from the data during the open reading of transcripts. Table 8.1 presents all inductive codes identified in this study, including what each code captures and how it extends or supplements the deductive framework.

Data Structure

Table 8.2 presents the full data structure for this study. It shows the path from participant language (first-order concepts) to researcher groupings (second-order themes) to the theoretical and analytical categories they connect to (aggregate dimensions). This structure shows how both deductive and inductive coding were built from the interview material and how the findings in Chapters 4 and 5 were derived. The aggregate dimensions in bold mark the start of each major group.

Table 8.1: Inductive codebook: codes emerging from the data

Inductive code	What it captures	Relation to deductive framework
Prototyping vs. full-scale production	The distinction between using AM to develop and test a design and using it for routine production at scale	Extends STS-T; deductive codes did not distinguish these two modes of use
Hybrid manufacturing	AM functioning as one component within a broader production or repair process rather than as a standalone method	Extends STS-T: Technical fit; adds the workflow integration dimension
Digital files as crisis-crossing infrastructure	The capacity of digital design files to cross physical and political borders that block material goods, enabling production in siege or disrupted conditions	Extends STS-T: Digital design infrastructure; adds crisis-specific bypass value
Open-source design as shared resilience infrastructure	The circulation of open design files across organisations and settings as a collective resilience resource	New; not captured by any deductive code
Context-specific material and design adaptation	The need to change materials and designs in response to local climate, body conditions, and user environments	Extends STS-T: Technical fit; adds iterative, user-driven and environment-driven adaptation
Restoration of dignity and social participation	Resilience outcomes extending beyond service restoration to emotional recovery, social reintegration, and personal dignity	New inductive extension; 4Rs focuses on system function, not individual social recovery
Community empowerment over one-off delivery	An orientation toward building local problem-solving capacity and community agency rather than delivering finished solutions	Extends STS-S: Community participation; adds the normative empowerment versus service distinction
Institutional friction and bureaucratic obstruction	Governance and security barriers, including security-framing scrutiny, funder constraints, and missing institutional pathways, that slowed or blocked implementation	New; deductive STS-S codes focused on enabling rather than obstructing institutional conditions
Maintenance gap as structural vulnerability	The structural absence of systems, funding, and responsibility for ongoing spare-part supply and repair in humanitarian and crisis infrastructure	New; reveals a pre-existing structural gap that shapes AM's role in WASH and healthcare
Cost compression through local redesign	The ability to reduce solution costs dramatically through local adaptation and fabrication, making previously unaffordable tools accessible	Extends 4Rs: Resourcefulness; adds economic accessibility as a specific mechanism
Educational value of digital fabrication	The contribution of AM to learning, skill development, and engagement among children and community members	New; not captured by any deductive code
Maker-hub as community resilience model	The concept of a locally accessible fabrication space where community members can bring problems, learn skills, and generate income from digital manufacturing	Extends STS-S: Local skills; adds the spatial model and income-generation dimension

Table 8.2: data structure: from participant language to theoretical categories

First-order concepts (participant language)	Second-order themes	Aggregate dimensions
“Digital fabrication mainly enters at the prototype stage; study the need, define the problem, then use the printer to create and test a design” (P5)	AM as prototype and design-validation tool	**Technical and production conditions**
“Prototyping is one stage; manufacturing is another; a 3D printer proves the concept, but larger production needs factories and molds” (P5)	AM as prototype and design-validation tool	
“3D printing should be used selectively; the design and printing process takes a lot of effort even for a single part” (P4)	AM as prototype and design-validation tool	
“Not a giant warehouse with thousands of printers; more as smaller distributed production for tools, spare parts, and specific local needs” (P3)	AM as prototype and design-validation tool	
“In construction printing we do not print the whole building; we address the wall system; roof, utilities, and other systems are completed separately” (P8)	Hybrid workflows: AM as one component of broader production	
“Repairs involved manufacturing spare parts through 3D printing, CNC, or laser cutting” (P4)	Hybrid workflows: AM as one component of broader production	
“If materials are not in the country they must be imported, which adds cost and complexity” (P3)	Material availability as fundamental implementation bottleneck	
“Filament was all from outside; local market did not have it; even local printing still depends on another supply chain” (P6)	Material availability as fundamental implementation bottleneck	
“If material finishes, it is almost impossible to find the same type of filament in the whole Middle East” (P7)	Material availability as fundamental implementation bottleneck	
“Our approach allows 99% of the material to be local; the client uses local sand, aggregates, and cement” (P8)	Local material strategy as design response to dependency	
“Under siege, we could send filament and digital designs online; local teams could print items urgently needed” (P4)	Digital files enabling crisis-proof and border-crossing production	**Digital infrastructure as resilience enabler**
“Store the file; if tomorrow you need the same part, produce it directly or share it with another organisation; this creates a digital stock” (P5)	Digital files enabling crisis-proof and border-crossing production	
“Digital storage removes barriers for patients far away; the stored file allows design adjustment and continued support without travel” (P7)	Digital files enabling crisis-proof and border-crossing production	
“Open-source policy so others can improve, adapt, and build on it rather than starting from zero” (P5)	Open-source design as shared resilience infrastructure	
“Used open-source communities to access prosthetic designs; download, modify, and manufacture locally” (P6)	Open-source design as shared resilience infrastructure	
“Replacement-part designs open-sourced; handpump and water-well designs in Nepal circulated beyond one organisation” (P3)	Open-source design as shared resilience infrastructure	

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First-order concepts (participant language)	Second-order themes	Aggregate dimensions
"Not enough to have a printer; the printer, materials, and final product all have to meet the standard required for the use case" (P3)	Quality and machine performance as prerequisites for safe use	**Quality, fit, and context-specific conditions**
"We mostly had basic plastic; stronger materials came later; available material limited what we could safely make" (P6)	Quality and machine performance as prerequisites for safe use	
"Middle East cases are not the same as Europe or America; the climate affects what materials patients accept and what designs work" (P7)	Context-specific adaptation to local environment and user conditions	
"Gaza patients refused the silicone liner due to humidity and heat; we moved toward a foam liner that fitted local conditions" (P7)	Context-specific adaptation to local environment and user conditions	
"Our team had one Jordanian and the rest were internationals; there was a big gap in specialized staff" (P6)	Skills gap and regional expertise scarcity	**Social and human conditions**
"Scarcity of expertise; this field is not widely available in our region" (P7)	Skills gap and regional expertise scarcity	
"Even something like a 3D printer is relatively easy to use if you have the design file; a regular person can operate it without being a programmer" (P1)	Skills gap and regional expertise scarcity	
"Offered training in digital manufacturing, Fusion 360, manufacturing process, and design thinking" (P4)	Training and capacity-building as implementation pathway	
"Training local people was part of our policy around community empowerment and resilience; make people part of the solution, not recipients" (P5)	Training and capacity-building as implementation pathway	
"The dream was a hub where someone from the camp could learn the technology as a profession and a source of income" (P6)	Training and capacity-building as implementation pathway	
"The most underestimated area is education; when children design and print, they learn complex ideas that stay with them" (P6)	Training and capacity-building as implementation pathway	
"Rarely is the NGO directly manufacturing; the work is about finding local capacity and augmenting it with technical support" (P3)	Multi-actor collaboration and distributed coordination	
"Local specialist examines the patient, takes the scan, and sends it to us; we design and manufacture; the remaining challenge is logistics and delivery" (P7)	Multi-actor collaboration and distributed coordination	
"We are a technology provider: we sell the technology, support clients, teach install and operation, then they carry out the project themselves" (P8)	Multi-actor collaboration and distributed coordination	
"Misalignment between what people need and what humanitarian actors deliver; organisations move fast and bring standard packages" (P3)	Communication gap between organisations and communities	
"NGOs write a proposal, secure funding, and implement it; they do not typically consult the community first" (P2)	Communication gap between organisations and communities	

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First-order concepts (participant language)	**Second-order themes**	**Aggregate dimensions**
"They need to communicate with people in need; they should also listen and receive feedback, not only send information" (P3)	Communication gap between organisations and communities	
"Some people did not believe in the technology; when they saw something new, they became afraid; acceptance was not automatic" (P6)	Trust and user acceptance as conditions of use	
"Patients become more reassured when they understand the digital impression is stored and can be modified; that builds trust" (P7)	Trust and user acceptance as conditions of use	
"Technology alone is not enough; clients need training, operators need maintenance skills, and service support over time" (P8)	Trust and user acceptance as conditions of use	
"When institutions depend on contacts or corruption, people are less likely to participate" (P1)	Trust and user acceptance as conditions of use	
"Full prosthetic process takes one week to ten days; with 3D printing, in one day we can make a prosthetic" (P7)	Rapidity: shortened response times and faster lead times	**Resilience contributions (4Rs)**
"In one or two hours: design it, make ten prototypes, change density, test it, and walk with it" (P6)	Rapidity: shortened response times and faster lead times	
"From design to functional prototype in hours instead of weeks or months" (P5)	Rapidity: shortened response times and faster lead times	
"Innovation is the bridge between lack of resources and the solution; use available tools to create at least an initial solution" (P5)	Resourcefulness: adaptive and iterative problem-solving	
"Cost reduced from around $5,000 to approximately $400 through local redesign and fabrication" (P5)	Resourcefulness: adaptive and iterative problem-solving	
"Multiple rounds of prototyping and material adjustment were needed before a usable design emerged" (P5)	Resourcefulness: adaptive and iterative problem-solving	
"AM was a solution when the supply chain was disrupted; there was no other way to bring things in" (P4)	Redundancy: alternative production routes when supply chains fail	
"Critical parts that did not exist anywhere in Syria; local fabrication saved time, money, and logistics" (P5)	Redundancy: alternative production routes when supply chains fail	
"A connector with a shape not found in the market; 3D printing produced the missing part and kept the water system functioning" (P4)	Redundancy: alternative production routes when supply chains fail	
"Under siege, we could send digital designs online; local teams printed the items needed" (P4)	Redundancy: alternative production routes when supply chains fail	
"Repaired more than 400 critical medical devices; around half required printed spare parts" (P4)	Robustness: sustained function through repair and ongoing modification	
"The digital file allows device adjustment as the patient's condition or environment changes; replacement produced without requiring travel" (P7)	Robustness: sustained function through repair and ongoing modification	

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First-order concepts (participant language)	Second-order themes	Aggregate dimensions
"When a small part breaks, the whole infrastructure can stop working; solving that problem has enormous impact on long-term infrastructure resilience" (P3)	Robustness: sustained function through repair and ongoing modification	
"The goal is not only to manufacture a device, but to help the person return to daily life" (P7)	Restoration of dignity and social participation as a resilience outcome	**Dignity and social resilience outcomes (inductive extension)**
"Support children physically and emotionally so they can go to school, see their friends, and not feel broken inside" (P7)	Restoration of dignity and social participation as a resilience outcome	
"The patient also needs training, speech support, psychological support, and help integrating into society" (P7)	Restoration of dignity and social participation as a resilience outcome	
"Training was part of our policy around community empowerment and resilience; make local people part of the solution" (P5)	Community empowerment and shift from recipient to active participant	
"Communities want to be part of the solution, not just recipients of aid" (P5)	Community empowerment and shift from recipient to active participant	
"We provided courses and study tours for students; basic design and fabrication rather than only finished products" (P5)	Community empowerment and shift from recipient to active participant	
"I had to repeatedly justify that I was not designing a weapon" (participant)	Institutional friction and security-framing as implementation barrier	**Structural and governance barriers (inductive extension)**
"Strong ideas or initiatives remained unrealized because they lacked support, permissions, or institutional pathways" (P6)	Institutional friction and security-framing as implementation barrier	
"NGOs are constrained by their funders; they try to manage the crisis but cannot challenge the bigger picture" (P2)	Institutional friction and security-framing as implementation barrier	
"Money to build a well but no system to maintain it; when a small part breaks, the whole infrastructure stops" (P3)	Maintenance gap as structural system vulnerability	
"Humanitarian agencies buy low-cost imported products that are hard to maintain; spare parts become a constant problem" (P3)	Maintenance gap as structural system vulnerability	

Bibliography

Abdulrahman, M. D., Yuvaraj, M., et al. (2023). Improving agility and resilience of automotive spares supply chain: The additive manufacturing enabled truck model. *Socio-Economic Planning Sciences*, 85:101401.

Aburas, R., Najeeb, A., Baageel, L., and Mackey, T. K. (2018). The syrian conflict: a case study of the challenges and acute need for medical humanitarian operations for women and children internally displaced persons. *BMC medicine*, 16(1):65.

Alhaffar, M. B. A. and Janos, S. (2021). Public health consequences after ten years of the syrian crisis: a literature review. *Globalization and health*, 17(1):111.

Almaleh, A. (2023). Measuring resilience in smart infrastructures: A comprehensive review of metrics and methods. *Applied Sciences*, 13(11):6452.

Almoghathawi, Y. (2024). Optimal resilience-based restoration plan for disrupted interdependent infrastructure networks under uncertainty. *Journal of Engineering Research*.

Alogla, A. A., Baumers, M., Tuck, C., and Elmadih, W. (2021). The impact of additive manufacturing on the flexibility of a manufacturing supply chain. *Applied Sciences*, 11(8):3707.

Amir, S. and Kant, V. (2018). Sociotechnical resilience: A preliminary concept. *Risk Analysis*, 38(1):8–16.

Arabadzhiyski, P., Vasilev, V., and Sidova, D. (2025). Effective human resource management and environmental security: Protection of human environmental rights and critical infrastructure sustainability. In *Environment. Technology. Resources. Proceedings of the 16th International Scientific and Practical Conference*, volume 5, pages 23–28. RTU Rezekne Academy.

Attaran, M. (2017). The rise of 3-d printing: The advantages of additive manufacturing over traditional manufacturing. *Business horizons*, 60(5):677–688.

Bai, J., Ferreira, F. A., Ferreira, N. C., Ferreira, J. J., and Correia, R. J. (2024). Enhancing hospital resilience and planning capacity in scenarios of crisis using group decision-making and interpretive structural modeling. *Strategic Change*, 33(3):201–217.

Bakhtiari, S., Najafi, M. R., Goda, K., and Peerhossaini, H. (2025). A dynamic bayesian network approach to characterize multi-hazard risks and resilience in interconnected critical infrastructures. *Reliability Engineering & System Safety*, 257:110815.

Bazli, M., Ashrafi, H., Rajabipour, A., and Kutay, C. (2023). 3d printing for remote housing: Benefits and challenges. *Automation in Construction*, 148:104772.

Bektaş, N. and Yildiz, A. (2025). Critical infrastructures for disaster risk reduction. In *Encyclopedia of Disaster Risk Reduction*, pages 1–6. Springer.

Belhadi, A., Kamble, S., Subramanian, N., Singh, R. K., and Venkatesh, M. (2024). Digital capabilities to manage agri-food supply chain uncertainties and build supply chain resilience during compounding geopolitical disruptions. *International Journal of Operations & Production Management*, 44(11):1914–1950.

Besenyő, J. (2024). Africa and the russian-ukrainian war and its impact on africa. In *International Conference on Central European Infrastructure Protection*, pages 157–177. Springer.

Bhandari, P., Creighton, D., Gong, J., Boyle, C., and Law, K. M. (2023). Evolution of cyber-physical-human water systems: Challenges and gaps. *Technological Forecasting and Social Change*, 191:122540.

Bouchenine, A. and Abdel-Aal, M. A. (2023). Towards supply chain resilience with additive manufacturing: A bibliometric survey. *Supply Chain Analytics*, 2:100014.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., and Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake spectra*, 19(4):733–752.

Budzik, G., Tomaszewski, K., and Soboń, A. (2022). Opportunities for the application of 3d printing in the critical infrastructure system. *Energies*, 15(5):1656.

Camacho, D. D., Clayton, P., O'Brien, W. J., Seepersad, C., Juenger, M., Ferron, R., and Salamone, S. (2018). Applications of additive manufacturing in the construction industry–a forward-looking review. *Automation in construction*, 89:110–119.

Campoli, A., Luck, R., Shrestha, P., Pradhan, P., and Rana, P. (2024). 'it is not rocket science but it can change our lives': pluriversal design with fablab nepal at a spinal injury clinic. *CoDesign*, 20(1):20–35.

Chowdhury, P., Paul, S. K., Kaisar, S., and Moktadir, M. A. (2021). Covid-19 pandemic-related supply chain studies: A systematic review. *Transportation Research Part E: Logistics and Transportation Review*, 148:102271.

Cirik, A. A. and Mendonça, D. (2009). Responding to disaster in socio-technical systems. In *2009 IEEE International Conference on Systems, Man and Cybernetics*, pages 3928–3933. IEEE.

Corsini, L., Aranda-Jan, C. B., and Moultrie, J. (2022). The impact of 3d printing on the humanitarian supply chain. *Production Planning & Control*, 33(6-7):692–704.

Corsini, L. and Moultrie, J. (2019). Design for social sustainability: Using digital fabrication in the humanitarian and development sector. *Sustainability*, 11(13):3562.

Deelstra, A. and Bristow, D. N. (2023). Assessing the effectiveness of disaster risk reduction strategies on the regional recovery of critical infrastructure systems. *Resilient CIties and Structures*, 2(3):41–52.

DeJonckheere, M. and Vaughn, L. M. (2019). Semistructured interviewing in primary care research: a balance of relationship and rigour. *Family medicine and community health*, 7(2):e000057.

Delic, M. and Eyers, D. R. (2020). The effect of additive manufacturing adoption on supply chain flexibility and performance: An empirical analysis from the automotive industry. *International journal of production economics*, 228:107689.

Den Boer, J., Lambrechts, W., and Krikke, H. (2020). Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain. *Journal of Cleaner Production*, 257:120301.

Dzogbwu, T., Jnr, S. A., Amoah, N., Fianko, S. K., Imdaadulah, A., and De Beer, D. (2023). Supply chain disruptions and resilience in manufacturing industry during covid-19: additive manufacturing intervention in perspective. *Journal of Industrial Engineering and Management*, 16(3):509–520.

Ekzayez, A., Alhaj Ahmad, Y., Alhaleb, H., and Checchi, F. (2021). The impact of armed conflict on utilisation of health services in north-west syria: an observational study. *Conflict and health*, 15(1):91.

Elo, S. and Kyngäs, H. (2008). The qualitative content analysis process. *Journal of advanced nursing*, 62(1):107–115.

Emery, F. E. and Trist, E. L. (1960). Socio-technical systems. *Management science, models and techniques*, 2:83–97.

Engler, E., Baldauf, M., Banyś, P., Heymann, F., Gucma, M., and Sill Torres, F. (2019). Situation assessment—an essential functionality for resilient navigation systems. *Journal of Marine Science and Engineering*, 8(1):17.

Ewa, W. O., Ugwu, O. O., and Okafor, F. O. (2024). Resilient–vulnerability analysis of critical infrastructure, key resources, assets, and facilities. *Innovative Infrastructure Solutions*, 9(4):109.

Fernando, Y., Al-Madani, M. H. M., and Shaharudin, M. S. (2024). Covid-19 and global supply chain risks mitigation: systematic review using a scientometric technique. *Journal of Science and Technology Policy Management*, 15(6):1665–1690.

Frei, R., Bausch, N., et al. (2016). Additive manufacturing as a socio-technical system. *International Journal of Latest Engineering and Management Research*, 1(10).

Gordan, M., Kountche, D. A., McCrum, D., Schauer, S., König, S., Delannoy, S., Connolly, L., Iacob, M., Durante, N. G., Shekhawat, Y., et al. (2024). Protecting critical infrastructure against cascading effects: The precinct approach. *Resilient Cities and Structures*, 3(3):1–19.

Griffith, T. L. and Dougherty, D. J. (2001). Beyond socio-technical systems: introduction to the special issue. *Journal of Engineering and Technology Management*, 18(3-4):207–218.

Guo, D., Shan, M., and Owusu, E. K. (2021). Resilience assessment frameworks of critical infrastructures: state-of-the-art review. *Buildings*, 11(10):464.

Hassoun, A., Parra-López, C., Ben Hassen, T., Ben Abdallah, S., Shehadeh, L., Socol, C. T., Rajeb, A., Mahdi, N., Samadhiya, A., Buheji, M., et al. (2025). The gaza conflict and its implications for the sustainable development goals: a comprehensive analysis. *Environment, Development and Sustainability*, pages 1–33.

He, J., Liu, G., Mai, T. H. T., and Li, T. T. (2021). Research on the allocation of 3d printing emergency supplies in public health emergencies. *Frontiers in Public Health*, 9:657276.

Hsieh, H.-F. and Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative health research*, 15(9):1277–1288.

Irankunda, G., Zhang, W., Fernand, M., and Zhang, J. (2024). Assessing the resilience of critical infrastructure facilities toward a holistic and theoretical approach: A multi-scenario evidence and case study. *Sustainability*, 16(20):8735.

Ivanov, D. and Sokolov, B. (2020). Supply network dynamics and control. *Network*.

Kahlen, F.-J., Flumerfelt, S., and Alves, A. (2017). Transdisciplinary perspectives on complex systems. *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*.

Kalkanis, K., Kiskira, K., Papageorgas, P., Kaminaris, S. D., Piromalis, D., Banis, G., Mpelesis, D., and Batagiannis, A. (2023). Advanced manufacturing design of an emergency mechanical ventilator via 3d printing—effective crisis response. *Sustainability*, 15(4):2857.

Kallio, H., Pietilä, A.-M., Johnson, M., and Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of advanced nursing*, 72(12):2954–2965.

Kamble, S., Belhadi, A., Gupta, S., Islam, N., Verma, V. K., and Solima, L. (2023). Analyzing the barriers to building a 3-d printing enabled local medical supply chain ecosystem. *IEEE Transactions on Engineering Management*, 71:12974–12991.

Keskin, M. H., Koray, M., Kaya, E., Fidan, M. M., and Söğüt, M. Z. (2025). Additive manufacturing for remedying supply chain disruptions and building resilient and sustainable logistics support systems. *Sustainability*, 17(6):2783.

Kim, T., Yi, S.-r., Kim, J. H., and Byun, J.-E. (2025). Disaster resilience analysis framework for lifeline networks: Integrating reliability, redundancy, and recoverability. *International Journal of Disaster Risk Reduction*, 123:105436.

Kleer, R. and Piller, F. T. (2019). Local manufacturing and structural shifts in competition: Market dynamics of additive manufacturing. *International Journal of Production Economics*, 216:23–34.

Knodt, M., Fraune, C., and Engel, A. (2022). Local governance of critical infrastructure resilience: Types of coordination in german cities. *Journal of Contingencies and Crisis Management*, 30(3):307–316.

Kolade, O., Adegbile, A., and Sarpong, D. (2022). Can university-industry-government collaborations drive a 3d printing revolution in africa? a triple helix model of technological leapfrogging in additive manufacturing. *Technology in Society*, 69:101960.

Kozine, I., Petrenj, B., and Trucco, P. (2018). Resilience capacities assessment for critical infrastructures disruption: the read framework (part 1). *International Journal of Critical Infrastructures*, 14(3):199–220.

Kumar, A., Pal, I., Santoso, D. S., Ninsawat, S., and Islam, S. T. (2025). Identification of critical infrastructure sectors and their interdependencies in bangladesh: A step towards resilience planning: Kumar et al. *International Journal of Disaster Risk Science*, 16(4):682–698.

Kyngäs, H., Mikkonen, K., and Kääriäinen, M. (2020). *The application of content analysis in nursing science research*. Springer.

Lincoln, Y. S. (1985). *Naturalistic inquiry*, volume 75. sage.

Lipsky, S., Przyjemski, A., Velasquez, M., and Gershenson, J. (2019). 3d printing for humanitarian relief: the printer problem. In *2019 IEEE Global Humanitarian Technology Conference (GHTC)*, pages 1–7. IEEE.

Malterud, K., Siersma, V. D., and Guassora, A. D. (2016). Sample size in qualitative interview studies: guided by information power. *Qualitative health research*, 26(13):1753–1760.

Månefjord, J. L. and Johansson, J. (2024). Critical flows throughout the covid-19 pandemic–a longitudinal study on interdependencies and resilience in a swedish context. *International Journal of Disaster Risk Reduction*, 103:104295.

Manero, A., Smith, P., Koontz, A., Dombrowski, M., Sparkman, J., Courbin, D., and Chi, A. (2020). Leveraging 3d printing capacity in times of crisis: recommendations for covid-19 distributed manufacturing for medical equipment rapid response. *International journal of environmental research and public health*, 17(13):4634.

Mani, Z. A., Khorram-Manesh, A., Alotaibi, H., and Goniewicz, K. (2024). Global catastrophe of hospital disasters: a retrospective analysis (1976–2023). *Signa Vitae*, 1:12.

Marchetta-Cruz, G., Torres-Cedillo, S. G., and Jimenez-Martinez, M. (2025). Advancing humanitarian aid through additive manufacturing: Innovations, applications, and future prospects. In *2025 IEEE Mexican Humanitarian Technology Conference (MHTC)*, pages 108–115. IEEE.

Mentges, A., Halekotte, L., Schneider, M., Demmer, T., and Lichte, D. (2023). A resilience glossary shaped by context: Reviewing resilience-related terms for critical infrastructures. *International journal of disaster risk reduction*, 96:103893.

Moglen, R. L., Leibowicz, B. D., and Kwasinski, A. (2025). The value of coordination for restoring power and wireless communication networks. *Reliability Engineering & System Safety*, 256:110771.

Mohd Zahari, H., Mohammed Zain, R., Mohd Nasir, N., and Hidayah Azhar, N. (2025). Optimising humanitarian logistics: A lesson learned for rapid response to supply chain disruptions in crisis situations. In *Supply Chain in Humanitarian Operations: Managing Disruption Through Intervention and Innovation*, pages 19–30. Springer.

Muthukumarasamy, K., Balasubramanian, P., Marathe, A., and Awwad, M. (2018). Additive manufacturing—a future revolution in supply chain sustainability and disaster management. In *Proceedings of the 8th international Conference on industrial engineering and operations management, Bandung, Indonesia*, pages 6–8.

Muvunzi, R., Mpofu, K., Daniyan, I., and Fameso, F. (2022). Analysis of potential materials for local production of a rail car component using additive manufacturing. *Heliyon*, 8(5).

Naghshineh, B. and Carvalho, H. (2022). The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review. *International Journal of Production Economics*, 247:108387.

Nazir, A., Azhar, A., Nazir, U., Liu, Y.-F., Qureshi, W. S., Chen, J.-E., and Alanazi, E. (2021). The rise of 3d printing entangled with smart computer-aided design during covid-19 era. *Journal of Manufacturing Systems*, 60:774–786.

Nguyen, T. D., Zeng, Q., and Pishdad, P. (2025). Integrating construction 4.0 technologies to strengthen post-disaster construction supply chain. *Annual Conference of the International Group for Lean Construction*, pages 705–716.

Novak, J. I. and Loy, J. (2023). A critical review of initial 3d printed products responding to covid-19 health and supply chain challenges. *Emerald Open Research*, 1(1).

Olivares-Aguila, J. and Vital-Soto, A. (2021). Supply chain resilience roadmaps for major disruptions. *Logistics*, 5(4):78.

Pasmore, W., Winby, S., Mohrman, S. A., and Vanasse, R. (2019). Reflections: sociotechnical systems design and organization change. *Journal of Change Management*, 19(2):67–85.

Perera, U. S., Siriwardana, C., and Pitigala Liyana Arachchi, I. S. (2024). Development of critical infrastructure resilience index for cities in sri lanka. *International journal of disaster resilience in the built environment*, 15(2):193–211.

Petrenj, B., Piraina, M., Borghetti, F., Marchionni, G., Urbano, V., et al. (2023). Cross-border digital platform for transport critical infrastructure resilience: Functionalities and use-case. In *Proceedings of the International ISCRAM Conference*, volume 2023, pages 96–111. Information Systems for Crisis Response and Management, ISCRAM.

Priyadarshini, J., Singh, R. K., Mishra, R., Chaudhuri, A., and Kamble, S. (2025). Supply chain resilience and improving sustainability through additive manufacturing implementation: a systematic literature review and framework. *Production Planning & Control*, 36(3):309–332.

Rahman, N. A. A., Mahroof, K., and Simarmata, J. (2025). *Supply Chain in Humanitarian Operations: Managing Disruption Through Intervention and Innovation*. Springer Nature.

Rai, N. and Thapa, B. (2015). A study on purposive sampling method in research. *Kathmandu: Kathmandu School of Law*, 5(1):8–15.

Raja Santhi, A. and Muthuswamy, P. (2022). Pandemic, war, natural calamities, and sustainability: Industry 4.0 technologies to overcome traditional and contemporary supply chain challenges. *Logistics*, 6(4):81.

Rathnayaka, B., Robert, D., Adikariwattage, V., Siriwardana, C., Meegahapola, L., Setunge, S., and Amaratunga, D. (2024). A unified framework for evaluating the resilience of critical infrastructure: Delphi survey approach. *International Journal of Disaster Risk Reduction*, 110:104598.

Rehak, D., Splichalova, A., Janeckova, H., Oulehlova, A., Hromada, M., Kontogeorgos, M., and Ristvej, J. (2024). Critical entities resilience assessment (cera) to small-scale disasters. *International Journal of Disaster Risk Reduction*, 111:104748.

Reza, M. N. H., Jayashree, S., Malarvizhi, C. A. N., Rauf, M. A., Jayaraman, K., and Shareef, S. H. (2022). The implications of industry 4.0 on supply chains amid the covid-19 pandemic: a systematic review. *F1000Research*, 10:1008.

Rodríguez-Espíndola, O., Chowdhury, S., Beltagui, A., and Albores, P. (2020). The potential of emergent disruptive technologies for humanitarian supply chains: the integration of blockchain, artificial intelligence and 3d printing. *International Journal of Production Research*, 58(15):4610–4630.

Saha, N., Rezapour, S., Sahin, N. C., and Amini, M. H. (2024). Coordinated restoration of interdependent critical infrastructures: A novel distributed decision-making mechanism integrating optimization and reinforcement learning. *Sustainable Cities and Society*, 114:105761.

Sambowo, A. L. and Hidayatno, A. (2021). Resilience index development for the manufacturing industry based on robustness, resourcefulness, redundancy, and rapidity. *International Journal of Technology*, 12(6).

Sathurshan, M., Saja, A., Thamboo, J., Haraguchi, M., and Navaratnam, S. (2022). Resilience of critical infrastructure systems: a systematic literature review of measurement frameworks. *Infrastructures*, 7(5):67.

Saurin, T. A., Patriarca, R., Hegde, S., and Rayo, M. (2024). The influence of digital technologies on resilient performance: contributions, drawbacks, and a research agenda. *Applied Ergonomics*, 118:104290.

Sikder, M., Daraz, U., Lantagne, D., and Saltori, R. (2018). Water, sanitation, and hygiene access in southern syria: analysis of survey data and recommendations for response. *Conflict and health*, 12(1):17.

Singh, S., Misra, S. C., and Singh, G. (2024a). Greening the supply chain: Leveraging additive manufacturing for sustainable risk management. *Business Strategy and the Environment*, 33(8):8233–8246.

Singh, S., Misra, S. C., and Singh, G. (2024b). Leveraging additive manufacturing for enhanced supply chain resilience and sustainability: a strategic integration framework. *Global Journal of Flexible Systems Management*, 25(2):343–368.

Smith, R. J. (2015). Healthcare under siege: Geopolitics of medical service provision in the gaza strip. *Social Science & Medicine*, 146:332–340.

Spieske, A. and Birkel, H. (2021). Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the covid-19 pandemic. *Computers & Industrial Engineering*, 158:107452.

Tareq, M. S., Rahman, T., Hossain, M., and Dorrington, P. (2021). Additive manufacturing and the covid-19 challenges: An in-depth study. *Journal of Manufacturing systems*, 60:787–798.

Tofail, S. A., Koumoulos, E. P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., and Charitidis, C. (2018). Additive manufacturing: scientific and technological challenges, market uptake and opportunities. *Materials today*, 21(1):22–37.

Toroghi, S. S. H. and Thomas, V. M. (2020). A framework for the resilience analysis of electric infrastructure systems including temporary generation systems. *Reliability Engineering & System Safety*, 202:107013.

Ullah, H., Uzair, M., Jan, Z., and Ullah, M. (2024). Integrating industry 4.0 technologies in defense manufacturing: Challenges, solutions, and potential opportunities. *Array*, 23:100358.

United Nations Office for Disaster Risk Reduction (2017). Resilience. The Sendai Framework Terminology on Disaster Risk Reduction. Accessed: 2026-04-26.

Vears, D. F. and Gillam, L. (2022). Inductive content analysis: A guide for beginning qualitative researchers. *Focus on Health Professional Education: A Multi-Professional Journal*, 23(1):111–127.

Wang, Y., Ahmed, A., Azam, A., Bing, D., Shan, Z., Zhang, Z., Tariq, M. K., Sultana, J., Mushtaq, R. T., Mehboob, A., et al. (2021). Applications of additive manufacturing (am) in sustainable energy generation and battle against covid-19 pandemic: The knowledge evolution of 3d printing. *Journal of manufacturing systems*, 60:709–733.

Wysoczański, A., Kamyk, Z., and Yvinec, Y. (2021). Analysis of the possibility of employing 3d printing technology in crisis situations. *Technical Transactions*, 8.

Zezulova, E., Maňas, P., and Cibulova, K. (2023). Population protection and protection of critical infrastructure elements. In *2023 International Conference on Military Technologies (ICMT)*, pages 1–7. IEEE.

Zheng, C., Peng, X., Wang, Z., Ma, T., Lu, J., Chen, L., Dong, L., Wang, L., Cui, X., and Shen, Z. (2025). A review on blockchain applications in operational technology for food and agriculture critical infrastructure. *Foods*, 14(2):251.