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Enhancing Spare Part Availability Under Extreme Supply Chain Disruption:

The Role of Civilian Supply Bases in Supporting UGV
Systems Resilience

Master's thesis in Supply Chain Management

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SUMMARY

This study examines how spare part availability for Unmanned Ground Vehicle (UGV) systems can be strengthened through the use of alternative civilian component supply bases under extreme supply chain disruption. Such disruptions may arise in contexts characterized by armed conflict, degraded infrastructure, restricted logistics access, or the loss of conventional supplier and original equipment manufacturer channels. The purpose of the study is to develop principles for resilience-oriented component sourcing that support continued system operation when established supply routes are constrained, unreliable, or unavailable.

The study is based on a qualitative single-case design conducted in collaboration with a UGV startup and an established heavy vehicle manufacturer. Empirical data were collected through semi-structured interviews with eight respondents representing UGV development, heavy vehicle manufacturing, defense logistics, and operationally critical environments. The analysis followed an abductive approach, combining thematic analysis of the empirical material with theoretical insights from supply chain resilience, spare parts logistics, alternative sourcing approaches, and design for supply.

The findings show that spare part availability under extreme disruption is shaped by four interrelated dimensions: operational context, component criticality, lifecycle dynamics, and organizational dependencies. Civilian heavy vehicle supply networks can strengthen resilience by providing access to standardized components, modular architectures, component reuse opportunities, and distributed aftermarket structures. However, the findings also demonstrate that civilian availability alone is insufficient. To support operational continuity, components must be physically compatible, performance-equivalent, identifiable, accessible within relevant time constraints, and possible to install using available tools and competence. The use of civilian supply bases is further limited by commercial differentiation, regulatory requirements, lifecycle mismatches, and hidden dependencies within supplier networks.

Based on these findings, the study proposes four principles for resilience-oriented sourcing decisions. First, spare part needs should be evaluated at the functional level rather than solely at the component level, with priority given to functions that are critical for mission continuity. Second, civilian component availability must be converted into operational usability through operational adaptability. Third, components with broad and deep supply network commonality across platforms, applications, and aftermarket channels should be prioritized. Fourth, future availability and support continuity should be assessed alongside current availability, particularly for components exposed to obsolescence or software-related dependencies.

The study contributes to supply chain resilience literature by connecting resilience theory with component-level sourcing decisions for complex technical systems operating under extreme disruption. It also provides practical guidance for organizations developing UGVs or similar platforms where civilian-military integration, alternative sourcing approaches, and long-term spare part availability are strategically important. The findings are limited by the single-case design and the absence of operational UGV deployment data. Future research should validate the proposed principles across additional cases and examine the technical, economic, and operational feasibility of specific component substitutions.

Keywords: supply chain resilience, spare part availability, alternative sourcing, civilian networks, UGV, component criticality, standardization, modularity, extreme disruption

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1. Introduction

This thesis is conducted within the Department of Technology Management and Economics at Chalmers University of Technology, and in collaboration with a start-up company that will remain anonymous throughout this study. The company is developing unmanned ground vehicles (UGVs) intended for use in war situations; hence, the company will be referred to as UGV Inc hereafter. The project is also carried out in collaboration with an established truck manufacturer which will also remain anonymous and will hereafter be referred to as Truck Inc.

This chapter will introduce the area of the study by presenting a background and problem definition of the study. The objective is to provide a clear understanding of why this study is conducted and the area of research. Two central themes are found throughout this chapter: disruptions and resilience. These are two key themes, essential for understanding the relevance of the study, both for the company and broader research interests. The chapter concludes by stating the aim and research questions that guide the study.

1.1 Background

In recent years, UGVs have received increasing attention for use in complex, high-risk environments such as logistics support and rescue operations (Munasinghe et al., 2024). By reducing human exposure to danger, these systems enable continued operational capability in environments characterized by uncertainty, damaged infrastructure, and limited external support (Endsley, 2017; Mondal et al., 2025). However, in both civilian and military contexts, these vehicles are expected to operate under conditions where availability of spare parts is constrained due to disruptions in established supply chains.

Modern UGVs are complex systems relying on advanced electronics, integrated subsystems, and specialized components (La Regina et al., 2025). While this level of technological maturity enables improved performance and autonomy, it simultaneously increases dependence on reliable supply chains for spare parts, maintenance, and repair (Vodenicharova & Genova, 2025; Vieira & Herrmann, 2025). During normal operating conditions, such complexity and dependencies are typically addressed through efficiency-oriented practices such as centralized production, just-in-time logistics, and cost focused sourcing strategies (Lucker et al., 2025; Yang et al., 2025).

However, supply chain management research has consistently shown that supply chains designed primarily for efficiency tend to lack resilience and are therefore particularly vulnerable to major disruptions (Christopher & Peck, 2004; Sheffi & Rice, 2005; Lucker et al., 2025; Ivanova, 2025). In extreme disruption scenarios, such as in an armed conflict, or target attacks on infrastructure, access to core manufacturing facilities and established logistics networks may be severely constrained or completely cut off (Yan et al., 2023).

Therefore, the availability of spare parts becomes a critical determinant of operational continuity under conflict situations or other high-disruption scenarios. Research shows that system uptime is often constrained by the lack of timely access to critical spare parts, and not technical repair capability (Kolinska et al., 2017; Antosz & Ratnayake 2019; Zhu et al., 2025). This becomes especially vital for mission-critical platforms such as unmanned ambulance ground vehicles, as insufficient availability of key components may result in prolonged downtime, directly affecting mission effectiveness and potentially human safety.

As a result, supply chain resilience has emerged as a central concept within supply chain management research. Resilience-oriented supply chains focus on the ability to anticipate disruptions, the capacity to absorb their impacts, and the ability to recover quickly, rather than optimizing operations solely for stable conditions (Andersson & Klinga, 2023; Hosseini et al., 2025; Mohebbi et al., 2025). From this perspective, maintaining high availability of selected spare parts during extreme disruptive conditions constitutes a core capability of resilient supply chain design (Guo et al., 2024). However, achieving a high availability for complex systems such as UGVs in challenging environments to a unique challenge.

One potential, but less extensively explored, approach to improving spare parts availability during crisis situations is to use civilian vehicle supply networks, particularly those supporting mass-produced vehicles, as alternative supply bases (Sheffi & Rice, 2005; Pettit et al., 2010). While access to specialized UGV components may be completely disrupted, the vehicles core mechanical and critical functionality often depend on commercial off-the-shelf (COTS) or modified commercial parts. Civilian heavy-duty vehicles are produced in large volumes and are supported by established aftermarket and service networks, in which spare parts availability plays an important role in after-sales support activities (Cohen et al., 2006). In addition, it is common for civilian vehicles to have platform-based designs, which may further facilitate maintenance and repair in demanding operational environments (Ulrich, 1995; Hedvall, 2016).

Taken together, these characteristics suggest that compatible components from civilian vehicles systems could, under certain conditions, be leveraged to restore functionality and sustain operations of specialized platforms by enabling repair, replacement, and maintenance, when conventional supply sources are disrupted or unavailable (Sheffi & Rice, 2005; Inderfurth & Mukherjee, 2007; Guide & Van Wassenhove, 2009; Pettit et al., 2010). Although supply chain resilience has received increasing attention, research addressing how alternative supply bases can be systematically structured and prioritized at the component level for complex vehicle systems operating under conflict conditions remains limited. More specifically, there is a lack of structured approaches that link component criticality to sourcing strategies aimed at ensuring high spare parts availability during extreme disruptions, to contexts that combine civilian and military equipment.

1.1.1 Operational Context

UGVs intended for medical evacuation and logistics support are expected to operate in environments of high uncertainty where infrastructure is degraded, and access to centralized maintenance facilities is limited. In such contexts, operational continuity

is less dependent on production capacity and more on the ability to maintain functional systems at decentralized service points.

In the event of a disruption that limits or completely shuts down primary manufacturing facilities or original equipment manufacturer (OEM) supply chains, alternative sourcing channels must be leveraged to maintain maintenance operations. Service and maintenance points act critical nodes, where spare part availability directly impacts vehicle uptime and operational capability.

Therefore, the logistical challenge goes beyond upstream supply continuity. It requires the establishment of a resilient spare parts supply structure that can support rapid repair, preventive maintenance, and component replacement under constrained conditions. Within this framework, access to mass-produced civilian automotive components and their aftermarket supply networks could represent a strategically viable alternative source.

In this study, supply chain resilience is assessed based on spare part availability at the service point-level.

1.2 Problem statement

Despite extensive research on supply chain resilience, there remains limited understanding of how alternative sourcing approaches can support spare part availability for complex technical systems operating under conditions of high supply uncertainty. Resilience research emphasizes that system continuity depends not only on recovery speed, but on the ability to maintain critical functions when conventional supply networks fail (Christopher & Peck, 2004; Sheffi & Rice, 2005). For vehicle-based platforms, operational continuity is often constrained by spare part availability rather than repair capability, making component access a decisive factor in system uptime (Kolinska et al., 2017).

This challenge becomes particularly critical for unmanned emergency and crisis-response vehicles, which may operate in environments where centralized manufacturing and logistics infrastructures are partially or completely inaccessible. While civilian heavy vehicle networks provide large-scale distributed component networks, research has not yet established systematic frameworks for evaluating how such supply networks can be leveraged as resilience-oriented spare part resources at the component level (Guide & Van Wassenhove, 2009; Pettit et al., 2010). Approaches that link to spare part availability, maintenance logic, and alternative sourcing approaches are not always clearly structured in existing supply chain resilience research. Clarifying how these aspects relate to one another is important for understanding how vehicle operations can be maintained when established supply chains are disrupted.

1.3 Aim

The aim of this study is to explore how spare part availability for UGV systems can be enhanced through alternative civilian component supply bases, and to propose principles for resilience-oriented component sourcing under extreme disruption scenarios.

1.4 Research Questions

RQ1: What factors influence spare part availability for UGV systems under extreme supply chain disruption?

RQ2: What are the enablers and constraints for using civilian heavy vehicle component supply networks as alternative spare part supply bases for UGV platforms?

RQ3: How can spare part availability and sourcing logic be structured into a set of principles that support resilience-oriented decision making?

1.5 Scope of the Study

Figure 1 below illustrates the analytical scope of the study and the supply chain disruption that motivates it. The upper part of the figure provides a simplified representation of the UGV supply chain, consisting of suppliers, the UGV manufacturer, and logistics providers. Disruptions affecting these actors can lead to the access to original spare parts being limited, which creates the need for alternative sourcing approaches. The focus of the study is therefore on civilian vehicle supply networks as alternative supply bases, and on how these networks can enhance spare part availability at service and maintenance points. The study does not examine the full UGV supply chain or battlefield operations but focuses on alternative sourcing approaches of spare parts that support UGV maintenance under disrupted conditions.

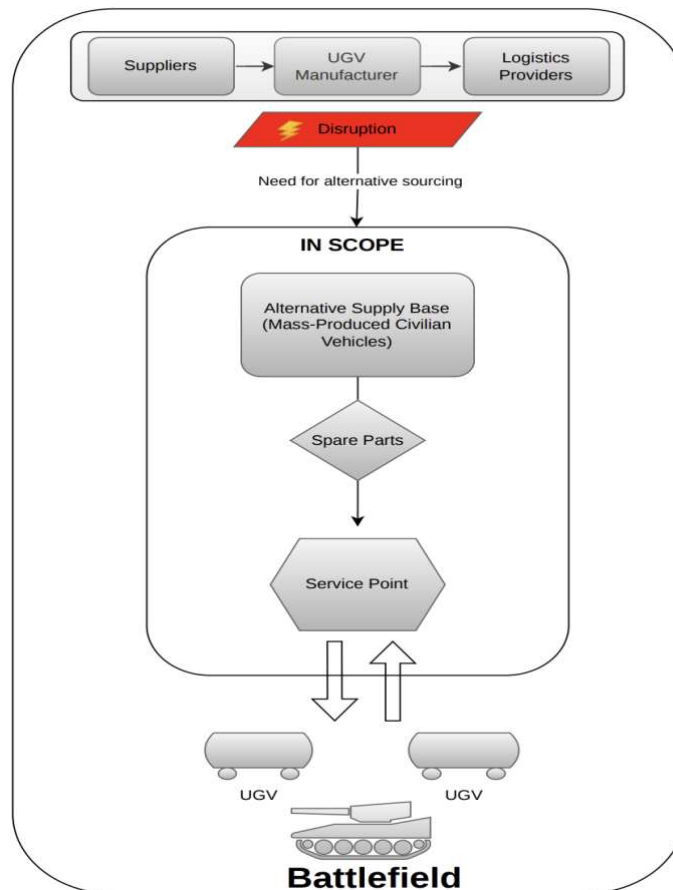


Figure 1: Scope of the study

2. Frame of Reference

This chapter presents the frame of reference for the study. It introduces the theoretical concepts and analytical perspectives relevant to understanding spare part availability, sourcing decisions, and supply chain resilience under disruption. The chapter further develops a conceptual understanding of how component characteristics, sourcing structures, and resilience capabilities influence spare part availability and resilience-oriented sourcing decision making. These concepts provide the foundation for empirical analysis and the interpretation of the findings in relation to the research questions.

2.1 Structure of the Frame of Reference

This section explains how the frame of reference is structured in relation to the aim and research questions of the study. Since the study examines spare part availability for UGV systems under extreme disruption, the chapter combines literature on supply chain resilience, service supply chains, alternative sourcing approaches, and component selection and design for supply.

Section 2.2 introduces supply chain resilience and disruptions, providing the broader theoretical context for understanding how supply chains prepare for, absorb, and recover from disruptions. Section 2.3 focuses on service supply chains and spare part availability, which is central for understanding how component access affects system uptime. Section 2.4 discusses alternative sourcing approaches under disruption, including civilian supply networks and contingency sourcing options. Section 2.5 addresses component selection and design characteristics, such as standardization, commonality, modularity, and COTS components, which influence whether civilian supply bases can be used in practice.

Together, these sections provide the theoretical basis for analyzing spare part availability, evaluating the feasibility of civilian supply networks, and developing principles for resilience-oriented sourcing decision making.

2.2 Supply Chain Resilience and Disruptions

In recent years, supply chain disruptions caused by natural disasters, pandemics, geopolitical conflicts, economic crises and more, have put a particular light on resilience in supply chain management research (Mohebbi et al., 2025; Yan et al., 2025; Ma et al., 2025). These man-made and natural events pose a serious challenge to operational continuity, and this has also exposed the vulnerability of efficiency driven supply chains to disruptions (Christopher & Peck, 2004; Sheffi & Rice, 2005). Traditional supply chain management practices have been implemented with the aim of minimizing costs and improve operational efficiency. These practices, however, reduce the chances of navigating through uncertainties, which can affect the ability to obtain necessary components and materials.

2.2.1 Defining Supply Chain Resilience

Supply chain resilience is according to (Pettit et al., 2010; Hosseini et al., 2019) defined as the ability of a supply chain to anticipate, absorb, and recover from disruptions while maintaining operational continuity. Christopher and Peck (2004, p. 4) define it as “the ability of a system to return to its original state or move to a new,

more desirable state after being disturbed.” While the definition differs among researchers, two key dimensions are emphasized: the ability to not only absorb but adapt to disturbances, and the capacity to recover (Ma et al., 2025). Ponomarov and Holcomb (2009) offers a multidimensional concept and describe it as “the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function.” This definition is widely cited in supply chain resilience research (Kamalahmadi and Parast, 2016). It suggests that resilience encompasses both proactive capabilities, i.e. anticipating and preparing for disruptions, and reactive capabilities, which involve effectively responding to and recovering from disruptions when they occur (Takamuhabwa et al., 2015; Mohebbi et al., 2025; Shekarabi et al., 2025).

The three common key dimensions that emerges from these definitions is listed in the bullet points below:

- Anticipate: The ability to foresee potential disruptions and prepare
- Absorb: The capacity to withstand impacts from disruptions without immediate failure in the system
- Recover: The capability to restore operations after disruption, potentially to a better state

Furthermore, rather than solely focusing on the speed of recovery, resilience involves the ability to sustain critical operational functions even when parts of the supply network become unavailable. The idea of resilience not only being about the speed of recovery is also echoed by Sheffi and Rice (2005), who proposes the disruption profile framework, which differentiates between preparing, responding and recovering from disruptions. Their study demonstrates that resilience extends beyond the recovery speed to managing the entire lifecycle of a disruption, from initial impact through sustained operations under constrained conditions (Sheffi and Rice, 2005).

This means that resilience is fundamentally about maintaining operations at desired levels despite disturbances (Ponomarov and Holcomb, 2009), which is a particularly relevant perspective for spare parts availability in conflict scenarios, where disruptions may last over longer periods.

2.2.2 Redundancy and Flexibility as Key Resilience Strategy Approaches

A key debate within the supply chain resilience literature is focused on whether redundancy or flexibility is the more effective strategy for enhancing resilience. Redundancy involves deliberate maintenance of additional resources, such as buffer inventory, alternative suppliers, or additional capacity in production. This slack is used when unexpected disturbances occur. On the other hand, flexibility refers to an organization’s ability to adapt quickly by modifying processes, reallocating resources, and adjusting relationships when disruptions occur. While redundancy relies on preparedness through extra capacity, flexibility depends on the capacity to rapidly reconfigure operations in response to an event. According to Yang et al. (2024), resilient supply chains often rely on a combination of these two approaches, where redundancy is more effective in terms of short-term protection and mitigation of risks,

while flexibility enables longer term adaptation and recovery. These two approaches represent two different approaches for dealing with uncertainty, and understanding their strengths and weaknesses is critical for determining how to enhance spare parts availability for a UGV operating under conflict scenarios. Resilience can be achieved by either creating redundancy or increasing flexibility (Sheffi and Rice, 2005).

Redundancy

Redundancy is the deliberate maintenance of additional resources that are used to absorb disruptions impacts, such as safety stock, multiple suppliers, buffer inventory, additional production capacity (Christopher and Peck, 2004; Sheffi and Rice, 2005).

In terms of resilience, redundancy primarily supports the absorptive capacity of the supply chain. By providing additional pre-positioned resources (Operational slack), it reduces the immediate impact of a disruption. Kamalahmadi and Parast (2016) suggest that redundancy in the form of inventory buffers and supplier diversification, reduces the scale of a disruption impact and enables critical activities to continue during early stages of a disruption. This means that redundancy contributes directly to robustness by reducing the immediate impact of disruptions through having a slack and ensuring that critical activities can continue even during supply disturbances (Ponomarev and Holcomb, 2009). The contribution to robustness comes primarily from having an inventory slack, as it allows supply chains to absorb the shock of disruptions and withstand the impact (Baghersad and Zobel, 2022). Furthermore, other types of operational slacks, such as capacity slack, instead assist in the ability to recover to a desired level of service after a disruption occurs. Baghersad and Zobel (2022) argue that operational slack is important for reducing losses resulting from a disruption, particularly in severe disruptions where inventory slack assists supply chains to absorb shocks and maintain operations.

Inventory positioning strategies is also a form of redundancy, and is often demonstrated in spare part supply chains, where critical components are often stored close to the point of use to ensure rapid availability and to minimize downtime (Kolinska et al., 2017; Zhu et al., 2025). This shows the critical role redundancy plays in ensuring availability at the operational level, which is of high priority in contexts where system functionality is dependent on timely access to specific components.

However, redundancy comes with limitations that are related to costs. Christopher and Peck (2004) and Sheffi and Rice (2005) both bring up the ongoing carrying costs that come incurred, for example, inventory degrades, extra capacity that is not used, and supplier governance. Sheffi and Rice (2005) argue that while redundancy represents a pure cost increase, it provides limited benefits for day-to-day operations and therefore should be a strategy purely for situations of disruptions (Sheffi and Rice, 2005; Yang et al., 2024).

Flexibility

Flexibility refers to the ability of a supply chain to adapt and reconfigure in response to disruptions by developing adaptable processes and relationships (Sheffi and Rice, 2005; Christopher and Peck, 2004; Nikookar et al., 2024). The strategy is built on responsiveness, adaptability, and the capacity to leverage alternative resources when unexpected events occur.

Ponomarov and Holcomb (2009) define flexibility as part of the adaptive capability of a supply chain to anticipate, respond to, and recover from disruptions while maintaining continuity in operations, i.e. it represents a core dimension of resilience. Kamalahmadi and Parast (2016) also highlight flexibility as a core principle of resilience, as it enables organizations to respond rapidly to unexpected events that change conditions in demand and supply. Yang et al. (2024) conceptualize flexibility as a key driver supporting the adaptive capacity of a supply chain. Therefore, investing in supply chain flexibility is of high importance.

Sheffi and Rice (2005) outlines five core aspects of supply chain flexibility, which is, flexibility in procurement and sourcing, manufacturing operations, distribution and customer related functions, control mechanisms, and organizational culture.

Furthermore, Pettit et al. (2010) and Manders et al. (2017), build on the idea that flexibility is a multidimensional concept that is operationalized through capabilities, such as flexibility in sourcing and order fulfillment. Flexibility in sourcing is about the ability to change input sources, which are enabled by factors such as part commonality, modular designs, multiple sources, and supplier flexibility. Flexibility in order fulfillment refers to the ability to change how outputs are delivered, e.g. the use of alternative distribution channels, postponement, inventory management, and re-routing of requirements (Pettit et al., 2010).

These capabilities are enabled through subfactors that determine the level of flexibility in the supply chain. For example, flexibility in sourcing which is defined as the ability to quickly change inputs or the mode of receiving inputs is supported by subfactors such as part commonality, modular product design, multiple sources, ability to use components across multiple applications (Pettit et al., 2010). These factors directly influence the ability to substitute components, switch suppliers and access alternative sources under disruptions.

Building on this, Yang et al. (2024) further structure flexibility into different levels, which are described in the bullet points below:

- Strategic: The ability of a supply chain to adjust long term decisions and respond to changes or uncertainties in the environment - e.g. developing rapid decision making, well established inter-organizational relationships, quick learning and adjusting (Yang et al., 2024).
- Structural: The ability of a supply chain to reconfigure its design, structure, and processes to adapt to changes in conditions - e.g. flexible design such as postponement, outsourcing, multi-channel procurement, rapid manufacturing, resource sharing (Yang et al., 2024; Mackay et al., 2020; Tang and Tomlin, 2008)
- Volume: The ability of a supply chain to adjust its processing capacity in response to changes in demand or disruptions - e.g. adjusting production volume through alternative suppliers or reallocating resources (Yang et al., 2024; Pettit et al., 2013; Tang and Tomlin, 2008)

- **Operational:** The ability of a supply to respond quickly to immediate changes in demand and supply conditions - e.g. adaptable processes through transferable production capabilities, modular product design, use of multiple operational pathways (Yang et al., 2024; Pettit et al., 2013; Tang and Tomlin, 2008)

The three dimensions presented above - strategic, structural, and volume flexibility - work together and form the foundation that enables operational flexibility.

Operational flexibility can further be divided across four operational dimensions: procurement and sourcing, manufacturing, distribution, and order fulfillment (Yang et al., 2024). This relationship is illustrated in Figure 2 below:

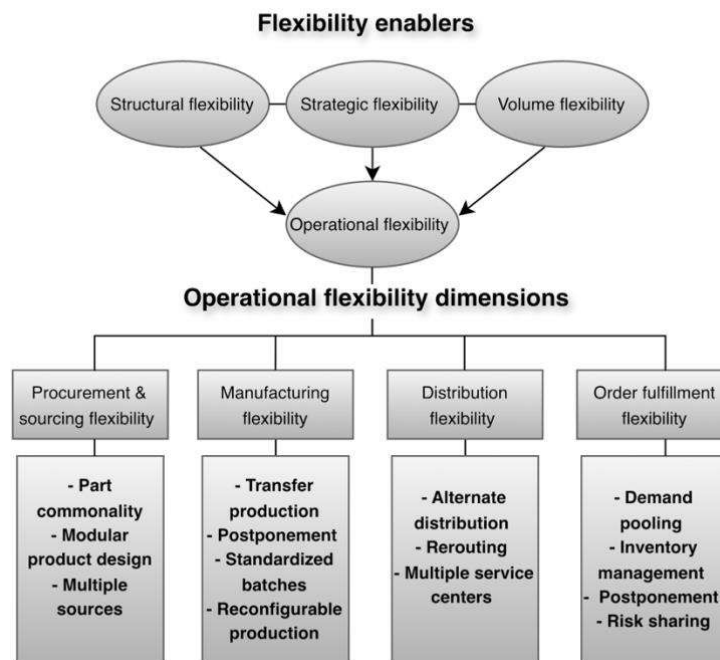


Figure 2: Supply chain flexibility: enablers and operational dimensions. Adapted from multiple sources including Sheffi and Rice (2005), Tang and Tomlin (2008), Pettit et al. (2010), Yang et al. (2024).

As shown in the figure, strategic, structural and volume flexibility serve as foundational enablers for operational flexibility. They do not directly determine supply chain operations but create conditions such as design choices that ultimately make operational flexibility possible. Operational flexibility is the capability that directly enables responses to disruptions (Yang et al., 2024). The four operational flexibility dimensions are built upon different subfactors that are presented in Figure 2.

Sheffi and Rice (2005) argue that flexibility requires lower investment upfront but depends on the ability to rapidly identify and access alternative resources. They furthermore state that investments in flexibility are of highest importance in terms of enhancing resilience, as its benefits extend beyond mitigating disruptions, to day-to-day operations (ibid.).

Synthesis of Strategies

Although redundancy and flexibility are treated as two distinct strategies or approaches contributing to resilience, authors such as Rice and Caniato (2003) view them as complementary functions within resilient supply chains. They argue that each approach presents unique cost and service characteristics that are both important when designing for resilience. Therefore, most resilient supply chains combine elements of both approaches (Rice and Caniato, 2003; Sheffi and Rice, 2005). Yang et al. (2024) builds upon this relational approach, where two relationships are presented: redundancy-based flexibility and flexibility related redundancy. Redundancy based flexibility refers to when redundant resources are used for the purpose of enabling flexible responses such as modular inventories that can be reconfigured for multiple applications or transferable production capacity, while flexibility related redundancy involves using flexible capabilities to access redundant resources, e.g. alternative distribution channels (Yang et al., 2024). Tukambawa et al. (2015) also highlights the redundancy-based flexibility relationship but also notes that various authors prefer flexibilities that do not rely on redundancy, as they are more resource efficient. However, both Tukambawa et al. (2015) and Yang et al. (2024) note that enhancing one enhances the other, as for example redundancy provides the extra resources needed to stay flexible and recover from disruptions, and flexibility enables accessing redundant resources, creating synergies and tradeoffs between them.

To illustrate this interplay, Yang et al. (2024) present a taxonomy of four supply chain operating modes that must be considered when configuring systems along the two dimensions (Figure 3). A vulnerable supply chain (SC) is characterized by low redundancy and low flexibility, which makes the impact of disruptions high. A supply chain that has invested in redundant resources but is not flexible is robust, which is a mode where the immediate impact of disruptions is mitigated through the redundancy but lacks adaptive capability. The lean mode prioritizes efficiency and rapid response but is vulnerable in the face of disruptions due to the lack of buffering capacity. This shows the tradeoffs between the two dimensions, and the need to balance both to become resilient, capable of both absorbing and adapting to disruptions (Yang et al., 2024).

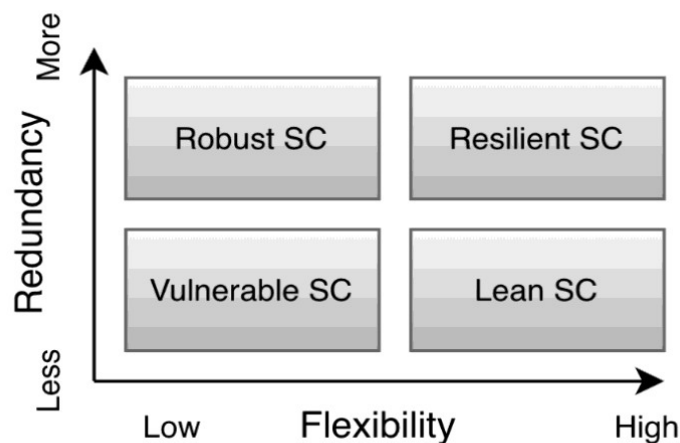


Figure 3: Interplay between redundancy and flexibility, based on Yang et al. (2020)

Building on this, the relationship between redundancy, flexibility and the core capabilities required throughout a disruption lifecycle can further be elaborated. Mackay et al. (2020) propose a conceptual framework that explains different ways

redundancy and flexibility is used proactively and reactively. Four different ways are identified: Insurance (proactive redundancy), expediting (reactive redundancy), strategic adaptive capability (proactive flexibility), and reconfiguration (reactive flexibility). Mackay et al. (2020) further emphasize that the usefulness of redundancy and flexibility depends on the specific context, where the characteristics of the supply chain and what type of disruption that has occurred influence their effectiveness. This echoes authors such as Rice and Caniato (2003), Tukambawa et al. (2015) and Yang et al. (2024), who see the two dimensions as strategic choices that vary depending on contextual and temporal factors.

As illustrated in Figure 4, the lifecycle of a supply chain disruption can be divided into three distinct phases: prepare, recover, adapt. The framework reflects the dynamic nature of resilience, where supply chains depend on capabilities to anticipate, absorb, and recover from disruptions (Christopher and Peck 2004; Ponomarov and Holcomb, 2009; Pettit et al., 2010), as well as adaptation, are enabled by redundancy and flexibility. Redundancy primarily supports absorptive capacity, enabling the supply chain to withstand immediate impact from disruptions, while flexibility enables recovery and adaptation, allowing reconfiguration (Sheffi and Rice, 2005; Yang et al., 2024)

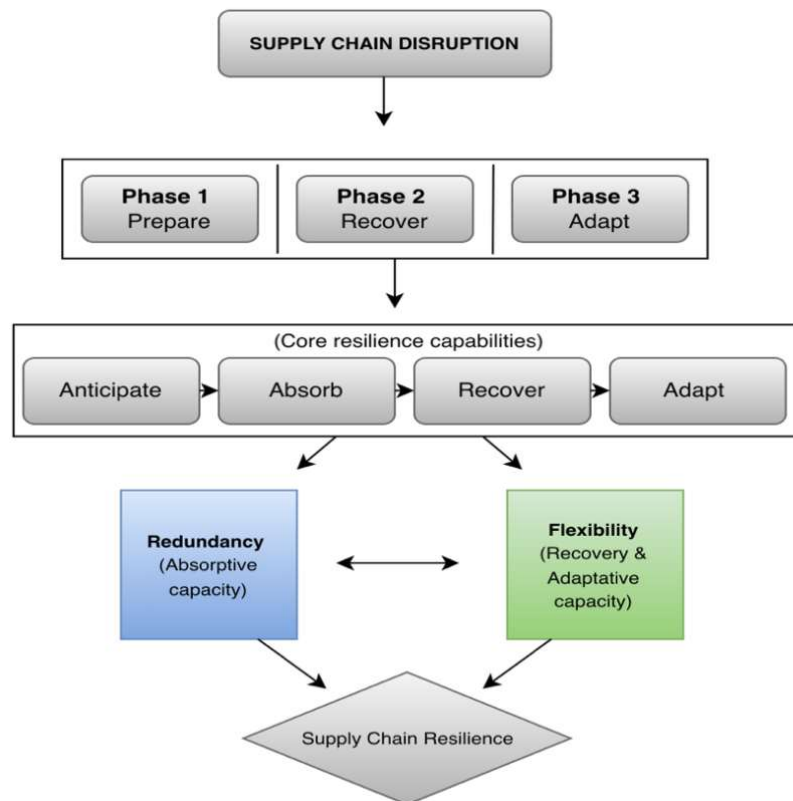


Figure 4: Conceptual framework of supply chain resilience illustrating the relationship between disruption phases, resilience capabilities and the interplay of redundancy and flexibility, based mainly on Yang et al. (2024) with input from Christopher and Peck (2004), Sheffi and Rice (2005), Ponomarov and Holcomb (2009)

The interplay between redundancy and flexibility in networked supply chains, as Christopher and Peck (2004) defines it, are complex, multi-tier networks of interconnected organizations. Within such networks, firms increasingly rely on redundancy found externally, such as partner capacity, shared logistics infrastructure

or resources, to buffer against disruptions (Christopher and Peck, 2004; Schloten and Schilder, 2015; Yang et al., 2024). Recognizing redundancy as an active capability and not only as a slack, is important to leverage these resources, as resilience depends not only on internal resources but also on the ability to mobilize resources across the network (Christopher and Peck, 2004; Schloten and Schilder, 2015; Yang et al., 2024). According to the literature, redundancy is not sufficient alone, and the time it provides after a disruption must be used to execute the planned strategies. Therefore, a resilient supply chain must be both flexible and redundant to manage disruptions throughout its lifecycle (Stewart and Ivanov, 2022), as these two dimensions enables core resilient capabilities (anticipate, absorb and recover) (Ponomarov and Holcomb, 2009; Pettit et al., 2010). This highlights that resilience is not solely a function of resource availability, but of how supply chains are structured and prepared to respond, stabilize, and recover from disruptions.

2.2.3 Resilience in Defense and Humanitarian Contexts

Supply chain resilience within contexts of defense and humanitarian environments, characterized by conflicts, natural disasters, etc. presents unique challenges that are different from commercial contexts. Unlike typical commercial supply chains, humanitarian and military supply systems must be designed to respond to disruptions that are unavoidable, such as natural disasters and complex emergency situations (Kovacs and Tatham, 2009). These supply chains operate in environments of extreme supply uncertainty, damaged or limited infrastructure, and the responsibility to assist injured or vulnerable populations. At the same time, they also require rapid mobilization of resources in time-critical situations (Heaslip and Barber, 2016).

Heaslip and Barber (2016) states that although humanitarian and military supply chains have different purposes, both contexts share the critical requirement of needing the ability to transition quickly from preparation to response and recovery phases, to maintain operational continuity. Additionally, they both share the difficulty of facing challenges such as restricted access to routes, damaged infrastructure, traditional sourcing channels being disrupted etc. (Heaslip et al., 2024; Heaslip and Barber, 2016).

Humanitarian logistics research offers several lessons applicable to supply chains operating under uncertainty. Kovacs and Sigala (2021) outline five key principles: The first, preparation, involves actions such as prepositioning inventory and setting up framework agreements with critical suppliers to ensure quick access to essential resources. The second, expedition, focuses on rapid decision making and timely assessments of needs during disruptions. The third, standardization, is about adopting common specifications. The fourth principle, innovation, refers to flexible strategies such as additive manufacturing and production changeovers to respond to shifting demands. Finally, the fifth principle, which is collaboration, highlights the value of cross-sector partnerships and coordinated efforts among different actors (Kovacs and Sigala, 2021). These principles work together to strengthen supply chain resilience by enhancing the ability to anticipate potential disruptions, absorb shocks, and recover from disruptions. Kovacs and Sigala (2021) notes that humanitarian supply chains rely on structural flexibility rather than dynamic flexibility, which is discussed in Section 2.2.3.2. Complementing this view, Thompson and Anderson (2021) argue that these supply chains must develop capabilities such as agility, robustness, efficiency, flexibility and redundancy: Similarly, Heaslip and Barber (2016) emphasize that

military organizations must enhance their agility and maneuverability to operate effectively in demanding, changing environments.

2.3 Service Supply Chains and Spare Part Availability

Supply chains that support maintenance and repair activities are commonly referred to as service supply chains, which are responsible for ensuring the availability of resources required to maintain installed equipment (Arts et al., 2019). In contrast to traditional product supply chains, these supply chains are concerned with providing the resources required to deliver maintenance services for installed equipment, including spare parts, tools, and service engineers (Arts et al., 2019). As Cohen et al. (2006) argue, the central objective of such systems is not production efficiency but the ability to sustain operational performance over time. Within these systems, spare part availability plays a crucial role in determining how quickly failed equipment can be restored to operational conditions. Spare part availability can broadly be understood as the ability to obtain required spare parts within a time frame that allows maintenance activities to be performed without causing significant operational disruption (Kennedy et al., 2002; Sherbrooke, 2004). If the required part is unavailable, systems may remain idle even when maintenance personnel and repair capabilities are present (Antosz and Ratnayake, 2019).

Supply chains can broadly be categorized into different types depending on their primary objective and operational focus. While production supply chains primarily support the manufacturing of new products, distribution supply chains focus on delivering finished products to customers. In contrast, service or aftermarket supply chains are designed to support maintenance and uptime of installed equipment (Cohen et al., 2006; Arts et al., 2019). The main differences between these supply chain types are summarized in Table 1.

Table 1: Types of supply chains and their primary objectives

Supply chain type	Primary objective
Production supply chains	Support manufacturing and production of new products
Distribution supply chains	Deliver finished products to customers and retail channels
Aftermarket/Service supply chains	Support maintenance, repair, and operation of installed equipment

As shown in Table 1, spare part supply chains belong to the category of service or aftermarket supply chains, where the primary objective is to maintain operational functionality of installed equipment rather than the production or distribution of new products.

2.3.1 Spare Part Availability and System Downtime

Delays in obtaining spare parts frequently represent a primary source of extended system downtime. Spare parts availability is directly linked to service performance in maintenance systems, as the absence of critical components may prevent maintenance tasks from being completed in a timely manner (Basten & van Houtum, 2014; Arts et al., 2019). According to Arts et al. (2019), spare parts availability is closely connected to the operational reliability of capital goods systems. Spare parts logistics constitutes a central operational challenge in industries where equipment uptime is essential.

Maintenance organizations must ensure access to thousands of components while simultaneously balancing inventory costs and service requirements (Topan et al., 2020). The operational importance of spare parts availability becomes particularly evident in environments where equipment failures may disrupt critical operations. In such contexts, ensuring that spare parts can be obtained quickly becomes a key requirement for maintaining operational continuity.

Another important characteristic of spare parts systems is the geographical dispersion of maintenance activities. Equipment may be installed in remote or operationally demanding environments, while spare parts are typically stored in centralized warehouses or distributed service locations (Topan et al., 2020). As a result, maintenance supply chains must be designed to ensure that required components can be delivered rapidly when failures occur. Basten and van Houtum (2014) argue that the complexity of spare parts logistics arises from the need to coordinate inventory policies, transportation networks, and supplier relationships in order to ensure that spare parts remain accessible across distributed maintenance networks. Ensuring that critical components are accessible when failures occur is therefore a central objective for operational continuity. Maintenance organizations must therefore design their supply structures and inventory policies in ways that prioritize rapid access to spare parts while still managing inventory costs.

Spare part demand is also influenced by the type of maintenance activity being performed. Driessen et al. (2015) distinguish between planned and unplanned spare part demand. Planned demand is associated with preventive or scheduled maintenance activities where spare parts can be ordered before maintenance begins, whereas unplanned demand arises during corrective maintenance or after inspections reveal unexpected replacement needs. This distinction is important because planned demand can often be managed through forecasting and inventory planning, while unplanned demand creates greater uncertainty and places higher requirements on spare part availability. Driessen et al. (2015) further distinguish between repairable and non-repairable spare parts. Repairable parts can be restored and returned to service if technically and economically feasible, while non-repairable parts are discarded after use and must be replaced through new supply. This distinction influences both inventory requirements and sourcing strategies, as repairable parts may create circular flows that reduce dependence on external supply.

2.3.2 Component Criticality in Spare Part Systems

In spare parts supply chains, not all components have the same level of importance for system functionality. Some components play a critical role in maintaining operational performance, while others may have a more limited impact if they are unavailable. Therefore, maintenance organizations often classify spare parts according to their operational criticality in order to prioritize inventory decisions and service targets (Molenaers et al., 2012; Antosz & Ratnayake, 2019). According to Molenaers et al. (2012), identifying critical spare parts is a fundamental step in spare parts logistics, since it enables organizations to determine which components require the highest availability levels within the maintenance supply systems. Antosz and Ratnayake (2019) also show that criticality assessments allow maintenance organizations to focus their resources on components whose failures would have the greatest impact on system performance and operational continuity. Critical components are typically those whose failures may lead to immediate system shutdowns, severe operational

disruptions, or significant safety risks. Ensuring the availability of spare parts for such components therefore becomes essential for maintaining operational continuity and enabling rapid system recovery (Sherbrooke, 2004; Molenaers et al., 2012). Antosz and Ratnayake (2019) explain that maintenance planning frequently relies on criticality assessments in order to identify components that require prioritized attention in spare part management. These assessments often consider multiple factors simultaneously, including the operational role of the component, the consequence of failure, failure frequency, and the time required to replace or repair the component (Cavalieri et al., 2008; Roda et al., 2014). The absence of critical spare parts may prevent defective equipment from being repaired when failures occur, potentially resulting in production losses or interruptions in operational activities (Molenaers et al., 2012; Antosz & Ratnayake, 2019). Therefore, component criticality is often evaluated by considering both the likelihood of failure and the operational consequences associated with that failure. Table 2 illustrates a simplified conceptual framework for prioritizing spare parts based on these dimensions and their implications for inventory policy (Roda et al., 2014; Antosz & Ratnayake, 2019).

Table 2: Conceptual prioritization of spare parts based on failure likelihood and failure consequences

Failure consequence	Failure likelihood	Criticality level	Inventory policy implication
High	High	Very high criticality	Highest service levels and local stocking
High	Low	High criticality	Strategic safety stock
Low	High	Medium criticality	Standard inventory control
Low	Low	Low criticality	Minimal inventory/on-demand sourcing

A commonly used method for operationalizing component criticality is the classification of spare parts into priority categories. ABC classification approaches are widely applied in maintenance environments, where a relatively small number of components (Class A) typically account for a large share of operational risk or maintenance impact, while Classes B and C represent components of decreasing importance (Teunter et al., 2010; Roda et al., 2014). Kareem and Lawal (2015) demonstrate that such classification systems can help identify the components whose failures generate the highest operational consequences, thereby allowing maintenance organizations to focus resources on the most critical spare parts. In many applications, these components are categorized as Class A items and therefore require closer monitoring and stricter inventory control. Gong et al. (2022) similarly emphasize that spare part classification systems play an important role in maintenance management because they help decision-makers determine appropriate inventory control strategies for different groups of components. However, Gong et al. (2022) also argue that traditional classification approaches based solely on economic indicators may not adequately reflect the operational importance of spare parts, particularly in complex technical systems where reliability and safety are crucial. As a result, more comprehensive approaches to spare part classification increasingly incorporate reliability and risk-related indicators alongside economic metrics. Gong et al. (2022) show that integrating factors such as failure probability, failure severity, and maintenance cost allows organizations to obtain a more complete understanding of

component importance within complex systems. Gong et al. (2022) propose a framework in which reliability indicators such as failure rates and safety-related consequences are combined with cost-based metrics in order to identify key maintenance components. Antosz and Ratnayake (2019) show that spare part prioritization should consider both operational and economic factors in order to improve equipment availability and reliability. By incorporating reliability analysis, failure data, and operational risk assessments into spare part classification, maintenance organizations can better identify the components that require prioritized inventory management.

Component criticality plays a central role in determining appropriate service-level targets and spare part availability requirements. Highly critical components typically require higher service levels, faster response times, and greater spare part availability in order to minimize potential downtime (Molenaers et al., 2012; Basten & van Houtum, 2014). Molenaers et al. (2012) emphasize that service-level differentiation across spare parts is necessary to align inventory policies with the operational importance of individual components. Critical spare parts are often assigned higher service targets because delays in obtaining these components may be managed with lower service levels or longer replenishment times without substantially affecting overall system performance (Molenaers et al., 2012). Such differentiation enables maintenance organizations to allocate inventory resources more efficiently while still ensuring that critical components remain available when failures occur. Furthermore, failures of highly critical components may have disproportionate effects on system performance, particularly in complex technical systems where components are interdependent. For this reason, reliability analysis and failure data are often used to identify which components require prioritized inventory management within spare part systems (Molenaers et al., 2012; Basten & van Houtum, 2014; Roda et al., 2014). According to Hu et al. (2018), reliability parameters such as failure rates and mean time between failures are frequently used to estimate expected spare part demand and identify components with higher operational importance. Additionally, Gong et al. (2022) explain that reliability-based analysis can help maintenance organizations better understand how individual component failures influence overall system safety and operational performance. Integrating reliability analysis with spare part planning therefore enables organizations to improve maintenance decision-making and ensure that critical components remain available where and when they are needed.

2.4 Alternative Sourcing Approaches and Spare Part Availability under Disruption

While spare part supply systems are often designed around established suppliers, planned replenishment flows, and predefined service targets, these arrangements become less reliable under severe disruption. Such disruptions may arise from geopolitical instability, supplier failures, transportation interruptions, or capacity constraints (Christopher & Peck, 2004; Wagner & Bode, 2008). Furthermore, Sarwar and Rye (2025) explain that geopolitical shocks show that war-related disruption tends to spread across sectors and regions through transportation bottlenecks, material shortages, and supply instability rather than remaining isolated at one supplier or node. In such situations, the issue is no longer only how to optimize inventory or cost efficiency, but how to preserve access to critical components when conventional supply routes, manufacturers, or logistics channels are constrained or unavailable.

This shifts managerial attention toward resilience and continuity of operational activities and supply (Pettit et al., 2010; Sheffi, 2013). In service supply chains, this shift is particularly critical due to the direct link between spare part availability and system uptime. Unlike conventional product flows, where delays may result in lost sales or backorders, disruptions in spare parts supply may lead to extended downtime and reduced operational performance (Hu et al., 2018; Arts et al., 2019).

Within this context, alternative sourcing approaches can be understood as the ability to access required components through multiple, flexible, or non-traditional supply paths when established supply routes are unavailable or constrained. This may include multi-sourcing arrangements, the use of distributed or civilian supply networks, recovery-based sourcing or emerging technologies such as additive manufacturing (AM), also known as 3D printing, depending on the characteristics of the component and the disruption faced (Foshammer et al., 2022; Echefaj et al., 2024; Guo et al., 2025). However, it is important to note that alternative sourcing approaches is not a uniform strategy applied across all components. Sourcing and inventory decisions must be aligned with component characteristics such as criticality, demand uncertainty, and supply risk (Molenaers et al., 2012; Antosz & Ratnayake, 2019). This implies that alternative sourcing approaches should be understood as a differentiated and context-dependent approach, where redundancy and flexibility are prioritized for components with high operational impact or limited supply availability.

2.4.1 Sourcing Under Disruption

Under disrupted conditions, sourcing becomes an even more critical determinant of operational continuity, as access to required components can no longer be taken for granted. In stable environments, sourcing decisions can often be based on expected lead times, contract efficiency, and routine replenishment logic (Ryczynski & Tubis, 2021; Rahbari et al., 2024). Under disruption, such assumptions become increasingly unreliable, as resilience in for example, military supply chains become inseparable from risk management because adverse events can arise at multiple stages of the supply process and directly affect the continuity of supply (Ryczynski & Tubis, 2021). For instance, studies conducted on the Russia-Ukraine war show that disruptions frequently combine transport problems, supply interruptions, and wider network instability which makes conventional sourcing plans insufficient on their own (Rahbari et al., 2024; Sarwar & Rye, 2025). For spare parts, this is particularly crucial because the operational value of a sourcing option depends on whether components can be accessed within the required time frame, as delayed availability may directly affect system recovery and operational continuity (Basten & van Houtum, 2014; Ryczynski & Tubis, 2021). This implies that under disruption, the existence of a supplier does not necessarily guarantee practical availability, as supply access may be constrained (Sarwar & Rye, 2025). Consequently, resilience-oriented literature emphasizes the use of back-up suppliers and pre-positioned inventory as strategies to ensure timely access to components when established sourcing routes are disrupted. Therefore, when disruption threatens continuity, sourcing must be evaluated in terms of accessible alternatives, not only nominal supplier relationships (Christopher & Peck, 2004; Sheffi & Rice, 2005; Rahbari et al., 2024).

2.4.2 Sourcing Feasibility

Alternative sourcing approaches are often discussed in terms of multiple sourcing arrangement, where firms rely on more than one supplier for a given component.

However, such a perspective does not fully capture sourcing feasibility in spare parts systems. Sourcing decisions and feasibility in spare parts logistics are influenced by various factors such as, lead time, supplier availability, technical documentation, and constraints in maintenance (Molenaers et al., 2012). Additionally, classifications of spare parts constitute a key input to subsequent logistics and management decisions, which indicates that sourcing strategies should be aligned with component characteristics rather than generic procurement approaches (Roda et al., 2014). Sawik (2014) demonstrates that sourcing feasibility is further shaped by disruption exposure, even in dual sourcing settings, disruption risk remains a critical decision variable as suppliers may be subject to both local and regional disruptions. This therefore means that the presence of multiple suppliers does not necessarily guarantee supply continuity, especially when disruption risks are correlated across suppliers or regions (Sawik, 2014). In spare parts systems, component characteristics further influence sourcing feasibility. Factors such as standardization, supplier base breadth, and verification requirements affect the ability to source components from multiple suppliers (Molenaers et al., 2012; Roda et al., 2014). Sourcing feasibility should therefore be assessed at the component level, where the critical issue is not the existence of alternative suppliers, but whether specific components can be sourced under disrupted conditions (Molenaers et al., 2012; Sawik, 2014).

2.4.3 Alternative Sourcing Approaches

Alternative sourcing approaches in spare part supply chains can take several forms, depending on both the structure of the supply network and the characteristics of the components involved (Molenaers et al., 2012). Rather than representing a single strategy, alternative sourcing approaches can be understood as a set of complementary approaches aimed at mitigating supply disruptions (Tang, 2006; Tomlin, 2006). Examples of potential approaches include strategies such as multi-sourcing and redundancy, decentralized sourcing structures, and flexible sourcing configurations (Tang, 2006; Tomlin, 2006; Guo et al., 2025).

Multi-sourcing and redundancy

Multi-sourcing refers to the use of multiple suppliers for the same component to reduce dependency on a single source. Redundancy involves maintaining additional supply capacity or inventory buffers to absorb disruptions, for example through back-up suppliers, safety stock or parallel sourcing options (Sheffi, 2013; Guo et al., 2025). Rahbari et al. (2024) model back-up suppliers and inventory pre-positioning as resilience strategies under war-related disruption and show that they improve flexibility and decision-making under crisis conditions. Likewise, Lin and Wang (2011) conclude that it is critical to have a second sourcing supplier to address supply disruptions and that parallel sourcing can reduce expected cost even when the probability of failure is relatively low.

Additionally, Gaur et al. (2020), find that multi-sourcing produces higher profit than single-sourcing under disruption in a closed-loop supply chain setting. Multi-sourcing reduces exposure to disruption by allowing the firm to reallocate sourcing when one route is impaired. In spare parts systems, where stockouts may create immediate downtime rather than delayed sales, which highlights the operational importance of supply continuity (Basten & van Houtum, 2014; Arts et al., 2019). However, redundancy is associated with significant costs, as it requires maintaining additional inventory, capacity, or alternative sourcing approaches (Christopher & Peck, 2004;

Guo et al., 2025). As a result, redundancy cannot be justified equally for all components but must be selectively applied. This selection is typically guided by component criticality, where components with higher operational impact and supply risk require higher levels of availability and redundancy (Molenaers et al., 2012; Antosz & Ratnayake, 2019).

Decentralized sourcing structures

Decentralized sourcing structures distribute stock, sourcing options, or production capability across multiple nodes rather than concentrating them in a single central node. Such structures reduce dependence on individual suppliers, facilities, or regions by dispersing risk across geographically distributed nodes (Mohebbi et al., 2025). Furthermore, Christopher and Peck (2004) argue that reducing reliance on single nodes is essential for mitigating disruption risk, as failures in centralized structures can spread across the entire supply network. By spreading the activities, firms gain a greater ability to adjust operations and material flows and continue meeting demand when disruptions occur at certain nodes. Decentralized structures often rely on broader supply networks, consisting of regional suppliers and alternative logistics routes. This lowers the risk related to localized disruptions and strengthens the recovery capacity of the supply chain (Mohebbi et al., 2025).

Decentralization also alters the trade-off between efficiency and resilience in a network design perspective. Snyder et al. (2016) demonstrate that centralized systems may offer cost advantages under stable conditions, but they increase vulnerability by concentrating inventory and flows in limited locations.

Under disruption, the value of decentralization becomes more evident, as distributed supply networks increase the number of feasible supply paths and thereby improve the system's ability to maintain operations when individual nodes or transport routes become unavailable (Ivanov & Dolgui, 2020). The positioning of inventory within the supply network is critical for ensuring timely access to components, as delays directly affect system availability and downtime (Bacchetti & Saccani, 2012). Additionally, supply chain configuration decisions, including the degree of centralization or decentralization, influence how effectively spare parts can be deployed across the network to meet service requirements (Cantini et al., 2022). Decentralized sourcing structures can therefore support faster access to components and reduce dependence on centralized supply points, improving supply continuity under disruption (Bacchetti & Saccani, 2012; Cantini et al., 2022).

Flexibility and sourcing responsiveness

In sourcing contexts, flexibility involves the ability to switch suppliers, adjust sourcing volumes, or utilize alternative supply channels when primary sources become unavailable. Sourcing responsiveness, in turn, concerns the speed at which such adjustments can be implemented in response to disruptions (Pettit et al., 2010; Wagner et al., 2018). Pettit et al. (2010) identify sourcing flexibility as a capability supported by factors such as multiple sourcing options, part commonality, and the ability to substitute components across different applications. Wagner et al. (2018) show that sourcing flexibility is a critical dimension of supply chain flexibility and is directly associated with improved delivery performance such as reduced stock-outs and shorter lead times, particularly under supply uncertainty.

Sheffi and Rice (2005) emphasize the importance of sourcing responsiveness particularly under disruption as the ability to respond quickly to supply disturbances is critical for maintaining operations, while noting that delays in adapting sourcing decisions may amplify the impact of disruptions. Ivanov (2021) similarly shows that supply chain resilience depends on the ability to dynamically reconfigure supply structures in response to changing conditions, rather than solely relying on predefined plans. Under such circumstances, the availability of alternative sourcing approaches is not sufficient on its own as these options must also be mobilized within the required time frame. This is particularly important in spare part systems, where delays in obtaining components may directly lead to system downtime (Basten & van Houtum, 2014).

2.4.4 Civilian Supply Networks

Civilian supply networks represent an important source of complementary capabilities and resources in supply chains, particularly in contexts involving civil-military integration and disrupted operations (Campioni et al., 2023; Qi et al., 2023). Such networks may provide access to production capacity, infrastructure, and supply capabilities beyond those available within dedicated or original supply chains. Qi et al. (2023) explain that in civil-military contexts, the inclusion of civilian actors and resources has been shown to enhance supply chain resilience by enabling access to broader capabilities, technologies, and production resources. Campioni et al. (2023) show that in disaster and humanitarian operations, leveraging existing civilian infrastructure and assets is important to maintain operational continuity when primary systems are degraded or unavailable.

From a sourcing perspective, the relevance of civilian supply networks is closely linked to component characteristics. Components that are standardized, widely produced, or based on commercial-off-the-shelf (COTS) designs are typically supported by broader supplier bases and established distribution systems, which increases sourcing flexibility (Molenaers et al., 2012; Roda et al., 2014). Such components may be available across multiple supply nodes, including aftermarket channels, reflecting the distributed structure of spare parts supply networks and their focus on ensuring component accessibility (Cohen et al., 2006; Topan et al., 2020). Access to multiple sourcing options is critical under disruption, as it enables firms to reallocate sourcing when established supply paths are constrained or unavailable (Tang, 2006; Tomlin, 2006).

However, Zhang and Qi (2025) state that the accessibility of civilian supply networks is not unconditional. The integration of civilian actors into defense-related supply chains often requires firms to transition into dual-use entities, which involves overcoming institutional, technical, and certification barriers (Zhang & Qi, 2025). These barriers include differences in technical standards, limited information exchange, and demanding qualification processes, all of which may restrict the ability of civilian suppliers to participate in specialized supply systems (Zhang & Qi, 2025).

2.4.5 Component Criticality and Sourcing

The effectiveness of alternative sourcing approaches is closely linked to the criticality of individual components. As discussed in section 2.2.4, spare parts differ in terms of their impact on system performance, and not all components require the same level of availability. Molenaers et al. (2012) emphasize that spare part management strategies

should be aligned with component importance, while Antosz and Ratnayake (2019) show that criticality assessments enable organizations to prioritize components based on their impact on system availability and reliability. This prioritization becomes particularly critical under disruption conditions, where constraints on capacity, inventory, and logistics resources force firms to make explicit trade-offs in how resilience is allocated across the supply base. Disruptions propagate unevenly through networks, with certain components or nodes creating disproportionately large performance losses due to their structural and operational importance (Craighead et al., 2007; Ivanov et al., 2017). Ivanov et al. (2017) further explain that disruption effects are amplified by the position and role of specific elements within the supply chain, meaning that failures in certain components can trigger cascading “ripple effects” that significantly degrade overall system performance. At the same time, resilience strategies such as redundancy, flexibility, and multi-sourcing are inherently costly and cannot be implemented universally without eroding efficiency, which necessitates selective deployment based on impact and risk exposure (Tang, 2006; Tomlin, 2006). Component criticality provides a basis for differentiating the application of sourcing strategies across spare parts. Components with higher operational importance are more likely to be associated with sourcing configurations that emphasize flexibility, redundancy, and responsiveness, such as the use of multiple supplier or contingency sourcing options (Tang, 2006; Tomlin, 2006). In contrast, less critical components may be managed through more standardized sourcing arrangements with lower levels of preparedness (Molenaers et al., 2012; Antosz & Ratnayake, 2019). As such, component criticality functions as a key decision variable in structuring sourcing strategies and allocating resilience measures across spare parts systems (Tang, 2006; Tomlin, 2006).

2.4.6 Contingency Sourcing Options

In addition to forward sourcing strategies, spare part supply chains may rely on contingency sourcing options when conventional supply is disrupted. These include recovery-based approaches such as repair, reuse, and cannibalization, as well as emerging technologies such as additive manufacturing (AM) also known as 3D printing (Sherbrooke, 2004; Basten & van Houtum, 2014; Foshammer et al., 2022).

Cannibalization refers to the practice of removing functional components from a non-operational system (often referred to as a donor system) in order to restore another system to an operational state and is commonly used in maintenance-intensive environments when spare parts are unavailable through conventional supply channels (Hoover et al., 2004; Di Gravio et al., 2019). Rather than increasing the overall supply of components, cannibalization involves reallocating existing parts between systems, allowing selected assets to be restored at the expense of others (Hoover et al., 2004; Sherbrooke, 2004). For example, components may be removed from non-operational or reserve aircraft and installed in operational units to maintain readiness when spare parts are unavailable (Sherbrooke, 2004). In military logistics contexts, cannibalization is often treated as an emergency sourcing mechanism used to maintain system availability when supply shortages occur (Sherbrooke, 2004). Di Gravio et al. (2019) further explain that it is typically applied in response to unexpected failures, where conventional spare part supply is insufficient to ensure timely access to required components. As such, it represents a reactive sourcing option that allows organizations to maintain operational continuity (Di Gravio et al., 2019). However, cannibalization also introduces additional complexity in maintenance operations, as it

increases disassembly and reassembly requirements which may lead to additional failures, and can reduce the readiness of donor systems (Hoover et al., 2004; Di Gravio et al., 2019). Di Gravio et al. (2019) further emphasize that donor systems may remain non-operational for extended periods, particularly when components are repeatedly removed. These effects indicate that cannibalization may improve short-term availability while potentially reducing overall system efficiency if applied extensively (Di Gravio et al., 2019).

Recovery-based sourcing refers to sourcing strategies in which components are recovered from use, restored, and returned to service instead of being replaced by newly procured parts (Hashemi et al., 2014; Echefaj et al., 2024). Such approaches are typically categorized into reuse, repair, and remanufacturing, which differ in the extent to which components are restored before being reintroduced into use (Echefaj et al., 2024). Reuse involves the direct installation of functional components, repair restores failed components to an operational state, and remanufacturing involves a more extensive process in which components are rebuilt to a new-like condition (Hashemi et al., 2014; Echefaj et al., 2024). While both reuse and cannibalization involve the reallocation of existing components, they differ in their operational context. Reuse typically occurs within planned repair and inventory systems, where components are recovered, inspected, and reintroduced to stock, whereas cannibalization involves the direct transfer of components between systems, often as a reactive measure under spare parts shortages (Basten & van Houtum, 2014; Di Gravio et al., 2019). These recovery-based strategies, including repair and reuse, can provide additional sourcing flexibility by extending the life of existing components and reducing dependence on external suppliers (Echefaj et al., 2024).

AM represents an emerging sourcing approach that enables the production of spare parts on demand, often closer to the point of use. In contrast to conventional manufacturing and sourcing processes, which rely on centralized production and established supply chains, AM allows for decentralized and flexible production of selected components (Foshammer et al., 2022). AM has been increasingly explored for aftermarket and legacy components, particularly where traditional supply chains are constrained by long lead times, low demand volumes, or discontinued production (Foshammer et al., 2022). By enabling local or on-site production, AM can reduce dependence on external suppliers and mitigate delays associated with transportation and inventory replenishments (Isasi-Sanchez et al., 2020; Foshammer et al., 2022). However, the applicability of AM as a sourcing option depends on several factors, including technical feasibility, material requirements, and certification constraints. Not all components can be produced using AM, and the process may be limited to specific types of parts or use cases. Therefore, AM is typically considered a complementary sourcing option rather than a universal solution, providing flexibility for selected components within the broader spare parts supply system (Isasi-Sanchez et al., 2020; Foshammer et al., 2022).

2.5 Component Selection and Design for Supply under Disruption

2.5.1 Component Selection and Decision Making

As discussed in Sections 2.2 and 2.3, spare parts systems are characterized by demand uncertainty and sourcing constraints. These characteristics are important to consider when making decisions on component selection.

Component selection in spare part systems represents a complex, multidimensional decision-making process (x). Under stable operating conditions, selection is typically guided by technical performance requirements, cost efficiency, and compatibility with existing system architectures. Spare parts environments require considerations of uncertainty, availability and operational impact as their demand is characterized by irregular and intermittent patterns (Basten and Van Houtum, 2014; Antosz and Ratnayake, 2019), which is also discussed in Section 2.2.

The sourcing, availability, and role of components vary significantly, and as outlined in Section 2.2.4 the criticality of components is commonly evaluated based on failure likelihood failure consequences, and repair or replacement time (Molenaers et al., 2012; Antosz and Ratnayake, 2019). The concept of component criticality is according to Teixeira et al. (2017) related to situations where failure or unavailability led to severe consequences to the operations. Spare parts are characterized by irregular demand patterns, high variability in usage, and have a direct correlation with system downtime (Antosz and Ratnayake, 2019). Furthermore, Roda et al. (2014) states that sourcing related challenges is common in procuring spare parts. Therefore, decision making must include both maintenance- and logistics related considerations. Sourcing related factors such as sourcing feasibility, lead time, supplier reliability, degree of component standardization or market availability, becomes of highest criticality, as they influence whether a component can be obtained when needed (Roda et al., 2014).

As outlined in previous sections, ensuring availability of spare parts in scenarios where supply is constrained, may require moving beyond traditional sourcing strategies. One approach is the use of commercial off the shelf (COTS) components, which are standardized components on the open market rather than custom designed. The feasibility of using COTS components is influenced by the degree of component standardization. Standardized components can increase interchangeability and substitution possibilities, which increases sourcing flexibility and improves the ability to access replacement parts through alternative channels (Perera et al., 1999; Roda et al., 2014). The benefits of COTS components are that it can improve availability through shorter development and procurement times and lower costs (Ayala and Franch, 2006). However, the use of such components introduces some constraints, as they are usually integrated with other components, they create interdependencies that can make substitution more challenging (Ayala and Franch, 2006). This requires a trade-off between improved availability and limitations related to compatibility and system integration.

Roda et al. (2014) and Teixeira et al. (2017) outlines that criticality is a multi-dimensional concept and distinguishes between process criticality and control

criticality. Process criticality is related to the consequences of failure/availability of spare parts, and control criticality is about the ability to ensure availability, which is related to lead times, number of suppliers, types of material (standardized or specialized) etc. (Roda et al., 2014; Teixeira et al., 2017). Antosz and Ratnayake (2019) build on this and states that spare parts differ across multiple dimensions such as maintenance, logistics, economics factors, and emphasize the need for a multiple criteria approach of selecting and prioritizing spare parts. Methods such as ABC analysis are commonly used to classify spare parts based on demand value and cost but according to Teixeira et al. (2017) not sufficient due to the diversity of spare parts. More advanced approaches adopt multi-criteria classification frameworks that integrate maintenance related, logistical and economic dimensions (Roda et al., 2014; Teixeira et al., 2017).

In addition to these considerations, research also shows that it is important to consider differences in types of suppliers. Spare parts may be sourced from multiple suppliers with varying lead times, costs, and product quality, which introduces other tradeoffs in component selection and stock planning (Zheng et al., 2024). For instance, a supplier used for emergency situations may offer shorter lead times but lower quality components, while regular suppliers provide high-quality components with longer lead times (Zheng et al., 2024).

2.5.2 Standardization and Commonality

The degree of component standardization and commonality plays an important role in the performance of a supply chain and the accessibility of spare parts (Pettit et al., 2013; Roda et al., 2014; Teixeira et al., 2017; Yang et al., 2024).

Component standardization or commonality can according to Perera et al. (1999) and Wang and Ning (2007) occur in three different ways: First, component standardization within a product, where several unique components are replaced by a common component. Second, standardization among products, where unique components across products are replaced by a common component. Third, component standardization among product generations, where common components are used in different products or in upgraded products (Perera et al., 1999; Wang and Ning, 2007).

There are several benefits of standardization in the context of spare parts. A key benefit of component standardization is the reduction of product variety, which reduces operational and managerial complexity. A high variety increases coordination requirements, while a reduced variety simplifies design and operations (Nagarur and Azeem, 1999; Perera et al., 1999). More critically, standardization means that the components can be provided from multiple suppliers as they are more widely used, which reduces dependency on single sources and increases sourcing flexibility (Goel and Brahmbhatt, 2024). Having the potential of using multiple suppliers for a component increases the chance of maintaining component availability in the face of a disruption, as it reduces the risk of relying on one supplier or region (Goel and Brahmbhatt, 2024).

Furthermore, from a lifecycle perspective, standardization offers benefits across multiple phases. Reduced component variety simplifies logistics, reduces the risk of obsolescence, and lowers material management costs (Perera et al., 1999; Roda et al.,

2014). The reuse of components also reduces costs in product development (Perera et al., 1999). Component commonality can enhance supply chain performance that extends beyond cost savings. When components are shared across products, demand can be aggregated, making it easier to predict and reduce the fluctuations that can occur at the component level (Perera et al., 1999; Wang and Ning, 2007; Takai and Sengupta, 2016). This is beneficial for inventory management, where inventory levels even can be reduced while maintaining service performance, which improves availability (Wang and Ning, 2007; Takai and Sengupta, 2016). Additionally, it simplifies procurement and allows for consolidation of orders which enables economies of scale, in both production and sourcing, and improves the responsiveness of the supply chain (Perera et al., 1999; Wang and Ning, 2007; Takai and Sengupta, 2016).

On the other hand, the authors also highlight that there are tradeoffs where while common components reduce complexity, it can also lead to e.g. overspecification and increased costs, when trying to have components that aim to satisfy multiple requirements (Perera et al., 1999). Excessive commonality may also increase the overall exposure to risks, as multiple systems depend on the same component, which means that standardization must be balanced against both performance requirements and risk exposure.

2.5.3 Modularity and Supply-Adapted Product Architecture

Modularity is a design strategy that decomposes complex products into smaller components that have relatively increased independence, enabling them to be developed and managed even when functioning in an integrated system (Mikkola, 2003; Villar et al., 2024). It is defined by Schilling (1999) as the degree to which system components can be separated and recombined, which enhances flexibility. A key feature of modularity is the use of standardized interface specifications, which enable components to be substituted or recombined without affecting the overall system (Mikkola, 2003; Inoue et al., 2024). This reduces interdependencies between components and allows for greater flexibility in design, sourcing, and maintenance (Villar et al., 2024; Inoue et al., 2024). Modules can be described as groups of closely connected components with limited interface with other groups, this results in reduced dependencies across the system (Ethiraj and Levinthal, 2004). Furthermore, modular architectures facilitate more efficient logistics, as components can be transported directly to final assembly sites, reducing lead times and increasing sourcing options (Inoue et al., 2024).

Ulrich (1995) further explains modularity from an architectural standpoint, which explains that modular designs separate functions into different physical components, while integral designs consist of components that are interconnected and dependent on each other. Modularity enables components to be modified, replaced, or sourced independently, since interfaces are loosely connected and each function has its own component without tight connection on other (Ulrich, 1995), which enhances flexibility.

Modularity is according to Martin et al. (2024) a multidimensional concept, and not a single design characteristic. It consists of two key dimensions, standardization and reconfigurability. Standardization, which is explained in section 2.4.2, refers to which extent a product is built on predefined and standardized components, while

reconfigurability is about the ability to recombine these components into different configurations (Martin et al., 2024). This influences flexibility and supply adaptability, and modularity should be understood as a spectrum of design choices (Salvador et al., 2002).

Salvador et al. (2002) outlines that modularity exists along a spectrum, with different types at each end:

- **Component swapping modularity:** A stable product architecture/base is maintained, and product variants are achieved by substituting individual components within that architecture. This allows for changing certain parts, without affecting the overall design, which is suitable when product variety is low, and production volume is high (Salvador et al., 2002).
- **Combinatorial modularity:** A product architecture in which components are grouped into component families, each with different variants, while interfaces between these families are standardized. This allows different combinations of components to be assembled into product variants, making it more suitable when product variety is high relative to production volumes (Salvador et al., 2002).

Salvador et al. (2002) also link the types of modularity to sourcing strategies. In the case of “Component swapping modularity”, a sourcing strategy of simple components from geographically close suppliers is beneficial as it shortens lead times and more control. Under “Combinatorial modularity”, the number of component families should be kept low, and each family should be modularized internally by the suppliers. This requires establishing a closer relationship with the suppliers, as they are responsible for managing the complexity within each component family (Salvador et al., 2002). Modularity plays an influential role in the supply chain and contributes to availability and supply in several ways, which is summarized in the table below:

Table 3: Modularity aspects and their contribution to sourcing strategies

Modularity Aspect	Description	Contribution	Author
Component swapping	Stable product architecture with interchangeable modules	Simplifies sourcing Reduces variety	Salvador et al. (2002)
Combinatorial Modularity	Multiple interchangeable component families with standardized interfaces	Enables multi-source substitution	Salvador et al. (2002)
Standardized interfaces	Defined and consistent connection rules between components	Cross-supplier compatibility	Salvador et al. (2002); Mikkola (2003)

Substitutability	Components interchangeable across suppliers or systems	Alternative sourcing approaches under disruption	Salvador et al. (2002); Inoue et al. (2024)
Maintenance	Independent replacement of failed components	Faster repair Less skill needed	Perera et al. (1999); Salvador et al. (2002)
Cannibalization	Reuse of components from other systems	Emergency sourcing	Di Gravio et al. (2019)
Postponement	Delayed differentiation to later stages	Reduces inventory complexity	Tang and Tomlin (2008); Inoue et al. (2024)

As shown in Table 3, the contributions of modularity to supply adaptability can be understood through different mechanisms that can be enabled. First, modularity enhances sourcing flexibility. Through component interchangeability, standardized interfaces, and substitutability, components can be sourced from multiple suppliers or changed between systems. This reduces dependency on individual suppliers and increases the potential options of sourcing (Salvador et al., 2002; Inoue et al., 2024; Villar et al., 2024).

Secondly, modularity improves maintenance and repair, by enabling independent replacements of components which allows systems to be repaired quickly, as it does not affect the entire system (Perera et al., 1999; Salvador et al., 2002). Not only does this reduce repair time, technical complexity, and faster restoration of a systems functionality, but it facilitates the use of cannibalization strategies. The strategy allows components from other systems to be reused as an emergency sourcing option when spare parts are unavailable (Di Gravio, 2019).

Another important contribution is the ability to implement postponement strategies, which refers to delaying product differentiation into later stages of the supply chain. By relying on standardized modules, inventory can be managed as the complexity is reduced, and the responsiveness to demand variability improves (Tang and Tomlin, 2008; Inoue et al., 2024).

In the perspective of supply chain resilience, modularity is linked to the ability to reconfigure systems in response to disruptions. Modularity enables reconfigurations, which allows for adjustments in response to changes in e.g. product design, demand, and capacity conditions (Villar et al., 2024). Additionally, the authors state that such systems support actions such as substitution in product and supply, as well as resource repurposing (ibid.).

Furthermore, modular designs enable recombination and reuse of components across different configurations, which supports adaptability. This, together with the use of standardized interfaces, which facilitate the integration of components from different sources, enables increased flexibility in sourcing and system configuration (Schilling, 1999; Inoue et al., 2024).

2.6 Connection Between the Frame of Reference and the Research Questions

To provide a structured overview of how the frame of reference supports the research questions, the key theoretical sections and their relationships to the research questions are visualized in Figure 5 below. As the concepts are broad and interconnected, it is important to clarify the structure of the chapters and how they contribute to the research questions. The figure distinguishes between strong (direct) and weak (contextual) contributions.

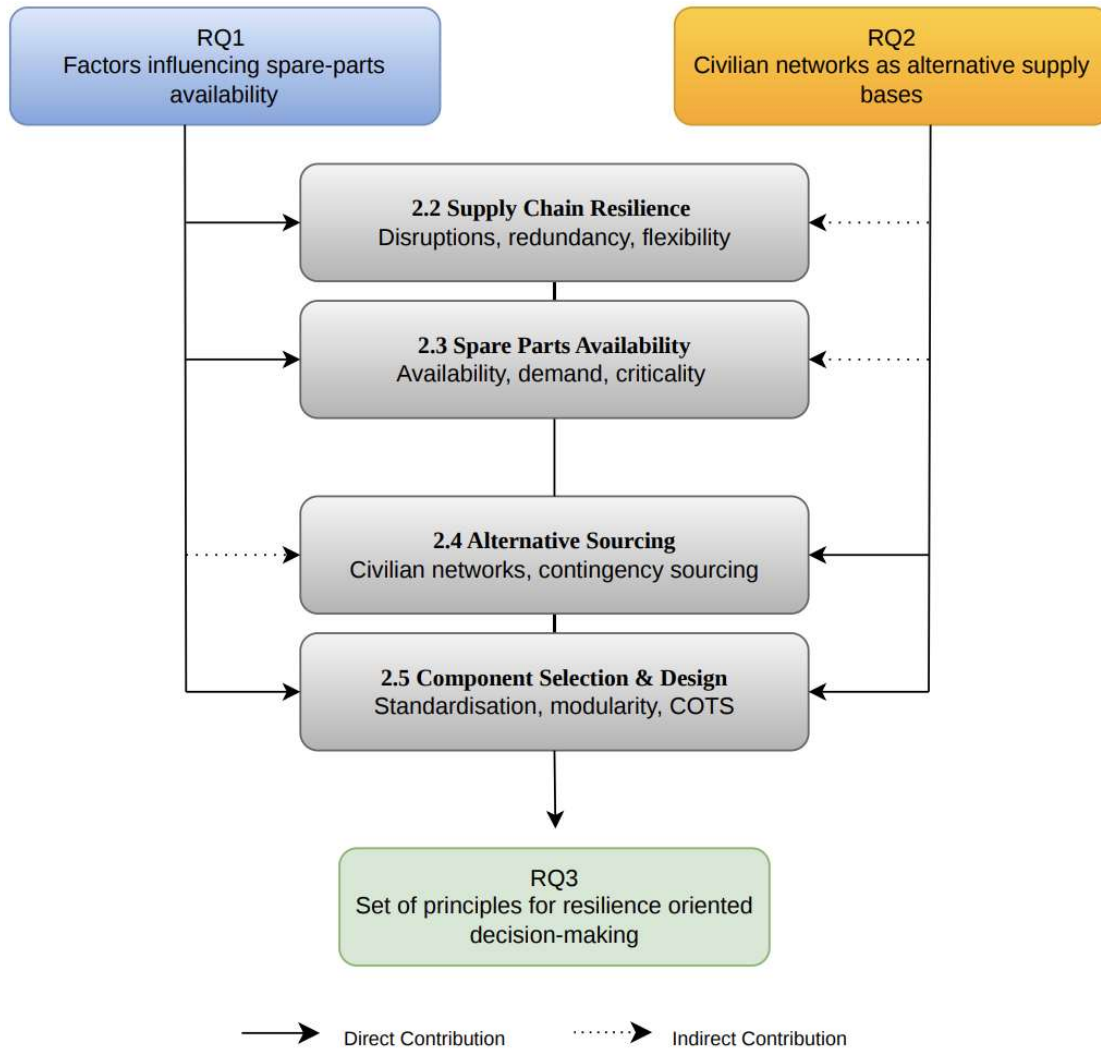


Figure 5: Connection between theoretical sections and research questions

RQ1 focuses on identifying the factors that influence spare part availability. The foundation for this lies in the discussions on supply chain resilience (Section 2.2) and spare part availability (Section 2.3). These sections provide an analytical lens for addressing how elements such as disruptions, flexibility, redundancy, and demand uncertainty affect availability in constrained environments. This analysis is further

supported by insights from the frame of reference (Section 2.4 and Section 2.5), which introduce factors related to sourcing feasibility, standardization, modularity and how design choices impact availability outcomes.

RQ2 is about how civilian networks can serve as alternative sources of supply. It primarily builds on Section 2.4, which discusses alternative sourcing approaches. Sections 2.2 and 2.3 provide the theoretical foundation, explaining why alternative sourcing approaches become critical in the face of disruptions. Section 2.5 also supports this by explaining how design choices such as standardization, and the use of COTS enable effective integration with civilian or external supply networks.

RQ3 brings together the thesis key insights to develop principles for resilience-driven decision making. It builds on perspectives from resilience theory, spare parts availability, alternative sourcing approaches, and component design. All sections of the frame of reference make a strong contribution.

3. Methodology

This chapter presents the methodological approach of the study, outlining the research design, case study context, data collection, and data analysis. It also addresses considerations of research quality, including validity and reliability. The methodological choices are guided by the exploratory nature of the research problem, which requires in-depth understanding of spare part availability and resilience in disruption-prone environments. A qualitative case study approach is therefore adopted to capture context-specific insights and expert perspectives. The chapter aims to ensure transparency in the research process and to support credibility and rigor of the study.

3.1 Research Design

This study adopts a qualitative research design to explore spare part availability and resilience in emergency logistics UGV systems. A qualitative approach is appropriate as the research aims to understand feasibility, compatibility, and supply chain structures in a complex industrial context where technical and organizational factors interact. The objective was to generate in-depth analytical insight into the factors influencing spare part availability and resilience in emergency logistics UGV systems. Qualitative research is particularly suitable for exploratory studies involving emerging technologies and system integration challenges, where expert knowledge plays a central role (Bryman, 2016). The study therefore emphasizes depth of understanding through expert perspectives and contextual interpretation.

3.2 Case Study and Context

The research is conducted as a single-case study based on an ongoing industrial collaboration between UGV Inc and Truck Inc. The study originates from a practical industrial challenge related to spare part availability under extreme disruption conditions. The case focuses on evaluating heavy vehicle components from Truck Inc as a potential source of spare part for a UGV platform developed by UGV Inc. A case study design is suitable when the phenomenon being studied is closely connected to its real-world context (Yin, 2018). A single-case design was considered appropriate because the case represents a specific and information-rich setting where an emerging UGV platform is studied in relation to an established civilian heavy vehicle supply network. The aim is to generate theoretically informed insights into spare part availability and sourcing feasibility under disrupted conditions, allowing the findings to be interpreted in relation to existing theory (Yin, 2018). Case studies are particularly valuable for generating in-depth insights into complex and context-dependent phenomena (Flyvbjerg, 2006).

The case provided access to technical and logistical expertise within dual-use vehicle context. The study examined the feasibility of component integration, spare part availability, and supply chain flows from manufacturer to service points, with particular emphasis on disruption scenarios. Case study methodology allowed these aspects to be examined in relation to one another within their operational setting (Saunders et al., 2019).

3.3 Literature Review

In this study, a literature review was conducted to provide a structured and comprehensive understanding of the existing research related to supply chain resilience, spare part availability, and sourcing strategies. A literature review is a fundamental research method that involves systematically collecting, evaluating, and synthesizing existing knowledge within a specific field (Snyder, 2019). By synthesizing findings from multiple sources, it assists in building a knowledge base, identifies research gaps, and supporting the development of the study's frame of reference. To maintain rigor and credibility, the review is conducted in a structured manner.

While this study does not constitute a full systematic literature review (SLR), elements of SLR methodology were employed. A key difference between a literature review and SLR is that a literature review provides a flexible synthesis of existing research, whereas an SLR follows a highly structured and predefined methodology with clear guidelines. As a result, literature reviews are more suitable for broader and multidisciplinary research areas, while SLRs are more typically used to address more specific research questions (Kitchenham and Charters, 2007; Snyder, 2019; Carrera-Rivera et al., 2022).

Similarly to literature review, SLR is a structured approach with a clear set of guidelines to identify, evaluate, and synthesize the literature in a specific research area. The method follows predefined steps for searching, selecting, and analyzing studies, which minimizes bias and ensures transparency, and the reliability of the findings (Kitchenham and Charters, 2007; Carrera-Rivera et al., 2022). In this study, selected elements of this approach were applied, including structured search strategies, predefined inclusion and exclusion criteria, and a systematic approach for selecting and analyzing sources. Although the study does not follow the guidelines of a SLR, the principles were used to strengthen the review.

The systematic approach was particularly appropriate for this study, as the research problem "*Enhancing spare part availability for UGVs through civilian vehicle component supply networks under extreme disruption*" involves interdisciplinary perspectives. It draws upon supply chain resilience, service logistics, sourcing strategies, design for availability etc. An SLR ensures comprehensive coverage across these fields and provides a way for synthesizing the findings with methodological rigour (Lame, 2019). This approach also ensures that the frame of reference is grounded with established research while systematically reviewing the existing literature that is relevant to the research questions presented in Section 1.5. The research questions focus on factors influencing spare part availability, the role of civilian supply networks, and the structuring of resilience-oriented strategies, and these determine the scope of review and guide the data extraction and analysis (Carrera-Rivera et al., 2022).

The literature search was conducted using academic databases such as Web of Science and Scopus. These databases were selected for their comprehensive coverage of the areas of research - supply chain management, operations research, and logistics literature. A systematic search strategy was developed based on key concepts drawn from the research questions. The search employed combinations of keywords

organized into thematic clusters related to the concepts of the study. Some of the primary search terms included:

- “Supply chain resilience”
- “Supply chain disruption”
- “Spare part availability”
- “Spare parts logistics” / “service supply chains”
- “Service supply chains”
- “Alternative sourcing” / “multi-sourcing”
- “Component criticality”
- “Maintenance logistics”

By using Boolean operators (AND, OR), a more comprehensive retrieval of relevant studies could be made, as they could be used to combine terms and refine search results (Kitchenham, 2007)

Table 4: Search strategy for literature review

Research Area	Keywords	Boolean Combinations	Example of Search
Supply Chain Resilience	Resilience, disruption, robustness, flexibility, redundancy	AND, OR	“Supply chain resilience” AND disruption OR flexibility OR redundancy
Disruption Context	Armed conflicts, natural disasters, crisis, extreme disruption, war, humanitarian	AND, OR	“Supply chain” AND “extreme disruption” OR conflict OR crisis
Spare Parts Management	Spare parts, availability, service level, downtime, criticality	AND, OR	“Spare parts” AND availability OR criticality AND “service supply chain”
Alternative Sourcing	Multi-sourcing, alternative suppliers, contingency sourcing, civilian networks, sourcing strategies	AND, OR	“Alternative sourcing” AND disruption AND flexibility OR redundancy
Component Design / Design for supply	Modularity, standardization, commonality, COTS, design for supply, part/component availability	AND, OR	Component selection AND modularity OR standardization

The selection of the literature followed a process involving multiple stages, which is illustrated in Table 4. Initially, the database search was conducted using predefined filters, including publication year (1990-2026), peer-reviewed status, language

(English), and access (open access or through institution). These filters ensured that the results of the searchers met the overall basic standards.

Following the identification stage (Stage 1, Figure 6), an initial screening was conducted based on the titles and abstracts of the articles. This step allowed for retrieving articles that were broadly relevant to the research topic. The selected articles were then reviewed further, to ensure consistency and reduce bias of the researchers, predefined inclusion and exclusion criteria were applied (Lame, 2019).

Studies were included if they:

- Addressed supply chain resilience, spare part logistics, or sourcing strategies
- Had aspects of disruption contexts (e.g. crises, conflict, uncertainty)
- Were peer-reviewed journal articles or conference papers

Studies were excluded if they:

- Were not directly relevant to the research questions
- Focused solely on stable supply chain environments
- Were non-academic
- Were of quantitative nature

Following the application of inclusion and exclusion criteria, articles that remained went under further assessment where a full text review was made (Step 3, Figure 6). During this stage, attention was given to how the studies addressed the research questions. During this review, additional articles could also be identified. A snowballing approach was applied, which is a strategy where references from selected articles is reviewed to identify additional relevant studies. This was very important, as it assisted in finding relevant sources not included or captured in the initial search (Wohlin, 2016). The method was particularly useful in finding articles in less defined

topics, such as “*Component Design / Design for Supply*”.

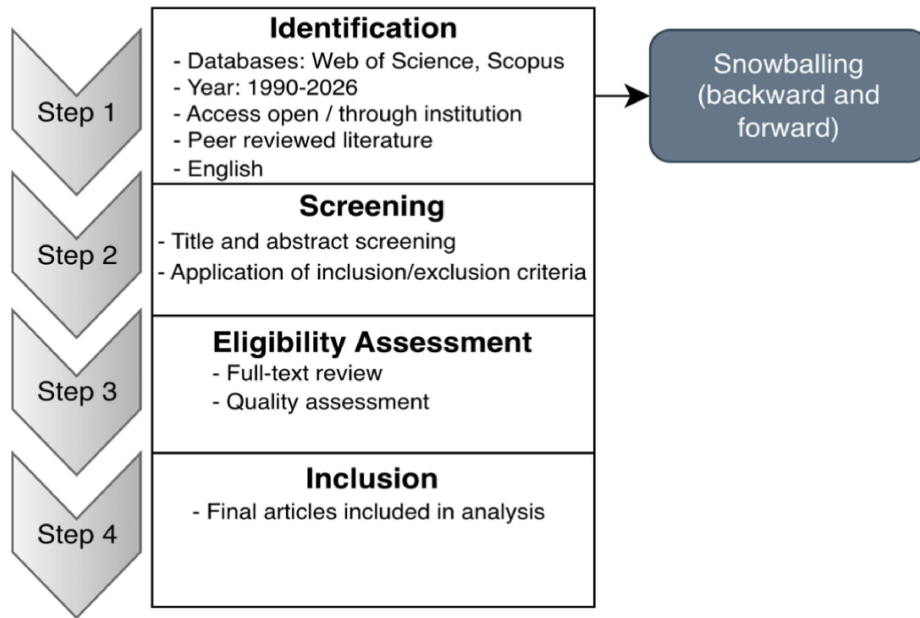


Figure 6: Process of literature selection, inspired by Xiao and Watson (2017)

3.4 Data Collection

Data collection was based on multiple qualitative sources in order to capture both expert insight and technical context. Semi-structured interviews constituted the primary data source, complemented by informal expert interactions. Using multiple sources enabled triangulation by allowing insights from different respondents be complemented and cross-checked through informal expert interactions and various perspectives, thereby strengthening the analytical foundation of the study (Yin, 2018). The overall objective of this data collection was to understand component feasibility, spare part availability, and logistics structures that influence resilience.

3.4.1 Interviews and sampling

Semi-structured interviews allow systematic coverage of key themes while providing flexibility for respondents to elaborate on technical and operational insights (Bryman, 2016). This was particularly relevant in this study, as it enabled the exploration of both predefined topics and emerging issues related to component use and supply chain structures. Primary data was collected through semi-structured interviews with three distinct groups of respondents. The first group consisted of representatives from Truck Inc., including respondents with expertise in logistics, manufacturing, product documentation, platform analytics, and product life cycle management. These respondents provided insights into component design, standardization, substitution possibilities, spare part availability, sourcing structures, and disruption response mechanisms. The second group consisted of a key representative from UGV Inc., who provided insights into the UGV platform, operational requirements, design constraints, and intended use context. The third group consisted of two external respondents representing organizations outside of the project. One respondent provided expertise in defense and crisis logistics, while the other provided an operational perspective from a high-dependency equipment environment where spare

part availability directly affects operational continuity. The inclusion of external respondents was motivated by the need to complement the focal case with additional perspectives on spare part availability under constrained conditions. While External-LOG (see Table 6) contributed domain-specific expertise in defense and crisis logistics, External-OPS provided an operational perspective from a different but comparable context characterized by high dependency on equipment uptime. Including a respondent from outside the focal industry enabled analytical comparison and strengthened the empirical basis by illustrating how spare part availability challenges manifest in practice across different operational settings with similar uptime requirements. This approach is consistent with qualitative case study research, where complementary perspectives are used to enhance analytical generalization rather than statistical representativeness (Yin, 2018).

In addition to formal interviews, multiple informal meetings were held with the key representative from UGV Inc. These interactions were not recorded as structured interviews but contributed to the development of the study. This iterative engagement aligns with an abductive research approach, where insights emerge through continuous interactions between empirical observations and theoretical development (Dubois & Gadde, 2002).

Participants were selected through purposive sampling, focusing on individuals with relevant expertise in component design, spare part logistics, and supply chain management. Purposive sampling is appropriate when the research requires specialized knowledge rather than representative sampling (Bryman, 2016). Additional participants were identified through snowball sampling, where initial respondents recommended further experts with relevant experience. The objective was to capture diverse technical and logistical perspectives in order to obtain a comprehensive understanding of spare part availability and resilience challenges. In total, eight semi-structured interviews were conducted with representatives from UGV Inc., Truck Inc., and external operational and defense logistics contexts.

Table 6: Overview of interview respondents

Respondent	Role	Organization	Theme of interview
UGV-CEO	Chief Executive Officer	UGV Inc.	Operational requirements, system use context, maintenance considerations
Truck-SC	Logistics Manager	Truck Inc.	Spare part management, sourcing, disruption response
Truck-ENG	Product Documentation Architect	Truck Inc.	Product architecture, standardization, component reuse
Truck-DATA	Senior Data Scientist & Platform Analytics	Truck Inc.	Operational data, lifecycle feedback, product performance
Truck-MFG	Manufacturing Director	Truck Inc.	Manufacturing constraints, component characteristics, logistics implications

Truck-PLM	Product Life Cycle Specialist	Truck Inc.	Life cycle management, spare part support, obsolescence
External-LOG	Professor (Defense Studies)	Defense University	Defense logistics, operational availability, resilience
External-OPS	Operations Manager	Ski Facility	Spare part practices, downtime management, operational continuity

All formal interviews were conducted digitally using video conferencing tools such as Microsoft Teams and Zoom. All respondents were informed of the purpose and nature of the study prior to their participation and provided informed consent. The participants were also informed that the interviews would be recorded for the purpose of transcription and analysis. The recordings were only accessible to the authors and were deleted after the completion of the study. To ensure confidentiality and encourage open responses, respondents were anonymized and are referred to by their roles and organizational affiliation in the study. For instance, “Truck-SC” refers to Supply Chain, “Truck-ENG” to Engineering, “External-OPS” to Operations. All recorded interviews were subsequently transcribed to support analysis and traceability. For informal meetings, detailed notes were taken and used as contextual support rather than as primary interview data.

The interviews were conducted using semi-structured interview guides tailored to the respondent’s area of expertise. While the specific focus varied across respondents, the interviews broadly addressed topics related to spare part availability, component characteristics, sourcing, operational requirements, and resilience under disruption. The main focus area for each interview are summarized in Table 6. The semi-structured approach enabled respondents to elaborate on their specific areas of expertise while maintaining sufficient overlap between interviews to support comparison across respondent groups.

3.5 Data Analysis

Collected data was analyzed using thematic analysis (Braun & Clarke, 2006). Interview transcripts and interview notes were reviewed iteratively to identify recurring patterns related to the study’s research questions. During the analysis, themes emerged around operational context and uncertainty, time sensitivity, and response requirements, component criticality, supply network vulnerabilities, standardization and component reuse, sourcing feasibility, and contingency sourcing options. These themes were subsequently compared across respondent groups and examined through pattern matching to identify consistencies and differences between empirical observations and theoretical concepts from literature. This analytical process enabled the findings to be interpreted in relation to supply chain resilience, spare part availability, alternative sourcing approaches, and design for supply.

The analytical process followed abductive logic, where empirical observations and theoretical concepts were continuously compared and refined. This approach is consistent with systematic combining, in which theory, empirical data, and analysis evolve iteratively through a process of matching and redirection (Dubois & Gadde, 2002). Rather than applying a fixed analytical framework, the study allowed

adjustments of both theoretical interpretation and empirical focus as new insights emerge. For example, while the theoretical focus was primarily directed towards supply chain resilience, spare part availability, and sourcing strategies, several respondents repeatedly emphasized the importance of standardized components, common architectures, and component reuse across products. These observations led to a deeper exploration of literature related to standardization, modularity, and design for supply, which subsequently became a more prominent part of the frame of reference. Pattern matching is used as a case study analytical strategy to link empirical findings with theoretical constructs, thereby increasing analytical rigor and explanatory depth (Yin, 2018). This involves comparing observed empirical patterns with expected patterns derived from theory in order to assess consistency and identify deviations. The analysis was therefore conducted as an iterative process, where data collection, and theoretical interpretation are closely interconnected. This enabled a deeper understanding of the relationships between component characteristics, sourcing strategies, and spare part availability under disruption.

3.6 Research Quality

The quality of the study was evaluated through validity and reliability criteria, in line with established case study research methodology (Yin, 2018). In qualitative research, transparency and the ability to trace how findings are derived are essential for assessing the trustworthiness of the study (Lincoln & Guba, 1985). The study therefore emphasizes a clear research process and alignment between data collection, analysis and theoretical development. Yin (2018) identifies four key criteria for evaluating case study research: construct validity, internal validity, external validity, and reliability. These criteria and their application in this study are summarized in Table 5.

Table 5: Research quality criteria and application based on Yin (2018).

Criteria	Explanation	Application in this study	Examples from the study
Construct validity	• Use multiple sources of evidence • Establish a chain of evidence	• Data was collected through semi-structured interviews with respondents from Truck Inc and UGV Inc, and external experts • Data collection and analysis were documented throughout the study, enabling transparency in how empirical observations informed the conclusions.	• Spare part criticality was discussed by UGV-CEO, Truck-SC, Truck-PLM and External-OPS, enabling comparison of perspectives across different contexts
Internal validity	• Do pattern matching • Do explanation building • Address rival	• Empirical findings were interpreted in relation to theoretical concepts to identify consistent relationships within the case.	• The importance of response times, local availability, and component criticality was compared with theoretical

	explanations	• Explanations were developed iteratively by linking empirical observations to theory through an abductive approach.	discussions on spare part availability and resilience
External validity	• Use theory in single-case studies (analytical generalization)	• Empirical findings were linked to existing literature to enable analytical generalization beyond the specific case context.	• Observations regarding standardization and component reuse were analyzed using theories on standardization, modularity and sourcing flexibility
Reliability	• Ensuring that the study can be replicated with consistent results	• Semi-structured interview guides were used to ensure consistency across interviews depending on expertise area. • Interview transcripts were stored and organized throughout the study.	• Common interview themes (e.g., spare part availability, sourcing feasibility, and component criticality) were covered across respondent groups, enabling comparison of responses

Construct validity was strengthened through the inclusion of respondents representing different perspectives relevant to the research problem. UGV Inc. contributed insights regarding operational requirements, intended system use, and the challenges associated with developing a UGV platform for disrupted environments. Respondents from Truck Inc. provided perspectives related to logistics, manufacturing, product lifecycle management, product documentation, and platform analytics. These perspectives were complemented by external respondents representing defense logistics and a high-dependency operational environment. By comparing these different viewpoints, the study was able to examine spare part availability, component criticality, sourcing feasibility, and disruption response from multiple perspectives, thereby reducing the risk of relying on a single organizational interpretation. This approach is consistent with recommendations regarding the use of multiple sources of evidence and triangulation in case study research (Yin, 2018).

Internal validity was addressed through pattern matching and explanation building (Yin, 2018). Empirical observations were continuously compared with concepts from the frame of reference throughout the analytical process. For example, findings related to response times, local spare part availability, and contingency sourcing strategies were compared with theoretical discussions on supply chain resilience and spare part availability. Similarly, observations regarding standardization, component reuse, and common product architectures were interpreted using literature on standardization, modularity, and sourcing flexibility. The analysis also revealed

nuances that extended beyond the initial theoretical understanding. For instance, component criticality was found to be influenced not only by failure likelihood and operational consequences, but also by factors such as accessibility, replacement complexity, redundancy, and the specific function performed by the component within the system. This iterative comparison between empirical observations and theoretical concepts enabled both consistencies and deviations to be identified and incorporated into the analysis. The approach is consistent with systematic combining and abductive reasoning, where theory and empirical observations are continuously refined throughout the research process (Dubois & Gadde, 2002).

External validity was addressed through analytical generalization by relating the empirical findings to established theoretical concepts and literature (Yin, 2018). Although the study focuses on a specific collaboration between UGV Inc. and Truck Inc., the findings were interpreted through broader concepts such as supply chain resilience, spare part availability, sourcing flexibility, standardization, modularity, and component criticality. By linking empirical observations to existing theory, the study develops theoretically informed insights that may be relevant to other contexts characterized by critical equipment, uncertain demand, disrupted supply conditions, and high requirements for operational continuity.

Reliability was supported through a transparent and well-documented research process (Yin, 2018). Semi-structured interview guides were developed for each respondent group while maintaining common themes related to spare part availability, sourcing strategies, component characteristics, and resilience. All formal interviews were conducted digitally, recorded with the participant's consent, and subsequently transcribed. In addition to the formal interviews, several informal meetings were held with the representative from UGV Inc. These interactions were documented through notes and used as contextual support than primary interview data. Interview transcripts, notes, and analytical decisions were documented throughout the study, providing a clear chain of evidence linking data collection, analysis and conclusions. Such transparency contributes to the trustworthiness and dependability of qualitative research (Lincoln & Guba, 1985).

3.7 Use of AI

In this thesis, the generative AI tool ChatGPT (OpenAI) has been used as support for language refinement, structural feedback, and clarification of academic phrasing. The AI tool was primarily used to improve linguistic clarity, coherence, and consistency in the written text. Furthermore, the tools were used in a limited and supportive capacity during the preliminary stages of this thesis, where it assisted in structuring the work and providing general guidance to ensure coherence and alignment with the overall research objectives.

The authors take full responsibility for the academic content, organization, and integrity of the work. No parts have been generated by the AI tool. All references and information have been independently and systematically identified, selected, and verified by the authors.

4. Empirical Findings

This chapter presents the empirical findings from the interviews conducted with respondents at UGV Inc., Truck Inc., and external experts. The findings are structured around the three research questions and focus on factors influencing spare part availability, the role of civilian supply networks, and strategies for resilience under disruption conditions.

4.1 Factors Influencing Spare Part Availability in Disrupted Environments

The empirical findings indicate that spare part availability for UGV systems is strongly shaped by the operational context in which these systems are intended to function. Unlike conventional industrial applications, the studied UGV system is developed for highly uncertain and potentially hostile environments, where access to established supply chains cannot be assumed. This creates fundamentally different conditions for design, sourcing decisions and maintenance strategies. The CEO of UGV Inc (Respondent UGV-CEO) described the intended operational envelope of the UGV system, emphasizing that the platform is being developed in two size categories, a smaller 500 kg platform and a larger variant ranging from four to eight tons depending on armor and equipment. The expected operating conditions were characterized by a need for mobility across varied and demanding terrain:

“Off-road is the general expectation [...] from a gravel road to rocks and stones, but it will not be dense forest. Forest roads, that’s probably where we want to get through. It will be worse than a tank, but it should be better than a pickup truck. Pickup trucks may only last a few weeks near the front line [...] I don’t think it’s even comparable to mining, components probably last ten times longer there.”

This description illustrates that the system is positioned between highly specialized military vehicles and more conventional civilian platforms, which has direct implications for both component requirements and maintenance conditions. The operational environment is expected to impose significantly higher stress on components than in typical industrial applications, leading to shorter lifetimes, more frequent failures, and an increased need for replaceability. When discussing maintenance and repair under such disrupted conditions, Respondent UGV-CEO acknowledged that no formalized framework currently exists for how such activities should be structured, indicating that these aspects remain under development.

A further challenge is that the UGV system is not yet in operation. This means that UGV Inc. does not have historical failure data, demand patterns, or field experience from the UGV. The lack of data changes the basis for spare part planning, since the company cannot rely on established consumption patterns in the same way as an organization managing spare parts for a mature vehicle platform.

Respondent Truck-SC explained that established spare part planning is normally built on movement and consumption. When there is little or no demand history, the planning logic becomes more difficult:

“Everything is built on having some kind of movement or consumption. If there is no

consumption, there is nothing to adjust. When the flow is very low, it becomes difficult”

The findings are particularly relevant for the UGV case because the system must be planned before operational data exists. Instead of planning based on historical demand and usage data, the planning for spare part must rely on other indicators, such as intended operating environment, component function, expected wear, consequences of downtime, lifecycle status, and sourcing feasibility.

4.1.1 Operational Context and Absence of Failure Data

The UGV system is indented to support logistics and medical evacuation in environments where infrastructure may be damaged and centralized maintenance facilities may be difficult to access. Respondent UGV-CEO explained that the initial focus was evacuation of injured personnel, but that logistics became a central part after observing current battlefield use cases:

“The basic idea comes from a need expressed by the armed forces for more effective and safer ways to evacuate injured people backwards, without risking the lives of medics and others”

The UGV is still under development, which means that maintenance and repair logic has not yet been fully defined. When asked about if there is any clear picture or defined ideas of how maintenance and repair should be organized the respondent simply stated that there was not.

This creates a need for considering spare part availability before the UGV is operational. When Respondent Truck-PLM got asked how spare part need could be predicted, the respondent asked for a clearer outline of the vehicle including size, protection, propulsion, configuration, and connectivity. These factors influence what kind of maintenance and spare part logic that can be developed.

To get a more practical understanding of this, an interview was held with a worker from a ski resort. Respondent External-OPS explained that for a new machine, it is difficult to know which components that will become problematic, since some failures only appear after years of operation:

“For a new machine, it is difficult to know what spare parts are needed. A new machine often runs for a quite a long time before things happen. Normal wear often cracks in hoses and things like that, but that may not come until after seven or eight years.”

The “snow-groomer case” therefore shows that even in less extreme environments, spare part planning often depends on practical experience and known wear mechanisms rather than complete data. Respondent Truck-DATA pointed out the importance of designing products in a way so that useful operational data can later be collected from the use phase and use it for service planning, quality assurance, and future product development. The respondent described the tasks they perform as focusing on how to design trucks so that they can collect data from usage, with the aim to “build service” and as input for the next generation of trucks.

Respondent Truck-PLM provided an additional example of how organizations can

reason when operational data is limited. When Truck Inc. introduced electric heavy trucks, as it was new, the organization could not rely on the same mature operating history as for the conventional platforms. Instead, pre-series vehicles and components were tested through road testing, heat chambers, cold chambers, vibration rigs, and component level simulations. These tests were used to estimate whether components could function in the expected conditions over time. Truck-PLM also noted that for new components, the organization may need to adjust the logistics chain after the vehicles have entered the market, depending on what is observed during the operation.

The respondent further explained that established truck manufacturers often work with product updates “incrementally” rather than entirely new products. The respondent highlighted that completely new components are relatively rare, and that new yearly models usually involve smaller modifications. This means that spare part needs can often be estimated from previous platforms and known wear parts.

4.1.2 Time Sensitivity and Operational Constraints

The findings further indicate that the required speed of component replacement under disruption is highly dependent on the operational context in which the system is deployed. In environments close to a battlefield or degraded area, spare part availability is not only about if the part exists somewhere in the supply chain, but whether it can be accessed and installed within the time frame required to maintain operational capability.

“If I were to set a requirement, I could think: three days. You have one day to evacuate the vehicle, one day to repair it, and one day to restore it and get out again. Some things are done at different times of day; evacuation is almost always done at night or twilight. There might be automatic time shifts in the logistics chain.”

This estimate reflects the complexity of operating in disrupted environments, where recovery and repair activities must be coordinated with factors such as visibility, security, and mobility constraints. As such, response times are not solely determined by logistical efficiency but are also shaped by operational conditions. This suggests that spare part availability is not only a supply chain issue, but also connected to how the vehicle is expected to be recovered and repaired in practice.

The importance of time and local access to spare parts is further reinforced by the external expert (External-LOG), who emphasized that availability must be understood relative to required response times. Components needed within short time frames must be located directly at the point of use, whereas longer repair windows allow for sourcing from further back in the supply chain. External-LOG further explained that availability in operational environments is influenced not only by spare parts, but also by access to critical resources such as fuel and protected transport. The UGV-CEO emphasized the importance of having critical parts available at the point of use.

The respondent explained that this could be achieved either by ensuring access to an established civilian spare part base or by developing another local solution. Spare parts may exist in a global supply chain, but if they cannot reach the service point quickly enough, they do not provide operational availability, which makes availability at the service point central.

The “snow-groomer case” illustrates this problem in practice. Respondent External-OPS described a situation where a drive motor failed during winter season, which is when peak demand hits. A replacement was ordered by express from Canada, but the part still took around a week to arrive, and when it arrived, it was the wrong motor:

“There were none available, so we ordered one by express from Canada. You think that should go quite fast, but it still took a week. Then we received it, it was the wrong motor. We were really limited by that situation”

This example proves that downtime can result not only from the technical failure itself, but from long lead times, incorrect identification, and lack of local availability. External-OPS further explained that planned maintenance is easier to manage because parts can be ordered in advance:

“If we know we need to replace tracks, then we need to order tracks well in advance. Together with a track replacement, you also replace wear pads, so you order everything at the same time.”

In more structured supply chain environments, such as those of Truck Inc., significantly shorter response times can be achieved in critical situations. This is enabled by dedicated prioritization mechanisms and flexible sourcing practices, which are further elaborated in Section 5.3. However, such responsiveness is contingent on the existence of established inventory networks, global logistics infrastructure, and a willingness to incur high costs. At the same time, the findings highlight that the feasibility of rapid response is not uniform across all component types. Respondent Truck-SC noted that physical characteristics of components play a significant role and pose logistical challenges:

“If it’s a heavy article, extremely heavy like a complete cab, or these batteries that will go into trucks which are very heavy. Then transport costs become very high to compensate for not keeping up with planning.”

Respondent Truck-MFG similarly emphasized that component specifications and storage requirements influence how components can be supplied:

“We look a lot at the geometry of the articles. That also has consequences for logistics, just transporting large and heavy things instead of small and light things”

This suggests that time sensitivity in spare part availability is not only a matter of organizational capability but also constrained by the physical and economic properties of the components themselves. Additional empirical findings indicate that the ability to anticipate spare part requirements is highly dependent on access to historical operational data. The product life cycle specialist (Respondent Truck-PLM) emphasized that organizations rely heavily on field data to identify failure patterns and determine which components are most likely to require replacement. In situations where such data is not yet available, for instance in early-stage development, alternative approaches must be used, including simulation, controlled testing, and engineering judgment.

The findings also show that local stock may not be a simple solution. Respondent External-LOG noted that many modern components “do not bear storage” in the same way as older mechanical components, due to factors such as battery degradation, continuous software updates and changing technical standards. Respondent Truck-MFG also stated that some components require specific storage conditions, such as temperature control or continuous use cycles. This leads to some stock-piling strategies not being viable for advanced components, particularly in resource-constraints or decentralized environments.

4.1.3 Component Criticality and Spare Part Need

A repeated theme across the interviews is the challenge of determining component criticality due to it being inherently complex, especially in disrupted or uncertain operating environments. Respondents described criticality as highly context-dependent and not fixed. The available data, consequences of failure and the possibility of continuing operation despite a fault are also repeated factors. This was evident in discussions about disrupted or uncertain operating environments, where the respondents described different ways of prioritizing spare parts depending on downtime consequences, redundancy, supply conditions and on system function.

In the context of the UGV, UGV-CEO described mobility, driveline, communication, and electronics as critical components:

“It is mainly things connected to the driveline, but also communication and electronics. As if you lose the connection, you lose the vehicle. There may need to be redundancy, more than one antenna, more than one camera and so on.”

The CEO also described that some failures may be accepted during operation while others compromise the use of the vehicle:

“You will try to drive the vehicle even if it is broken, until it absolutely does not work anymore.”

Respondents from Truck Inc. described various approaches to prioritizing spare parts. Respondent Truck-SC, the logistics manager with extensive experience within the field, explained that they use segmentation models to determine inventory policies. These models guide decisions such as setting safety stock levels and service targets by grouping items into categories. Components classified as critical are assigned higher stock levels and stricter service objectives:

“In our inventory optimization, we have a segment for critical articles. For those, we increase the desired service level, and that means they receive a larger safety stock than they otherwise would have.”

However, the respondent noted that there is no unified standard for defining “critical parts” across the organization. Instead, the label depends on the data available and how individual business units assess importance. This means that definitions of criticality vary between divisions, reflecting their differing priorities and operational perspectives.

This perspective is further supported by Respondent Truck-PLM, who explained that not all components are treated equally within spare parts systems. Instead, only a subset of components is actively managed as spare parts, based on their expected failure behavior and operational importance. In addition, criticality is influenced by not only failure likelihood but also by factors such as ease of replacement, expected lifetime, and the component's role within the system. Components that are difficult to access or require extensive disassembly are often prioritized differently compared to those that can be replaced quickly, even if their failure probability is similar.

Furthermore, Respondent Truck-PLM explained that ease of replacement is influenced by whether the component is physically accessible, if special tools are required, and how quickly replacement can be performed:

“Components that can be reached and replaced with standard tools are easier to manage in maintenance than components requiring more complex workshop procedures”.

Furthermore, Respondent Truck-MFG suggested that component analysis should not only be conducted at the article level, but also from a functional perspective, focusing on the role a component fulfills within the system rather than its specific part identity. This perspective is particularly relevant in early-stage system design, where exact component specifications may not yet be defined.

The “snow-groomer case” illustrates how descriptions of criticality is shaped by operational consequences and the availability of redundancy. Respondent External-OPS noted, as a side, that the ski lift had been a bigger problem than the snow-groomer because the facility could not transport customers if the lift stopped. The snow-groomer situation was different because the facility had two machines:

“We have two snow-groomers, so if one breaks down, we can get some help from the other. But the lift has been the biggest problem. If it breaks, we cannot transport people.”

This supports the broader finding that spare part need and component criticality must be assessed in relation to system function, backup capacity, and the consequences of downtime.

In the interviews, a distinction between service parts and repair parts were made. Respondent Truck-SC described service articles as parts that are expected to wear and be replaced at planned intervals:

“Service articles are things that wear and are normally consumed. You know they will not last the vehicles full lifetime. They may need to be replaced every year, every second year, or every fourth year”.

Some examples of such articles were mentioned, and these included: filters, seals, gaskets, brake pads, oil, and other consumables. Respondent External-OPS echoed this and stated:

“Oil and filters, you always replace. The snow-groomer has a Caterpillar engine, like Caterpillar excavators, so filters and things like that are in circulation.”

Repair parts were described as components intended to last longer, but which may experience an unexpected failure eventually. Respondent Truck-SC mentioned turbochargers, coolers and electronic units as examples:

“A repair article could be. A turbo, a cooler, or an electronic unit. It is more of a component that is intended to last a long time, but eventually it may also break. Then it becomes a more unplanned repair”

Respondent Truck-PLM also described that Truck Inc. may replace larger components during the vehicle lifecycle. An example of such case is if a truck has been heavily used, if the engine wears out before the rest of the vehicle, the customer may be provided with either a new or remanufactured engine, in which worn parts have been replaced and the unit has been restored for further use.

External-OPS described drive motors, circuit boards, and tracks as examples of parts that had been difficult to access:

“In this case it was a drive motor. We also had problems with circuit boards. There were no circuit boards available. Drive motors, circuit boards, and tracks are probably the most difficult to get hold of.”

Respondent External-OPS explained that the difficulty of finding the parts was partly connected to the use of older machines. The facility relied on older machines, which made finding suitable components more challenging.

Respondent Truck-PLM outlined that spare part planning is influenced by the level at which replacement is practically organized. The respondent estimated that around half of the articles on a truck are provided as spare parts in some form. However, not every article on a vehicle is necessarily supplied as an individual spare part. In some case, several articles may be supplied together as a kit, module, or as a larger exchange unit. Spare part prioritizations may therefore need to consider whether the relevant replacement unit is a component, module, kit, or subsystem.

Respondent External-OPS was also asked how he would prepare spare parts for a newer machine that they have little experience with. External-OPS explained that they would start with items that could be expected to require replacement, such as oil and filters, and would also include hoses and extra wheels. This shows that components that are known to be consumables, exposed to wear, or likely be needed during operation, are most likely prioritized as spare parts.

When discussing what influences how easy or difficult it is to maintain component availability, Respondent Truck-SC pointed to volume, cost, and lead time as key determinants. Items that are inexpensive, widely used and standardized, such as commodity parts like nuts, bolts, and gaskets, are the easiest to manage because they are produced in high volumes and can be stocked by both the company and suppliers at relatively low cost. At the opposite side, specialized components, such as unique transmissions, priced between 150 000 and 200 000 SEK and sold in very low

quantities “only few units per year”, present a major challenge. These items are costly to hold in inventory and difficult to forecast due to their low demand. A related availability challenge mentioned by Respondent Truck-SC concerned low-frequency parts that have gone out of production as one of the main availability challenges. While the previous examples show how low demand and high-cost make certain parts difficult to stock, Respondent Truck-SC explained that the challenge increases when the part is no longer used in ongoing production. Parts that are still relevant and still produced benefit from continuous demand and suppliers that have strong incentives to keep them available. On the other hand, aftermarket only parts, i.e. parts that are no longer used in current production but are needed for repair and replacement, often have lower and more irregular demand, which makes them harder to source and maintain over time. As Respondent Truck-SC summarized:

“Items that are low-cost and frequently used are straightforward to manage, whereas those that are high-cost and infrequently demanded are much more complex”.

Respondent Truck-PLM provided a similar lifecycle perspective by explaining that Truck Inc. is required to provide original spare parts for vehicles sold for 15 years. During this period, both the vehicle platform and its components may change substantially. Truck-PLM explained that trucks change significantly over a 15-year period and estimated that “an article has an average lifetime of around 10 years”. As a result, several generations of trucks and components must be supported in the spare parts assortment at the same time. This is an availability challenge, as spare part needs are not only linked to current production conditions, but also to continued support for older vehicle generations.

Respondent Truck-PLM further explained that replacement parts are not always identical to the original article but may be later versions that have “qualified” as compatible with the existing platforms. Truck-PLM described this as: “It requires the same form, fit and function. Meaning that updated parts must still work as replacement for previously produced vehicles.”

Respondent Truck-SC identified differences between mechanical and electronic components, where they vary significantly regarding product lifecycles. Electronic components have shorter lifecycles, and development moves faster, which makes it harder for suppliers to source materials for older units. Truck-SC stated:

“Getting a twelve-year-old ECU can be very difficult for the supplier because their suppliers have stopped making the materials used for it”.

Respondent Truck-PLM also mentioned semiconductors as a component category that had been difficult to access in recent years, especially during Covid-19. The respondent explained that Truck Inc. analyzes components containing critical raw materials, since these materials may be difficult to source or sensitive from a supply perspective.

Repeating what Respondent External-LOG stated that many modern components cannot be placed in storage for long times due to factors such as battery degradation and continuous software updates, and the storage constraints described by Respondent

Truck-MFG (Section 5.1.2), this introduces additional complexity in determining feasible inventory strategies.

4.1.4 Supply Network Vulnerability and Organizational Dependencies

Increasing product variety was identified as a significant challenge from a logistics perspective. Respondent Truck-MFG noted that increasing product variety requires parallel inventory and handling processes, which can become particularly problematic in constrained operational environments such as forward service points. This reinforces the importance of limiting unnecessary variation to maintain logistical efficiency. These constraints are also reflected in the underlying business logic. Respondent Truck-MFG noted that in disrupted or crisis scenarios, traditional cost considerations may become secondary, as operational functionality and speed of response take precedence. This shows that supply chain design should be aligned with operational requirements rather than solely economic optimization. A notable finding is that Truck Inc. often relies on single suppliers for many components, and this is especially the case for those components that have a high degree of specialization or unique to their brand. Respondent Truck-SC explained that a single supplier in Europe or North America is typically responsible for the global need. This creates a vulnerability in the supply chain, as the respondent said:

“If we get a problem with that supplier, for instance a fire or a bankruptcy, we lose the entire global production. However, we are moving towards a more regional supply chains, but no significant progress has been made yet”.

Similar vulnerabilities are observed in other operational contexts characterized by high dependency on equipment uptime. The operations manager (Respondent External-OPS) described how delays in spare part availability during peak operational periods can have immediate and significant consequences. In one instance, a critical component had to be sourced internationally, resulting in a lead time of approximately one week, which severely constrained operations during peak season. The findings further indicate that supply risk is not limited to complex or highly specialized components. Even relatively simple components can become bottlenecks if they are unavailable within the supply network. As described by External-OPS, minor components such as small pipes or connectors may cause operational disruptions if they fail and cannot be replaced in time, requiring improvised solutions to maintain functionality. An example was provided by External-OPS which illustrated how simple, easy to get parts can still create problems:

“A small copper pipe connected to the snow-groomer’s heated windshield wipers wore through and started leaking. Although this part appeared simple, a replacement could not be sourced, so the facility cut the copper pipe and replaced it with a hose instead.”

The move towards regional supply chains is also echoed by Respondent Truck-DATA, who added that a recent reorganization has brought purchasing and engineering closer together to improve efficiency. Respondent Truck-DATA explained that these two functions had been “quite far apart, both physically and organizationally”, and that this is a limitation, as in the ideal world engineering sets requirement and purchasing negotiates price.

In summary, these findings indicate that spare part availability in disrupted environments is not determined by individual components, but an emergent property of the system, shaped by the interplay between operational conditions, design decisions, and the resilience of the underlying supply networks.

4.2 Enablers and Constraints for Using Civilian Supply Networks

A central enabler for using civilian supply networks was the underlying design philosophy that was clearly articulated by Respondent UGV-CEO, centered around the use of standardized, widely available components:

“In an ideal scenario, wear parts and common parts are not specifically adapted. Instead, we have adapted the product to what exists, volume-based standard products from for example, Truck Inc. We develop no own axles or similar. In a war scenario, you can take parts from broken vehicles. You drive past, and there’s a truck in the ditch, and you can take parts from it when you need them and continue driving. Of course, it won’t be that easy, but you express it that way and have that ambition.”

This reflects an approach where system design is aligned with existing supply networks rather than optimized solely for technical performance. This approach is closely linked to the use of platform-based product architecture. Respondent Truck-PLM described how Truck Inc. applies a common architecture strategy, where components are reused across multiple products and applications. This enables increased standardization and reduces the number of unique components, which in turn simplifies sourcing and improves spare part availability. By designing systems around shared components, organizations can leverage existing supply networks and benefit from higher productions volumes and broader supplier bases. However, some level of differentiation remains necessary, particularly for components that are physically visible to customers or tied to brand identity.

4.2.1 Standardization, Modularity, and Reuse

Respondent Truck-ENG, the product documentation architect, described the bottom-up logic that enables component reuse. They have a common architecture across all trucks, and each component is linked to specific customer-selected variants.

“Many different cabs should fit on many different chassis. Our entire setup is really designed to be able to reuse as much as possible”

The respondent further elaborated on this by comparing the architecture to a Lego box of about 20 000 article numbers combined into roughly 5000 components per truck. Yet Truck-ENG admitted that complexity may have been taken too far:

“Between the lines, perhaps we have taken it too far.”

The documentation logic supports replaceability because components can be connected to specific configurations and substituted when necessary. This also shows that component reuse is not solely about component availability, but also about which configuration the part belongs to, how it connects to surrounding systems, and how replacement should be documented.

Truck-ENG further explained that component reuse is not limited to trucks but can extend across different business areas of Truck Inc (group company), including trucks, construction equipment, buses, and industrial or marine engines. Since components can be used across multiple platforms/applications, they are supported by larger volumes and spare part flows, which strengthens the potential aftermarket base.

Furthermore, the ambition of enabling cannibalization and field-level repairs illustrates an attempt to mitigate supply chain disruptions by reducing dependency on centralized logistics structures. At the same time, Respondent UGV-CEO explicitly recognizes the gap between this idealized vision and practical implementation, indicating that such strategies introduce additional complexities that must be addressed. Additionally, Respondent UGV-CEO stated that availability must be treated as a fundamental design constraint rather than a downstream logistical concern. Rather than specifying and subsequently ensuring their availability, the system must be adapted to what is already accessible within existing supply networks:

“The system needs to be cheap to build and cheap to maintain. Instead of developing our own components, we try to adapt the product to what already exists. If you design something unique, you immediately create a dependency on a specific supply chain, and that becomes a problem in disrupted environments.”

In this context, system feasibility is directly influenced by the accessibility of components within existing supply networks. Components that are produced at large volumes and widely distributed in the civilian sector are described by Respondent UGV-CEO as particularly advantageous, as they are supported by established supply infrastructures and do not require the creation of dedicated sourcing channels:

“If a component is already used in large volumes in the civilian sector, then there is already a supply network around it. That means you don’t need to build one from scratch, and you can rely on something that is already proven and accessible.”

This highlights a clear link between component selection and supply chain resilience, where alignment with existing industrial actors enhances availability under disruption.

At Truck Inc. Standardization differs across the vehicle architecture. As explained by Respondent Truck-PLM, components connected to visible brand identity such as cab exterior, interior surfaces, lighting, and other customer-facing features, are more likely to remain unique. Chassis related and less brand exposed mechanical components are generally similar across brands. This shows that civilian sourcing opportunities may be stronger for mechanical, structural or less visible components than for brand specific components.

4.2.2 Integration and Performance Constraints

While civilian supply networks provide opportunities, the findings also shows that availability alone does not make a component feasible for integration. Respondent Truck-MFG emphasized that physical integration constraints, particularly related to geometry and packaging, represent a major challenge. Even if components are available, their size and integration requirements may limit feasibility, especially in compact or highly constrained system architecture. For example, while electric

drivetrains may simplify certain aspects, large battery systems introduce new spatial and safety constraints that must be considered early in the design process. This reuse logic also affects substitution possibilities, Respondent Truck-ENG explained that the documentation system allows components to be replaced relatively quickly when supplier changes occur. When a new supplier is introduced, a new article number is added, and the link is updated from a specific week. Regarding what they do when a component is not available, Respondent Truck-ENG states:

“From a documentation perspective, we can replace that component relatively quickly, because the building blocks have no tight couplings [...]. For instance, the steering wheel has no specific connections to the components around it.”

The respondent further stated that the main challenge when a component is not available is to find a new supplier but did not further dive deep into it as it is a purchasing task.

Truck-DATA emphasized that component selection is not solely a technical decision. For some components, especially those related affecting emissions, regulation, patents, local supplier relationships, and purchasing considerations strongly influence what can be used. The respondent stated that “Ideally engineering specifies the component requirements and purchasing finds and negotiates with suppliers that can fulfill them”, but also noted that cost and conflicting priorities between the departments can influence the final component choice.

However, Respondent Truck-DATA warned that the most important aspect of reusing or replacing a component is that it is physical fit, but that it is only half the challenge. Even if a component can be screwed on, it is important that it performs in the application. Different loads, dynamic behavior, and certification requirements mean that reuse require deep understanding:

“The more complex a component is, the harder it is to replace [...] When you replace a component, it’s supposed to be performance neutral, which it never is.”

Respondent Truck-DATA further explained that if he would have the freedom to redesign the platform for resilience rather than solely performance and variety, “I would simplify, try to reduce the number of variants.”. But Truck-DATA acknowledged that there is a fundamental tradeoff between market-driven variety and resilience-oriented simplification. This aligns with Respondent Truck-MFG, who emphasized the importance of developing a structured understanding of component needs, including factors such as failure frequency, sourcing options, storage requirements, and criticality. Rather than evaluating components in isolation, this approach highlights the need for a holistic “needs profile” that integrates both technical and logistical considerations.

Respondent Truck-PLM suggested that for the UGV, components from medium-duty trucks may be more relevant candidates compared to heavy-truck components. Heavy-truck drivetrains and engines may be too large for the UGV, while medium-duty frames, drivetrains, axles, and chassis components may be more suitable.

4.2.3 Supply Network Structure and External Constraints

While dependencies remain within the supply structure, Truck Inc. makes deliberate efforts to maximize component standardization across its product portfolio. As described by Respondent Truck-DATA, the core components are widely shared between different brands and vehicle types, where for example the engine is the same across the models and vehicle types, ranging from truck to buses. The respondent expanded on this point by illustrating to what extent standardization is applied in practice:

“If you buy our construction equipment machines, it’s the same oil filter for all of them, the same oil filter for the truck that you use to pull the excavator”.

In other words, the company deliberately uses identical components across different types of equipment and vehicles. This reduces complexity in maintenance and spare parts management, as the same part can be used in multiple applications, simplifying inventory, lowering costs, and making service more efficient. However, there is a commercial differentiation which can limit sharing components: “Our unique brand is considered as luxury, which means that they should have slightly better equipment compared to the other trucks that is produced.”

When asked about civilian supply networks as alternative sources, Respondent Truck-SC was positive:

“If you are a small niche manufacturer, and you can team up with Truck Inc. and gain access to its purchasing network, that is an enormous bonus”.

However, both Respondent Truck-SC and Truck-ENG raised concerns about dual use regulations, calling the area sensitive with a lot of restrictions. When Respondent UGV-CEO was asked about these regulations, the answer was that:

- They are not subject to the military export controls
- If they do not export the system, they can operate within domestic regulations without major legal barriers.

From UGV Inc.’s perspective, legal issues are therefore not considered a major limiting factor, since the company relies on standard, commercially available parts “off the shelf components”, rather than needing specialized, regulated military grade supply chains.

4.3 Structuring Resilient Spare Part Strategies

The empirical findings provide insights into how organizations respond to spare part shortages and supply disruptions in practice. The empirical findings show a range of approaches related to disruption response, sourcing flexibility, component standardization, and contingency actions used when conventional channels are constrained. In particular, the empirical findings illustrate how Truck Inc. manages spare part shortages through structured prioritization mechanisms and various actions aimed at restoring component availability under different levels of urgency.

4.3.1 Disruption Response and Prioritization Mechanisms

A central mechanism identified in the empirical data is the use of differentiated order classes to signal urgency and allocate resources accordingly. Respondent Truck-SC explained that requests are categorized based on their criticality, with specific organizational structures in place to handle the most urgent cases:

“We have different order classes. We have something called VHR which is used in the most acute situations. Then we have day orders for repairs that are not roadside emergencies. Then we have stock orders for inventory replenishment. If we have a shortage on a VHR order, that is very acute because a vehicle is probably standing still somewhere, and every hour counts to get it running again. For VHR, we have a special group that handles it. They have a ‘back-order recovery team’ dedicated to only working with the most acute shortage situations. They have many tools at their disposal; they can spend more time and burn more money on solving a shortage situation.”

This tiered system enables the organization to prioritize resources toward critical downtime situations, where operational impact is immediate and significant. In such cases, standard cost considerations are temporarily deprioritized in favor of rapid solution. Respondent Truck-SC further described a range of concrete actions employed in acute shortage situations, illustrating the extent to which the organization is willing to mobilize global resources to resolve disruptions:

“They can take material from production. They can retrieve materials from around the world. If a dealer in France needs something that is out of stock at the central warehouse in Belgium, but we have the article in United Arab Emirates, we might fly the article from UAE back to Belgium and then out to the dealer in France. We are prepared to spend much more of our own time finding solutions. We might search the dealer network and find another dealer in the same country that has the article, and we can buy it back from them and send it to the one who needs it.”

These examples demonstrate a high degree of flexibility in sourcing, including internal reallocation of materials, global redistribution, and lateral sourcing within the dealer network. However, such responses are resource-intensive and rely on the existence of alternative supply paths within the system. For less critical situations, the response is more conventional and cost-conscious. As described by Respondent Truck-SC, stock-related shortages are typically managed through supplier coordination and logistical adjustments:

“For stock orders, it’s the regular planning team that handles it. Usually, we chase the supplier and tell them to hurry up the next delivery. Maybe take an air transport depending on the situation.”

This shows that disruption response is not uniform, but rather contingent on urgency, with more extreme measures reserved for critical operational cases.

Respondent Truck-SC also described Truck Inc.’s spare parts network as a multi-level-structure, consisting of central warehouses, regional warehouses, support warehouses, and dealer inventory management, where availability is built in each level except from support warehouses.

Truck-SC also explained that some large suppliers have their own aftermarket divisions and warehouses. Suppliers producing transmissions, axles, or similar components may sell it other companies than Truck Inc., and directly to the aftermarket. In such cases, the supplier may already hold stock, and the component will not need to be produced in response to what Truck Inc. demands.

In contrast to traditional inventory-based strategies, External-LOG emphasized that availability in defense-related contexts is often ensured through supply agreements rather than extensive stockpiling. Both suppliers and buyers aim to avoid holding inventory that may become obsolete, resulting in reliance on contractual arrangements and production planning instead of stored inventory. This adds an important distinction to the UGV context, where availability may need to be secured through both physical stock and pre-established sourcing arrangements.

External-LOG broadened the understanding of spare part availability by explaining that the spare part alone does not restore operational capability. A component may be technically available, but if necessities such as fuel, protected transport, tools, repair competence, or the ability to move the vehicles has been compromised, the vehicle may remain unavailable. This means that resilience in the case of spare parts must consider the surrounding repair system, not only the spare part itself.

4.3.2 Contingency Strategies and Limitations

In addition to these structured response mechanisms, the findings also highlight alternative contingency strategies that may be considered in more severe or constrained environments. Respondent UGV-CEO discussed cannibalization, previously introduced as part of the underlying design logic (see Section 5.2), as a potential contingency mechanism in highly disrupted environments. While the concept is based on the idea of leveraging available components from non-operational vehicles, it is primarily described as an aspirational approach rather than a fully developed solution. This perspective is supported by External-LOG, who described cannibalization as a primary and frequently used strategy in practice. These observations are further reinforced by Respondent External-OPS, who described similar practices in operational environments where spare part availability is constrained. In such cases, organizations rely on a combination of repair, reuse, and substitution strategies to maintain functionality. For instance, when specific components were unavailable, alternative solutions were implemented using available materials, such as replacing damaged parts with functionally equivalent substitutes. When a system is assessed as irreparable within a limited timeframe, components are instead extracted and reused in other operational units. According to External-LOG, this decision is largely time-driven, where repair is only pursued if it can be completed within a relatively short time-window. Otherwise, cannibalization becomes the preferred option for maintaining operational capability.

Respondent External-OPS also provided examples of components that can be repaired or reused:

“Hydraulic motors, for example, can be repaired and put back into use. Truck belts may also sometimes be reused, even if they are not new. A facility with very worn tracks may be able to replace them with used tracks that are in better condition and thereby gain additional seasons of use.”

This illustrates that under constrained conditions, contingency strategies may involve using components that are not ideal, but good enough to extend operational use.

Respondent UGV-CEO also discussed additive manufacturing as another potential contingency mechanism in situations where conventional supply channels are unavailable. However, like cannibalization, this approach is associated with significant limitations that restrict its practical applicability. Respondent UGV-CEO highlighted that while 3D printing has been explored in defense-related contexts, particularly for producing spare parts close to the point of use, it introduces a different set of challenges related to cost, quality, and scalability:

“There is an alternative that has been tested quite a bit, 3D printed spare parts. But then you have a different type of problem. You might not get quite the same quality. The cost per spare part becomes astronomically high in 3D printing [...]. If you calculated the cost for each spare part, it would be like a million SEK per spare part. A defense organization has made these container factories to be able to produce spare parts close to the front, primarily for tanks and combat vehicles. But I think this concept of using standard components is better. For special parts that cannot be sourced from existing suppliers, you could have 3D printing. Mass production is still cheaper than 3D printing.”

This statement shows that while additive manufacturing may offer a degree of flexibility and localized production capability, it is not considered a viable large-scale substitute for established supply chains in terms of scalability and cost-efficiency. Instead, it appears to be limited to niche applications, particularly for components that cannot be sourced through existing supply networks. The importance of component standardization in enabling flexible sourcing is further reinforced by Respondent Truck-SC, who explained how standard components are inherently more resilient from a supply perspective:

“If it is a standard article that not only, we consume, then it also runs in high volumes at the supplier. They might have it in stock, and we can get it with short lead time. If it is a unique article that the supplier only makes for us, a complicated article, then it is naturally lower volumes at the supplier. They become completely dependent on our planning and might not want to hold stock because they are worried, they won't sell it.”

This illustrates a structural trade-off between customization and availability, where unique components increase dependency on specific suppliers and reduce flexibility in disruption scenarios. Additionally, the findings also provide insights into how large-scale disruptions have historically impacted spare part availability. Reflecting on events such as the COVID-19 pandemic and global supply chain disturbances, Respondent Truck-SC noted that Truck Inc. performed relatively well compared to competitors, largely due to strong supplier relationships and operational continuity:

“During COVID and supply crisis, I think Truck Inc. was one of the companies that managed best compared to competitors. I think that was largely because we had good cooperation with suppliers. We also didn't shut down ourselves; we kept our

warehouses running, and we served customers. Given the difficulty, I think we managed well.”

Despite this relative resilience, vulnerabilities in global supply chains were also acknowledged. Respondent Truck-SC referred to the Suez Canal obstruction as an example of how geographically concentrated logistics flow can create systemic risks. This disruption affected multiple regional warehouses and required rerouting of shipments, which in turn led to delays and reduced transport capacity due to longer lead times and slower circulation of containers. This was described as illustrating a broader vulnerability in global material flows, where disruptions in critical transport corridors can have cascading effects across the supply network.

5. Analysis

This chapter analyzes the empirical findings in relation to the frame of reference presented in Chapter 2. The analysis is structured according to the three research questions. Throughout the analysis, empirical observations are compared with the frame of reference to identify patterns of alignment, divergence, and practical extension.

5.1 Factors Influencing Spare Part Availability Under Extreme Disruption (RQ1)

RQ1 asks what factors influence spare part availability for UGV systems under extreme supply chain disruption. The empirical findings show that spare part availability in this context cannot be understood as a purely logistical issue. Instead, it is shaped by a combination of operational severity, absence of failure data, component criticality, response time requirements, lifecycle constraints, and the robustness of underlying supply network.

5.1.1 Operational Context and Challenge of Planning

A key finding from the empirical data is that the UGV system is being developed without historical operational data, which significantly affects the conditions for spare parts planning. The CEO of the UGV company, Respondent UGV-CEO stated that no formal maintenance framework has yet been established and that they do not possess field data. As a result, spare parts planning cannot be based on previous failure patterns, maintenance records, or historical consumption data. This reflects a challenge that is recognized in spare parts logistics, to plan for new systems where future demand is uncertain due to absence of historical usage data (Basten and van Houtum, 2014; Arts et al., 2019).

The literature (Frame of Reference, Chapter 2) established that spare part planning in established systems relies on movement and consumption data to adjust inventory levels and service targets. This was directly confirmed by Respondent Truck-SC: “Everything is built on having some kind of movement or consumption. If there is no consumption, there is nothing to adjust.” This statement reflects the theoretical position regarding demand history being foundational for conventional spare part planning (Kennedy et al., 2002; Sherbrooke, 2004). However, the findings indicate that organizations must rely on alternative indicators when such data does not exist.

Respondent Truck-PLM described how Truck Inc. approached the introduction of heavy electric trucks, a case of a new platform without operational history, through controlled testing including road tests, heat chambers, cold chambers, vibration rigs, and component-level simulations. This illustrates how testing and simulation can be used to estimate future maintenance requirements before operational data becomes available.

Furthermore, the “snow-groomer case”, Respondent External-OPS illustrated that even in less extreme environments, spare part planning often depends on practical experience and known wear mechanisms rather than complete data. The observation that “normal wear often cracks in hoses and things like that, but that may not come until after seven or eight years” shows that spare part needs are not static but evolves

or develops over the systems lifecycle. This suggests that component demand will vary depending on both system age and accumulated usage. This observation aligns with Driessen et al. (2015), who argue that spare part demand emerges through maintenance activities and therefore develops throughout the operational life of a system. As components accumulate wear and are exposed to different operating conditions, maintenance requirements change and generate different spare part needs over time. The empirical findings suggest that this challenge becomes particularly significant for UGV systems, where historical failure data is limited and future operating conditions remain uncertain. Rather than relying solely on predefined spare part lists, organizations may therefore need to continuously adapt spare part planning based on operational experience and observed wear patterns. This supports the argument presented by Arts et al. (2019) that spare part planning is closely linked to maintenance activities and operational context, rather than being a static inventory decision.

The empirical findings also revealed a temporal constraint that differs from conventional spare parts literature. Respondent UGV-CEO made an estimation of how quick spare parts may be needed, where a three-day repair window, consisting of “one day to evacuate the vehicle, one day to repair it, and one day to restore it and get out again” was stated. Although this was a pure estimation, it indicates that repair time in this context is not only a technical or logistical issue but is also shaped by the operational environment in which the system is deployed. Traditional inventory models often treat lead time as primarily dependent on logistics distances, transport modes, and supply chain structure (Basten and van Houtum, 2014; Topan et al., 2020). In the contexts that the UGV will operate in, response times are also influenced by security conditions, exposure risks, visibility constraints, and tactical considerations. These factors fall outside of the scope of traditional supply chain management frameworks but are central to spare parts planning in extreme disrupted environments such as in military operations.

Respondent External-LOG further supported this view by highlighting that components needed within short time frames must be positioned close to the point of use “At the Service Points”, while components with longer acceptable repair windows can be sourced from further back in the supply chain: This suggests that spare parts should be categorized according to how quickly they must be available under operational conditions, and not only according to criticality or demand frequency.

Thus, the empirical findings broaden the theoretical understanding of time sensitivity in spare parts logistics by emphasizing the role of *operationally constrained response time*. In this setting, the maximum acceptable lead time is not defined only based on logistical capacity, but also by tactical and security conditions that determine when, where, and how repairs can realistically be carried out.

5.1.2 Component Criticality as a Multidimensional Construct

In the frame of reference, the concept of component criticality is presented as a multidimensional and context-dependent construct, rather than a fixed property of components (Roda et al., 2014; Teixeira et al., 2017; Antosz and Ratnayake, 2019). This is strongly supported by the empirical findings, where for example Respondent UGV-CEO identified mobility, driveline, communication, and electronics as critical areas, noting that “if you lose the connection, you lose the vehicle.” This aligns with

the process criticality dimension identified by Roda et al. (2014) and Teixeira et al. (2017), who defined it as the consequences of failure or unavailability directly determining operational impact.

However, a notable finding revealed that there are more complexities regarding this. Respondent Truck-SC explained that criticality is there is no standardized definition for defining critical parts across the organization. Instead, criticality is interpreted differently across business units and is influenced by the data available, and the operational priorities of each unit. This finding contradicts prescriptive classification frameworks traditionally used, such as ABC analysis and failure likelihood-consequence matrices (Teunter et al., 2010; Roda et al., 2014; Antosz and Ratnayake, 2019). These frameworks tried to assess criticality through standardized criteria objectively. But the findings show that what is defined as critical is shaped by organizational interpretation and the availability of data.

Respondent Truck-PLM added that ease of replacement influences spare parts prioritization, where components that are difficult to access or require extensive disassembly are usually prioritized differently from those that can be replaced quickly, even if they have a similar failure rate or probability. This *maintenance accessibility dimension* is not broadly established in the literature regarding spare part criticality. Accessibility, meaning ease of replacement (i.e. if it requires special tools, where the component is located etc.) is related to repair time presented by Molenaers et al. (2012) and Antosz and Ratnayake (2019) as a factor, but is unique.

Respondent External-OPS provided a practical example of how system redundancy shapes how criticality is perceived. The respondent noted that the ski lift was considered more critical than the snow-groomer as if it broke, they could not transport people. The facility had two snow-groomers, so “if one breaks down, we can get some help from the other.” This indicated that the snow-groomer was not considered less important because the grooming function itself was unimportant, but because the failure of one machine would not necessarily stop the function from being performed. This observation is connected to the concept of redundancy as a resilience strategy, which helps absorb disruptions and maintain system availability (Christopher and Peck, 2004; Sheffi and Rice, 2005; Yang et al., 2024). At the same time, the case shows that redundancy influences how criticality is perceived. The failure of one snow-groomer can be absorbed by another, it was seen as less critical than the ski lift, whose failure would immediately interrupt the transport function. This suggests that criticality assessments should also incorporate system level redundancy and substitutability, rather than focusing solely on component-level characteristics.

Respondent Truck SC distinguished between service parts and repair parts, which reflects the theoretical separation between planned and unplanned spare part demand outlined by Driessen et al. (2015). Service parts, including filters, seals, brake pads, and oil, were characterized as components that are routinely consumed through normal use. Since these parts are replaced at predictable intervals, they can usually be planned and ordered before maintenance takes place. Repair parts, that in the findings were exemplified as turbochargers, coolers, and electronic units, differ in that they are expected to last for a longer period but may face a unexpected failure. These components are characterized by unplanned demand and corrective maintenance, where the need for replacement only becomes clear after a failure has occurred

(Driessen et al., 2015). Additionally, Repairable parts are also defined according to Driessen et al. (2015) as those who can be fixed and used again, which creates a circular type of flow. The empirical data further distinguishes these categories by their different sourcing implications, where service articles, i.e. parts used for regular maintenance and planned service activates, are typically easier to manage because demand is more predictable and the components are standardized, while repair articles present greater availability challenges because demand is irregular and components may be more specialized.

5.1.3 Long-Term Spare Part Availability

The empirical findings show that spare part availability is strongly influenced by component lifecycle dynamics, especially for systems that must remain operational over longer periods. Respondent Truck-PLM explained that Truck Inc. is obligated to supply original spare parts for vehicles for 15 years after sale. A challenge was pointed out regarding this responsibility, where the respondent stated that “an article has an average lifetime of around 10 years.” As a result, multiple generations of components must be supported simultaneously. This creates a long-term availability challenge, where spare parts planning must account for both current in-production components and for older articles that may still be required for operations. This aligns with the literature on spare part planning and maintenance systems, which emphasizes that component requirements evolve over time as systems age, operating conditions change, and different generations of components must be supported simultaneously (Basten & van Houtum, 2014; Driessen et al., 2015). Therefore, spare part management must include the evolution of demand over time, and how support can be maintained even after components have been replaced, updated, or phased out.

A clear and recurring finding in the empirical data is that electronic components are more problematic compared to mechanical components, as the lifecycles are shorter. Respondent Truck-SC explained that “getting a 12-year-old ECU can be very difficult for the supplier because their suppliers have stopped making the materials used for it”. In this case, the availability of the spare part is not only dependent on the component itself, but also on the continued availability of its surrounding subcomponents, materials, technologies, and upstream suppliers. Respondent Truck-PLM similarly pointed this out, noting that semiconductors have been difficult to access in recent years, and that components containing critical raw materials require monitoring. This indicates that for electronic components, obsolescence can occur because the materials or technologies required to produce them are no longer available. These findings suggest that spare parts planning from a component lifecycle perspective should include dependencies in the upstream supply chain, such as material availability and supplier continuity. This means that availability cannot be assessed only at the final spare part level, but also the system required to produce it.

Respondent External-LOG identified an additional challenge related to this. The respondent stated that many modern components “do not bear storage” in the same ways as mechanical parts, due to e.g. battery degradation, continuous software updates, and changing technical standards. This was also confirmed by Truck-MFG, who explained that some components require specific storage conditions such as temperature control or regular use cycles. The theory outlines redundancy strategies, where a traditional one is pre-positioning inventory, which is seen as a strong resilience measure (Christopher and Peck, 2004; Sheffi and Rice, 2005). The findings

indicate that this strategy is not viable for some modern components, as they have limited storage life, software dependencies, or rapid technological obsolescence. The strategy is more suitable for mechanical parts with long shelf lives. This suggests that redundancy strategies should be adapted to the characteristics of the component. Redundancy is seen as an important driver for resilience in the literature (Yang et al., 2024), but the findings show that the usefulness of redundancy-based inventory strategies depends on whether the component can be stored over time.

Respondent Truck-PLM explained that replacement parts are not always the same as the original components. The replacement might be newer versions that have fulfilled the criteria's to be compatible, "the same form, fit and function" as the original article. This finding indicates that spare part availability over long system lifecycles does not only depend on whether the original component can still be sources, but also on whether newer components can be approved as suitable replacements. This relates to Perera et al. (1999) and Roda et al. (2014) claims about component standardization and substitution but incorporates a lifecycle perspective. For systems in use over longer periods, some components may be removed or replaced by newer versions. In these cases, the spare part availability is dependent on the ability to find new parts that can qualify as compatible. This makes the possibility of compatibility an important factor in spare parts planning for systems with longer lifecycles.

5.1.4 Supply Network Dependencies and Vulnerabilities

The structure and vulnerability of the underlying supply network determine spare part availability. The findings show that Truck Inc. often relies on single suppliers for specialized or brand unique components, creating a risk where if that supplier experiences disruption, they lose the entire global production. This is directly related to the issue of efficiency-driven supply chains, which the literature says is particularly vulnerable to disruptions (Christopher and Peck, 2004; Sheffi and Rice, 2005; Sawik, 2014). Truck Inc. has not yet made significant progress towards regional supply chains, despite recognizing that they are exposed to risks that can disrupt their supply chain. This reflects the trade-off of balancing efficiency and resilience (Yang et al., 2024; Lucker et al., 2025). The findings further suggest that awareness of supply chain vulnerability does not automatically result in structural changes to the supply network. Although Truck Inc. recognizes the risks associated with concentrated supplier structures, sourcing decisions must simultaneously account for factors such as supplier capabilities, scale economies, existing supplier relationships, and cost efficiency. This indicates that resilience is not solely a supply chain design issue, but also an organizational and strategic decision-making challenge where competing objectives must be balanced.

The Covid-19 pandemic and Suez Canal obstruction were outlined by Respondent Truck-SC as examples of disruptions that heavily affected spare part availability. The Suez Canal example specifically showed how dependencies in the supply chain creates a systematic risk, as disruption affected multiple regional warehouses and required rerouting, which led to longer lead times. This finding is aligned with the idea that disruptions do not have a uniform effect on all parts of the supply network, as Craighead et al. (2007) and Ivanov et al. (2017) claim, some nodes can have a much larger impact on overall performance if they fail. Reducing these dependencies therefore becomes an important contributor for resilience, where decentralizing

inventory and sourcing across several locations can mitigate (Snyder et al., 2016; Mohebbi et al., 2025)

The empirical findings indicate that product variety can reduce spare part resilience by increasing the number of components that must be identified, stored, handled, and sourced. Respondent Truck-MFG explained that greater product variety requires parallel inventory and handling processes, which becomes particularly challenging in operational environments where resources, storage capacity, and coordination capabilities are limited. This aligns with the claims about product variety increasing coordination needs and logistical complexity (Nagarur and Azeem, 1999; Perera et al., 1999). In disrupted environments, this complexity becomes more problematic because the ability to access, transport, and manage the right spare part at the right time is already constrained. Therefore, reducing unnecessary variation and prioritizing standardized or commonly used components can support spare part availability and improve resilience.

This also shows that component selection cannot be treated as a purely technical decision. Several authors emphasize the need for multi-criteria decision-making for spare part selection, where technical requirements, sourcing, feasibility, criticality, cost, and availability are considered together (Roda et al., 2014; Teixeira et al., 2017). Respondent Truck-DATA explained that Truck Inc. has recently reorganized so that purchasing and engineering work more closely together. This supports the cross-functional decision-making, as resilience-oriented component choices requires both engineering and sourcing knowledge.

5.2 Enablers and Constraints for Using Civilian Supply Networks (RQ2)

The empirical identify several enablers for using civilian heavy vehicle supply networks as alternative spare part bases, while also revealing significant constraints related to integration, performance, and regulatory factors.

5.2.1 Standardization and Component Reuse as Enablers of Civilian Sourcing

The most fundamental enabler identified in the empirical data is the alignment between UGV Inc.'s design philosophy and the structure of civilian supply networks. Respondent UGV-CEO described a philosophy centered on adapting the UGV platform to already existing high-volume commercial components, rather than developing proprietary solutions such as custom axles. This reflects the theoretical emphasis on sourcing flexibility through component standardization and commonality, where the use of widely available commercial components increases supplier accessibility and alternative sourcing possibilities under disruption (Perera et al., 1999; Roda et al., 2014; Goel & Brahmabhatt, 2024). The frame of reference established that standardization enhances sourcing flexibility because standardized components can be provided by multiple suppliers and are supported by broader supplier bases (Pettit et al., 2010; Yang et al., 2024). UGV Inc.'s approach of adapting the system to existing components rather than developing unique components represents a strong application of this logic. The empirical findings indicate that the company views unique component development as creating unnecessary dependence on narrow supply chains, which aligns with Christopher and

Peck (2004) and Sheffi and Rice (2005), who argue that high levels of customization increase supply chain vulnerability under disruption.

The empirical findings further show that this sourcing philosophy is reinforced by Truck Inc.'s platform-based product architecture. Respondent Truck-ENG described a common architecture across vehicle platforms designed around extensive component reuse across different configurations and business areas. This corresponds closely with Salvador et al.'s (2002) concept of combinatorial modularity, where standardized interfaces and reusable component families enable multiple product variants to be assembled from shared modules. In line with Mikkola (2003), Salvador et al. (2002), and Inoue et al. (2024), the empirical findings suggest that such modular architectures strengthen sourcing flexibility by improving interchangeability, increasing cross-platform compatibility, and simplifying maintenance and spare part management. The benefit of modularity is reflected in the empirical findings. Although the modular architecture was originally intended to simplify reuse and sourcing, Respondent Truck-ENG acknowledged that the system may have become excessively complex over time. This suggests that modular architectures do not automatically reduce complexity indefinitely. Instead, increasing numbers of variants, interfaces, and combinations may gradually create new layers of system complexity. This observation is important because modularity literature tends to emphasize the benefits of reuse and flexibility more strongly than the long-term risk of accumulated architectural complexity. The findings therefore suggest that modularity can enhance resilience, but only if variant proliferation and system complexity remain controlled.

The reuse of components across Truck Inc.'s different business areas, including trucks, buses, construction equipment, and industrial engines, emerged as another enabler of civilian sourcing. Respondent Truck-ENG explained that since components can be used across multiple platforms, they are supported by larger volumes and spare part flows, strengthening the aftermarket base. This finding aligns with the theoretical argument that component commonality across products aggregates demand, reduces fluctuations, and improves availability (Wang & Ning, 2007; Takai & Sengupta, 2016).

5.2.2 Standardization Boundaries and Commercial Differentiation

Although standardization improves sourcing flexibility and spare part availability, the empirical findings also reveal important limitations to how far standardization can realistically be implemented. Respondent Truck-PLM explained that components strongly connected to visible brand identity, such as cab design, interior surfaces, and lighting systems, are more likely to remain unique between brands, whereas less visible mechanical and chassis-related components are generally standardized across platforms. This introduces a commercial differentiation constraint that is less developed in resilience and sourcing literature. While Roda et al. (2014) and Teixeira et al. (2017) acknowledge that specialized components typically reduce supplier availability, the empirical findings demonstrate that specialization is not only driven by technical requirements. Instead, variation is also deliberately maintained for strategic and commercial reasons related to branding, market positioning, and product differentiation. This extends the theoretical discussion by showing that sourcing flexibility is constrained not only by engineering limitations, but also competitive business strategies. This tension became particularly clear when Respondent Truck-DATA reflected on the trade-off between resilience and product variety. From a

resilience perspective, the respondent argued that reducing the number of variants and simplifying the architecture would improve sourcing flexibility and spare part management. However, the findings also showed that market demands for product differentiation often drive increased variation. This aligns with the broader efficiency-resilience tension discussed by Christopher and Peck (2004) and Lucker et al. (2025) but extends the discussion from supply chain configuration to product architecture and design strategy. Therefore, the empirical findings suggest that resilience-oriented standardization may conflict directly with commercial incentives for customization and differentiation.

5.2.3 Integration and Performance Constraints

The empirical findings further demonstrate that availability alone does not make a component feasible for integration into the UGV platform. Respondent Truck-MFG emphasized that physical integration constraints, particularly geometry, packaging, and spatial limitations, represent significant barriers even when components are commercially available. This supports Ayala and Franch (2006), who argue that COTS-based sourcing introduces integration dependencies that may complicate substitution and system adaptation. However, the empirical findings also show that physical compatibility represents only part of the challenge. Respondent Truck-DATA described that even when a component can technically be mounted or connected, it may still behave differently under actual operating conditions due to differences in load distribution, dynamic behavior, durability requirements, and certification constraints. This finding significantly nuances parts of alternative sourcing approaches literature, which often treats substitution primarily as a compatibility verification issue. Instead, the findings indicate that successful substitution requires a deeper understanding of how components perform within the operational context of the UGV system.

This becomes especially important because the UGV is intended to operate under conditions that may differ substantially from conventional civilian vehicle applications. A component that functions adequately in a standard commercial truck may perform differently when exposed to battlefield-related vibration, terrain stress, payload variation, or environmental exposure. Consequently, the empirical findings suggest that sourcing feasibility must be evaluated not only in terms of physical interchangeability, but also in terms of functional and operational equivalence. This extends Sawik's (2014) and Roda et al.'s (2014) conceptualization of sourcing feasibility by showing that technically accessible components may still be unsuitable if they cannot maintain required performance under operational conditions. The findings also show that sourcing decisions are influenced by factors beyond technical compatibility. Respondent Truck-DATA noted that regulation, patents, supplier relationships, purchasing structures, and local sourcing conditions influence what can realistically be integrated into the system. This broadens the theoretical understanding of sourcing feasibility by demonstrating that sourcing constraints are institutional and relational as well as technical.

5.2.4 Civilian Supply Network Accessibility and Regulatory Constraints

The empirical findings present a mixed picture regarding the accessibility of civilian supply networks. On one hand, Respondent Truck-SC described Truck Inc.'s purchasing and supplier network as a major advantage for smaller firms seeking

access to established supply structures. This supports Campioni et al. (2023) and Qi et al. (2023), who argue that civilian supply networks can provide complementary capabilities, infrastructures, and sourcing flexibility that smaller organizations would struggle to develop independently. The findings therefore support the theoretical argument that civilian supply networks can function as external resilience resources by providing access to existing logistics, supplier relationships, distributed inventories, and large-scale aftermarket structures. For UGV Inc., such access could significantly improve spare part availability without requiring the company to internally replicate the same level of supply chain infrastructure.

At the same time, the empirical findings also highlight significant institutional and regulatory constraints. Respondents Truck-SC and Truck-ENG described dual-use areas as sensitive and heavily regulated, particularly when components or systems may be associated with military applications. This aligns closely with Zhang and Qi (2025), who argue that integrating civilian actors into defense-related supply chains requires overcoming institutional, technical and certification-related barriers. The findings also revealed that differing perceptions regarding the severity of these constraints. Respondent UGV-CEO viewed regulatory issues as less problematic because the company relies on commercially available off-the-shelf components rather than specialized military-grade technologies. Furthermore, domestic use without export was perceived as reducing exposure to military export regulations. This suggests that regulatory constraints are context dependent and may vary depending on the degree of militarization, export exposure, and component specialization. The empirical findings therefore nuance the literature by showing that civilian sourcing accessibility is not universally restricted, but depends on how the system is positioned technologically, commercially, and legally.

5.2.5 Cannibalization as a Contingency Enabler

The empirical findings also identified cannibalization as a potential contingency sourcing mechanism enabled by component commonality and standardization. UGV Inc.'s vision of being able to retrieve usable parts from damaged or abandoned vehicles reflects the theoretical concept of cannibalization described by Hoover et al. (2004), Sherbrooke (2004), and Di Gravio et al. (2019), where functional components are removed from non-operational systems to restore other systems to operational condition. The findings from External-LOG support this perspective by showing that cannibalization is already used in practice as time-driven response mechanism when conventional repair or sourcing becomes too slow. Similarly, the "snow-groomer case" described by External-OPS illustrated how repair, reuse, and replacement with previously used but functional components can sustain operational continuity under constrained conditions. These findings therefore validate the theoretical argument that cannibalization can improve short-term spare part availability and maintain system uptime when traditional supply channels fail.

However, the findings also support the limitations emphasized by Di Gravio et al. (2019). Although UGV Inc. viewed cannibalization as an attractive resilience mechanism, the respondent also acknowledged that practical implementation would likely be far more complicated than the idealized concept suggests. This aligns with the theoretical argument that cannibalization increases maintenance complexity, creates additional disassembly and reassembly requirements, and may reduce the readiness of donor systems. The empirical findings therefore suggest that

cannibalization should not be understood as a complete sourcing solution, but rather as a contingency mechanism that can temporarily support operational continuity under severe disruption.

5.3 Structuring Resilience-Oriented Spare Part Strategies (RQ3)

This section builds on the insights developed in the previous sections by examining how spare part availability and sourcing logic can be structured into practical principle for resilience-oriented decision making. RQ3 addresses how spare part availability and sourcing logic can be structured into a set of principles that support resilience-oriented decision making. RQ1 identified the factors that influence spare part availability, and RQ2 examined the enabler and constraints of using civilian supply networks. RQ3 uses insights from the two research questions and synthesizes them into a coherent sourcing logic.

5.3.1 Operational Need

Several authors (Molenaers et al., 2012; Roda et al., 2014; Antosz & Ratnayake, 2019) emphasize that the classification of what is critical is typically based on failure consequences, failure frequency, and repair time. Roda et al. (2014) and Teixeira et al. (2017) distinguish between process criticality (consequences of failure) and control criticality (ability to ensure availability) However, the empirical findings show that criticality is not a static attribute of a component, but that it emerges from the interaction between the components function, the operational context, and the system's capacity to tolerate declining performance.

Components that enable mobility, communication, power supply, braking, steering, or payload handling (i.e carrying, securing, positioning, or realizing cargo/equipment) under disruption have high operational importance. Components that affect only comfort or non-essential features have lower operational importance. Moreover, a component that is classified as mission-critical in a conflict-related operating environment, may represent only a maintenance issue in a controlled service setting. This shows that one aspect of component criticality is operational context. A failure may have different consequences depending on how quickly the component must be restored, and whether backup systems are available.

The example, presented in the empirical data, of the ski lift being considered more critical than the snow-groomer illustrates how system level redundancy influences perceived criticality. Because the facility had two groomers but only one lift, the loss of the lift had greater operational consequences. This finding connects directly to the absorptive capability of redundancy (Christopher and Peck, 2004; Sheffi and Rice, 2005; Yang et al., 2024). For UGV Inc., this suggests that criticality assessments should consider not only the component itself, but also the presence of backup systems, alternative operating modes, and the vehicles ability to continue operating temporarily without that function.

This leads to the first analytical dimension for sourcing decision, which is operational need. Operational need refers to the function that the component enables and the consequence of losing that function under disrupted conditions. Components supporting functions essential to missions should receive greater attention in resilient

sourcing, while components supporting secondary functions may be prioritized lower. However, operational need alone does not solely determine whether a component should be sourced from Truck Inc. it only determines if the component is worth evaluating further.

5.3.2 Operational Adaptability: From Civilian Availability to Operational Availability

The theoretical concepts presented in the frame of reference regarding alternative sourcing approaches show that civilian supply networks can enhance resilience by providing multiple access points and reducing dependence on single original supply chain. This is consistent with Sheffi & Rice (2005); Pettit et al., (2010) and Yang et al., (2024) who argues that resilience is enhanced by having flexibility in sourcing, multiple access channels, and external resources, as they are important ways to respond to disruptions. Furthermore, civilian actors can complement military logistics (Campioni et al., 2023; Qi et al., 2023)

However, the empirical findings from Truck Inc. and the snow-groomer case reveal a critical gap, which is that civilian availability does not automatically translate into operational availability for a specialized UGV platform. A component may exist in a civilian supply network but still fail to restore UGV functionality if it cannot be identified, verified, integrated, accessed in time, or installed under the available repair conditions. This gap can be broken into five sub-conditions:

First, a component must be physically compatible. It must fit the UGVs geometry, interfaces, and packaging constraints. This was indirectly supported by Respondent Truck-PLM, who suggested that certain medium-duty truck components may be more relevant for UGV Inc. than heavy-truck components, since heavy-truck drivetrains and engines may be too large. This shows that a components origin in Truck Inc's system is not enough; the component must fit the scale and architecture of the UGV. This is aligned with Ayala and Franch (2006), who note that COTS-based sourcing introduces integration dependencies that may complicate substitution.

Second it must be performance-equivalent under the UGVs operating conditions, which may include higher vibration, terrain stress, environmental exposure, and mission-specific loads compared with normal civilian use. This is important because UGV Inc. will use the components in other applications compared to a civilian truck. A component that may perform well in a civilian vehicle may still therefore require validation before it can be considered for the UGVs operating environment.

Third, it must be identifiable and verifiable. Respondent External-OPS described difficulties in sourcing suitable components for older machines, including drive motors, circuit boards, and tracks. The case where a replacement motor arrived but was the wrong type, shows that even when a component exist in the supply network, incorrect identification or lack of compatibility verification can effectively make the component unavailable. This is particularly important in the UGV context, as incorrect identification could result in delays, failed repairs, or the installation of unsuitable parts.

Fourth, it must be accessible within the required time window, which is influenced not only by distance from the supply point but also by security conditions,

infrastructure limitations, visibility constraints, and tactical considerations. Truck Inc's. differentiated order logic is relevant here (VHR). Respondent Truck-SC distinguished between different types of spare part demand, including planned service articles and more planned repair articles. This distinction indicates that urgency varies depending on whether the component is needed for planned maintenance, corrective repair, or immediate restoration of a vehicle that is unavailable.

Fifth, the component must be installable with the tools, competence, documentation, and diagnostics available in the repair environment under disruption (the service points illustrated in Figure 1). Respondent Truck-PLM confirmed this by explaining that components that can be reached and replaced with standard tools are easier to manage in maintenance than components requiring more complex workshop procedures. This is particularly important for the operational context of the UGVs, since extreme disruption may limit access to specialized equipment and advanced services. A component should therefore not be considered operationally available simply because it can be sourced, it must also be possible to install and restore it under the repair conditions available near the operational environment.

Together, these five sub conditions define a problem regarding the transformation or conversion of components, more specifically, turning a component from civilian supply network into a spare part that can restore or support UGV functionality in extreme conditions. The empirical findings indicate that alternative sourcing is not enough on its own in this context. While standard sourcing logic can help identify another supply source, the UGV context also requires assessing whether the component can be used in the specific system and repair setting.

This leads to the second analytical dimension, which will be referred to as operational adaptability. Operational adaptability is about the feasibility of conversion, meaning, the ease with which a civilian component can be integrated, tested, verified, accessed, and installed for UGV use. This dimension is strongly related with component characteristics. A standardized hose, filter, seal, or mechanical wear part may require little effort for conversion, while a complex electronic module may require more effort for conversion, such as testing and software integration. Therefore, this dimension separates components that are only available, from components that can contribute to UGV operational availability.

5.3.3 Standardization and Commonality

Standardization and commonality are key enhancements of sourcing flexibility. When a component is used across many products, demand aggregates, suppliers have stronger incentives to hold stock, and multiple sourcing options become available (Perera et al., 1990; Roda et al., 2014; Goel and Brahmabhatt, 2024). This also aligns with Pettit et al. (2010) and Yang et al. (2024), who argues that part commonality and multiple sourcing options are related with procurement flexibility and adaptive capacity. This is reflected in the empirical findings. Respondent Truck-DATA and other respondents from Truck Inc. described how certain components are used across several platforms and product areas. This broad use makes some parts easier to manage because demand is higher, the supplier base has stronger incentives to maintain availability, and the aftermarket network is more likely to hold stock. The contrast between inexpensive, high-volume components and low volume, high-cost components illustrate this clearly. A standard oil filter is easier to manage than a

specialized transmission priced at 150,000-200,000 SEK with few sales per year. This example provided in the empirical findings, shows that components within the same OEM system can differ substantially in sourcing difficulty. Respondent External-OPS provided a similar illustration from the snow-groomer context. Oil and filters were described as components that are routinely replaced and remain in circulation, partly because the snow-groomer used a Caterpillar engine like those used in Caterpillar excavators. This shows that components that are used broadly across platforms are more likely to be stocked, recognized, repaired, and supported by several actors in the aftermarket network.

However, the empirical findings also reveal that there are structural limits to standardization. Within Truck Inc., components that are visible to customers, such as cab exteriors, interior surfaces, and lightning, may remain brand unique due to commercial differentiation. This means that even within a company that uses platform logic and component reuse, some components are deliberately kept different. Respondent Truck-DATA also indicated that product variety and brand-specific solutions create complexity for spare part management. Respondent Truck-MFG echoed this by explaining that increasing product variety requires parallel inventory and handling processes, which can become problematic in constrained operational environments, such as in service points (See, Figure 1). More variation creates more parts to identify, store, transport, and manage: In a disrupted environment, this complexity can reduce resilience.

Therefore, standardization should be treated as an enabler of sourcing potential, and not as evidence of resilience. A component may be standardized within Truck Inc.'s own product architecture but still be unsuitable for UGV Inc.'s due to physical fit, performance requirements, repair conditions, or operational environment. The question that is relevant for UGV Inc. is not simply whether a component is standardized within Truck Inc., but how deeply it is integrated in the civilian supply network, meaning whether it is also widely available, supported, and replaceable within the civilian supply network.

Schilling (1999), Salvador et al. (2002); and Mikkola (2003) argue that modular architecture and standardized interfaces can improve substitution, maintenance, and reconfiguration: The empirical findings support this logic when components have stable interfaces and are broadly used. However, the comments made by Respondent Truck-Data and Respondent Truck-MFG, regarding brand-specific components and increasing product variety show that modularity and standardization can be limited by commercial differentiation and complexity. Thus, standardization should not be treated as a proof of resilience, but as an enabler.

This leads to the third analytical dimension, which will be called Supply network commonality. Supply network commonality refers to the extent to which a component is used across multiple platforms, business areas, applications, and aftermarket channels: Components shared across multiple applications have a broader network depth than components that are unique to a single truck model or brand. High supply network commonality increases the probability that the component is stocked at multiple levels, held by suppliers, known by service actors, and supported by repair infrastructure, as suggested in the empirical findings. A subdimension of this is network reach, which is about whether the component is held not only centrally but

also at regional warehouses, dealers, and supplier aftermarket divisions. For UGV Inc., this means that commonality should be assessed as a supply network feature, not only as a product design feature.

5.3.4 Support Commitments and Component Obsolescence

A crucial insight from the empirical findings concerns the tension between Truck Inc.'s formal spare part support obligation and the actual lifecycle of components. Truck Inc. is required to provide original spare parts for vehicles for 15 years after sale. However, Respondent Truck-PLM explained that individual articles may have an average lifetime of around 10 years. This creates a mismatch in their supportability, where the vehicle support period exceeds the lifecycle of many individual components, especially electronic articles.

Cohen et al. (2006) and Arts et al. (2019) emphasizes that aftermarket systems exist to sustain installed equipment after production and delivery. The empirical data show that this obligation does not require all components to remain equally resilient throughout the period during which they must be supported.

The mismatch in supportability is especially visible for electronic, and software dependent components as stated earlier. Respondent Truck-SC stated that obtaining a 12-year-old electronic control unit can be very difficult because the suppliers own suppliers may have stopped producing the required materials. This means that the supportability problem does not always begin with Truck Inc. or their immediate supplier, but that it may emerge further upstream when subcomponents, materials, or technologies are discontinued. This creates cascading obsolescence, where supportability problems spread upstream through the supply chain.

Respondent Truck-PLM stated semiconductors as a problematic component category that had been difficult to access in recent years, which was particularly evident during Covid-19, where there was a major shortage. The respondent explained that Truck Inc. analyses components containing critical raw materials because these materials may be sensitive from a supply perspective. This shows that obsolescence and availability risks are not limited to finished components. They may also exist within the materials and subcomponents that make up the part. In such cases, the redundancy logic described by Christopher and Peck (2004), Sheffi and Rice (2005), and Yang et al. (2024) becomes limited. Inventory or alternative ordering routes cannot fully compensate if the underlying technology or material base is no longer available.

Replacement logic also becomes important. Truck-PLM explained that newer parts may be qualified as compatible if they satisfy form, fit, and function requirements. This qualification process is both a resilience enabler and a risk. It is an enabler because it allows the supply system to continue providing support even after the original component is discontinued. It is a risk because qualification takes time, and requires e.g. testing and validation, and may fail, which can lead to a gap in availability. For UGV Inc., replacement only supports resilience if it can happen quickly enough during disruption, as the UGVs need to be maintained under constrained time conditions. This means that reliance on qualified replacements introduces uncertainty.

The mechanical and electronic divide, i.e the distinction between mechanical and electronic components, also affects storage strategies. Christopher and Peck (2004); Sheffi and Rice (2005), and Yang et al. (2024) describe redundancy as an important absorptive capability, often linked with buffers and spare capacity. The empirical findings indicates that this logic works better for many mechanical parts rather than for electronic or storage sensitive components. Respondent External-LOG noted that batteries and software dependent components may not be suitable for long term storage, which means that stockpiling creates a false redundancy. The component may physically exist in the inventory, but no longer be usable, compatible, or technically relevant when needed.

These findings lead to the formation of two analytical dimensions. The first is obsolescence exposure. Obsolescence exposure refers to whether the component is mechanically stable or electronic/software dependent, and therefore more exposed to technological change, software updates, supplier discontinuity, or material obsolescence. The second dimension is supporting pathway, which refers to how a component can continue to be supported over time. It considers whether the component is still produced, available through the aftermarket, replaceable by a qualified alternative, or discontinued without a clear replacement. Together, these two dimensions capture time-related risks. To this, a subdimension is storage suitability, which is about whether the component can be stockpiled without degradation, software dependency, or special conditions such as climate requirements.

5.3.5 Synthesis of Analytical Dimensions for Sourcing Decisions

The analysis in the previous subsections (Section 5.3.1-5.3.4) has identified five analytical dimensions that determine whether a civilian heavy vehicle component from Truck Inc. can support UGV spare part resilience under extreme disruption. These dimensions are derived from the empirical findings and are grounded in the frame of reference regarding resilience, spare part availability, criticality, alternative sourcing, standardization, modularity, and sourcing feasibility.

Table 7: Summary of the five analytical dimensions

Dimension	Key question	Main empirical support	Main theoretical support
1. Operational need	Does the component support a mission-critical function (mobility, communication, power, braking, steering, payload)?	UGV-CEO on driveline and communication, ski lift vs snow-groomer redundancy	(Molenaers et al., 2012; Roda et al., 2014; Teixeira et al., 2017)
2. Operational adaptability	Can the component be integrated, tested, verified, accessed within the required time window, and installed with available tools/competence?	Five sub-conditions from Truck Inc. and snow-groomer case (wrong motor, long lead time, installation constraints)	(Ayala and Franch, 2006; Roda et al., 2014; Sawik, 2014)

	(includes repairability)		
3. Supply Network Commonality	Is the component used across multiple platforms, business areas, and aftermarket channels? (Includes network reach)	Truck Inc. platform reuse: oil filter vs unique transmission (Caterpillar engine cross-use)	(Perera et al., 1999; Wang and Ning, 2007; Pettit et al., 2010; Takai and Sengupta, 2016; Yang et al., 2024)
4. Obsolescence exposure	Is the component mechanical (stable) or electronic/software dependent (short lifecycle, upstream discontinuation)?	12-year-old ECU: semiconductors, battery degradation	(Arts et al., 2019)
5. Supporting pathway	Is the component still in active production, aftermarket only, replaceable by qualified alternative or discontinued? (Includes storage suitability)	Truck Inc. 15-year obligation vs 10-year article lifetime: form, fit, function replacement.	(Christopher and Peck, 2004; Sheffi and Rice, 2005; Cohen et al., 2006 Yang et al., 2024)

These five dimensions interact with one another. For example, a component may be operationally critical (high need) but have low operational adaptability (difficult to install), such a component therefore requires a different strategy than one that is both critical and adaptable. Similarly, high supply network commonality can offset some obsolescence risk, but electronic components remain exposed to upstream discontinuation whether inventory-based redundancy is viable, which interacts with the supporting pathway (e.g. an aftermarket only mechanical part may still be storable, while an active production battery may not).

The dimensions should therefore not be applied as an independent checklist. Instead, they form the analytical basis for a set of principles for sourcing based on roles that will be presented in Chapter 6.

6. Concluding Discussion

The aim of this study was to explore how spare part availability for UGV systems can be enhanced through alternative civilian component supply bases, and to propose principles for resilience-oriented component sourcing under extreme disruption scenarios. This was investigated within the context of UGV systems intended for operation in disrupted and uncertain environments such as in conflict scenarios, where access to spare parts, manufacturing facilities, and established logistics networks may be limited or unavailable. The purpose was therefore to understand how spare part availability can be maintained through alternative sourcing logic, and how civilian heavy vehicle supply networks can support resilience-oriented decision making. This was structured into the following three research questions which were addressed through the frame of reference, empirical findings, and analysis.

RQ1: What factors influence spare part availability for UGV systems under extreme supply chain disruption?

The findings suggest that spare part availability under extreme disruption is shaped by five interrelated factors: operational context, component criticality, lifecycle dynamics, organizational dependencies, and repair conditions. Together, these factors determine not only whether a spare part can be sourced, but whether operational functionality can be restored and maintained when conventional supply channels are disrupted. Operational context matters because UGV systems intended for logistics support, evacuation, and operations in degraded environments face highly uncertain conditions characterized by damaged infrastructure, limited maintenance access, disrupted transportation routes, and strict recovery time requirements. In such conditions, spare part availability cannot be understood only as the existence of a part in stock or in a supplier network. Instead, availability depends on if the component can restore operational functionality at the service point within the time and resource constraints resulted in the disruption.

Component criticality is central because components differ in how their failure affects the UGV's ability to perform essential functions such as mobility, steering, braking, power supply, communication, control, and mission-specific operations. Moreover, criticality is multidimensional and influenced by operational context, redundancy, and the availability of alternative operating modes. Components that are simultaneously operationally critical, technically difficult to replace, and supported by limited sourcing options represent particularly significant resilience challenges and require proactive planning. Spare part availability is also influenced by how components evolve over time. Lifecycle dynamics also influence availability, since components that are available through civilian supply networks during development may become difficult to source later. Components embedded in civilian heavy vehicle networks are subject to commercial product lifecycles that may not align with the expected operational lifetime of a UGV platform. While a component may be widely available today, future availability may be affected by product updates, supplier discontinuation, technological change, or platform replacement. These challenges are particularly pronounced for electronics, sensors, batteries, control units, and software-dependent components, which are generally more vulnerable to obsolescence and compatibility issues than traditional mechanical parts. Organizational dependencies further shape availability by the extent to which organizations depend on external

actors for technical knowledge, documentation, supplier access, aftermarket information, and repair expertise. Such dependencies may strengthen resilience when they provide access to extensive civilian supply bases, but they may also create vulnerabilities if information, expertise, or sourcing channels become unavailable during disruption. The findings therefore suggest that resilience depends not only on physical component availability, but also on the ability to access and utilize the resources required to identify, source, verify, and integrate those components. Finally, spare part availability is also dependent on the repair conditions, including the tools, competence, and repairability of components (e.g., hydraulic motors, belts, hoses) at the service point under disruption. The conclusions for RQ1 are therefore that spare part availability should be understood as an operational capability, not only as a logistics outcome. It depends on whether the organization can identify, access, verify, replace, repair, and integrate the right component under constrained conditions.

RQ2: What are the enablers and constraints for using civilian heavy vehicle component supply networks as alternative spare part supply bases for UGV platforms?

The findings show that civilian heavy vehicle component supply networks can contribute to spare part resilience for UGV platforms, but only under certain conditions. Their main value lies in the fact that many civilian components are produced in large volumes, used across several vehicle platforms, and supported by established aftermarket structures. These networks can therefore reduce dependence on narrow supply chains that are designed for a specific purpose. The most important enablers are standardization, modularity, and component reuse, since these factors increase the number of possible sourcing channels and improve the possibility that spare parts can be accessed when the conventional supply chain is disrupted.

However, the analysis also proves that civilian availability is not the same as operational availability. A component may exist physically in a civilian supply network but not be suitable for restoring UGV functionality. To support resilience, the component must fit the UGV architecture, meet relevant performance requirements, be identifiable and verifiable, and be possible to integrate within the required time frame. The usefulness of civilian supply networks therefore depends not only on whether a spare part can be found, but on if it can be transformed into a functional and mission-relevant repair solution.

The strongest opportunities for civilian sourcing are found among components that are standardized, mechanically stable, repairable, and shared across several vehicle or equipment categories. These components are more likely to benefit from broad supply bases, aftermarket circulation, and cross-platform reuse. Components that are highly integrated, software-dependent, electronically complex, safety-critical, or closely linked to brand-specific design are more difficult to source through civilian networks. Additionally, it is important to note that civilian networks can create redundancy as well as dependency. While distributed aftermarket networks provide several access points, they may still rely on the same upstream suppliers, logistics routes, technical documentation, or commercial agreements. Cannibalization can serve as an emergency option, but only when components are standardized, reusable, identifiable, and technically feasible to reintegrate.

The conclusion for RQ2 is therefore that civilian heavy vehicle supply networks should be understood as a conditional resilience resource. They are most useful for standardized, mechanical, widely shared, and repairable components. On the contrary, they provide limited resilience value for brand-unique, software-dependent, highly integrated, or upstream-concentrated (e.g. same upstream suppliers) components. Resilience through civilian sourcing is therefore not only about access to the market. It is dependent on selecting the right components and designing the UGV platform so that civilian availability can become operational availability. Civilian supply networks can be highly valuable when component characteristics align with the structure of the civilian market, but they cannot compensate for sourcing and design choices that restrict compatibility, interchangeability, or access to alternative supply channels.

RQ3: How can spare part availability and sourcing logic be structured into a set of principles that support resilience-oriented decision making?

The findings suggest that resilience-oriented spare part sourcing should not be treated as a generic inventory or supplier-selection problem. Instead, sourcing decisions need to be structured through a set of principles that evaluate whether a component is operationally necessary, practically adaptable, available through a sufficiently broad supply network, exposed to obsolescence risk, and supported by a viable continuity pathway.

Based on the analysis in section 5.3, this study identifies four principles that can support resilience-oriented decisions under extreme disruption. These principles should not be understood as a checklist of separate elements, but as interacting decisions dimensions. Together, they help determine whether a civilian component can contribute to operational spare part availability for UGV systems when conventional supply sources are disrupted.

Principle 1: Evaluate spare part needs at the functional level rather than the component level

The first principle is that spare part needs should be evaluated at the functional level rather than the component level. The findings indicate that resilience-oriented sourcing decisions should be made at the functional level rather than the component level. The critical question is not whether a component is important in isolation, but whether the function it supports is essential for maintaining operational capability under disruption. Components that support mission-critical functions such as mobility, communication, power supply, braking, steering, and payload handling, should receive prioritized attention. Components primarily related to comfort, convenience, or non-essential functions may receive lower prioritization.

Component criticality should therefore be evaluated from a broader system perspective rather than being determined only by the importance of the individual part itself. The empirical findings showed that system-level redundancy can significantly alter perceived criticality, as illustrated by the difference between a component failure in a system with available backup functionality and a failure that immediately stops the system.

This means that organizations should map components to function relationships, identify which functions are essential under disruption, and assess whether

redundancy already exists within the system architecture. Only components that are operationally necessary should proceed to further sourcing evaluation.

Principle 2: Civilian availability must be converted into operational usability

The analysis shows that while a component may be physically available in a civilian supply network, it can still fail to restore UGV functionality if it cannot be identified, verified, integrated, accessed in time, or installed under disrupted conditions.

Therefore, the second principle is that civilian availability does not automatically create operational availability.

Operational adaptability is about the extent to which a civilian component can be converted into a usable spare part for the UGV system, and this conversion depends on five conditions:

1. Physical compatibility: The component fits the UGV's geometry, interfaces, and packaging
2. Performance equivalence: The component can perform as intended under the UGV's operating conditions
3. Identifiability and verifiability: The correct component can be identified and verified within the supply network
4. Time-constrained accessibility: The component can be accessed within the required operational time window
5. Ease of integration under disruption: The component can be installed with the tools, competence, and service available at the service point.

This principle shows that resilience is not only about if a part exists, but whether it can be made usable under the conditions which the system operates.

Components such as standardized hoses, filters, seals, and mechanical wear parts should be prioritized for civilian sourcing as it requires little conversion effort.

Principle 3: Components used across broad and deep civilian supply networks offer greater sourcing flexibility during disruption

The third principle is that the broader and deeper a component is present across the civilian supply network, the greater the resilience. Supply network commonality refers to the extent to which a component is used across multiple platforms, applications, suppliers, and aftermarket channels. The wider its use across the civilian network, the more potential points of supply are available if normal supply channels are disrupted.

This shows that the relevant question should not be whether a component is standardized within one OEM's product architecture, but whether it is widely embedded in the broader civilian supply network. A component that is stocked by several actors (such as suppliers), used across different vehicle types, known by the personnel that performs the service, and is supported by existing repair infrastructure

offers greater sourcing flexibility during disruption compared to a component with limited use and narrow availability (e.g. not stocked by the suppliers).

This is important to note, as commonality shows how many points of supply exist within a given time (i.e. the breadth), while the supporting pathway, which is a principle that is addressed later, concerns the continuity of access over time.

This means that organizations should map component commonality across the supply network, not only within the specific system architecture. This includes assessing if the component is stocked at central warehouses, regional nodes, dealers, aftermarket suppliers, and service points, and if it is used in other equipment types that may provide alternative access routes.

Principle 4: Evaluate future availability and continuity of support rather than current availability

The findings suggest that resilience-oriented sourcing decisions should focus on a component's ability to remain available and supportable throughout its intended lifecycle rather than on its current availability. Components that are readily accessible today may provide limited resilience value if they are exposed to technological change, supplier discontinuation, lifecycle mismatch, software dependency, or uncertain replacement pathways.

The analysis demonstrated that future availability is influenced by obsolescence exposure and continuity of support. Components embedded in rapidly evolving technologies may become difficult to source despite being widely available today, while components lacking qualified replacements, aftermarket support, or long-term supplier commitments may become operationally unavailable even when inventories exist.

An important distinction exists between mechanical and electronic components. Mechanical components are often more stable over time and may be easier to store, repair, substitute, or source through aftermarket channels. Electronic and software-dependent components are generally more vulnerable to technological change, discontinued subcomponents, software incompatibilities, battery degradation, and limited storage suitability.

The findings further indicate that resilience cannot be achieved solely through inventory-based redundancy. Components that appear available may still represent future vulnerabilities if they cannot be effectively stored, maintained, updated, validated, or replaced throughout the expected operational lifetime of the system. Consequently, organizations should assess not only whether a component is available today, but also whether viable support pathways exist in the future.

This includes evaluating supplier commitments, aftermarket availability, qualified replacement options, alternative sourcing possibilities, storage suitability, and the expected effort required to maintain functionality throughout the lifecycle of the component. Components characterized by high obsolescence exposure and weak support pathways may require proactive measures such as redesign, modular updates, early replacement qualification, or strategic sourcing arrangements before disruptions occur.

The answer to RQ3 is therefore that resilience-oriented sourcing decisions should be guided by operational need, operational adaptability, supply network commonality, and long-term supportability rather than by inventory availability alone. Together, these principles provide a structured basis for evaluating whether a component can support operational functionality under disruption. A component contributes to resilience not simply because it exists within a supply network, but because it can be accessed, integrated, maintained, and supported throughout its intended lifecycle under the conditions in which the UGV system is expected to operate.

6.1 Contributions of the Study

This study shows how resilience can be incorporated into component-level spare part decisions. While resilience is often discussed in terms of supply chains, supplier networks, and organizational capabilities, the findings demonstrate how resilience considerations can be applied directly to the evaluation of individual components. Specifically, the study identifies four dimensions: functional criticality, operational adaptability, supply network commonality, and supporting pathways which influence whether a component can contribute to spare part availability under disruption.

The study also highlights the need for alternative sourcing approaches in disrupted environments. Existing research often associates sourcing flexibility with access to multiple suppliers or alternative supply channels. The findings suggest that supplier availability alone is insufficient. A component contributes to resilience only when it can be identified, accessed, integrated, repaired, and used to restore operational functionality. Hence, it suggests that sourcing feasibility includes technical compatibility and repair-system considerations alongside traditional sourcing considerations.

Finally, the study conceptualizes spare part availability as an operational capability rather than solely an inventory outcome. The findings show that availability depends not only on whether a component exists within a supply network, but also on whether it can be transported, installed, verified, and used to restore a critical function within operational constraints created by disruption.

6.2 Limitations

This study should be interpreted considering several limitations. The findings are derived from a single-case study involving UGV Inc., Truck Inc., and a limited number of respondents. While the study provides analytical insights that may be relevant beyond the specific case, the findings should be interpreted in light of the study's contextual setting and empirical scope.

Furthermore, the UGV platform examined in this study remains under development, meaning that extensive operational data, failure statistics, and spare part consumption records were unavailable. Consequently, the findings and proposed sourcing principles are based primarily on qualitative analysis, expert knowledge, and functional reasoning rather than observed operational performance.

The scope of the study was limited to spare part availability and sourcing logic. Quantitative aspects such as inventory optimization, service-level modelling, cost

analysis, and sourcing optimization were intentionally excluded and therefore remain outside the explanatory power of the findings.

Finally, the study did not validate the technical feasibility of specific civilian component substitutions through engineering testing. Although important enablers and constraints were identified, further technical verification would be required before implementing specific sourcing decisions.

6.3 Future Research

Several opportunities for future research emerge from the findings of this study. First, future studies should evaluate the proposed sourcing principles using operational data generated through UGV testing and deployment. Such research would strengthen the empirical foundation of resilience-oriented spare part planning and enable comparison between anticipated sourcing risks and actual failure behavior.

Second, future research could develop quantitative decision-support approaches that combine operational criticality, sourcing accessibility, lifecycle risk, repair complexity, and disruption exposure. Such approaches could support more systematic prioritization of resilience investments and sourcing decisions.

Third, additional research is needed on the relationship between civilian and defense supply networks. In particular, studies examining supplier access, public-private collaboration, information sharing, and resource prioritization during major disruptions could improve understanding of how civilian supply resources can support operational resilience.

Fourth, future research should investigate the technical feasibility of integrating civilian components into specialized UGV platforms, particularly for electronic and software-dependent systems where compatibility, lifecycle management, and obsolescence challenges are most pronounced.

Finally, comparative studies involving multiple UGV platforms, defense systems, or crisis-response vehicles would help determine the transferability of the findings beyond the specific context examined in this thesis.

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Appendix

Example of interview guide

The interview guides were tailored to the respondent's areas of expertise while maintaining common themes across interviews. Appendix A presents an example of an interview guide used during the data collection process.

Appendix A

Background and Role

1. Can you briefly describe your role and responsibilities within your organization?
2. How does your role relate to spare parts, sourcing, or maintenance activities?

Spare Part Availability

3. What factors do you consider most important for ensuring spare part availability?
4. Which types of components are typically most difficult to keep available?

Component Criticality

5. How do you identify critical components?
6. What factors influence whether a component is considered critical?

Sourcing and Supply Networks

7. How are spare parts normally sourced?
8. What challenges arise when suppliers or supply routes become unavailable?
9. What role do alternative suppliers or supply networks play in maintaining availability?

Disruptions and Response

10. How does your organization respond when a critical component is unavailable?
11. Can you describe an example of a significant supply disruption?

Design and Standardization

12. How do standardization and component reuse affect availability?
13. To what extent can components be substituted between products or systems?

Closing Questions

14. Are there any additional factors influencing spare part availability that we have not discussed?
15. Is there anything else you would like to add?

