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System architecture for information visibility in humanitarian logistics:
Innovative lateral information sharing in a low trust, high risk, volatile environment for coordination

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BCom, The University of Auckland (2010)
BCom(Hons), The University of Auckland (2011)

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Operations and Supply Chain Management, The University of Auckland, 2019
Abstract

Interagency coordination is one of the most enduring and intractable problems affecting humanitarian logistics performance in disaster relief. This thesis seeks to understand the reasons and solutions to poor interagency performance. A literature review surveys seminal and recent research for supply chain coordination issues in disaster relief. A primary driver of supply chain coordination is information sharing, which requires information visibility. Many supply chain strategies and coordination mechanisms in the traditional literature are inappropriate for disaster relief. By integrating supply chain theory into design science, the combined framework outlines the research plan to prototype a system for information sharing.

System dynamics simulations with volatile demand are used to test the effects of different information sharing scenarios across multiple supply chains on backlogs. Results show horizontal information sharing between competing retailers is as effective as other scenarios after an initial 18 day delay, as orders filter upstream to suppliers. Select supply chain theories are turned into design principles and a conceptual framework, which is then instantiated as a generic system architecture and practical artefact.

The practical artefact functions by using autonomous decentralised mesh networks to facilitate an automated data collection and anonymisation application, which forwards securely anonymised and semi-aggregated data through an information sharing process called “lateral information sharing”. This allows supply chain competitors to share information without needing to trust each other, but still gaining the benefits of information sharing as if they were in a strategic partnership. This has limited generalisability beyond disaster relief due to competition laws, while security issues around implementation together with trust issues around adoption will determine whether this approach is feasible beyond a laboratory scenario.
I would like to thank my immediate family for all their support through these years of hardship, as well as my extended family in Hong Kong for their hospitality during my annual visits home. Included in that immediate family are my late cat, Jack, and, my current dog, Laci, for many years of noble companionship. I would like to thank my doctoral advisor, Dr. Tiru Arthanari, for his understanding, compassion, and wisdom; he often went above and beyond what I expected of an advisor. I would also like to thank my co-advisor Prof. David Sundaram for the useful feedback he gave me during the early years of my research, which were instrumental in developing my research proposal, and when finalising my thesis. Special thanks to former fellow doctoral student, now Dr. Foad Marzoughi for reviewing my papers. Thank you to all the humanitarian logisticians I talked to over the years for your advice, encouragement, and for letting me pick your brains on this very complicated research topic.
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## Organisations

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<tr>
<td>CRED</td>
<td>Centre for Research on the Epidemiology of Disasters</td>
</tr>
<tr>
<td>EM-DAT</td>
<td>Emergency Events Database</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FCC</td>
<td>United States Federal Communications Commission</td>
</tr>
<tr>
<td>GAO</td>
<td>United States Government Accountability Office</td>
</tr>
<tr>
<td>HDX</td>
<td>Humanitarian Data Exchange</td>
</tr>
<tr>
<td>IFRC</td>
<td>International Federation of Red Cross and Red Crescent Societies</td>
</tr>
<tr>
<td>InSTEDD</td>
<td>Innovative Support to Emergencies Diseases and Disasters</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>NGO(s)</td>
<td>Non-Governmental Organisation(s) (aka &quot;Non-Profit Organisation(s)&quot;)</td>
</tr>
<tr>
<td>OSOCC</td>
<td>On-Site Operations Coordination Centre</td>
</tr>
<tr>
<td>UNESCAP</td>
<td>United Nations Economic and Social Commission for Asia and the Pacific</td>
</tr>
<tr>
<td>UNHCR</td>
<td>United Nations High Commissioner for Refugees</td>
</tr>
<tr>
<td>UNISDR</td>
<td>United Nations InternationalStrategy for Disaster Reduction</td>
</tr>
<tr>
<td>UNOCHA</td>
<td>United Nations Office for the Coordination of Humanitarian Affairs</td>
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<td>USAID</td>
<td>United States Agency for International Development</td>
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## Technology standards

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<td>2G</td>
<td>Second Generation Cellular Technology (includes GSM as one of its standards)</td>
</tr>
<tr>
<td>3G</td>
<td>Third Generation Cellular Technology</td>
</tr>
<tr>
<td>BLE</td>
<td>Bluetooth Low Energy</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>GSM</td>
<td>Global System for Mobile communications</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific, and Medical Radio Band</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution (incorrectly marketed as “4G”, “4G LTE”, or “Advance 4G”)</td>
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<tr>
<td>MQTT</td>
<td>Message Queuing Telemetry Transport</td>
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<td>SMS</td>
<td>Short Message Service</td>
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## Units of measurement

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<td>GHz</td>
<td>Gigahertz</td>
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<tr>
<td>km</td>
<td>Kilometres</td>
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<tr>
<td>m</td>
<td>Metres</td>
</tr>
<tr>
<td>Mbps</td>
<td>Megabits per second</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
</tr>
<tr>
<td>USD</td>
<td>United States Dollars</td>
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1. Introduction

1.1. Introduction

Interagency coordination and information sharing are the most important determinants of disaster relief performance, yet they remain limited, and are still one of the most enduring and intractable problems in humanitarian logistics. This thesis explores and attempts to partially resolve this issue through an unusual information sharing approach tentatively called “lateral information sharing”, which will be first introduced in the Conceptual model chapter (pp. 125-131). To lay the groundwork, a brief description of disaster relief and humanitarian logistics is given, then a research plan is made to define the purpose of the thesis research as a series of research problems, a research objective, and a research question. Lastly, the logical progression of the thesis structure is described.

1.2. Motivation

My family has a long history of involvement in humanitarian work for many decades in Hong Kong, China, and New Zealand. For 12 years, I was a regular volunteer in Tzu Chi Foundation, a secular humanitarian non-governmental organisation (NGO) headquartered in Hualien, Taiwan. Tzu Chi delivers medical aid, disaster relief, and environmental work through a professional cadre of permanent staff and over 10 million volunteers across 47 countries. Because I grew up in this system of values, I wanted to make my own unique contributions to the wider humanitarian system. Luckily, at the time I started this degree the topic of disaster relief and humanitarian logistics was becoming a prominent issue in academic research and
was openly discussed in the media, not just as a humanitarian story but also a story about the effectiveness of relief operations.

### 1.3. Background to disaster relief

The United Nations (UNISDR, 2009, p. 9) provides an umbrella definition for what constitutes a humanitarian disaster:

> “A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and which exceeds the ability of the affected community or society to cope using its own resources.”

The number of natural disaster events increased sharply from 24 events in 1950 onwards, peaking at 526 events in 2000, and has steadily decreased to 291 in 2017 (Ritchie & Roser, 2018). Historically, the most lethal disasters are tectonic in nature, such as earthquakes and tsunamis, and or hydrological in nature, such as hurricanes and droughts (Adikari & Yoshitani, 2009, p. 7). Tectonic activity will always be present, but hurricanes are becoming more destructive and prevalent. Although there is no definitive causal link yet, many suspect meteorological and hydrological disasters are exacerbated by warming oceans due to climate change (Banholzer & Donner, 2014). The United States has seen three of its most intense hurricanes since records were first kept in 1851 in just the last two years, in the 2017 Hurricane Irma, 2017 Hurricane Maria, and 2018 Hurricane Michael (National Hurricane Center, 2017). As the danger of natural disasters grows exponentially, greater disaster prevention and relief efforts are needed to address them.
Natural disasters are classified by their primary causes (Nelow, Wirtz, & Guha-Sapir, 2009): (1) Geophysical (e.g. earthquakes), (2) Meteorological (e.g. storms), (3) Hydrological (e.g. floods), (4) Climatological (e.g. forest fires), (5) Biological (e.g. epidemics) and (6) Extra-terrestrial (e.g. meteor impacts). This thesis focuses on sudden-onset disasters, which are disasters that occur with little to no warning, as compared with long-running disasters. Different types of disasters cause different types of environmental damage that affect disaster relief efforts in different ways. For example, a flood not only destroys infrastructure but submerges parts of the disaster zone, including roads and streets, thus limiting responders’ ability to access the affected population.

The disaster management cycle is a commonly accepted framework for viewing the lifecycle of disaster relief efforts, which has the following sequence (Carter, 1999, p. 416): (1) Preparedness, (2) Disaster event, (3) Response, which occurs in the first few months, (4) Recovery, which can possibly take years to decades, and (5) Mitigation. This thesis focuses solely on the disaster response stage. Supply chain operations within the disaster zone consist of search and rescue, distributing aid, constructing temporary housing, giving basic medical care, and burying corpses (Fritz Institute, 2005). The geography of a disaster zone and the damage to transportation infrastructure from the disaster event can render certain areas inaccessible. Disaster relief supply chains utilise different modes of transportation to suit the time sensitivity and capacity requirements for the affected population (Armbruster, 2011; UNHCR, 2007, p. 551). For example, helicopters are extremely expensive and can only carry a

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1 The term “disaster victim” has fallen out of use, because it incorrectly implies that the affected communities are helpless (De Goyet, 2000). Usually, the communities affected by disaster events become their own first responders (Thomas & Fritz, 2006, p.119) and prevent many time-critical issues from spiralling out of control (der Heide, 2004, pp. 341-347, 350-354). Today, the term “affected population” is used in place of “victim”.
very limited tonnage, but they can reach anywhere they can land, while sea freight is extremely inexpensive and can carry an enormous tonnage but is very slow.

Aid agencies use different performance characteristics and requirements for each mode of freight (Logistics Cluster, n.d.) to overcome the causes of friction in humanitarian logistics (Hesse & Rodrigue, 2004, p. 12). Once within the disaster zone at the downstream supply chain echelon, operations are far less orderly and involve a heavy amount of improvisation (Balcik & Beamon, 2008; IFRC, 2000, p. 8). The type of disaster will inherently affect the type of damage sustained by the transportation infrastructure. For example, earthquakes may destroy specific lengths of road, while flooding renders whole areas inaccessible except by boat or helicopter. The United Nations’ key performance indicators for the disaster response stage measure the survivability of the affected population and what is required to ensure continued survival (UNHCR, 2007, p. 546).

While it has been more than a decade since the 2005 Hurricane Katrina, it remains one of the most intensively studied and well-documented disaster relief efforts in history, perhaps because it was widely considered a massive failure, especially for the newly reorganised Federal Emergency Management Agency that had been integrated with the Department of Homeland Security (GAO, 2006). For the first 48 hours after the hurricane’s impact, national authorities had not yet arrived, leaving local authorities to shoulder the burden of providing disaster relief (Fritz Institute, 2006). This is normal for natural disasters, where the primary first responders come from within the disaster zone and/or are part of the affected population. For the first 48 hours after the 2004 Indian Ocean Earthquake and Tsunami that struck Indonesia, India and Sri Lanka, the greatest contributor to search and rescue, burials, water and
food provisioning, clothing, shelter, medical care and counselling came from private individuals without any affiliation with government or NGOs (Fritz Institute, 2005).

A popular misconception is that most of the affected population is severely injured and that medical attention takes greatest priority. People require the necessities of life, such as food, clean water, shelter, and sanitation, before medical aid (McClintock, 2009). In a disaster zone with no sanitation, no medication, no clean water and decomposing bodies, the area becomes a breeding ground for disease (Shears, 1991). However, epidemics rarely materialise (Lemonick, 2011, p. 151) due to the efforts of affected populations in the aftermath of a disaster as communities pull together to manage as well as they can with what they have (e.g. Fritz Institute, 2005). The lack of resources makes preventative healthcare essential. One of the most effective means of medical aid are vaccinations against common diseases (Cranmer, 2005), which can be dispensed without qualified nurses or physicians.

1.3.1. Disaster relief is mostly logistics

For historical reasons, the disaster relief supply chain is called “humanitarian logistics”, rather than the commercially and academically accepted term “supply chain management” that has emerged in the last few decades (Lummus, Krumwiede, & Vokurka, 2001). Humanitarian logistics encompasses operations management, logistics management, and supply chain management functions. The Fritz Institute (2005, p. 2) defines humanitarian logistics as follows:

“The process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for... alleviating the suffering of vulnerable people. The function encompasses a range of activities,
including preparedness, planning, procurement, transport, warehousing, tracking and tracing, and customs clearance.”

Logistics is the means of delivering aid (e.g. food, water, shelter, temporary housing, and medical supplies), representing 80% of costs in the relief effort (Trunick, 2005, p. 8). The first 72 hours after the disaster impact is considered the critical period for delivering aid (Özerdem & Jacoby, 2006, p. 61), and if help is not received within that period most of the affected population will die. In the immediate aftermath of a disaster, search and rescue operations and medical attention are required, but this usually only involves a small fraction of those affected (Cranmer, 2005). It is not only necessary simply save a life at a single point in time, but also essential to sustain life over a long period of time. Catastrophic disasters can destroy housing, commerce, transportation networks, clean water sources and food sources. This destroys the affected population’s ability to access to the necessities of life, which significantly compromises their survival.

To address the danger of natural disasters, humanitarian logistics has historically introduced innovations from traditional supply chain management. However, this has not always been possible due to the unique difficulties of the disaster relief environment. The main difference between humanitarian logistics and traditional supply chain management is that disaster relief suffers from high uncertainty (Balcik & Beamon, 2008). Upstream supply chain echelons are often far away from the disaster zone and refugee camps. They can benefit from optimisation strategies that are traditionally found in the commercial sector and require high

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2 There is a technical distinction between a “refugee”, who has been displaced from their country of residence, and an “internal displaced person” (IDP), who has been displaced within their country of residence but away from their homes. For the sake of simplicity and because this distinction is not explored in depth in this thesis, here they are both referred to as “refugees”. 
degrees of information visibility and environmental stability, such as inventory and supply chain optimisation through operations research. Downstream supply chain echelons include the disaster zone, which is a highly uncertain environment. Supply chain visibility is the greatest difference between disaster relief and the commercial supply chain (Henderson, 2007). For a significant time after arriving at the disaster zone, aid agencies still do not know the exact location and extent of infrastructure damage, number and location of individuals within the affected population, and the speed at which aid supplies can be distributed. However, there are increasing efforts towards creating and automating better estimates of infrastructure damage (e.g. UNOCHA, n.d.a).

One of the primary determinants of humanitarian logistics performance is supply chain coordination (McLachlin & Larson, 2011), which the humanitarian sector refers to as “interagency coordination”. No single aid agency, whether it is the national government, local government, military, or large NGOs, have sufficient capacity, personnel, and local knowledge to adequately serve the affected population by themselves (Tomasini & Van Wassenhove, 2009). This means that interagency coordination is simply an inevitable consequence of disaster relief, yet serious challenges limit coordination. The primary means of interagency coordination is information sharing, which enables all other forms of coordination from resource pooling and joint capacity planning to forecasting. Many individuals and organisations, from academics and governments to humanitarian workers themselves, have consistently stated that information sharing is vital to effective disaster relief, but also that currently information sharing between organisations delivering aid is very limited and that more needs to be done (Harvard Humanitarian Initiative, 2011).
1.3.2. **Limited interagency coordination**

Following a disaster event, the earlier aid is distributed the more lives can be saved. However, it is not enough to merely save lives in the short term, but it is essential to sustain lives over the long-term through the provision of the necessities of life (e.g. food, water, shelter, warmth, medicine), thus allowing an affected community to eventually move to disaster recovery to rebuild their lives, communities, and infrastructure. One of the enduring issues affecting humanitarian logistics performance is the lack of information visibility in ground operations (Thomas & Kopczak, 2005), which is exacerbated by damage to infrastructure and limited telecommunications coverage (Henderson, 2007; UNESCAP, 2011, p. 110).

Even under the best conditions, depending on the scale of the disaster event it may take a few weeks before widespread telecommunications access and coverage is re-established (Allenbach, Andreoli, Battiston, Bestault, Clandillon, Fellah, Henry, Meyer, Scius, Tholey, Yesou, & de Fraipont, 2005; O’Reilly, Jrad, Nagarajan, Brown, & Conrad, 2006; Kwasinski, Weaver, Chapman, & Krein, 2009). Disruptions to transportation networks significantly affect supply chain performance (Wilson, 2007) and efforts to repair existing telecommunications or install temporary telecommunications. If affected individuals do not receive aid within the first 72 hours of a disaster event, most will die (Özerdem & Jacoby, 2006, p. 61). With limited telecommunications and time, aid agencies distribute supplies to the affected area with a partial understanding of the (in)efficiency of their transportation and distribution plans, and a highly limited ability to accurately forecast and validate the consumption of relief supplies within the disaster zone (Beamon, 2004; Long & Wood, 1995).

The nature of the disaster relief environment creates unique challenges to information sharing that are not commonly encountered in the private sector. The disaster relief
environment has several common characteristics that cluster around issues of significant uncertainty, extreme initial demand spikes, insufficient capacity for delivering aid, and a mostly ad hoc and highly decentralised operating environment (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012). Together, these environmental characteristics create challenges to information sharing and interagency coordination, and both problems are closely related.

The lack of information visibility at downstream supply chain echelons is very concerning. There has been over two decades of research into the “bullwhip effect”, or the tendency for a lack of information sharing along a supply chain to exacerbate inventory and backlog volatility (Lee, Padmanabhan, & Whang, 1997; Chen, Drezner, Ryan, & Simchi-Levi, 2000; Cao & Zhang, 2011). Without information visibility of the affected population’s needs and a way to disseminate what each aid agency can see to other aid agencies, the disaster relief supply chain will be managed using other operational criteria (Benini, Conley, Dittemore, & Waksman, 2009), in its attempt to estimate ways to achieve supply chain efficiency without knowing where it is needed. Organisational orientation, learning practices, and external and internal integration create supply chain agility and therefore visibility (Braunscheidel & Suresh, 2009), yet these are severely lacking in aid agencies (Thomas & Kopczak, 2005, p. 5).

Interagency coordination has been firmly established as critical to disaster relief performance (Thomas & Kopczak, 2005; Kapucu, 2006; Schulz & Blecken, 2010; Crowley & Chan, 2011), yet without widespread access to telecommunications and a common sharing platform, coordination remains ad hoc and sparse. The key elements to dealing with supply chain uncertainty are as follows (Van Wassenhove, 2006): (1) Rapid deployment, (2) Collaboration, (3) Risk sharing and (4) Resource sharing. Communications facilitated by
technology have been found to support interagency coordination, significantly improving information visibility and supply chain performance (Chen, Rao, Sharman, Upadhyaya & Kim, 2009). Generally, collaborative networks across virtual organisations unlock new capabilities (Noran, 2009).

1.3.2.1. **Difficulties constraining all solutions**

While interagency coordination is widely understood to be instrumental to performance, there is too much emphasis on purely technological solutions with the assumption of there being absolute trust and no barriers to adoption (Barratt, 2004, p. 39), such as switching costs or training needs. Communications involve formal and informal controls, which must be considered during the design of a communications system (Amrit, 2010). In disaster relief, most controls are informal and ad hoc, but there is an understanding between aid agencies and humanitarian logisticians in how their work is conducted according to social and professional norms (Balcik & Beamon, 2008; IFRC, 2000, p. 8). In the context of a disaster, a lack of information sharing, miscommunications and poor information management negatively affect interagency coordination during disaster relief (Salmon, Stanton, Jenkins, & Walker, 2011). Common standards are insufficient to ensure information visibility, because the processes and information systems used as facilitators must be interoperable (Charles, Markus, & Wigand, 2011).

Disaster events isolate the affected population by damaging and/or destroying infrastructure that connect people (Sheller, 2013), rendering decentralised operations an unavoidable reality. In an absolute sense, there is massive capacity in the humanitarian sector to address disaster efforts yet compared to the scale and prevalence of some catastrophic
disasters, interagency coordination is crucial to disaster relief performance (Thomas & Kopczak, 2005; Schulz & Blecken, 2010; Crowley & Chan, 2011). In 2008, there were over 210,000 aid workers in the humanitarian sector, NGOs had over USD $3 billion (United States Dollars) in funding without donations, and yet the United Nations reported that the humanitarian sector still saw a shortfall of USD $0.9 billion between available funds and stated requirements (Harvey, Stoddard, Harmer, Taylor, DiDomenico, & Brander, 2010, pp. 18-25).

The United Nations and International Red Cross are the largest NGOs, with 23% of aid workers in the entire humanitarian sector, but 54% of aid workers come from a vast collection of much smaller NGOs, where most have budgets under USD $10 million (Harvey, Stoddard, Harmer, Taylor, DiDomenico, & Brander, 2010, pp. 18-20). Supply chain collaboration requires supply chain coordination mechanisms, yet certain mechanisms from the supply chain literature and commercial practice are inappropriate for downstream relief chain operations. Most coordination mechanisms require a high degree of information visibility, a stable environment, and/or rigorously implemented processes that are facilitated by virtual integration (Balcik, Beamon, Krejci, Muramatsu, & Ramirez, 2010, p. 30).

Real-time communication has long been considered essential for effective interagency coordination during disaster relief (Long & Wood, 1995). There is disagreement about whether real-time information visibility is needed for flexibility in the commercial sector or whether sufficiently short time increments give the same result (Chan, Bhagwat, & Wadhwas, 2009), but the situation in the humanitarian sector is always uncertain, making information visibility progressively more valuable as it moves closer to real-time. Most disaster communications are implemented by the following means: (1) Two-way radio, which consumes very little power and is cheap (Zavazava, Zimmermann, Wood, Bisnath, & Walter, 2005; Oh, 2003; FCC, n.d.), (2)
Satellite or Wi-Fi, which both consume enormous amounts of power but have high transmission range and/or data rates (Garshnek & Burkle, 2004; Zavazava, Zimmermann, Wood, Bisnath, & Walter, 2005; Oh, 2003; FCC, n.d.), (3) Paper forms (Fritz Institute, 2005) and (4) Conversations in-person.

Most aid agencies still heavily rely on manual processes, such as word-of-mouth instructions and paper forms for ordering relief items (Thomas & Kopczak, 2005). Since aid agencies have their own personnel, relief item procurement, and internal procedures, it is more common than not for disaster relief operations to involve compatibility issues, such as using incompatible technologies, different terminology and definitions, and/or conflicting policies (Manoj & Baker, 2007). In some cases, this may lead to distrust between aid agencies (Perry, 2007). Currently, there are no technologies, systems, and/or processes in place to aggregate downstream supply chain data in disaster relief with any accuracy or detail. Information visibility and interagency coordination in disaster relief remains an elusive goal.

However, these difficulties have not stopped authorities, humanitarian logisticians, and academics from continuing to push ahead and there have been many solutions proposed and applied over the years. Taking lessons from the commercial sector and military practice (Henderson, 2007), there are predictable impulses for authorities to solve these challenges based around some form of centralisation, though such impulses have historically underperformed. Academics have devised their own proposals for solutions, which often focus around an unreasonable expectation of information visibility or rely on resources which most NGOs do not have and cannot access. Practitioners often attempt to directly control uncertainty using centralisation. In a decentralised, ad hoc environment, and unstable
environment, the natural impulse of aid agencies, especially government authorities and militaries, are to impose a top-down hierarchy to force all aid agencies to coordinate.

### 1.3.2.2. Common solutions from authorities

Authorities often impose direct control over the disaster zone and related disaster relief camps and impose strict constraints over how all aid agencies operate, directly controlling what is done and who goes where at what specific time. This leads to bureaucratic inefficiency and inflexibility (Neal & Phillips, 1995), compromising disaster relief performance. Albeit some measure of direct centralised authority will always be necessary, having it in excess is negative—and it frequently becomes excessive. Instead of direct control, authorities often give a *centralised coordination authority* canonical control over an area, but only for the purposes of coordination, but this solution is not scalable. The more aid agencies are involved, the greater the number of languages spoken, the greater the socio-cultural divide between NGOs and the government, the less effective such coordination becomes, often to the point of becoming self-defeating (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012). Because authorities understand the impracticality of full centralised direct control, this is the most common solution.

Although largely unused, there has been a push towards *imposing centralised standards* to regulate how NGOs coordinate, while leaving coordination independent. The issue is that these standards are imposed after a disaster event (e.g. Jahre & Jensen, 2010), which gives NGOs several days to completely rearchitect their organisational processes around a new standard imposed from an external organisation with no direct authority over them. Many NGOs do not specialise in disaster relief and were simply adjacent to the disaster when it
occurred. Once the disaster relief effort reaches its terminal stage, those NGOs will be extremely unlikely to be directly involved in disaster relief efforts again. Consequently, such standards are almost never adopted during disaster relief efforts (cf. Fabbe-Costes & Jahre, 2015).

Because this centralised approach has been impractical, some academics such as Tatham, Spens, and Kovács, (2017) have been suggesting common operating standards before a disaster event strikes, but this suffers from many of the same issues as well as the added issue of a lack of immediate impetus to enact painful organisational reforms. Centralised standards suggested before disaster relief events are not adopted because there are extremely heterogeneous organisational processes in NGOs, especially for information sharing and its role in decision-making (Day, Junglas, & Silva, 2009), because there is a lack of resources to affect such an adoption (Thomas & Kopczak, 2005), and because those proposing the standard having absolutely no authority or influence over NGOs (Fabbe-Costes & Jahre, 2015).

1.3.2.3. Common solutions from logisticians

Aid agencies can mitigate demand variability by configuring the push-pull boundary. In the immediate aftermath of a disaster event, demand information is scarce, and time is limited, so the initial response is purely “push” with top-down allocation of resources based on estimates, especially for common items consumed in volume (USAID, 2011), which can be augmented by pre-positioning supplies in regional warehouses located close to high risk areas (Rawls & Turnquist, 2010). As the response develops, the downstream supply chain becomes increasingly “pull” with demand information collected from end users leading to inventory requests that move upstream to the supply chain, especially for less common items (USAID,
This approach is virtually universally used. Aid agencies can standardise their inventory items, which reduces demand variation to a comparatively smaller set of standardised items as opposed to an enormous variety of specific items that cannot serve in multiple roles (Tomasini & Van Wassenhove, 2009). This can also reduce procurement costs per unit through bulk purchases. For NGOs that specialise in disaster relief, this approach is universally used.

1.3.2.4. Common solutions from academics

Academics often pose solutions that can hypothetically overcome coordination issues by improving coordination directly, though these often rely on impractical assumptions and resources. Most solutions developed by academics are rationalist mathematical models and simulations for optimising supply chain distribution or supply chain coordination (e.g. see a rationalist model based on a ‘case study’ without any historical data in Banomyong & Sopadang, 2010). None of these models or simulations have been validated using historical data collected from actual field experience, so their validity and accuracy is completely unknown.

Yet those papers’ authors and others who cite them use such papers as proof of fundamental dynamic relationships that exist in the real world. While rationalist models can uncover some dynamics, they often miss out emergent properties, where constraints in the real world cause a friction that is not considered in the original model. The greatest issue in model validation is that there is no widely available historical data, which makes validation near impossible. Consequently, there has never been an explanation within those papers proposing rationalist models of how their variables, relationships, and quantification have been derived. These approaches almost universally rely on at least one of two assumptions that are highly
unrealistic. There is an assumption of centralised distribution by perfectly coordinated suppliers and that information visibility is extremely high (Caunhye, Nie, & Pokharel, 2012).

There have been some nascent proposals for developing common logistics standards, or at least a roughly standardised way to share information. These proposals almost never come with any practical implementable standards, but merely suggest creating some vague, unspecified standard by pointing to other areas of organisational operations where similar approaches have been beneficial (e.g. Tatham, Spens, & Kovács, 2017). These suffer from the same problems as authorities trying to introduce centralised coordination standards, as mentioned previously.

1.4. Research plan

Now that a general problem area has been identified, the research plan is defined to give the thesis investigation a purpose. The research plan only involves research problems, a research objective, and a research question. The Literature review chapter (pp. 21-73) will define the boundaries of the research area, while the Methodology chapter (pp. 74-102) will provide a more detailed research statement, covering how the research question can be answered by using methodologies to create research artefacts.

1.4.1. Research problems

The impetus behind this thesis is the overall research problem of enabling information visibility and information sharing in disaster relief supply chains to support interagency coordination. This problem can be split into two halves:
Research problem 1: How can real time demand information be captured in disaster response efforts?

Research problem 2: How can logistics data be shared across aid agencies in disaster response efforts?

Real time demand information has been something of an elusive ambition by humanitarian logisticians (Day, Junglas, & Silva, 2009; Scott & Batchelor, 2013), hypothetically enabling targeted aid relief for maximum efficiency and minimum response times (Lee & Zbinden, 2003). Data capture and sharing are perhaps the simpler of the challenges, while the primary challenge lies with data analysis of heterogeneous data, or what is known in big data research as “unstructured data” (Gandomi & Haider, 2015). Currently logistics information sharing across agencies is limited, often involving physical documents or interpersonal interactions (Thomas & Kopczak, 2005). The primary challenges are the scalability and timeliness of information sharing, which would inevitably require a great deal of automation through information systems and wireless communications networks. Current supply chain management literature has explored the types of information shared between supply chain partners (Petersen, Ragatz, & Monczka, 2005) and the value of information sharing (Lee & Whang, 2000); but have rarely evaluated the means of information sharing, especially for information technology-enabled solutions.

1.4.2. Research objective and research question

Given the boundaries of the research area, certain research approaches intuitively appear to be more suitable than others. If there is a lack of data collection, the first task will be to enable it, and all other tasks must follow from this fundamental requirement. This thesis chooses a
specific solution approach that is based on a technologically-supported process solution that can meet all the requirements identified in the research area’s boundaries. These generate the research objective and research question below:

**Research objective:** Develop a practical solution based on supply chain theory to overcome the problems in interagency coordination in disaster relief.

**Research question:** How can a solution to problems in interagency coordination in disaster relief be developed that integrates multiple disciplines, to address problems that are simultaneously related to technology, process, culture, and politics?

In the *Literature review* chapter (pp. 21-73), existing research is surveyed and synthesised, which implies that certain theoretical lenses and methodologies are more appropriate than others to answer the research question. In the *Methodology* chapter (pp. 74-102), the methodologies and associated techniques are chosen after being informed by the literature, then logically connected to produce a series of research artefacts as proof for or against each facet of the research question.

### 1.5. Thesis structure

This thesis is structured in a strict linear progression, with each research artefact building on previous artefacts. The *Introduction* chapter (pp. 1-20) defines poor interagency coordination in disaster relief as the research topic, gives some general background information, then provides a research plan for the purpose of the thesis.

The *Literature review* chapter (pp. 21-73) defines the scope of the thesis, surveys and synthesises existing and related research in interagency coordination, information sharing, and
supply chain strategies and coordination mechanisms from various theoretical perspectives, and finally compares existing solutions with the research problem, to understand why it has not yet been solved. The resulting literature and capability gap indicate that there is an opportunity to make an original contribution. The Methodology chapter (pp. 74-102) details the design science research framework and development process, how it is adapted to certain supply chain theories, and how a system dynamics simulation can be used as a litmus test for different information sharing scenarios in supply chains.

The Supply chain simulation chapter (pp. 103-124) experiments in whether horizontal information sharing reduces inventory backlogs sufficiently across supply chains with highly variable demand to be worthwhile pursuing. The simulation uses stock and flow models of an adapted beer game from system dynamics for testing vertical, horizontal, and both vertical and horizontal information sharing across multiple supply chains. The Conceptual model chapter (pp. 125-139) defines a technology and process integration strategy for enabling a lateral form of horizontal information sharing adapted to the low trust, high risk, and high uncertainty disaster relief environment, which is tentatively called “lateral information sharing”.

The System architecture chapter (pp. 140-166) defines a specific blueprint of a technological artefact that enables lateral information sharing, then provides a partially instantiated prototype as an illustrated example, with accompanying description of missing components that are mature, proven, and readily accessible capabilities that do not constitute original research. Most of the technical details are not necessary in order to understand how the system functions and have been moved to the appendices to avoid clutter and confusion. While many of the system’s details are unnecessary for academic research, it would be invaluable for others actively pursuing the solution.
The Discussion chapter (pp. 167-191) describes the implications and limitations of the findings in previous chapters, and the limitations of the methodologies used. The core assumptions underlying different parts of the research process are stated and their falsifiability discussed. The Conclusion chapter (pp. 192-202) briefly restates the original contributions, their implications for research and practice, and outlines future research directions for interagency coordination, lateral information sharing, and related topics.

At the end of the thesis there are two appendices. Appendix A: Vensim equations (pp. 230-240) covers the equations used in the system dynamics simulations in the Supply chain simulation chapter (pp. 103-124). Appendix B: Technical annex (pp. 241-270) covers the technical specifications and implementation instructions for the prototype instantiation of the system architecture in the System architecture chapter (pp. 140-166), however it is included ‘for your information’ only and is not ready for field deployment.
2. Literature review

2.1. Introduction

The previous Introduction chapter (pp. 1-20) identified poor interagency coordination in disaster relief as the research problem and defined the research question. The current state of humanitarian logistics is examined to identify unresolved issues related to interagency coordination, then synthesised to define the boundaries of the thesis research. Then the disaster relief environment is viewed from several theoretical perspectives to explain why these problems remain unresolved. Interagency coordination continues to be problematic because of environmental issues that have never been resolved using supply chain strategies and techniques. Traditional approaches have limited applicability to a volatile yet seemingly non-competitive environment. Academia continues to publish proposals for solutions, but many of these approaches are unsuitable due to unrealistic assumptions regarding high information visibility and/or assumptions of scalable information sharing processes. By surveying the academic and practitioner literature, research gaps are identified.

2.2. Current state of humanitarian logistics

There are fundamental differences between humanitarian logistics for disaster relief and traditional supply chains. Most of these differences stem from a highly uncertain environment, a largely decentralised and ad hoc community of aid agencies, and inadequate resources. Arguably, natural disasters are sources of supply chain disruption. There is a lack of interagency coordination in disaster relief, which is caused by a lack of information sharing.
Since information visibility is generally very poor, and what information is gathered often does not meet the needs of humanitarian logisticians, little information is shared. The existing literature on their relationships is surveyed to explain why interagency coordination remains an unresolved issue.

2.2.1. **Disasters as supply chain disruptions**

Interagency coordination problems in disaster relief can be seen from the perspective of supply chain disruption, which is part of the wider field of supply chain risk management. This is only partially correct, since disruption implies a disturbance in the normal flow of goods and services, whereas high demand variability and uncertainty are normal in the response stage of disaster relief. The occurrence of supply chain disruptions is inextricably tied to supply chain coordination, supply chain risk mitigation, and information visibility. Research into supply chain disruption is cross-disciplinary (Sodhi, Son, & Tang, 2012). While there has been increasing research into both supply chain vulnerability due to globalisation and development of increasingly agile supply chains, disaster relief is inherently vulnerable due to its natural uncertainty (Balcik & Beamon, 2008). Supply chain networks are at risk of disruption, and failure at any node can create cascading network effects, causing the entire network to fail (Danese, Romano, & Formentini, 2013). Disruptions in one node of the supply chain can be amplified across the rest of the supply chain (e.g. Lee, Padmanabhan, & Whang, 1997). To mitigate vulnerabilities, supply chain resilience is required (Christopher, Lowson, & Peck, 2004) to protect against supply chain ‘errors’, which is an umbrella term for mistakes in planning and execution. Risk is inherently about uncertainty and can be described as the intersection of the likelihood and the impact of any given risk (Waters, 2011).
Before a risk can be assessed, it must first be identified. Peck (2005, p. 218) suggests viewing the supply chain as an adaptive system, with various levels of integration (e.g. operational processes, infrastructure dependencies, trading relationships) that must be examined independently and in conjunction with one another for comprehensive risk analysis. Blackhurst, Craighead, Elkins, and Handfield (2005, p. 4073) state that supply chain visibility is critical to identifying supply chain risks, which must be coupled with predictive analyses to actively search for risks. Yet in disaster relief, supply chain uncertainty is not only rife (Balcik & Beamon, 2008), but humanitarian disaster events are an inescapable driver of supply chain disruption (Chopra & Sodhi, 2004, p. 54).

Tang and Musa (2011, pp. 28-30) comprehensively categorise the standard risk mitigation techniques, stating that supply chain visibility is critical to risks associated with information flow, which incidentally is related to all other risk categories. Beyond issues of information visibility, transportation disruptions are an inherent part of disaster relief (Wilson, 2007), where transportation networks will be disrupted by damage from the disaster reducing capacity throughput (Kwasinski, Weaver, Chapman, & Krein, 2009), while traffic congestion from refugees and incoming aid increases the strain on the network. Chopra & Sodhi (2004, p.60) provide a comprehensive and dynamic approach to risk mitigation yet underlying all their approaches is the implicit assumption of supply chain visibility.

Braunscheidel and Suresh (2009, p. 134) states that the operational drivers to supply chain resilience are as follows: (1) Product mix flexibility, or quickly changing the product mix being produced, (2) Volume flexibility, or quickly changing production volume, (3) Internal integration, or being able to integrate with other departments within an organisation, (4) External integration with suppliers, such as formal information sharing agreements, and (5)
External integration with customers. Arguably, all those drivers are related to information visibility. For example, internal integration cannot occur without visibility of supply chain processes and its information flow. Tang and Tomlin (2008, p. 15) suggest that supply chain flexibility can be used to mitigate supply chain risks, but its underlying mechanisms all rely on either internal or external information visibility.

### 2.2.2. Lack of interagency coordination

Supply chain coordination and supply chain collaboration in disaster relief are collectively called “interagency coordination” in the humanitarian sector and constitute the primary determinants of disaster relief supply chain performance (Akhtar, Marr, & Garnevska, 2012). No organisation has either the capacity or the expertise to effectively respond to a disaster alone (Haver & Foley, 2011, p. 7). For example, although large national organisations such as the military have vast resources, they lack the interpersonal linkages that small local NGOs have with the community (e.g. local churches). Interagency coordination is essential to achieving what little information visibility can be gained in the downstream supply chain (Tatham, Spens, & Kovács, 2017). However, interagency coordination is problematic and chaotic, with repeated calls by researchers (van der Laan, de Brito, & van Fenema, 2009) and practitioners (Balcik, Beamon, Krejci, Muramatsu, & Ramirez, 2010) alike for greater cooperation for almost a decade.

It is typical for hundreds of aid agencies, most of which are small local organisations, to be involved in disaster relief in a disaster zone (Van Wassenhove, 2006). For example, interagency coordination was practically impossible using manual coordination methods during the 2010 Haiti Earthquake, when over 900 NGOs converged on a United Nations
coordination meeting (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012),
most of whom could not fit in the room and many of whom could not speak the same language
as United Nations personnel. Often a lack of trust between organisations impedes disaster
response, as different cultures (Dowty & Wallace, 2010), incentives, and values systems clash
(Harvey & Harmer, 2011), as well as the fear of a media ‘witch hunt’ after supply chain risks
materialise and the public, aid agency senior management, and/or donors want to find
someone to blame (Büscher, Easton, Kuhnert, Wietfeld, Ahlsén, Pottebaum, & Van Veelen,

In a case study of the massive training exercise in the United Kingdom, Salmon,
Stanton, Jenkins, and Walker (2011, p. 153) outlined over two dozen factors negatively affecting
interagency coordination, mostly clustering around the following issues: (1) Coordination
issues, such as inappropriate command structures for a decentralised environment, and
uncertain and conflicting procedures, roles, and objectives across aid agencies, (2) Incomplete
operating pictures, which were highly fragmented and inconsistently viewed across aid
agencies, (3) Inadequate information flows, which often involved gathering and recording
incomplete and inconsistent information, delivered using incompatible processes and
technology and (4) Lack of interagency competence, such as lack of experience and training in
interagency coordination issues, and a lack of common coordination frameworks.

The disaster relief environment is typified by uncertainty (Carroll & Neu, 2009) and
there is a natural impulse to want to control that uncertainty through centralisation (Bunker,
Ehnis, Levine, Babar, & Sleigh, 2018), such as through centralised information spaces (e.g.
Tatham, Spens, & Kovács, 2017), centralised coordination authorities (e.g. Akhtar, Marr, &
Garnevska, 2012), centralised information standards (e.g. Fabbe-Costes & Jahre, 2015), or the
centralised, widespread adoption of a single solution (Day, Junglas, & Silva, 2009). The introduction of commonly held standards (Fabbe-Costes & Jahre, 2015) would improve information flows and visibility by creating commonly held assumptions, yet in such a highly fragmented (Maon, Lindgreen, & Vanhamme, 2009) and ad hoc environment (Day, Junglas, & Silva, 2009) a centralised standard and/or centralised coordination authority is unlikely to be adopted. As humorously illustrated in Figure 2.1 (p. 27) below, there is a tendency for experts to cause multiple standards to proliferate. When there are many competing standards with limited interoperability, and those standards already have things built using them, and/or authorities have no way to force the widespread adoption of their preferred standard, experts tend to create and promote a new unified standard. Instead of everyone migrating to the new standard, there is limited adoption at best, which leads to even more confusion and splintering of the market.

For information flows to be improved, the information must be visible in the first place. Both in academia (e.g. Maon, Lindgreen, & Vanhamme, 2009; Jahre & Jensen, 2010; Schulz & Blecken, 2010) and humanitarian logistics (e.g. Larson, Metzger, & Cahn, 2006; Patel, 2009; Bozkurt & Duran, 2012), there has been a reflexive move towards solutions to enable supply chain coordination that involve high degrees of centralisation. However, the disaster relief environment is widely understood to be highly and inescapably decentralised (Gatignon, Van Wassenhove, & Charles, 2010; Akhtar, Marr, & Garnevska, 2012; Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012), which affects the feasibility of proposed solutions based heavily in centralisation. The problem of centralisation is that it is usually inflexible (Kovács & Tatham, 2009, pp. 220-224), or involves some degree of coordination in the middle and/or bottom (Overstreet, Hall, Hanna, & Rainer, 2011, p. 123) where the larger the network,
the more connections a network has, and the more valuable the network becomes. However, conversely, more connections also result in more coordination costs. Until the costs of coordination in time, resources, and personnel become negligible across a large network of independent aid agencies, centralised coordination will continue to unfeasible or inefficient.

Figure 2.1: Comic strip illustrating problem of introducing new standards
(Munroe, n.d.)

The key inhibitors to these forms of centralisation are the large numbers of aid agencies of different sizes and missions (Moshtari & Gonçalves, 2016), the ad hoc nature of interactions (Taylor & Pettit, 2009), the lack of interoperable information sharing standards and their technological facilitators (Fabbe-Costes & Jahre, 2015), the lack of interoperable equipment (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012) and, perhaps most importantly, the lack of supply chain visibility when operations move closer to the disaster zone (Ngwenya and Naude, 2016). Humanitarian logisticians have consistently stated their
concerns about information visibility and interagency coordination (Sheu, 2007b; Kovács & Spens, 2009; Tatham & Pettit, 2010), with some resigning themselves to the near impossibility of gaining near real-time information visibility (Sheu, 2007b).

Increased virtual integration can enable information visibility (Rai, Patnayakuni, & Seth, 2006) by capturing and disseminating available data, but humanitarian logisticians typically lack digitised processes and information systems (Thomas & Kopczak, 2005). Data collection is difficult enough in disaster relief, but the aggregation of heterogeneous data standards and formats, as well as the uncertainty around data accuracy, render aggregation and analysis very difficult (Day, Junglas, & Silva, 2009, p. 651). The issues limiting interagency coordination are varied, but inextricably linked to one another. Any solution to enabling greater interagency coordination must address all these issues simultaneously, whether using a single solution, or a framework involving multiple solutions.

2.2.3. Lack of information visibility

Francis (2008, p. 182) compared different definitions of supply chain visibility and unified them into a comprehensive definition:

“Supply chain visibility is the identity, location and status of entities transiting the supply chain, captured in timely messages about events, along with the planned and actual dates/times for these events.”

Aid agencies have long known and complained about the lack of information visibility in disaster relief (Henderson, 2007). Information visibility is essential to achieving situational awareness (Harrald, 2006), which is crucial to effectively orient an organisation’s operations
within its environment. The lack of communications equipment, damage to infrastructure, and difficulties accessing the disaster zone limit information visibility to what each individual aid worker can see in their direct field of view. Even with GPS-enabled phones, cellular towers, mobile phones, and radio, there is currently no system to aggregate individual aid workers’ supply chain visibility into a cohesive picture, even across a single aid agency, let alone the entire disaster zone. This is particularly pertinent when considering that the disaster relief effort commonly involves hundreds of organisations operating as aid agencies of varying sizes, all struggling to coordinate their efforts with each other.

There have been some notable attempts to aggregate information on the location of disaster incidents and plot them onto Google Maps, such as during the 2007 San Diego County Fires (Majchrzak & More, 2011) and the 2010 Haiti Earthquake (Yates & Paquette, 2011). In both scenarios, cellular towers were either already available or quickly erected (Crowley & Chan, 2011), enabling mobile phone use. Most regions experiencing a disaster will suffer from severe infrastructure disruption (Coles & Buckle, 2004), such as that seen during the 2011 Tōhoku earthquake and tsunami (UNESCAP, 2011, p. 110). In a catastrophic disaster, everything must be transported from outside the disaster zone, including temporary telecommunications infrastructure and basic supplies. Furthermore, while humanitarian logistics is central to disaster relief operations, it is usually afforded very little attention or recognition of its significance by aid agencies.

The Fritz Institute (Thomas & Kopczak, 2005, p. 5) identified five systemic shortcomings in humanitarian logistics, all of which significantly affect information visibility: (1) Lack of technology, such as information systems automation of logistics, (2) Lack of recognition of the importance of logistics, as shown by aid agencies’ spending priorities, (3) Lack of professional
logisticians, which is caused by extreme work stress, low pay, low support, and a lack of career prospects, (4) Lack of institutional learning, which is affected by the lack of data collection and dissemination, and (5) Limited collaboration between aid agencies. While laptop computers are often involved, there is generally a lack of information systems and an almost purely manual supply chain driven by physical paperwork and Microsoft Excel spreadsheets (Thomas & Kopczak, 2005, p. 6). It has been almost a decade-and-a-half since the Fritz Institute (2005) published their landmark report, but conditions concerning interagency coordination remain largely the same (e.g. Jabbour, Sobreiro, de Sousa Jabbour, de Souza Campos, Mariano, & Renwick, 2017), proving one of the most intractable problems in the field. However, there is increasing recognition from aid agencies that humanitarian logistics is critically important, and that modernisation is needed (Harvard Humanitarian Initiative, 2011). Nevertheless, there are still many hurdles and questions about how to achieve that.

Two examples of this manual approach are detailed by USAID logistics standards (2011, pp. 20-23) and delivery and inventory log sheets by the United Nations (UNHCR, 2007, pp. 447-449). While this is understandable in downstream logistics, since a stable electricity supply becomes scarcer as logistics move closer to the disaster zone, the upstream supply chain is still conducted in areas where there are ample technological resources, undamaged infrastructure, and a stable environment. The Fritz Institute reports that 26% respondents had access to track-and-trace software and 58% claimed information received was accurate and timely, ironically without any means to determine information accuracy or timeliness (Thomas & Kopczak, 2005, p. 6). This may indicate of a lack of understanding or appreciation of modern technology and the time value of data for disaster relief operations. Alternatively, such an inconsistent view could come from the belief and/or experience that the information accuracy and timeliness
achieved during disaster relief operations using existing methods constitute the best possible scenario under trying conditions. The question remains whether or not there are better alternatives.

The importance of supply chain visibility to supply chain disruption has long been established (e.g. Lee, Padmanabhan, & Whang, 1997). Bartlett, Julien, and Baines (2007, pp. 311-312) build on Lamming, Caldwell, Harrison, and Phillips’ (2001) concept of supply chain transparency to develop a framework for assessing levels of information visibility, and by using a case study they find that information sharing (e.g. audits, joint programmes, formal sharing agreements) underlies all dimensions of supply chain visibility. Barratt and Oke (2007, p. 1219) uncovered the antecedents of supply chain visibility: (1) External linkages, (2) Technological antecedents to information sharing, such as electronic data interchange and collaborative planning systems and (3) Non-technological antecedents to information sharing, such as face-to-face coordination meetings. Caridi, Crippa, Perrego, Sianesi, and Tumino (2009) found that the degree of supply chain complexity affects supply chain visibility, stating that with increasing complexity, such as with uncertain supply agreements and many supply chain partners and echelons, increasing information visibility is required to mitigate supply chain risks.

Disaster relief supply chains are inherently complex due to the high incidence of supply chain disruptions (Carroll & Neu, 2009) from infrastructure damage, congestion, and the ad hoc nature of their downstream distribution patterns (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012). Information visibility underlies risk identification and risk mitigation for supply chain disruptions. Bhimani and Song (2016, p. 22) identified that most academic research into humanitarian logistics focused on mathematical models (e.g. risk
analysis, prepositioning supplies, supply distribution) with an implicit assumption of high degrees of information visibility, whereas practitioner needs differed significantly, where the main issues for aid agencies were achieving information visibility (e.g. decision support systems, coordination mechanisms, efficiency indicators) and adopting best practices from traditional supply chains (e.g. radio frequency identification, agile).

2.2.4. Information needs of humanitarian logistics

Bharosa, Lee, and Janssen (2010, pp. 55-57) state that interagency coordination through information sharing is a critical disaster communication need in the form of feedback mechanisms, procedures, interagency communication channels, information filtering, and selective dissemination. Day, Junglas, and Silva (2009, p. 643) note that data unreliability, inaccessibility, and the presence of heterogeneous data standards inhibit information flows in disaster relief. A major issue is the willingness to trust others with their own information (Harvey & Harmer, 2011) in the face of legal, ethical, and competence concerns (Büscher, Easton, Kuhnert, Wietfeld, Ahlsén, Pottebaum, & Van Veelen, 2014). Bharosa, Lee, and Janssen (2010, p. 57) claim that if the users have faith in the systems used in disaster communications and have knowledge of their partners’ processes and procedures, they will be more willing to share information. Tatham and Kovács (2010) explain that swift trust is necessary given the time and resource constraints in a highly uncertain environment, which can be summarised as trust now, but verify later.

The specific information needed by humanitarian logisticians relate to the order fulfilment cycle (USAID, 2011), such as requisition orders, inventory levels, and lead times, and those variables that affect them. What has not been addressed in the literature (cf. Comfort, Ko,
whether the means of information sharing are scalable. The need for demand information on relief supplies required and disaster zone conditions are usually satisfied by manual processes such as telephone calls to individuals from the affected population and physical questionnaires (Tapia, Bajpai, Jansen, Yen, & Giles, 2011), which are slow, personnel-, time-, and resource-intensive and therefore not scalable. In disaster response there is either a deluge of data with no means to analyse it or the near complete absence of any data (Comfort, Ko, & Zagorecki, 2004). Disaster relief is typically understaffed and underfunded, which implies that instead of using more resources, the only means to scale up information sharing is to at least partially automate the information flow, particularly around data collection and analysis.

2.3. Perspectives from strategic management theory

The problems in the current state of humanitarian logistics can be interpreted from the perspective of strategic management theory. Several theories of the firm offer useful insights for why NGOs exist and what are the nature of their capabilities and problems. While the concept of competitive advantage in theories of the firm is not perfectly applicable to disaster relief, aid agencies can be viewed as competing against a common ‘adversary’ in the form of a disaster event during disaster relief operations. Between disaster relief operations, NGOs will have to compete with one another for funding from major donors, who will judge NGOs’ performance against their historical operations. Here several theories of the firm are used to interpret the nature of interagency coordination capabilities and by extension their problems.
2.3.1. Resource-based view

The resource-based view of the firm (Barney, 1991) explains how firms can develop a sustainable competitive advantage through their resources. These resources can be physical or intangible; knowledge is often considered the most strategic resource in a firm (Hult, Ketchen, Cavusgil, & Calantone, 2006). In industry, bundles of resources (Barney, 1991) determine the different product and service attributes of a firm (Schulze, 1994), yet in humanitarian logistics while each agency is competing with one another for donations they are also in cooperation towards a common humanitarian objective (Calhoun, 2008). In a sense, in disaster relief each agency offering humanitarian logistics aid is providing similar, if not identical products and services (Martens, 2005).

However, NGOs do in fact differentiate from one another through their humanitarian scope (Barnett, 2011) and control of information as a resource directly affects its position in the wider relief effort. One crucial resource that larger NGOs and particularly international NGOs lack is the tacit local knowledge as to the environmental conditions, customs, and culture of the disaster zone which are socially complex (Dierickx & Cool, 1989), whereas they are more likely to possess expert technical knowledge (Wisner, 1995). It is a widely accepted humanitarian principle to create sustainable disaster relief outcomes by including small and local NGOs (Slim, 2015), precisely because they possess that local knowledge (Grant, 1996), which creates a distinctive form of information visibility that delivers a sustainable competitive advantage. For example, if an NGO goes into a disaster zone and immediately distributes aid without consideration of local markets, they may inadvertently flood the market of a good and crash the price, leading to widespread poverty, whereas perhaps a wiser approach is to use the local markets to deliver aid. This is not an unusual outcome of noble humanitarian intentions.
Resources must have the following characteristics to deliver a sustainable competitive advantage (Barney, 1991): (1) Improve firm performance, which here would be supply chain efficiency as measured by deprivation costs and/or inventory backlogs, (2) Rare, desirable, and controlled by the firm, where the advantage gained is useful and belongs to the organisation; (3) Imperfectly imitable to prevent development by competitors, so rivals cannot simply easily replicate an organisation’s advantage and eliminate it, (4) Imperfectly mobile, where the advantage is difficult to transfer from one place to another, which also makes it difficult to copy on a large scale, and (5) Not easily substitutable, where the advantage cannot be replaced by an alternative that still meets the customers’ expectations. Downstream demand information in humanitarian logistics is rarely achieved (Sheu, 2010), yet would improve disaster relief efforts immensely. Such information, extracted through local knowledge, is difficult to replicate (Kogut & Zander, 1992). Instead, humanitarian logisticians usually must rely on push strategies to estimate aggregate demand (Afshar & Haghani, 2012) as a poor substitute for real-time demand information. Information visibility is the outcome of information sharing, which improves firm performance and creates a sustainable competitive advantage (Barratt & Oke, 2007, p. 1219).

Information technology is a strategic resource where humanitarian logistics tends to be lacking (Thomas & Kopczak, 2005, p. 6). Developments in information technology have enabled increasing supply chain integration (Rai, Patnayakuni, & Seth, 2006), information sharing (Monczka & Carter, 1988) and real-time demand information (Christopher, Lowson, & Peck, 2004) from point-of-sale data at the customer end. Given the lack of resources at humanitarian logisticians’ disposal, they do not possess the necessary financial capital to invest in complex information systems or training in their uses (Thomas & Kopczak, 2005, p. 6), even if these
systems would improve supply chain performance. While information technology can be an enabler of information sharing (Barratt & Oke, 2007, p. 1228), it is by no means a guarantor. There may be behavioural, cultural, political, legal, ethical, and competitive (Fawcett, Osterhaus, Magnan, Brau, & McCarter, 2007) issues inhibiting information sharing (Day, Junglas, & Silva, 2009) that go beyond technological means.

### 2.3.2. Knowledge-based view

The knowledge-based view of the firm extends the resource-based view to see knowledge as a unique strategic resource with special characteristics (Conner, 1991). Knowledge acquisition will inherently affect knowledge dissemination, and both types of activities inherently affect the cycle time between knowledge generation and creating a shared meaning (Hult, Ketchen, & Slater, 2004, p. 242). The knowledge-based view posits that sustainable competitive advantages arise from the cooperative creation, coordination, transfer, and integration of knowledge (Conner & Prahalad, 1996). Here knowledge is referred to as expert insight (Conner, 1991), going beyond mere information to include the ability to process that information and develop useful insights. Knowledge can be tacit, such as the learned improvisation strategies by aid agencies, or explicit, such as formalised procedures for order fulfilment (Nonaka, 1994). The dynamic process of knowledge creation occurs through the combination of prior knowledge, internalisation of newly created knowledge, socialisation of knowledge outcomes, and externalisation of knowledge to other individuals and organisations (Nonaka, 1994).

The question becomes, why is knowledge being referred to when discussing the inherent inhibitors to information sharing in humanitarian logistics? The information available to aid agencies can be overwhelming in its volume (Day, Junglas, & Silva, 2009, p. 647). Yet it is
not necessarily the high volume of data that is the issue, but that non-scalable processes of data analysis and dissemination (Thomas & Kopczak, 2005; Cayirci & Coplu, 2007; Gao, Barbier, & Goolsby, 2011) within aid agencies are easily overwhelmed. Many resource-based solutions to information visibility and supply chain collaboration (e.g. Privett, 2015) argue that the introduction of these strategic resources can help humanitarian logisticians. Humanitarian logistics lacks the professionalisation and training to develop insights from information (Thomas & Kopczak, 2005, pp. 5-6), so without the means to develop insights and knowledge from information, increased information sharing alone will not benefit aid agencies’ firm performance. This is exacerbated by the low pay, high workload, and high stress environment humanitarian logisticians face, leading to exceptionally high turnover rates (Thomas & Kopczak, 2005), inhibiting the retention and communication of knowledge.

Organisations can create knowledge by supply chain collaboration, but when the context is not considered beneficial to both parties the knowledge creation process fails (Samuel, Goury, Gunasekaran, & Spalanzani, 2011, p. 297). A novel form of knowledge creation is the crowdsourcing of social media data for disaster relief (Tapia, Bajpai, Jansen, Yen, & Giles, 2011), where the creation and dissemination ostensibly occur outside humanitarian logisticians’ aid agencies. With the advent of big data analytics, there is now a means to automate the creation of knowledge from large data sets (Chen, Chiang, Storey, 2012), including unstructured data sets (Gandomi & Haider, 2015). This avoids the issue of humanitarian logisticians’ lack of resources by placing data analysis outside the aid agency
2.3.3. **Transaction cost theory**

Transaction cost theory contends that organisations exist because they can organise resources to minimise transaction costs to achieve a competitive advantage, while transaction cost economics consider organisational activities as having coordination and usage costs when viewed as transactions (Barney, 1991). The transaction costs of information sharing are significant in the disaster relief environment (Day, Junglas, & Silva, 2009), which make interagency coordination difficult (Akhtar, Marr, & Garnevska, 2012), while the formation of aid agencies as organisations and their partnerships reduces the transaction costs of this coordination through common mental frameworks and existing relationships. Transaction costs associated with coordination are reduced with information systems and information sharing (Lewis & Talalayevsky, 2004). Trust affects the transaction costs of information sharing and coordination (Kwon & Suh, 2004), such as by inhibiting information sharing or by requiring onerous conditions to offset perceived risks. Although swift trust is used by humanitarian logisticians (Tatham & Kovács, 2010), there are still significant trust issues (Day, Junglas, & Silva, 2009; Büscher, Easton, Kuhnert, Wietfeld, Ahlsén, Pottebaum, & Van Veelen, 2014).

2.4. **Current solutions to interagency coordination problems**

There are marked differences between the environments for disaster relief and traditional supply chains. While they are technically from the same discipline, their wildly different challenges and available resources cause differences in supply chain behaviour. Information sharing is one of the most important advances in supply chain theory and practice. However, the difficulty of accessing and sharing information in disaster relief due to environmental
factors and a lack of available resources means that many of the most advanced supply chain
techniques and strategies are not available to humanitarian logisticians. This section deals with
some standard ways to circumvent the issues of poor interagency coordination without dealing
with the expensive and time-consuming underlying structural issues. Despite the difficulties
and inhibitors of interagency coordination, aid agencies continue to try to improve. Ultimately,
a ‘good-enough’ solution needs to arrive in 72 hours and be maintained, rather than a perfect
solution arriving several days late.

The most modern operations and supply chain management techniques in a commercial
supply chain relies on using information systems and telecommunication technologies that are
often absent from disaster zones and their associated refugee camps. Operations research relies
on optimising the mathematical relationships between variables, yet uncovering those
relationships requires a high degree of information visibility in the first place. Aid agencies
lack information visibility in their supply chains (Henderson, 2007), flexibility in their
operations, and interagency coordination, which leads to inefficient aid distribution to the
affected population, due to incorrect demand identification and/or estimates, and problems
with inventory control, due to supply chain volatility. While the resources supplied to disaster
zones are usually insufficient, this does not make supply chain volatility an inescapable issue—it
is fundamentally a question of degree of effect. The supply chain throughput capacity
entering a disaster zone is usually highly limited. When aid agencies discover that resources
are being used up, destroyed, or lost at an accelerated rate, they must replenish those resources
and anticipate future needs of the affected population.

The severe lack of information visibility intensifies the supply chain volatility in
inventory levels and ordering quantities, as demand variability is amplified when moving from
downstream to upstream echelons of a supply chain, a phenomenon called the “bullwhip effect” (Lee, Padmanabhan, & Whang, 1997). Information sharing and business integration, which requires information sharing, have become the cornerstones of modern supply chain theory and practice, yet they currently have limited applicability to disaster relief. To put it bluntly, the reliability of mathematical supply chain models, and the technology-supported processes using those models, will always be constrained by downstream information visibility and its effect on timely and accurate data collection (Caunhye, Nie, & Pokharel, 2012).

2.4.1. Traditional supply chain approaches to volatility

When faced with highly volatile markets, there are strategies from traditional supply chains that directly address volatility with flexibility and responsiveness. However, they may require adaptation before being applied to disaster relief. Table 2.1 (p. 41) below compares some common supply chain coordination mechanisms currently used in disaster relief with those used in traditional supply chains for volatile markets, across the dimensions of resource sharing, control, risks and rewards, and styles of decision-making. Many of these mechanisms require a close level of business integration, while others have highly centralised decision-making structures that are incompatible with the highly decentralised disaster environment.
Agile, leagile, and quick response supply chains are various closely related strategies for channel coordination. Baramichai, Zimmers, and Marangos (2007, p. 335) define agility as follows:

“An agile supply chain is an integration of business partners to enable new competencies to... respond to rapidly changing, continually fragmenting markets. The key enablers of the agile supply chain are the dynamics of structures and relationship configuration, the end-to-end visibility of information, and the event-driven and event-based management. An agile supply chain is a key enabler for an enterprise’s agility.”

There is anything but end-to-end information visibility in disaster relief (Thomas & Kopczak, 2005, p. 5), but the agile strategy is more relevant to the hybrid strategy of leagile, which combines agile and lean strategies. Naylor, Naim, and Berry (1999, p. 108) define agility and leaness in the context of leagility as follows:

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<table>
<thead>
<tr>
<th>Coordination Mechanism</th>
<th>Resource Sharing Structure</th>
<th>Level of Control</th>
<th>Risk/Reward Sharing</th>
<th>Decision Style</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quick Response</td>
<td>Operational</td>
<td>High</td>
<td>Unfair</td>
<td>Centralized</td>
</tr>
<tr>
<td>Continuous Replenishment</td>
<td>Operational</td>
<td>High</td>
<td>Unfair</td>
<td>Centralized</td>
</tr>
<tr>
<td>Vendor Managed Inventory (VMI)</td>
<td>Tactical</td>
<td>High</td>
<td>Fair</td>
<td>Decentralized</td>
</tr>
<tr>
<td>Consignment VMI</td>
<td>Tactical</td>
<td>High</td>
<td>Unfair</td>
<td>Decentralized</td>
</tr>
<tr>
<td>Collaborative Procurement</td>
<td>Tactical</td>
<td>Low</td>
<td>Fair</td>
<td>Decentralized</td>
</tr>
<tr>
<td>Warehouse Standardization</td>
<td>Operational</td>
<td>High</td>
<td>Unfair</td>
<td>Centralized</td>
</tr>
<tr>
<td>Third Party Warehousing</td>
<td>Strategic</td>
<td>Low</td>
<td>Fair</td>
<td>Decentralized</td>
</tr>
<tr>
<td>Transportation Shipper Collaboration</td>
<td>Strategic</td>
<td>Low</td>
<td>Fair</td>
<td>Decentralized</td>
</tr>
<tr>
<td>Forth Party Logistics (4PL)</td>
<td>Strategic</td>
<td>Low</td>
<td>Fair</td>
<td>Decentralized</td>
</tr>
</tbody>
</table>

Table 2.1: Characteristics of supply chain coordination mechanisms
(Balcik, Beamon, Krejci, Muramatsu, & Ramirez, 2010, p.30)
“Agility means using market knowledge and a virtual corporation to exploit profitable opportunities in a volatile market place. Leanness means developing a value stream to eliminate all waste, including time, and to ensure a level schedule... The decoupling point separates the... part of the organisation [supply chain] oriented towards customer orders from the part of the organisation [supply chain] based on planning.”

“Push” refers to top-down supply allocation near the original supplier, while “pull” refers to bottom-up requisitions from the retailers as they observe demand from end-customers, while the push-pull boundary, or ‘decoupling point’, refers to the point in the supply chain where top-down allocation switches to bottom-up requisition for determining order quantities (USAID, 2011, pp. 11-14). Postponing the pull portion of the supply chain is critical to achieving efficiency while still retaining flexibility. This strategy is heavily used in humanitarian logistics and manifests itself in several ways. Demand pull can be postponed through standardising products around a few multi-role relief items (Tomasini & Van Wassenhove, 2009, p. 551), centralising supplies into pre-positioned regional warehouses (Bozkurt & Duran, 2012), and utilising push as the primary means of coordination in the initial phases of disaster response before increasingly transitioning towards pull (Oloruntoba & Gray, 2006, pp. 117-118).

Quick response is a related technique that pushes agile and some parts of leagile into the extreme to deal with extreme volatility and short time horizons, but its applicability to disaster relief is highly questionable. Lowson, King, and Hunter (1999) define quick response as follows:
“A state of responsiveness and flexibility in which an organisation seeks to provide a highly diverse range of products and services to a customer in the exact quantity, variety and quality, and at the right time, place and price as dictated by real-time customer/consumer demand.”

Originally, quick response was an operations management paradigm from manufacturing (Upton, 1995; Fisher & Raman, 1996) to quickly change purchasing processes, production processes, pricing policies, and was soon integrated into supply chain distribution (Lummus & Vokurka, 1999, p. 13; de Treville, Shapiro, & Hameri, 2004; Cachon & Swinney, 2009), to quickly meet changes in customer demand. The paradigm was found to be particularly suitable for application in the fast-moving consumer goods industries (e.g. Fiorito, May, Straughn, 1995; Fernie & Staines, 2001; Birtwistle, Fiorito & Moore, 2006) or in fashionable apparel and accessories (e.g. Christopher, Lowson, & Peck, 2004; Cachon & Swinney, 2011), where demand can be volatile. Components of quick response can be categorised according to where they are found (Fiorito, May, & Straughn, 1995, p. 13-15): (1) Partnerships (e.g. vertical integration), (2) Virtual integration (e.g. electronic data interchange) and (3) Process engineering (e.g. just in time).

Currently, the humanitarian logistics and disaster relief literature has interpreted the related fields of quick response and agility in supply chain management only from an operations research perspective (Simpson & Hancock, 2009; Caunhye, Nie, & Pokharel, 2012, pp. 6-9; de la Torre, Dolinskaya, & Smilowitz, 2012, p. 91) or in terms of general lean and agile principles (Van Wassenhove, 2006; Oloruntoba & Gray, 2006; Scholten, Scott, & Fynes, 2010). The operations research literature focuses on inventory modelling (Ozbay & Ozguven, 2007; Taskina & Lodree, 2010; Lodree, 2011; Bozkurt & Duran, 2012) and distribution patterns (Sheu, 2007b; Yuan & Wang, 2009; Saith & Wilfredo, 2009) in the event of different emergencies and
disasters. There have been some notable attempts to integrate the visibility component in quick response, such as ‘demand’ reporting of the location and type of disasters by individuals from the affected population (e.g. Morrow, Mock, Papendieck, & Kocmich, 2011, p. 19) ostensibly from outside academia, or the recommended adoption of radio frequency identification tagging to manage inventory and supply chain flows (Ozguven & Ozbay, 2012; Yang, Yang, & Yang, 2011). However, quick response has largely been out of reach due to the high visibility requirements (Sheu, 2007a, pp. 655-656; Choi & Sethi, 2010; Day, Junglas, & Silva, 2009, pp. 251-652).

There are also some nascent efforts to improve information sharing directly. Humanitarian Data Exchange (HDX, n.d.) programme shares spreadsheets with standardised metadata tagging according to a common Humanitarian Exchange Language (HXL). While the online platform is available to everyone, tagging each part of a spreadsheet is still done manually, which is time and personnel-intensive and therefore not particularly scalable. Salmon, Stanton, Jenkins, and Walker (2011, p. 156) describe an approach from the opposite direction, where simple common mental frameworks are used during planning and coordination meetings to address interagency coordination issues. These include maintaining a mission analysis record and list of resources, developing critical information requirements, and assigning roles for aid agencies on a synchronisation matrix. Again, these manual solutions are heavily personnel- and time-intensive and of questionable scalability.

2.4.2. Barriers to traditional supply chain strategies to managing volatility

In disaster relief, information visibility is lacking in and near the disaster zone (Thomas & Kopczak, 2005, p. 5) due to damage to telecommunications infrastructure (Coles & Buckle,
2004; Henderson, 2007; UNESCAP, 2011, p. 110) and a lack of resources and funding (McEntire, 1999, p. 356; de la Torre, Dolinskaya, & Smilowitz, 2012, p. 92). Technologies for track-and-trace (e.g. RFID) are limited due to the highly fragmented and ad hoc nature of the supply chain (Thomas & Kopczak, 2005, p. 12; Van Wassenhove, 2006, p. 477; Carroll & Neu, 2009, p. 1034), particularly as one moves further downstream. Additionally, implementing widespread track-and-trace capabilities carries prohibitive costs, high risks, and involves standardising processes (Wu & Lirn, 2011; Baldini, Oliveri, Braun, Seuschek, & Hess, 2012) in what are technologically backward organisations (Thomas & Kopczak, 2005, p. 6). Widely volatile demand and lead times (Sheu, 2007a, pp. 655-656) make the need for information visibility more crucial.

Quick response offers a lot of promise, but it is uncertain how the centralisation and technology requirements could ever be met in a disaster relief environment. Quick response has three main characteristics (Choi & Sethi, 2010, pp. 2-6): (1) Supply information management (e.g. different modes of delivery, routing, coordination through contracts), (2) Demand information management (e.g. advance demand data, dynamic pricing) and (3) Value of information and supporting technology (e.g. VMI, RFID, ERP). The most common theme in quick response literature for commercial supply chains is the need for high levels of information visibility (Sabath, 1995; Richardson, 1996; Christopher, 2000; Perry & Sohal, 2000, p. 638; Gunasekaran, Patel, & Tirtiroglu, 2001, p. 83; Choi & Sethi, 2010, pp. 2-6), or at least an approximation through close partnerships and information sharing (e.g. Whiteoak, 1993, p. 9; Fiorito, May, & Straughn, 1995, pp. 13-15; Day, Junglas, & Silva, 2009, pp. 651-652).

Choi and Sethi (2010) describe a selection of innovative quick response solutions in commercial supply chains (e.g. enterprise resource planning, radio frequency identification,
advance demand information). Many of these solutions are not currently used or widely adopted in disaster relief (Fritz Institute, 2005) due to technological or information visibility constraints (Harvey, Stoddard, Harmer, Taylor, DiDomenico, & Brander, 2010), whereas others are considered inappropriate for the humanitarian objective of minimising deprivation costs (e.g. dynamic pricing). Humanitarian logistics already heavily employs leagility to ‘push’ standardised items in high volume and ‘pull’ low volume items (USAID, 2011, pp. 11-13), but it has yet to integrate the more technological elements of pulling demand information.

There are two overarching and systemic shortcomings in the current NGO ecosystem that serve as barriers to the implementation of quick response, both of which are heavily interrelated: (1) Lack of information visibility and (2) Lack of interagency coordination. This lack of visibility has varied causes (Day, Junglas, & Silva, 2009, pp. 651-652), most of which are technical difficulties related to resources and processes, and some of which are related to a lack of trust (Perry, 2007). Due to the lack of accurate and usable information, extreme time pressure, and the enormous amount of resources required to implement existing technological solutions, perhaps the lack of trust is caused by the inherent instability and dynamism of disaster relief, as opposed to a genuine distrust of the intentions or competence of others. Without further research, this only remains a suspicion.

By examining and comparing the antecedents (i.e. characteristics, determinants, drivers) behind agile, leagile, and quick response strategies, common themes are identified. The common antecedents are: (1) Partnerships, (2) Information technology integration, (3) Market responsiveness, (4) Process engineering and (5) Supply chain flexibility. Partnerships (e.g. Christopher, 2000) involve information sharing, but also collaborative planning (e.g. Agarwal, Shankar, & Tiwari, 2007). Information technology integration (e.g. Ngai, Chau, & Chan, 2011),
can help facilitate partnerships, as well as enable performance measurement for market responsiveness (Choi & Sethi, 2010). Process engineering can make processes more efficient by eliminating waste and streamlining complexity (Ismail & Sharifi, 2006), enabling supply chain flexibility (Baramichai, Zimmers, & Marangos, 2007), and potentially reducing supply chain risks (Caridi, Crippa, Perrego, Sianesi, and Tumino, 2009). A comparison of current solutions and unresolved challenges in disaster relief are summarised in Table 2.5 (p. 49) below, which are viewed through the intersection of common themes for antecedents to agile in Table 2.2 (p. 48) below, leagile in Table 2.3 (p. 48) below, and quick response in Table 2.4 (p. 49) below. Using Lee’s (2002, pp. 108-109) framework for matching supply chain strategy with product uncertainties, the supply chain strategy most suitable to the disaster relief environment sits between the responsive and agile supply chain.

By examining the intersection between supply chain strategy antecedents with the disaster relief environment in Table 2.6 (p. 50) below and Table 2.7 (p. 51) below, missing antecedents to supply chain strategies, common strategies used to resolve challenges, and outstanding issues can be identified. For example, the lack of trust (Day, Junglas, & Silva, 2009) and coordination (Gatignon, Van Wassenhove, & Charles, 2010) exacerbates competition between agencies. Whereas in commercial supply chain, coopetition models (i.e. simultaneous cooperation and competition, Bakshi & Kleindorfer, 2009) and supply contracts (Cachon & Lariviere, 2001), humanitarian logisticians can use swift trust to temporarily assume trustworthiness (Tatham & Kovács, 2010), form partnerships (Thomas & Fritz, 2006), and/or rely on centralised means of coordination (Gatignon, Van Wassenhove, & Charles, 2010). What emerges is that there are multiple unresolved issues in humanitarian logistics that make direct application of agile, leagile, and quick response inappropriate or unfeasible.
### Table 2.2: Antecedents of the agile supply chain strategy by theme

(adapted from Taylor & Arthanari, 2017, p. 2)

<table>
<thead>
<tr>
<th>Antecedent Themes</th>
<th>Antecedents</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A1) Partnerships</td>
<td>Partnerships</td>
<td>Christopher, 2000; Yusuf et al., 2004; Ismail &amp; Sharifi, 2006; Baramichai et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Collaborative Planning</td>
<td>Agarwal et al., 2007</td>
</tr>
<tr>
<td>(A2) IT Integration</td>
<td>IT Integration</td>
<td>Christopher, 2000; Yusuf et al., 2004; White et al., 2005; Ismail &amp; Sharifi, 2006; Agarwal et al., 2007; Baramichai et al., 2007; Swafford et al., 2008; Ngai et al., 2011</td>
</tr>
<tr>
<td></td>
<td>Technological Integration</td>
<td>Ismail &amp; Sharifi, 2006</td>
</tr>
<tr>
<td>(A3) Market Responsiveness</td>
<td>Market Responsiveness</td>
<td>Christopher, 2000; Agarwal et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Performance Measurement</td>
<td>Agarwal et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Process Integration</td>
<td>Agarwal et al., 2007; Christopher, 2000</td>
</tr>
<tr>
<td>(A5) Supply Chain Flexibility</td>
<td>Supply Chain Flexibility</td>
<td>Ismail &amp; Sharifi, 2006; Swafford et al., 2006; Swafford et al., 2008; Ngai et al., 2011</td>
</tr>
<tr>
<td></td>
<td>Supply Chain Integration</td>
<td>Ismail &amp; Sharifi, 2006; Baramichai et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Postponement</td>
<td>Christopher, 2000; Baramichai et al., 2007</td>
</tr>
</tbody>
</table>

Notes: The codes for antecedent themes (e.g. A1) are used in the “Interaction” section of subsequent tables. The codes for antecedent themes are common across multiple tables.

### Table 2.3: Antecedents of leagile supply chain strategy by theme

(adapted from Taylor & Arthanari, 2017, p. 2)

<table>
<thead>
<tr>
<th>Antecedent Themes</th>
<th>Antecedents</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A1) Partnerships</td>
<td>Partnerships</td>
<td>Scholten et al., 2010</td>
</tr>
<tr>
<td>(A2) IT Integration</td>
<td>IT Integration</td>
<td>Naylor et al., 1999; Mason-Jones et al., 2000; Herer et al., 2002; Scholten et al., 2010</td>
</tr>
<tr>
<td>(A3) Market Responsiveness</td>
<td>Market Sensitivity</td>
<td>Naylor et al., 1999; Scholten et al., 2010</td>
</tr>
<tr>
<td></td>
<td>Lead Time Reduction</td>
<td>Naylor et al., 1999</td>
</tr>
<tr>
<td>(A5) Supply Chain Flexibility</td>
<td>Supply Chain Flexibility</td>
<td>Herer et al., 2002</td>
</tr>
<tr>
<td></td>
<td>Supply Chain Integration</td>
<td>Herer et al., 2002; Scholten et al., 2010</td>
</tr>
<tr>
<td></td>
<td>Postponement</td>
<td>Naylor et al., 1999; Scholten et al., 2010</td>
</tr>
<tr>
<td></td>
<td>Continuous Replenishment</td>
<td>Mason-Jones et al., 2000</td>
</tr>
<tr>
<td></td>
<td>Transshipment</td>
<td>Herer et al., 2002</td>
</tr>
</tbody>
</table>

Notes: The codes for antecedent themes (e.g. A1) are used in the “Interaction” section of subsequent tables. The codes for antecedent themes are common across multiple tables.
<table>
<thead>
<tr>
<th>Antecedent Themes</th>
<th>Antecedents</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A1) Partnerships</td>
<td>Partnerships</td>
<td>Perry &amp; Sohal, 2000; Christopher et al., 2004</td>
</tr>
<tr>
<td>(A2) IT Integration</td>
<td>IT Integration</td>
<td>Sabath, 1995; Perry &amp; Sohal, 2000; Christopher et al., 2004; Choi &amp; Sethi, 2010</td>
</tr>
<tr>
<td>(A3) Market Responsiveness</td>
<td>Market Sensitivity</td>
<td>Christopher et al., 2004</td>
</tr>
<tr>
<td></td>
<td>Demand Information</td>
<td>Choi &amp; Sethi, 2010</td>
</tr>
<tr>
<td></td>
<td>Information Sharing</td>
<td>Perry &amp; Sohal, 2000</td>
</tr>
<tr>
<td>(A4) Process Engineering</td>
<td>Process Integration</td>
<td>Christopher et al., 2004</td>
</tr>
<tr>
<td></td>
<td>Lead Time Reduction</td>
<td>Perry &amp; Sohal, 2000</td>
</tr>
<tr>
<td>(A5) Supply Chain Flexibility</td>
<td>Supply Chain Flexibility</td>
<td>Sabath, 1995; Choi &amp; Sethi, 2010</td>
</tr>
<tr>
<td></td>
<td>Supply Chain Integration</td>
<td>Choi &amp; Sethi, 2010</td>
</tr>
<tr>
<td></td>
<td>Supply Contracts</td>
<td>Choi &amp; Sethi, 2010</td>
</tr>
</tbody>
</table>

Notes: The codes for antecedent themes (e.g. A1) are used in the “Interaction” section of subsequent tables. The codes for antecedent themes are common across multiple tables.

Table 2.4: Antecedents of the quick response supply chain strategy by theme
(adapted from Taylor & Arthanari, 2017, p. 2)

<table>
<thead>
<tr>
<th>Characteristic Themes</th>
<th>Characteristics</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C1) Uncertainty</td>
<td>Unstable Environment</td>
<td>Oloruntoba &amp; Gray, 2006; Carroll &amp; Neu, 2009; Charles et al., 2010; Holguín-Veras et al., 2012</td>
</tr>
<tr>
<td></td>
<td>Demand Spike</td>
<td>Carroll &amp; Neu, 2009; Holguín-Veras et al., 2012</td>
</tr>
<tr>
<td>(C2) Lack of Information Visibility</td>
<td>Lack of Information Visibility</td>
<td>Day et al., 2009; Charles et al., 2010; Holguín-Veras et al., 2012</td>
</tr>
<tr>
<td></td>
<td>Lack of Information Processing Capability</td>
<td>Day et al., 2009</td>
</tr>
<tr>
<td>(C3) Lack of Coordination</td>
<td>Fragmented Decision Making</td>
<td>Kovács &amp; Spens, 2009; Holguín-Veras et al., 2012</td>
</tr>
<tr>
<td></td>
<td>Lack of Trust</td>
<td>Day et al., 2009</td>
</tr>
<tr>
<td>(C4) Lack of Resources</td>
<td>Lack of Funding</td>
<td>Oloruntoba &amp; Gray, 2006; Kovács &amp; Spens, 2009</td>
</tr>
<tr>
<td></td>
<td>Lack of Resources</td>
<td>Kovács &amp; Spens, 2009</td>
</tr>
<tr>
<td></td>
<td>Lack of IT</td>
<td>Kovács &amp; Spens, 2009</td>
</tr>
<tr>
<td></td>
<td>Deprivation Costs</td>
<td>Holguín-Veras et al., 2012</td>
</tr>
<tr>
<td>(C5) Material Convergence</td>
<td>Material Convergence</td>
<td>Kovács &amp; Spens, 2009; Holguín-Veras et al., 2012</td>
</tr>
</tbody>
</table>

Notes: The codes for characteristic themes (e.g. C1) are used in the “Interaction” section of subsequent tables. The codes for characteristic themes are common across multiple tables.

Table 2.5: Characteristics of the disaster relief environment by theme
(adapted from Taylor & Arthanari, 2017, p. 2)
<table>
<thead>
<tr>
<th>Interactions</th>
<th>Challenges</th>
<th>Commercial Solutions</th>
<th>Disaster Relief Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1, A1 C3, A1</td>
<td>Lack of Trust (e.g. Day et al., 2009), Lack of Coordination (e.g. Gatignon et al., 2010), Competition between Agencies (e.g. Banomyong et al., 2009)</td>
<td>Coopetition Models (e.g. Bakshi &amp; Kleindorfer, 2009), Supply Contracts (e.g. Cachon &amp; Lariviére, 2001)</td>
<td>Swift Trust (e.g. Tatham &amp; Kovács, 2010), Corporate Partnerships (e.g. Thomas &amp; Fritz, 2006), Centralised Coordination Authority (e.g. Gatignon et al., 2010)</td>
</tr>
<tr>
<td>C1, A2 C2, A2</td>
<td>Lack of IT Usage (e.g. Fritz Institute, 2005), Slow Adoption (e.g. Andresen &amp; Nilsson, 2014)</td>
<td>Increase Investment, Resource Pooling (e.g. Hoang &amp; Rothaermel, 2005)</td>
<td>Free and Open Source Software (e.g. Careem et al., 2007)</td>
</tr>
<tr>
<td>C1, A3</td>
<td>Lack of Information Visibility (e.g. Day et al., 2009)</td>
<td>Formalised Information Sharing (e.g. Lee &amp; Whang, 2000)</td>
<td>Ad Hoc Information Sharing (e.g. Day et al., 2009), Information Sharing Standards (e.g. HDX, n.d.)</td>
</tr>
<tr>
<td>C1, A4</td>
<td>Ad Hoc Processes (Tatham &amp; Pettit, 2010)</td>
<td>Process Standardisation (e.g. Münstermann et al., 2010)</td>
<td>Common Information Space (e.g. Kuhnert et al., 2015)</td>
</tr>
<tr>
<td>C1, A5 C2, A5</td>
<td>Demand Spikes (e.g. Carroll &amp; Neu, 2009)</td>
<td>Safety Stock (e.g. Graves &amp; Willems, 2003), Information Sharing (e.g. Lee &amp; Whang, 2000)</td>
<td>Prepositioned Stock (e.g. Salmerón &amp; Apte, 2010), Standardised Items (e.g. USAID, 2011), Postponement (e.g. Scholten et al., 2010)</td>
</tr>
<tr>
<td>C2, A1 C2, A4</td>
<td>Limited Information Sharing (e.g. Day et al., 2009), Lack of Common Process Standards (e.g. Schultz &amp; Blecken, 2010)</td>
<td>Formalised Information Sharing (e.g. Lee &amp; Whang, 2000), Process Standardisation (e.g. Münstermann et al., 2010)</td>
<td>Ad Hoc Information Sharing (e.g. Day et al., 2009), Information Sharing Standards (e.g. HDX, n.d.)</td>
</tr>
<tr>
<td>C2, A3 C3, A3</td>
<td>Information Inaccessible (e.g. Sheu, 2007b)</td>
<td>Capture Demand Information (e.g. Lummus &amp; Vokurka, 1999), Forecasting (e.g. Chen et al., 2000)</td>
<td>Prepositioned Stock (e.g. Salmerón &amp; Apte, 2010), Standardised Items (e.g. USAID, 2011), Postponement (e.g. Scholten et al., 2010)</td>
</tr>
<tr>
<td>C3, A2</td>
<td>Issues about Access and Power (e.g. Stephens &amp; Ford, 2014)</td>
<td>Partnerships (e.g. Christopher &amp; Jüttner, 2000)</td>
<td>Partnerships (e.g. Tomasini &amp; Van Wassenhove, 2009)</td>
</tr>
</tbody>
</table>

Notes: The codes for characteristic themes (e.g. C1) are used in the “Interaction” section of subsequent tables. The codes for characteristic themes are common across multiple tables.

Table 2.6: Interactions between disaster relief and supply chain strategy antecedents (Part 1)
(adapted from Taylor & Arthanari, 2017, p. 2)
<table>
<thead>
<tr>
<th>Interactions</th>
<th>Challenges</th>
<th>Commercial Solutions</th>
<th>Disaster Relief Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3, A4</td>
<td>Lack of Common Process Standards (e.g. Schultz &amp; Blecken, 2010)</td>
<td>Virtual Integration (e.g. Wang et al., 2006), Supply Chain Integration (e.g. Mason et al., 2003), Process Standardisation (e.g. Münstermann et al., 2010)</td>
<td>Process Standardisation amongst Large NGOs (USAID, 2011)</td>
</tr>
<tr>
<td>C3, A5</td>
<td>Lack of Coordination (e.g. Gatignon et al., 2010), Competition between Agencies (e.g. Banomyong et al., 2009)</td>
<td>Coopetition Models (e.g. Bakshi &amp; Kleindorfer, 2009), Supply Chain Contracts (e.g. Cachon &amp; Lariviere, 2001), Supply Chain Integration (Frohlich &amp; Westbrook, 2001)</td>
<td>Prepositioned Stock (e.g. Salmerón &amp; Apte, 2010), Corporate Partnerships (e.g. Thomas &amp; Fritz, 2006)</td>
</tr>
<tr>
<td>C4, A1</td>
<td>Partnerships Compromise Independence (e.g. Patterson et al., 2010)</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>C4, A2</td>
<td>Lack of Funding for IT Projects (e.g. Fritz Institute, 2005)</td>
<td>Increase Investment, Resource Pooling (e.g. Hoang &amp; Rothaermel, 2005)</td>
<td>Free and Open Source Software (e.g. Careem et al., 2007)</td>
</tr>
<tr>
<td>C4, A3</td>
<td>Material Convergence (e.g. Holguín-Veras et al., 2012)</td>
<td>None</td>
<td>Inform Public of Inappropriate Donations (e.g. Holguín-Veras et al., 2012), Prioritising Items (e.g. Holguín-Veras et al., 2012)</td>
</tr>
<tr>
<td>C4, A4</td>
<td>Lack of Funding for Process Engineering and Lack of Professionalisation (e.g. Fritz Institute, 2005)</td>
<td>Increase Investment, Resource Pooling (e.g. Hoang &amp; Rothaermel, 2005)</td>
<td>None</td>
</tr>
</tbody>
</table>

Notes: The codes for characteristic themes (e.g. C1) are used in the "Interaction" section of subsequent tables. The codes for characteristic themes are common across multiple tables.

Table 2.7: Interactions between disaster relief and supply chain strategy antecedents (Part 2)
(adapted from Taylor & Arthanari, 2017, p. 2)

2.4.3. Information systems

The lack of information visibility and interagency coordination provides the impetus for a variety of state of the art techniques in disaster relief humanitarian logistics (Privett, 2015). Some novel crowdsourcing approaches have been used in recent years. Ushahidi is one of the most famous examples and one of the few that does not rely primarily on centralisation.
Ushahidi is a web service that collects and aggregates Twitter messages about disaster incidents within a disaster zone, then plots each incident onto Google Maps (Sheller, 2012), providing both demand visibility and interagency coordination at the lowest level. Ushahidi requires a proliferation of mobile phones amongst the affected population, which is very common across the world, and a power source for recharging phones. Microblogging with Facebook has also been used as a tool for authorities to engage with affected communities, such as broadcasting information from a central source to appealing for information (Ehnis & Bunker, 2012, pp. 5-6).

Crowdsourcing approaches come with unique challenges around the limitations of the platform used to facilitate them, such as overwhelming volumes of data with insufficient capacity to process incoming data, incompatibility/interoperability issues, and difficulty reaching the right people in younger demographics that are usually quite social media-savvy (Gill & Bunker, 2012, pp. 4-6). Since crowdsourcing is literally a form of community involvement in data collection, there are inherently issues of trustworthiness and accuracy of information, maliciously planted false information, a latency/delay in receiving information, affected populations not having access to telecommunications services needed to post social media information, and the splintering of the same issues across several competing social media platforms (e.g. Facebook, Twitter, etc.) (Gill & Bunker, 2012, pp. 6-8).

Resource Map is a tool for tracking and visualising information on a live map (InSTEDD, n.d.), with the added feature of being able to define triggers for automated alerts when certain conditions are met (e.g. demand exceeds stocks, stocks are low, etc.), enabling visibility and coordination from the ground-up and from the top-down, depending on who receives the trigger alerts. However, there is no data collection mechanism and the system must be paired with another solution. Sahana Eden is an enterprise resource planning
system (Careem, Silva, Silva, Raschidt, & Weerawarana, 2007) that is a free and open source software specifically tailored to disaster relief, designed to be relatively easy to set up and use (Maon, Lindgreen, & Vanhamme, 2009), which can enable information visibility and coordination within a single organisation. Sahana Eden has no ability to coordinate across organisations and its information sharing mechanisms are limited to importing and exporting CSV files from its database.

HELIOS is an information system that enables limited track-and-trace for products (Tatham, Spens, & Kovács, 2017), enabling information visibility and interagency coordination across a single supply chain, but it lacks the features of a warehouse management system, fleet management system, or materials resource planning system. Like HELIOS, LSS/SUMA allows limited product registration and track-and-trace (Blecken & Hellingrath, 2008), but the same limitations to HELIOS apply. The limitations of these solutions are compared in Table 2.8 (p. 54) below and Table 2.9 (p. 55) below. Humanitarian Logistics Software (HLS) (Fritz Institute, n.d.; Kopczak & Johnson, 2004) is an information system for digitising and managing supply chain data flows within an organisation and is effectively a self-contained supply chain module without the rest of an enterprise resource planning system. There have been many calls to implement social media in disasters (Merchant, Elmer, & Lurie, 2011; White, 2011). Some of the most novel uses of social media are perhaps the use of data from the Twitter platform (Hossmann, Legendre, Carta, Gunningberg, & Rohner, 2011) to create alerts, which can be mapped onto a geographic information system such as Google Maps (Morrow et al., 2011).

Existing solutions only enable traditional information sharing and information systems models and techniques from traditional supply chains. What is missing is a unified platform to integrate information visibility and interagency coordination across multiple heterogeneous organisations at the downstream level in a decentralised manner. Some have
proposed the creation of a common space (e.g. Kuhnert, Wietfeld, Paterour, Georgiev, Petersen, Büscher, & Pottebaum, 2015), where a centralised authority provides a common platform for all organisations to coordinate. Others have advocated a centralised coordination authority overseeing all interagency coordination efforts (e.g. Akhtar, Marr, & Garnev ska, 2012).

A few people advocate adopting a centralised process for data collection and dissemination using common standards (e.g. Fabbe-Costes & Jahre, 2015), though there are currently no means to enforce or encourage adoption. The common thread between these solutions is the idea of heavy centralisation. Decentralised (Gatignon, Van Wassenhove, & Charles, 2010) and ad hoc (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012) interactions in humanitarian logistics are not due to a lack of centralisation, but are an inherent characteristic defining disaster relief operations that are fragmented and uncertain. Therefore, any solution to enable information visibility and interagency coordination in disaster relief must work within these constraints, otherwise they will be inefficient at best and impossible at worst.

<table>
<thead>
<tr>
<th>Type of Information Visibility</th>
<th>Type of Coordination</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intraorganisational</strong></td>
<td><strong>Interorganisational</strong></td>
</tr>
<tr>
<td>Bottom-Up</td>
<td></td>
</tr>
<tr>
<td>• HELIOS (Tatham et al., 2017)</td>
<td>• Resource Map (InSTEDD, n.d.)</td>
</tr>
<tr>
<td>• HLS (Kopczak &amp; Johnson, 2004)</td>
<td>• Ushahidi (Sheller, 2012)</td>
</tr>
<tr>
<td>• LLS/SUMA (Blecken &amp; Hellingrath, 2008)</td>
<td>• Virtual OSOCC (Bjerge et al., 2016)</td>
</tr>
<tr>
<td>• Sahana Eden (Careem et al., 2007)</td>
<td></td>
</tr>
<tr>
<td>Top-Down</td>
<td></td>
</tr>
<tr>
<td>• Resource Map (InSTEDD, n.d.)</td>
<td>• Facebook (Ehnis &amp; Bunker, 2012)</td>
</tr>
<tr>
<td>• GDACS (Bjerge et al., 2016)</td>
<td>• Resource Map (InSTEDD, n.d.)</td>
</tr>
<tr>
<td>• Ushahidi (Sheller, 2012)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.8: State of the art solutions to information visibility by type of visibility
Table 2.9: State of the art solutions to information visibility by type of centralisation

<table>
<thead>
<tr>
<th>Type of Coordination</th>
<th>Type of Centralisation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Information Space</td>
</tr>
<tr>
<td>Intraorganisational</td>
<td>• Resource Map</td>
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<td></td>
<td>• Resource Map</td>
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<td>• Resource Map</td>
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<tr>
<td></td>
<td>• Resource Map</td>
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<td></td>
<td>• HELOIS</td>
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<td></td>
<td>• HLS</td>
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<td></td>
<td>• LLS/SUMA</td>
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<tr>
<td></td>
<td>• Sahana Eden</td>
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<td></td>
<td>• HELOIS</td>
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<td></td>
<td>• HLS</td>
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<td></td>
<td>• LLS/SUMA</td>
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<tr>
<td></td>
<td>• Sahana Eden</td>
</tr>
<tr>
<td>Interorganisational</td>
<td>• Resource Map</td>
</tr>
<tr>
<td></td>
<td>• Virtual OSOCC</td>
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<tr>
<td></td>
<td>• Virtual OSOCC</td>
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<tr>
<td></td>
<td>• Resource Map</td>
</tr>
<tr>
<td></td>
<td>• Resource Map</td>
</tr>
</tbody>
</table>

The most advanced solutions currently available are the integration between GDACS (UNOCHA, n.d.a) and Virtual OSOCC (UNOCHA, n.d.b). Together, these two systems allow humanitarian logistics to coordinate information exchanges in a very general way and receive disaster-related environmental alerts, telling them exactly what is happening and where they need to focus their efforts (Bjerge, Clark, Fisker, & Raju, 2016). The Global Disaster Alert and Coordination System (GDACS) is an information system for creating and delivering alerts and automated risk analysis for earthquakes and tsunamis via e-mail, fax, and SMS. GDACS is a joint operation between UNOCHA and the European Commission. Disaster events are assigned a universal GLIDE identifier and reporting is integrated into the EM-DAT online database of historical disaster events maintained by CRED. The Virtual On-Site Operations Coordination Centre (Virtual OSOCC) is an information system implementation of the OSOCC concept (OCHA, 2018) to provide a common portal for virtual interagency coordination via internet connection. Virtual OSOCC is run by UNOCHA. It includes a common file and message repository for registered users.

The above information system approaches seek to create a common operating picture within and/or across organisations (Tatham, Spens, & Kovács, 2017), but
coordination is difficult due to the splintering and disaggregation of information management (Bunker, Levine, & Woody, 2015, p. 63) due to heterogeneous processes and standards across highly heterogeneous organisations (Day, Junglas, & Silva, 2009, pp. 651-652). One of the central issues with any interagency coordination approach is achieving coordination in a scalable manner (Bunker, Levine, and Woody (2015, p. 63), so that organisations are not overwhelmed (Day, Junglas, & Silva, 2009, pp. 647). Data needs to be processed by contextualisation before it becomes usable information, while information must be synthesised before it becomes knowledge (Frické, 2009). If there is not enough capacity for an information management process to analyse the data, the data remains unusable. By contrast, disaster relief is extremely time-sensitive, so whatever data processing exists must be fast and timely.

2.5. Understanding interagency coordination as a wicked problem

The problem of interagency coordination has long been recognised as a classic wicked problem (Tatham & Houghton, 2011). Wicked problems are not understood until a solution has been created, those solutions are not necessarily right or wrong, but are considered better or worse compared to other solutions, and the resources required to develop and/or implement a solution are so onerous that failure has a very high cost. Understanding a wicked problem requires a certain amount of interpretation on the priority of issues and how they are connected and synthesising the problem area is the most critical step to enabling the search for a solution—without it, failure is almost guaranteed. The research area can be framed as a series of intersecting categories linked by cause and effect, which helps define the research problem more specifically in preparation for developing a strategy.
for using methodologies and techniques to create research artefacts that answer the research question in the Methodology chapter (pp. 74-102):

1. **Intentions** are the final overarching objectives that determine how academic research or practitioner operations are oriented to what purpose. For example, academic research seeks to enlighten the world through knowledge obtained ethically, aid agencies seek to reduce human suffering, and private companies seek to increase and sustain profits.

2. **Problems** are the distal causes that lead to causing other problems. Identifying what constitutes a distal cause is primarily due to expert judgement.

3. **Issues** are the proximal causes, or specific, archetypical ways in which problems manifest themselves. Issues do not appear in isolation, usually appear in groups, and are always caused by former problems.

4. **Requirements** are the fundamental environmental, operational, and resource constraints that cannot be overcome directly. Together, these boundaries form an abstract ‘solution space’. By defining this space, the search area for a solution is minimised. Although not every possibility in the space is desirable or practical, the best solution must lie somewhere within that space, if it exists at all.

This thesis focuses on the problems of a lack of interagency coordination in disaster relief humanitarian logistics, caused by a lack of information sharing, which stems from a lack of information visibility and the means to share information. The problem area can be categorised according to its direction of causation when the above background is framed in the format of intent, problems, issues, and requirements in the sections below.
2.5.1. Intent

The intent, or overall strategic objectives of parties, affects how problems are perceived. Clearly identifying the intent is the first step to solving a problem. Aid agencies engaged in disaster relief want to save and sustain lives to relieve human suffering, allowing communities to recover from disaster events and become self-sufficient again. Academic researchers want to enlighten the world with knowledge that has been obtained ethically and is useful to aid agencies, while also publishing results to further their career prospects. The overall intent of this thesis can be summarised as coming up with practical solutions to information visibility and information sharing problems to support interagency coordination in disaster relief humanitarian logistics, which improve disaster relief performance. From this perspective, certain environmental and operational characteristics in disaster relief are interpreted as barriers to higher performance, which can be linked by causality, and then reinterpreted as a set of fundamental requirements that constrain any solutions to the problem.

2.5.2. Problems

Disaster relief humanitarian logistics suffers from multiple performance problems that stem from a lack of resources and an unstable, fragmented operating environment, coupled with extremely high costs for aid delivery failure within narrow time constraints. Together, these interrelated problems form the distal causes that are the source of all subsequent issues. There is generally poor interagency coordination within the humanitarian sector (Scott & Batchelor, 2013). Interagency coordination is critical to delivering aid effectively. Aid agencies must cooperate and coordinate their resources and personnel, and no one NGO, government, or military has the capacity and knowledge to effectively deliver aid on
their own. The disaster relief environment is heavily decentralised, with extensive ad hoc agreements, highly limited resources, and extreme time constraints (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012).

2.5.3. Issues

There is a lack of academic literature and practitioner research on information visibility and information sharing issues in disaster relief, primarily due to a lack of data and data access. The literature for disaster relief humanitarian logistics is fragmented across the fields of operations management, supply chain management, operations research, emergency management, disaster research, and many others.

Aid agencies will likely find their disaster relief efforts highly politicised (Duffield, 1993), with perceptions of their performance being distorted by onlooking bystanders or reporters from the media (Thomas & Fritz, 2006, p. 119; Kovács & Spens, 2009, p. 512), who likely lack subject knowledge to interpret what is happening and what are norms in disaster relief operations. If there is a major human factor involved in causing or exacerbating a disaster event, the risk is even greater as the public, media, and officials scramble to find someone to blame, which can quickly bleed into assigning blame to aid agencies (McClintock, 2009). Additionally, political manoeuvring by rival agencies and internal rivalries can lead to perverse incentives (Howitt & Leonard, 2006). Just as likely, aid agencies may have performed terribly or acted improperly, which is information they would want to keep secret.

Aid agencies generally operate in a low trust environment. There significant nuances in how trust works during disaster relief. Aid agencies need some level of trust to coordinate, so they typically operate on the concept of “swift trust” (Tatham & Kovács, 2010) where limited trust is given up-front, then verified later when time and resources
allow for it. Aid agencies are forced to trust each other to some extent, but their trust increases their exposure to the risk of politicisation as mentioned previously, which limits the extent to which aid agencies trust one another, and leads to aid agencies almost always refraining from talking to the media or to outsiders unless the interaction is carefully managed and controlled by public relations personnel (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012).

Except for the largest, most well-funded, and professionalised aid agencies, most aid agencies lack resources, leading in turn to a lack of academic research and practitioners’ institutional learning. This leads to subsequent issues around data collection, analysis, and dissemination. There is generally a lack of initial impetus for gathering and analysing the data needed for institutional learning for most NGOs (Thomas & Kopczak, 2005, p. 6). Most NGOs involved are small local organisations that do not specialise in disaster relief as their primary mission, but were simply caught adjacent to the disaster, such as being in or near the disaster zone (de Goyet, 2000). These NGOs are unlikely to engage in disaster relief operations in the future and find institutional learning for non-existent future disaster relief operations a fruitless venture. Micro-donations are small donations in increments as small as USD $2 by hundreds of thousands of charitable individuals when an emergency donation drive is announced by an NGO, which only occurs when a disaster relief effort is currently underway during the initial ramp-up stage. Once the disaster relief response winds down, the sense of urgency that spurs micro-donations disappears until the next disaster event.

Humanitarian logisticians do not have time to be involved in research, whether it is by academic researchers or their own aid agencies. Humanitarian logisticians have very low pay compared to positions for comparable experience and qualifications in the private sector (Dubey, 2016), and the enormity, urgency, and importance of disaster relief operations, combined with a lack of resources, personnel, technology, and equipment
available to deliver such operations, across extremely long hours, sometimes as high as 16 hours per day during the most critical periods (e.g. Cranmer, 2005, p. 1541), and low career development prospects all lead to extremely high stress for minimal personal reward. Obviously, those who become humanitarian logisticians are not motivated by self-gain, but a healthy and sustainable working environment are vitally important to recruitment and staff retention. Consequently, humanitarian logisticians have an annual turnover rate of around 80% (Thomas & Kopczak, 2005, p. 6). Those few that remain are extremely overworked. Key personnel in a disaster relief operation are only available until the next disaster occurs, which can lead to humanitarian logisticians being recalled to service, leaving them with no time and possibly in a different geographic location than where the institutional learning was to take place (Sohn, 2018).

Humanitarian logisticians have little time to spend on data collection for institutional learning and mostly view it as a nuisance that takes time away from logistics activities (Maiers, Reynolds, & Haselkorn, 2005, p. 84). During what little research activity there is, humanitarian logisticians’ answers avoid topics only discussed amongst organisational insiders, such as corruption of local authorities in a disaster zone and/or the incompetence of their own aid agency or others. The standard response when the news media are trying to interview aid workers is blanket refusal, “No comment.” Humanitarian logisticians must deliver humanitarian aid impartially (Slim, 2015, p. 56), which means frequently dealing with unsavoury political regimes (e.g. Duffield, 1993) and keeping strict confidences if NGOs believe that keeping silent and delivering aid would save more lives (Slim, 2015, pp. 169-181), which can quickly become incredibly ethically problematic. Otherwise, other regimes will deny them access and participation, even if it harms the affected population. Surveys suffer from the same problems as interviews, but with the
added limitation that surveys are usually brief, and either very general or highly specific to a few issues.

There is a lack of expertise in how to conduct rigorous archival research. It is best practice to hold all case files for an operation in a single repository (Thomas, 2004), but researchers still must conduct extensive archival research across many thousands of relevant documents to form a cohesive, synthesised picture of what happened. Aid agencies will not allow outsiders to perform such research without strict editorial control, which is something many academic researchers would find unacceptable, while aid agencies lack the capacity and expertise to do it themselves. Donor groups often strictly earmark funds for specific uses, such as requiring a certain percentage of their donations reaching the affected population as end products, which looks good on donor groups own financial documents but can significantly compromise NGOs’ long-term performance (Pallotta, 2013). Often taken to the extreme, a total focus on administrative overheads leaves no funding for the support required to increase productivity and reduce waste in disaster relief operations.

Data is often locked in organisational silos, sometimes because there is no centralised repository for smaller NGOs (Day, Junglas, & Silva, 2009). The information is spread across thousands to tens of thousands of individual reports and spreadsheets, and this problem becomes exponentially worse the larger the NGO and the more international their reach. Additionally, most of these reports only contain demand estimates for the needs of the affected population (Sheu, 2007b), which are often crude and based on rules of thumb developed over time through previous operations. Those operations are not necessarily comparable to present or future operations, but in the absence of usable empirical data it often serves as a planning compromise. Direct demand data is almost never captured, so a direct relationship is difficult to establish between an NGO’s
operations and the needs of the affected population, especially to the level of quantifying cause and effect (Sheu, 2007b).

There have long been calls for such information capture across the humanitarian sector (e.g. Harvard Humanitarian Initiative, 2011; Akhtar, Marr, & Garnevska, 2012; Altay & Labonte, 2014), but there is currently no practical and deployable solution, and there are questions as to whether it is even possible (Sheu, 2007b). Obviously, the most basic and straightforward needs of the affected population can be readily deduced (Blecken, 2010), such as basic daily nutritional requirements for long-term survival, modified by dietary restrictions due to socio-cultural factors and religious observances. One way NGOs try to mitigate this knowledge gap is to perform post hoc surveys on a small sample of the affected population (Fritz Institute, 2006), but these are prone to post hoc rationalisations, inaccuracy, a lack of detail, and a lack of generalisability.

Where post-disaster reports are available, they usually focus on operational failures, and often it cannot be turned into usable knowledge because of a lack of data and/or statistics expertise (Moore, Trujillo, Stearns, Basurto-Dávila, & Evans, 2007, p. 11-12). Across the few publicly released institutional learning reports from major NGOs, none have applied any statistics beyond basic arithmetic and using averages. There are no multivariate statistics or operations research that would be considered standard in private industry. Obviously, if there is no data to analyse, there cannot be any statistical analysis.

2.5.4. Requirements

Any solution to enabling information visibility and information sharing in disaster relief must cope with a lack of resources, personnel, and training, and address issues of politicisation and trust. To meet these challenges several very specific constraints must be managed. The solution must very inexpensive to be affordable to NGOs. Although the
solution is substantially partially technological, NGOs lack the funding and resources to procure information systems and train or retain staff in their use. If the solution is substantially process-oriented, NGOs that adopt the solution must be able to use it with minimal change to their own organisational processes, since a complete rearchitecting of organisational process, cultures, and norms is an unreasonable expectation. Ideally, the solution would integrate with existing organisational processes and be almost completely automated, bypassing the need for additional staff or training. If substantially technological, the solution should rely on inexpensive and, ideally, free components, such as free and open source software, and open source hardware.

Usable data on the needs of the affected population must be captured, along with barriers to meeting them. There are two primary ways to achieve this. Either direct demand data is captured, or indirect demand data is aggregated and analysed to allow NGOs to develop a clear operational perspective on what needs to be done to fulfil their mission. Since there are no processes to capture such data, a new process must be introduced. Since there are almost no resources to architect a new process, the new process must be highly automated. This automation should extent to data analysis in the form of data science and machine learning techniques, which should then be reformatted into usable reports released periodically to NGOs that do not require advanced statistical knowledge to understand.

Ethical and political concerns are an ever present factor in disaster relief, and the solution must adequately address these concerns. Whenever a new capability is being introduced, there are issues of power dynamics, questions of how widespread access to the capability is gained, control of organisational data and operations, privacy and security concerns, and appropriate representation of community and minority voices (Büscher, Easton, Kuhnert, Wietfeld, Ahlsén, Pottebaum, & Van Veelen, 2014). These concerns can
manifest themselves as legal requirements, such as requirements for local repositories for information sharing and data warehousing.

2.5.5. Summary of research area

The research area can be summarised as a flowchart of related issues. The problems, issues, requirements, and existing mechanisms of the research area from the literature review are numbered and linked together in Figure 2.2 (p. 67) below. The figure includes the perspectives from strategic management theory used to interpret each area. The main sources for identifying and linking these problems, issues, requirements can be summarised by their type of origin in Table 2.10 (p. 69) below.
<table>
<thead>
<tr>
<th>Problems (distal causes)</th>
<th>Issues (proximal causes)</th>
<th>Requirements (constraints)</th>
<th>Existing Mechanisms (common solutions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1: Poor interagency coordination between aid agencies in disaster relief.</td>
<td>I1: Humanitarian logisticians operate in a low trust environment.</td>
<td>R1: Direct demand data for affected population must be captured or approximated.</td>
<td>M1: Standardised information processes.</td>
</tr>
<tr>
<td>P2: Lack of information visibility of demand requirements for affected population in disaster relief.</td>
<td>I2: Disaster relief efforts often highly politicised and visible to the media.</td>
<td>R2: Solution must be inexpensive to procure and practically free to maintain.</td>
<td>M2: Digitised information processes.</td>
</tr>
<tr>
<td>P3: Lack of systematic information sharing between aid agencies beyond ad hoc agreements.</td>
<td>I3: Major donor groups can be quite myopic in their donor requirements.</td>
<td>R3: Solution must be highly to near fully-automated.</td>
<td>M3: Standardised automated information processes.</td>
</tr>
<tr>
<td>I4: Humanitarian logisticians almost universally overworked, underpaid, and under-resourced.</td>
<td>I5: Important lessons are lost as humanitarian logisticians leave the humanitarian sector.</td>
<td></td>
<td>M4: Automated data collection.</td>
</tr>
<tr>
<td>I6: Humanitarian logisticians do not give answers to outsiders for fear of political fallout.</td>
<td>I7: Most aid agencies lack the expertise to conduct rigorous archival research.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I8: Data useful to institutional learning is often locked in organisational silos.</td>
<td>I9: Direct demand data almost never captured.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1: Direct demand data for affected population must be captured or approximated.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>R2: Solution must be inexpensive to procure and practically free to maintain.</td>
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<tr>
<td>R3: Solution must be highly to near fully-automated.</td>
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</tr>
<tr>
<td>M1: Standardised information processes.</td>
<td></td>
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<tr>
<td>M2: Digitised information processes.</td>
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<tr>
<td>M3: Standardised automated information processes.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>M4: Automated data collection.</td>
<td></td>
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</tbody>
</table>
M5: Automated data anonymisation for security and privacy. \textsuperscript{a c}
M6: Automated data analysis. \textsuperscript{a c}
M7: Automated analysis reporting. \textsuperscript{a c}
M8: Common information space for interagency coordination. \textsuperscript{a c}
M9: Swift trust between NGOs to handle critical, time-sensitive issues. \textsuperscript{b c}

\textsuperscript{a}: Perspective from resource-based view, or RBV.
\textsuperscript{b}: Perspective from knowledge-based view, or KBV.
\textsuperscript{c}: Perspective from transaction cost theory, or TCT.

Figure 2.2: Causal links between problems, issues, requirements, and existing mechanisms
Academic and government research on humanitarian logistics operations tracks closely with practitioner developments because practitioners are usually the primary sources or are producing their own publications from their own experiences. Academia is merely following the example of practitioners and leveraging their direct expertise, rather than hypothesising and theorising without practitioner input. Much like in the rest of the operations management and supply chain management literature, academic humanitarian logistics literature tends to follow practitioners rather than the other way around. What quickly emerges from even a cursory reading of the literature is that practitioners are acutely aware of these interagency coordination problems, that there is a consensus among practitioners about what problems exist, how they exist, and why they exist. However, there is sparse literature support for creating and implementing solutions to these problems.

None of the main sources indicate these solutions come directly from industry. Virtually all of the solutions come from aid agencies themselves or are applications of standard supply chain theory. Additionally, certain mechanisms that are common in industry for information systems and interorganisational coordination are rare or absent, (e.g. see mechanisms coded “M4”, “M5”, “M6”, “M7”, and “M8” in Table 2.10, p. 69). When we contrast the lack of the more advanced, yet still highly necessary capabilities seen in industry to the previously mentioned deficiencies in aid agencies (Fritz Institute, 2005), with their manual processes and lack of investment in backend information systems, it is understandable why these mechanisms are not prevalent in disaster relief.
<table>
<thead>
<tr>
<th>Object Code</th>
<th>References</th>
<th>Type of Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Chen et al., 2009; Crowley &amp; Chan, 2011; Long &amp; Wood, 1995; McLachlin &amp; Larson, 2011; Thomas &amp; Kopczak, 2005; Salmon, Stanton, Jenkins, &amp; Walker, 2011; Schulz &amp; Blecken, 2010; Tomasini &amp; Van Wassenhove, 2009.</td>
<td>1 5 5 3</td>
</tr>
<tr>
<td>P2, I8</td>
<td>Caunhye, Nie, &amp; Pokharel, 2012; Harraff, 2006; Harvey et al., 2010; Henderson, 2007; Thomas &amp; Kopczak, 2005; Privett, 2015</td>
<td>1 5 4 4</td>
</tr>
<tr>
<td>P3, I8, I11</td>
<td>Day et al., 2009; Fritz Institute, 2005; HDX, n.d.; Holguín-Veras et al., 2012; Perry, 2007; Schulz &amp; Blecken, 2010</td>
<td>– 6 3 –</td>
</tr>
<tr>
<td>I1</td>
<td>Day et al., 2009; Dowty &amp; Wallace, 2010; Harvey &amp; Harmer, 2011</td>
<td>– 3 1 –</td>
</tr>
<tr>
<td>I2</td>
<td>Kovács &amp; Spens, 2009; Thomas &amp; Fritz, 2006</td>
<td>– 2 2 –</td>
</tr>
<tr>
<td>I3</td>
<td>None. (There are sources that make this general point, but there is not a source that attributes it to anyone or any organisation, for obvious political reasons.)</td>
<td>– – – –</td>
</tr>
<tr>
<td>I4</td>
<td>Thomas &amp; Kopczak, 2005</td>
<td>– 1 – –</td>
</tr>
<tr>
<td>I5, I7</td>
<td>Maiers et al., 2005; Thomas &amp; Kopczak, 2005</td>
<td>– 3 1 –</td>
</tr>
<tr>
<td>I6</td>
<td>None. (This is the author’s impression from informal talks with several current and former humanitarian logisticians.)</td>
<td>– – – –</td>
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<tr>
<td>I9</td>
<td>Day et al., 2009, USAID, 2011; Tapia et al., 2011</td>
<td>– 3 – –</td>
</tr>
<tr>
<td>I10</td>
<td>None. (Although this would undeniably be useful to humanitarian logisticians, it is not their role.)</td>
<td>– – – –</td>
</tr>
<tr>
<td>I11</td>
<td>Harvard Humanitarian Initiative, 2011 (Additionally, see P3.)</td>
<td>– 6 3 1</td>
</tr>
<tr>
<td>R1</td>
<td>Blecken &amp; Hellingrath, 2008; Bjerge et al., 2016; Ehnis &amp; Bunker, 2012; InSTEDD, n.d.; Kopczak &amp; Johnson, 2004; Tatham et al., 2017</td>
<td>1 5 – –</td>
</tr>
<tr>
<td>R2</td>
<td>None. (Logical deduction by the author.)</td>
<td>– – – –</td>
</tr>
<tr>
<td>R3</td>
<td>None. (Logical deduction by the author.)</td>
<td>– – – –</td>
</tr>
<tr>
<td>M1</td>
<td>HDX, n.d.; Münstermann et al., 2010; USAID, 2011</td>
<td>2 1</td>
</tr>
<tr>
<td>M2</td>
<td>InSTEDD, n.d.; Kopczak &amp; Johnson, 2004; Careem et al., 2007; Blecken &amp; Hellingrath, 2008; Ehnis &amp; Bunker, 2012; Sheller, 2012; Bjerge et al., 2016; Tatham et al., 2017</td>
<td>1 7 – –</td>
</tr>
<tr>
<td>M4, M3</td>
<td>Sheller, 2012</td>
<td>– 1 – –</td>
</tr>
<tr>
<td>M5, M3</td>
<td>None.</td>
<td>– – – –</td>
</tr>
<tr>
<td>M6, M3</td>
<td>Ehnis &amp; Bunker, 2012</td>
<td>– 1 – –</td>
</tr>
<tr>
<td>M7, M3</td>
<td>Ehnis &amp; Bunker, 2012; Bjerge et al., 2016</td>
<td>– 2 – –</td>
</tr>
<tr>
<td>M8</td>
<td>Bjerge et al., 2016</td>
<td>– 1 – –</td>
</tr>
<tr>
<td>M9</td>
<td>Thomas &amp; Fritz, 2006; Tatham &amp; Kovács, 2010; Tatham et al., 2017</td>
<td>– 2 – 1</td>
</tr>
</tbody>
</table>

I: Practitioner publications.
II: Academic publications with practitioners as primary sources.
III: Regulatory body publications.
IV: Advisory body publications.

Table 2.10: Types of sources in main argument
Each problem, issue, requirement, and existing mechanism that could be interpreted from a theory of the firm to explain the existence and performance of aid agencies was marked by the relevant theories. The resource-based view and knowledge-based view of the firm are fairly straightforward in their interpretation as lacking resources or knowledge and expertise, but the transaction cost theory of the firm is more multi-faceted. While the perspective of transaction cost theory suggests that aid agencies exist because interagency coordination is useful, equally there may be such a large number of aid agencies present in any relief operation because there is always a tension between the usefulness and the inhibitors of coordination.

2.5.6. Problem solving approach

The unique difficulties of the disaster relief environment and heavy constraints affecting aid agencies requires a solution tailored to disaster relief, rather than just a minimally adapted solution from the commercial sector. Here I present the problem solving approach used in this thesis to create a proposed solution. Roberts (2000, p. 3) provides a framework for choosing appropriate problem solving approaches to different kinds of wicked problems by whether power is dispersed and/or contested in the environment, as shown in Figure 2.3, (p. 71), below. Unfortunately, the framework only considers problems as purely distinct categories, whereas interagency coordination is simultaneously a wicked problem that has power dispersed and contested at various levels, which messily crosses over the neat and tidy categories in the framework. A solution that is feasible may have to have qualities of authoritative, collaborative, and competitive strategies whilst attempting to bypass their limitations and incompatibility with each other.
Due to the fragmented and dynamic nature of disaster relief chains and the disaster environment, it is unfeasible to centralise supply chain authority entirely or to centralise coordination and expect all NGOs to act in concert, especially since NGOs can barely see the environmental and supply chain conditions beyond their immediate field of view. Using quick response as the core design concept, a new method of information sharing is proposed to create information visibility in downstream supply chain echelons. The proposed solution involves automated data collection, anonymisation, aggregation, analysis, and dissemination.
Meding, Oyedele and Cleland (2009, p. 39) see three primary types of methods for developing NGO competencies: (1) Resource-based view, (2) Competence-based view and (3) Dynamic capabilities view. Although the framework was designed primarily for operations after disaster relief efforts have been completed, its principles can be applied to disaster response. The problem solving approach used in this thesis is to develop an automated process solution with telecommunication and information systems facilitators that increase information visibility without being mired in a deluge or irrelevant data [resource-based view] while removing technological and personnel bottlenecks to interagency coordination [competence-based view]. The resulting increase in information visibility allows aid agencies to monitor the needs of the affected population and reorient their operations to suit the changing environment [dynamic capabilities view].

This approach essentially views the requirements identified in Figure 2.2 (p. 67) above and Table 2.10, p. 69) above as constraints from the basic concept of the theory of constraints (Goldratt, 1990), where the constraints should either be broken if possible, or bypassed. The question is how to gain the benefits of supply chain collaboration, chiefly information sharing to synchronise goals, decisions, and incentives (Cao & Zhang, 2011, p.165), without incurring any of the costs of its basic requirements of business integration or strategic partnerships.

2.6. Conclusion

Information visibility is both a determinant and outcome of supply chain collaboration, yet it is inhibited by extreme uncertainty in disaster relief. Interagency coordination is essential to mitigating risks, but some traditional supply chain strategies and coordination mechanisms for channel coordination in highly volatile have antecedents that conflict with certain characteristics of the disaster relief environment, bringing into question their
feasibility. If these issues could be resolved, interagency coordination should theoretically be substantially improved. The question remains, “What can remove and/or bypass characteristics of disaster relief that render some highly robust and responsive traditional supply chain approaches infeasible for disaster relief?”
3. **Methodology**

3.1. **Introduction**

The *Literature review* chapter (pp. 21-73) outlined the elements of the problem area and how they relate to one another, and explored the causes and various solutions that have not resolved the problem (pp. 33-56). This chapter details the problem-solving approach that addresses the problem area as a research statement of intent, objectives, and questions. These are answered using a philosophical and methodological research approach to produce several research artefacts. Design science is the chosen primary methodology, which offers a meta-framework for integrating multiple theoretical perspectives and methodologies. Within the design science research process, system dynamics is used as a complementary theory to simulate the utility of the planned practical artefact. If the simulation is successful, the planned artefact is at least of hypothetical value and the development process should continue onto designing the prototype itself. By integrating supply chain and strategic management theory into design science, a hybrid supply chain/information systems approach can be used to create the practical artefact. Each stage of the design science research process builds on itself and creates research artefacts. Once the practical artefact is created and validated, it serves as positivist proof of the new theories created previously throughout the design process.

3.2. **Research statement**

Though this thesis is for a doctoral degree in supply chain management, and not in information systems, it relies on a cross-disciplinary approach to create artefacts. The means to square this difference lies in how supply chain management theory is used and
incorporated into every stage of the design science process, thereby integrating the design science process, originally from the field of information systems, into the field of supply chain management. To answer the research objectives and derived research questions, the design science process will be used to create an instantiation of a product artefact, going through multiple iterations of the design process before arriving at a finalised prototype, which will then be evaluated across several dimensions of quality. In the early stages of the design science process, a simple system dynamics model will be used to simulate the effects of information sharing in a supply chain, where the simulation results will inform the design science process so that the artefact is in theory useful, and the process can advance to the next stage or not, in which case the process stops.

Since this foundation is based on a design science approach, both new theory and physical technological systems must be then architected and instantiated to fulfil the research question. The practical problem this thesis has identified in the Introduction chapter (pp. 8-13) and Literature review chapter (pp. 24-73) is that there is a severe lack of supply chain coordination in disaster relief, which is heavily influenced by the lack of information sharing between aid agencies. There are many underlying reasons behind why information is not shared, from political, organisational, and resource to technical factors, but amongst the most significant is that demand information is neither visible nor directly observable. After all, there may be reasons for keeping information within an aid agency, but if they cannot collect, analyse, and disseminate the necessary demand data within their own aid agencies, that points to significant technical barriers within their own agency operations, not just an unwillingness to share existing data with other aid agencies. Therefore, the research problem to be solved is how to enable information visibility and information sharing between aid agencies.
When taken together, the research area identified in the Literature review chapter (pp. 21-73) as a series of causal problems, issues, and requirements can be developed into a research statement. A research statement should cover the original research plan from the Introduction chapter (pp. 16-18), then explain how methodologies and associated techniques are used to create research artefacts to answer the research question.

3.2.1. Research approach

The research plan in the Introduction chapter (pp. 16-18) defines the purpose of the thesis research, while the framing of the research area in the Literature review chapter (pp. 21-73) defines the scope of the thesis topic. Recall from the Introduction chapter the research question: How can a solution to problems in interagency coordination in disaster relief be developed that integrates multiple disciplines, to address problems that are simultaneously related to technology, process, culture, and politics? The research approach incorporates elements from many different fields, but supply chain theory is used as the primary perspective to serve as an anchor for this thesis. Theories and techniques from other fields will be used to complement this core. Due to the nature of the research area, which is quite technical and straddles many fields, any research that even attempts to solve interagency coordination problems must inherently be highly interdisciplinary.

The research question is can be answered through using a meta-methodology that can integrate multiple methodologies, techniques, and theoretical perspectives. This thesis will use design science as the central framework for both interpreting challenges and developing solutions. Design science originally comes from information systems research, but it is robust enough to be adapted in this thesis for supply chain research. Along the way, theory from process management, supply chain coordination mechanisms, and system dynamics will be used to complement design science. Programming from computer science,
databases from information systems, and telecommunications networks from electronics and telecommunications engineering will be used to create an artefact that exhibits the solution.

3.2.2. **Research artefacts**

Research creates the research artefacts and practical artefacts in Table 3.1 (p. 78) below. By creating the practical artefact, namely a solution to interagency coordination problems in disaster relief, the following research artefacts are created. Each research artefact builds on subsequent research artefacts in a sequential process. After all these research artefacts are created, the practical artefact can be created. Creating the practical artefact is also a research artefact that serves as empirical support for the research artefacts that came before it. These serve as the original research contributions to the body of knowledge in disaster relief humanitarian logistics for this thesis.
### Research Artefact Description

<table>
<thead>
<tr>
<th>Research Artefact</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research artefact 1</td>
<td>The academic and practitioner literature on interagency coordination issues stemming from characteristics of disaster relief is synthesised into several tables, which provides a cross-section of disaster relief challenges but also serves to highlight capability and literature gaps.</td>
</tr>
<tr>
<td>Research artefact 2</td>
<td>A design science framework is adapted to supply chain theory to address interagency coordination issues. This new framework exemplifies how different theoretical perspectives can serve as design principles and approaches during the design science development process.</td>
</tr>
<tr>
<td>Research artefact 3</td>
<td>A simplified supply chain simulation using stock and flow diagrams from system dynamics is produced, illustrating the effects of different information sharing scenarios. This serves as the litmus test for whether it is at least hypothetically worthwhile to develop the practical artefact.</td>
</tr>
<tr>
<td>Research artefact 4</td>
<td>A system architecture is defined for integrating multiple generic technologies into a technologically-supported process solution for automated data collection, analysis, and dissemination to support interagency coordination in disaster relief.</td>
</tr>
<tr>
<td>Research artefact 5</td>
<td>An instantiation/implementation of the system architecture is defined, with specific technologies serving as constituent components in an integrated solution.</td>
</tr>
</tbody>
</table>

**Table 3.1: Research artefacts**

#### 3.2.3. Progression across the research statement

The research artefacts are original contributions, but they are created to directly answer the research question that was generated for the research statement. Their implications require some interpretation and generalisation to turn them into main contributions. Research artefacts 1 and 2 view interagency coordination problems as wicked problems, which involves interpreting the relationship between variables with a preferred problem solving approach before the problem is solved [Main contribution 1: Synthesis of the nature of the problem]. Research artefacts 3 and 4 attempt to solve interagency coordination problems by viewing interagency coordination problems as information sharing process problems.

From this process view, a lateral approach to information sharing is developed, tested using simulations, and then defined as a generic process to hypothetically solve the problem [Main contribution 2: Lateral information sharing as a novel information sharing strategy]. Until a solution is instantiated, main contributions 1 and 2 remain hypotheses,
but after they are instantiated, they become theories; in other words, they do not become main contributions until instantiation. Finally, research artefact 5 instantiates the lateral information sharing approach by providing a system architecture as a technological and process integration strategy [Main contribution 3: Proof that lateral information sharing is feasible].

3.2.4. Outside of scope

While the scope has been previously defined in the boundaries of the research area and research statement, certain research areas are inherently adjacent, overlap, or follow on from the thesis research that would seem like obvious avenues to explore, serving as a source of infinite scope creep. It could easily take a lifelong, distinguished career to achieve the objectives below. It is necessary to unambiguously state what is beyond the scope of this thesis and why it is not included. In-depth interviews and surveys are unfeasible without surrendering research independence to the strict editorial control of participants and their affiliated NGOs. There are serious trust and transparency issues that no researcher has ever been able to satisfactorily resolve, and I will not attempt to do so here.

Additionally, in-depth interviews and surveys are of very limited value to this thesis, because of the problem-solving approach to the process solution. There is extensive existing research on the nature of interagency coordination issues and how they manifest in disaster relief, and these are covered in detail in the Introduction (pp. 1-20) and Literature review chapter (pp. 21-73). There exist generic information sharing processes for interorganisational coordination, which contain the bare minimum elements. Research into specific manifestations of this process in aid agencies is not useful, since the process solution is an automated solution that sits on top of existing organisational processes without ever modifying them. In a very real sense, the precise information sharing process
within an aid agency is irrelevant to how the process solution functions. Given the extreme heterogeneity of aid agencies in funding, number of personnel, geographic scope, mission scope, socio-cultural factors, and internal processes, it is far more likely that an industry standard for information collection, analysis, and dissemination does not exist in the humanitarian sector.

Field testing and case studies of systems implementation are unfeasible, since no sane NGO would allow an untested system to be used to coordinate their entire operations, even on a preliminary basis, while there is no known publicly available data source to conduct field tests in the first place. If dummy data is used, then field testing is completely meaningless and laboratory tests offer the same validity at much greater convenience and lower cost. This creates a dilemma: sufficient OR adequate trust needs to be gained with an NGO with a proven solution to allow implementation for a disaster relief operation, yet to have that trust and testing in the first place requires that the solution already has a proven history of deployment success. This problem is not a question of capabilities or supply chain theory but is primarily diplomatic and business-oriented.

Proven capabilities that require rote application with minor adaptation are not included in this thesis, such as data analytic methods and ruggedisation of electronics components. The data analytics methods, from machine learning techniques to data anonymisation procedures, are industry standard and are not original contributions, but merely stock implementations of existing work with minimal adaptation. Ruggedisation is used to protect electronics from weather conditions, such as wind, heat, cold, and moisture, and this thesis has nothing to contribute in this area. Only feasible areas of research and research that has at least some element of originality have been included in the main body of the thesis.
3.3. Theoretical foundation

The challenge of enabling information sharing in humanitarian logistics in disaster relief is a complex and sophisticated cross-disciplinary issue which requires a multi-disciplinary approach to answer appropriately. Five separate disciplines serve as the theoretical foundation for this thesis. The core of the research is situated in operations management and supply chain management, towards the context of humanitarian logistics, intersected with useful theories and techniques from strategic management and systems theory. Until the last 15 years, in academic research humanitarian logistics was a sub-topic under disaster management, while supply chain management tended to concern itself only with ‘traditional’ commercial logistics and supply chain management issues. This thesis will focus on the paradigms of information sharing for supply chain coordination between partners (Lee & Whang, 2000) and quick response supply chain strategy (Christopher, 2000).

In its most literal statement, this investigation enables information visibility and information sharing [supply chain management] coordination in disaster relief humanitarian logistics [humanitarian logistics] in a low trust environment by designing and implementing an automated process solution [information systems, computer science, and operations management], which is enabled through the instantiation of a mobile communications system based on wireless telecommunications [telecommunications engineering, electronics engineering, and information systems]. The philosophical position of this research will be a combination of constructionism (Kafai & Resnick, 1996) for seeing what is physically possible with the technology by building capabilities within systems to test and/or develop theories (Holstein & Gubrium, 2008), and positivism (Ayer, 1959) for seeing how agents interact with the technology where the performance of the system can
be objectively observed and measured. Different interdisciplinary frameworks are required for researching the problem, defining a solution, and implementing that solution. Understanding the problem requires a more strategic view of higher-level behaviours, which are built on low level behaviours. In this case, taking a higher-level view allows a process solution to be architected, but to build it requires programming and technology.

3.3.1. Theories and methodologies relevant to the research area

The problem area is highly cross-disciplinary, so a combination of different theories and methodologies across multiple fields is required to fully complement all aspects of the problem. The relationship between different theories and methodologies in the research area are summarised in Figure 3.1 (p. 84) below. The solution is principally a process engineering solution that perceives information visibility and information sharing as a business process (re)engineering issue centred around demand sensing [operations management], which can be viewed from multiple theories of the firm [strategic management]. In the most basic sense, the resourced-based view can be used to perceive the issue as a lack of necessary resources, while the knowledge-based view alternately perceives the issue as a lack of skill and experience in the areas required to create use and/or create resources and capabilities.

The transaction cost theory of the firm provides some nuance to these perspectives. Very briefly, transaction cost economics perceives business problems as a series of transactional processes with costs, whereby lowering transaction costs makes a firm more efficient, effective, and responsive. Transaction cost theory uses the perspective of transaction cost economics to explain the nature of a firm’s competitive advantage as being the quality of its processes. These strategic management theories of the firm are inherently about competitive advantage in the private sector, which is an adversarial system. By
contrast, humanitarian logistics is primarily cooperative/collaborative and centred around *interagency coordination* [humanitarian logistics], despite its shortcomings. By slightly modifying the concept of competition, instead of the opportunity for financial profit driving private firms, humanitarian outcomes drive aid agencies and disaster events compel aid agencies to act.

Integrating a process solution across multiple organisations in a supply network of multiple supply chains naturally involves *information sharing* on issues of *inventory management* to prevent *supply chain disruption* [supply chain management]. The *quick response* supply chain is a promising technical base for implementing this approach, though to make it fit with the disaster relief environment requires substantial restructuring. Even though quick response was used as the original concept for the solution presented in this thesis, adapting information sharing processes to the constraints in disaster relief has led to the final result being different it barely resembles the characteristics of quick response.

Using systems thinking, system dynamics and *stock and flow modelling* [systems theory] can be used to explore different types of information sharing in supply chains. By identifying the constraints in the disaster relief environment, then applying them to a simulation, the dynamic relationships affecting supply chain performance can be manipulated to theorise alternative information sharing methods. If these alternative methods create acceptable performance and are feasible, then the best of these information sharing methods should be chosen. Once the information sharing scenario is chosen, the task of designing the process solution can begin. After the process has been defined, it must be built, which requires a new set of cross-disciplines.
3.3.2. **Techniques, topics, and tasks needed to answer research problems**

Once the boundaries of the research area are outlined and the research problem is chosen, a solution must be created. The solution is created using the *design science* methodology integrated with several disciplines. (Design science originates from various fields of engineering and is a methodology, not a ‘discipline’.) The techniques required to create a solution using design science are summarised in Figure 3.2 (p. 86) below. *Operations management* and *supply chain management* are increasingly closely intertwined with information systems as organisational processes become more digitised and automated (Sambamurthy, Bharadwaj, & Grover, 2003), to the point where it is often impossible or
impractical to separate them. The final practical artefact involves an information system built on top of a network of physical electronics devices, which requires the combination of electronics engineering, computer science, and information systems.

Using design science to produce the artefact, information systems are used to integrate the components of the practical artefact, providing elements such as a relational database to store data, web interface for users to interact with the network artefact, and a message broker to handle the order of message queues. Programming is required to link together the relational database, web interface, and message broker. In total there are eight complementary disciplines and one major methodological approach. Using this research approach, research objectives can be generated, along with their intended artefacts.
3.4. **System dynamics**

System dynamics plays a minor supporting role to design science in this thesis. Within the design science process there is a need to observe and define the problem, as well as evaluate the utility of an instantiation. To do so, in the next chapter an existing simplified order fulfilment supply chain model is adapted to include various information sharing scenarios. By simulating various information sharing scenarios and comparing them to the constraints of the disaster relief environment, the highest performing information sharing scenario can be identified. This information sharing scenario will serve as the rough blueprint for the process solution to the practical problems outlined in the section *Practical problems as research impetus* above.

In computer process simulation, by far the two most popular modelling paradigms are system dynamics and discrete-event simulation (Zhang, Kitchenham, & Pfahl, 2008, p. 353). Four basic techniques are used in supply chain modelling (Angerhofer & Angelides,
(1) Causal loop diagrams, (2) Operations research techniques, (3) Continuous simulation and (4) Discrete simulation. The generally accepted view is that system dynamics is best suited for strategic level modelling (Tako & Robinson, 2012, p. 804), though here it is used in an operational context in subsequent chapters. System dynamics helps explain the origins of unintended consequences in a complex and dynamic system, despite the inherent rationality of the actors and decision-making processes involved (Friedman, 2004). Since we are primarily concerned with overall dynamics, rather than quantifying relationships within and across actual organisations for prediction purposes, system dynamics will be used.

3.4.1. Stock and flow diagrams

System dynamics simulations represent systems as stocks and flows, and their changes over continuous time (Brailsford & Hilton, 2001). A system consists of elements and their interactions, where the whole is greater than the sum of its parts (von Bertalanffy, 1968). Dynamic systems are characterised by the following (Sterman, 2000): (1) Strong interactions, (2) Strong dependency on time, (3) Complex causal structures and (4) Delays between cause and effect. Complex systems are characterised by the following (Sterman, 2000): (1) High number of elements, (2) High number of interactions between elements and (3) High number of inter-functional connections between elements. These interactions manifest themselves in two ways (Forrester, 1975): (1) Positive feedback loops, which creates exponential effects, and (2) Negative feedback loops, which brings a system to equilibrium.
3.5. Design science

Design science research originated in various fields of engineering. Essentially, design science seeks to create implementations, or what are called “instantiations”, and provide the framework for their creation, to solve a practical problem. The process to create a solution to a practical problem inherently creates research artefacts, usually in the form of theoretical frameworks, while the solution itself serves as proof of the theory used to create it. Design research is the study of design, whereas design science research is the use of design and implementation as a research methodology (Kuechler & Vaishnavi, 2011). Prat, Comyn-Wattiau, and Akoka (2014, pp. 6, 9) created a hierarchy of dimensions for evaluating artefacts produced using design science, as well as a model for generic evaluation methods. Evaluation can be implemented artefact, also called an instantiation, or uninstantiated artefact (Pries-Heje & Baskerville, 2008). This instantiation may be an artificial representation or a real-world application.

March and Smith (1995, pp. 253-254) explain the difference between design science, focused on prescriptive building and evaluation, and the natural sciences, focused on the descriptive and explanatory. Design science differs from natural science in that instead of observation of natural phenomena, design science seeks to manipulate the environment for the benefit of users (Simon, 1996, p. 55). Benbasat and Zmud (1999, p. 5) state that design science is directly related to information systems and that research should be implementable. Information systems research has fundamentally shifted towards an engineering approach, focusing on applied methodologies (Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007, p. 47). There is a difference between research (i.e. designing instantiations) and meta-research (i.e. research on design science as a
methodology) (Hevner, March, Park, & Ram, 2004), and this thesis is mostly concerned with the former.

Design science enables the development of information systems, as well as providing a framework for their successful implementation (March & Smith, 1995). The design science process is highly iterative (Markus, Majchrzak, & Gasser, 2002), involving the building and evaluation (March & Smith, 1995) of the artefact, which creates feedback for further creation and evaluation, until the instantiation is finalised (Nunamaker, Chen, & Purdin, 1991, p. 98). Information systems research is fundamentally centred around the creation, implementation, and evaluation of information technology artefacts (Orlikowski & Iacono, 2001).

Design science research artefacts can be categorised as follows (March & Smith, 1995): (1) Constructs, (2) Models, (3) Methods and (4) Instantiations. Constructs comprise language used to define problems and solutions (Schön, 1983). Models use constructs as an artificial representation of the boundaries of problems and solutions (Simon, 1996). The relevance of the problem should be established (Hevner, March, Park, & Ram, 2004, pp. 84-85), such as by conducting a thorough review of the body of knowledge (Nunamaker, Chen, & Purdin, 1991, p. 92), before the potential utility of the instantiation is estimated. Methods define the process of designing and evaluating instantiations (Hevner, March, Park, & Ram, 2004, pp. 85-87), which includes feasibility issues, best practices, and varied design and research paradigms. Instantiations are the physical implementation of a system to prove that the constructs, models, and methods used to produce it are valid, and are evaluated by their utility to users (Hevner, March, Park, & Ram, 2004, pp. 85-87).

According to Iivari’s (2007, p. 46) epistemological framework, this design process will use the conceptual knowledge derived from the literature review in the previous chapter, descriptive knowledge in the subsequent chapter for existing technological
solutions, and finally prescriptive knowledge in designing an instantiation in the final chapters. There are three levels of design science contributions by their level of abstraction, from most to least abstract (Gregor & Hevner, 2013, p. 342): (1) Theory about embedded phenomena, (2) Knowledge of operation principles and architecture, and (2) Situated implementation of an artefact (i.e. instantiation). According to the same authors’ framework for the maturity of knowledge contribution, instantiations are the least mature (Gregor & Hevner, 2013, pp. 345-346).

3.5.1. Meta-methodology for integrating multiple methodologies and methods

Hevner, March, Park, and Ram (2004, pp. 79-80) integrate behavioural science and design science to describe the two phases necessary in the design science process: (1) Theory building, such as through the creation and evaluation of instantiations, and (2) Justifying the instantiation, through means such as case studies, experiments, and simulations. Together, these two phases allow for an empirical evaluation of instantiations and the means to create them. Similarly, Nunamaker, Chen, and Purdin (1991, p. 92) describe a process of how knowledge research relates to the body of knowledge.

Nunamaker, Chen, and Purdin (1991) offer a practical multi-methodological process for the creation of instantiations, but due to its focus on the highly iterative nature of systems development, they do not specify precisely where the design science process begins. March and Smith (1995) provide a conceptual framework for classifying research activity and research artefacts, though its usefulness as a practical guide is limited. Hevner, March, Park, and Ram (2004, p. 76) identified that design science and behavioural science were complementary, but their main contribution is a series of practical guidelines for conducting design science (p. 83), and although it lacks a sequential view of the process it can be argued that use of each guideline is concurrent.
Mingers (2001, pp. 247-249) identified four common issues with multi-methodological approaches: (1) Philosophical problems, such as competing paradigms, (2) Cultural problems, such as the suitability of multi-methods in a study area, (3) Psychological problems, mostly pertaining to researchers themselves, and (4) Practical problems, such as the complementary and conflicting aspects of multi-methods. Regarding practical problems, using multi-methods can produce complementary research artefacts, provided the rigidity of one method does not unduly constrain another.

This study will use the multi-methodological framework and developmental cycle developed by Nunamaker, Chen, and Purdin (1991) to produce an instantiation in Figure 3.3 (p. 92) below, while observing the research guidelines by Hevner, March, Park, and Ram (2004, p. 83). This framework combines multiple research methodologies at different stages of the development cycle, as well as allowing for any necessary iterations. By using an inclusive and flexible framework, which allows for multiple methodologies, the researcher is not restricted to one methodology. Observations during research will only be as accurate as the instrument used. This is arguably made more pertinent due to the nature of technology, where technological limitations may not be properly analysed and understood by certain methodologies.
3.5.2. **Design science research process**

The design science process requires changing methodologies to appropriately serve each situation, as well as the ability to move fluidly between different stages of the design process, since chronological progress is rarely strictly linear or procedural (Nunamaker, Chen, & Purdin, 1991, p. 98). The design science research process is shown in Figure 3.4 (p. 94) below. To start with the value of the artefact must be hypothesised to see if it is worthwhile initiating the design process (Hevner, 2007, pp. 88-89), which requires a literature search to define the problem space. Upon moving to the ‘build’ and ‘observe’
stages, estimated capabilities (e.g. theory building, simulation) are less useful than actual capabilities (e.g. field experimentation). At the ‘theory building’ stage, the conceptual network is theorised (e.g. systems architecture, system components, available technology) and mathematical models developed to test its theoretical feasibility (e.g. network mapping, technological limitations).

Once the artefact has been instantiated, Venable, Pries-Heje, and Baskerville (2012, pp. 425-426) explain that systems evaluation is necessary for the following reasons: (1) Establish utility and efficacy, (2) Establish whether it is fit for the purpose, (3) Comparisons with other similar solutions, (4) Discover possible unintended consequences from its use and (5) Identify weaknesses and opportunities for further development. The most common means of evaluating an instantiation is as follows (Peffers, Rothenberger, Tuunanen, & Vaezi, 2012): (1) Logical argument, (2) Expert evaluation, (3) Prototype, (4) Case study and (5) Illustrative scenario. Since this thesis aims to create an automated process solution built on a telecommunications infrastructure, the instantiation can be termed a socio-technical artefact, which serves as the primary research artefact.
Systems evaluation is the weakest part of the research area in general, which includes this thesis. It is extremely difficult for anyone to implement related and similar solutions in aid agencies due to the problems identified in the Literature review chapter (pp. 21-73). The most significant limitation to evaluating the prototype is that it is limited to a laboratory experiment, instead of a field experiment. This is because the technology has not yet been developed with a long-range antenna or a ruggedised casing to withstand the weather. As alluded to above, the issues surrounding adoption will likely be the deciding factor behind the actual utility of the system. No humanitarian logistician is going to accept the introduction of an automated process solution and/or telecommunications system for disaster relief without extensive testing and case studies, which creates something of a
dilemma: A system must be successfully deployed before used, but how does it get deployed in the first place? However, this is primarily a business issue, and so lies outside the scope of this thesis.

So how do new communications technologies come to be adopted by humanitarian logisticians? The answer is from extensive testing and case studies from industry. Industry takes all the risk of early adoption, while the comparatively risk-averse humanitarian logisticians choose to adopt mature technologies that can be relied upon in the field. ZigBee is exactly that, a mature technology that has seen extensive deployment in industry for logistics automation (Lin, Liu, & Fang, 2007), but is now making its way into automating parts of consumer lives. However, the testing and case studies are ostensibly for a commercial context, and the supply chain volatility and lack of information visibility in any arena of commerce can scarcely compare to the extreme case of disaster relief, so there will be some necessary adjustment to the unique features of disaster relief (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012).

3.5.3. Supply chain and strategic management theory as design principles

Design science frameworks are generic and lack a design approach because they are intended to be used for the design process, rather than being tailored towards a specific solution. As mentioned previously, design science is a methodology that originates in various fields of engineering. The iteration of design science used in this thesis is from an adaptation used in the field of information systems. To adapt it to a process problem from supply chain management, there needs to be some integration with existing supply chain theories, as well as complementary and/or overlapping theories from adjacent fields. This section integrates supply chain and strategic management theory into the design science
research process in a way that is specific to the research problems in this thesis. The
relevant theories and their relationships are summarised in Figure 3.5 (p. 98) below.

Each stage of the design science research process integrates with related supply
chain theory. This was touched upon in the previous Venn diagram showing the
interdisciplinary overlap of the research problem. Strategic management theory, especially
theories of the firm, have often been integrated into operations management and supply
chain management simply because of its utility in perceiving organisational problems from
a certain perspective. The various theories of the firm used in this thesis were briefly
covered in the Literature review chapter (pp. 21-73). Paradigms within supply chain theory
are used as core design principles within the design science research process, while related
type can be used to explain and/or evaluate subcomponents of planned and produced
instantiations. The diagram below shows exactly how the theories and concepts relate to
one another in the overall design science research process.

During the conceptual framework stage (Nunamaker, Chen, & Purdin, 1991), by
surveying the supply chain literature a meaningful research question is developed out of
the literature gap. Literature from related disciplines are included in this search. Existing
solutions are examined for their capabilities and limitations in addressing the literature gap,
including solutions from other fields with similar challenges. Quick response supply chain
was identified in the Literature review chapter (pp. 21-73) as being both absent from the
disaster relief environment and potentially beneficial, while the reasons inhibiting its
adoption were detailed and synthesised with environmental and behavioural factors.

One of the lenses used from strategic management is the resource based view
(Barney, 1991), which perceives the control of imperfectly imitable resources as the source
of a sustainable competitive advantage. This is contrasted with the knowledge based view
(Conner, 1991) that sees the inherent characteristics of knowledge creation and
dissemination forming the source of a sustainable competitive advantage. Both lenses view resources as the source of competitive advantage, but the knowledge-based view sees knowledge as a unique resource unlike physical resources, whereas the resource-based view tends to classify knowledge as simply another form of resource.

In this thesis, the control of strategic tangible resources such as information systems (Gunasekaran & Ngai, 2004), and intangible resources such as tacit logistics knowledge and experience with interagency coordination (Akhtar, Marr, & Garnevska, 2012), improve supply chain performance. The core design concepts that emerge from the literature search are the requirement for both resources (Barney, 1991) and knowledge (Conner, 1991) to enable supply chain collaboration, which is a source of competitive advantage. Initially, it appears strange that competitive advantage would be considered by aid agencies delivering disaster relief. There is no perfect analogue between private sector competition for profits and the unusual competitive and collaborative relationships found in the humanitarian sector. However, this difference can be squared if competition is re-contextualised in disaster relief as being between aid agencies and the disaster event in the short to medium term, and between aid agencies competing for donor funding in the medium to long term. From that perspective, aid agencies do compete for sustainable profits, but they measure ‘profit’ in humanitarian outcomes instead of financial gains.

Using these strategic management perspectives, the issues of supply chain collaboration are resolved through information sharing, which is enabled by virtual integration, horizontal integration, and coordinating mechanisms in supply chains (Balcik, Beamon, Krejci, Muramatsu, & Ramirez, 2010, p. 30). Strategic information sharing of the insights gleaned from logistics data is what separates knowledge from mere information (Conner, 1991), while appropriate analysis and contextualisation is what separates information from mere data.
The above supply chain theories, which are viewed from strategic management theories of the firm, form core design concepts for solving the research problem. As mentioned in the Literature review chapter (pp. 21-73), there is extensive literature support on the importance of information sharing in supply chains for coordinating orders and inventories to prevent supply chain volatility (e.g. Francis, 2008). These design concepts can be examined from the view of transaction cost economics, the theory of constraints, and information visibility to form a specific design approach. Using transaction cost economics (David & Han, 2004), information sharing can be perceived as a transactional process,
where transaction delays, throughput, and both the quantity and quality of information determines supply chain performance. If the costs of this process are lowered, performance increases, vice versa. The feasibility of any information sharing process will be bound by the theory of constraints (Rahman, 1998). Environmental uncertainty and interagency trust issues are some examples of these constraints identified in the Literature review chapter (pp. 21-73). There is currently no direct solution to certain constraints, although various forms of centralisation have been tried extensively, so any functional solution must operate within the bounds of these constraints until a direct solution emerges.

During the “Systems Architecture” stage (Nunamaker, Chen, & Purdin, 1991), the literature search in the previous stage was used to inform the architecture’s design. The necessary components and capabilities that need to be built into the architecture are identified in the literature and perceived using the lens of core design concepts. The antecedents of agile, leagile, and quick response supply chain strategies can be examined using the resource based view (Barney, 1991) and knowledge based view (Conner, 1991) to identify the implicit foundations of those antecedents, such as information visibility being a prerequisite of information sharing.

The maturity of information sharing and closeness of coordination between supply chain partners can be perceived as a progression from basic information sharing to supply chain collaboration (Simatupang & Sridharan, 2002), and finally to some form of supply chain integration (e.g. horizontal integration in Markham & Westbrook, 2001), including means such as electronic data interchange (Hill & Scudder, 2002), enterprise resource planning integration (Akkermans, Bogerd, Yücesan, & Van Wassenhove, 2003), and other formal methods of information sharing. As previously mentioned in the Literature review chapter (pp. 21-73), interagency coordination is difficult between aid agencies because of the fragmented and ad hoc nature of decision-making in disaster relief (Holguín-Veras,
Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012), so the more formal means of coordination maybe unfeasible. The history of highly centralised approaches to coordination so far tend to lean heavily towards this conclusion, although some centralisation will always be necessary for effective coordination. As a brief example of an extremely low complexity coordination capability, some information systems such as Sahana Eden (Careem, Silva, Silva, Raschidt, & Weerawarana, 2007) can integrate with other systems through the simple import and export function for .CSV files, although data preparation (e.g. cleaning and reformatting) remains an issue.

The antecedents to agile, leagile, and quick response are analysed using transaction cost theory (Grover & Malhotra, 2003) to explain why supply chain coordination strategies benefit from information sharing and information visibility (Barratt & Oke, 2007). The theory of constraints (Rahman, 1998) places limitations of the levels of supply chain coordination (Kampstra, Ashayeri, & Gattorna, 2006) and information sharing (Day, Junglas, & Silva, 2009), which helps define the problem space for the systems architecture to solve. The previous search for telecommunications solutions is used to explore how different architectures (e.g. Yang & Deng, 2011), network topologies (e.g. Iland & Belding, 2014), and wireless communications standards (e.g. Midkiff & Bostian, 2002) contribute to information visibility and information sharing.

During the “Systems Design” phase (Nunamaker, Chen, & Purdin, 1991), the processes within the system architecture were defined, modelled, and integrated. This is where the design concepts are implemented within the information flow through system components. Here the transaction costs associated with the information flow are made explicit, such as internal and external linkages, determinants of lead times, and the means of information processing.
During the “Systems Prototyping” stage (Nunamaker, Chen, & Purdin, 1991), the core design concepts from the literature were used to build the practical artefact. Through the process of building the practical artefact, the designer learns about the design concepts and their application, they can see the research framework make the evolution from hypothesis to theory and practice, and gain insight about the system and the process used to create it. During the “Systems Evaluation” stage (Nunamaker, Chen, & Purdin, 1991), key theoretical lenses were used to examine, explain, and predict the practical artefact’s operation and performance through demonstrations in a laboratory setting. In the future, those same lenses can be used to evaluate the system in a case study or field study, though this is outside the scope of this thesis. The transaction costs and benefits associated with information visibility (Lee & Whang, 2000) and information sharing (Barratt & Oke, 2007) can be measured, validating the systems utility (Hevner, March, Park, & Ram, 2004). Now that the design science process has been clearly defined after being adapted to the research problem, the process of prototyping a practical artefact can properly begin.

3.6. Conclusion

From the framing of the research area in the previous Literature review chapter (pp. 21-73), this chapter details how specific research artefacts are created to answer the research question. This thesis solves the problem of a lack of interagency coordination in disaster relief by creating a technology-enabled process solution to information visibility and information sharing between aid agencies’ supply chains. To answer the research question to achieve the research objective, supply chain theory is integrated into the design science development process. The iterative design process is designed around core design concepts derived from supply chain and strategic management theory. To begin the development process, the potential of the planned solution must be assessed by some method. System
dynamics simulations were chosen to model the effects of different information sharing scenarios on aid agencies’ supply chain performance. The next chapter covers the development and testing of the simulation, and the subsequent chapter advances the development process to the design and definition of the system architecture for the solution.
4. Supply chain simulation

4.1. Introduction

As part of the design science research process for prototype development, the hypothetical value of the prototype is simulated to justify the fundamental problem solving approach. To test the value of information visibility and information sharing in supply chain management under different scenarios, system dynamics is used as a simulation methodology. Conceptual models are developed showing the flow of goods and order information across four information sharing scenarios: (1) Null hypothesis with no information sharing, (2) Vertical information sharing between partners of their own supply chains, (3) Horizontal information sharing across retailers from different supply chains and (4) Combining vertical and horizontal information sharing approaches. These conceptual models were converted into stock and flow diagrams built using the Vensim computer application, which were adapted from an existing model of the famous beer game for illustrating the supply chain volatility when there is no information sharing. The simulation results inform the design science process and either confirm or deny the hypothetical utility of the problem solving approach to supporting interagency coordination in previous chapters, which determines whether the development process progresses to the next stage, or whether it must iterate backwards using a different problem solving solution.

4.2. Information sharing models in supply chains

Most existing information sharing models in supply chain management and operations research focus on vertical information sharing between supply echelons to reduce variability
As an alternative information sharing model, horizontal information sharing could occur between competing downstream retailers. However, horizontal information sharing could be considered by regulators as collusion, price fixing, or other forms of anti-competitive behaviour in violation of competition laws when applied to private industry (EU, 2011). But in the context of disaster relief, very limited ad hoc horizontal information sharing already exists (Schulz & Blecken, 2010), does not run afoul of commercial competition laws, and is considered necessary for humanitarian logistics performance.

4.2.1. Lack of vertical information sharing in disaster relief

Vertical information sharing requires formalised information sharing agreements between mature supply chain partners (Huang, Lau, & Mak, 2003), usually with some form of vertical integration or virtual integration (e.g. Sari, 2008). Many of the supply chains in disaster relief are ad hoc and hastily assembled in the immediate aftermath of a disaster. There are existing strategic partnerships for resource pooling between aid agencies (e.g. Gatignon, Van Wassenhove, & Charles, 2010, pp. 107, 109) as well as strategic corporate partnerships (Thomas & Fritz, 2006; Stewart, Kolluru, & Smith, 2009) for the procurement of relief items in sufficient quantities at short notice, but they do not rise to the level of vertical or virtual integration. This is especially the case for aid agencies that are temporarily involved in disaster relief and do not have disaster relief delivery as part of their usually organisational mission, who are unlikely to have any information sharing or procurement agreements with suppliers or wholesalers or any kind for relief items. Many aid agencies lack the information systems and investment to pursue any kind of organisational integration with suppliers. For various reasons, many of which were covered in depth in the Literature review chapter (pp. 21-73), if information sharing is a major
determinant or interagency coordination, yet it is unfeasible for aid agencies, those agencies will simply have to use other forms of information sharing.

4.2.2. Social media analysis for disaster incident reporting

One novel approach that has emerged and has proven very successful is using social media platforms for disaster incident reporting (Tatham, Spens, & Kovács, 2017, p. 90). Ushahidi was one of the original solutions using this approach (Sheller, 2012). Essentially, if the affected population has access to telecommunications, they can post user content on social media platforms (e.g. Twitter, Facebook) describing problems they are facing related to the disaster event (e.g. roads blocked, lack of supplies, dangerous areas). These user posts can then be mined by data analytics to serve as a facsimile of direct demand information. In the case of Ushahidi, each incident was mapped onto the Google Maps service to show clusters of incidents. Inevitably, this approach involves assessing the quality and time-sensitivity of each user post in an automated way. It is a long way from direct demand data, but in the absence of anything else it has been invaluable to improving aid agencies’ information coverage of a disaster zone and in improving their responsiveness in the early response stage of disaster management.

Such incident reporting approaches have been a valuable practical and theoretical contribution to humanitarian logistics, but it falls short of information sharing between aid agencies, especially on operational problems (e.g. direct demand, capacity, bottlenecks, shortages, and surpluses). Ultimately, social media analysis is another tool in the overall information sharing mix that can complement relief operations, but it does not rise to the level of being so effective it becomes a definitive solution. While aid agencies have a better overall understanding of the affected population’s needs with these approaches, the fundamental problem of interagency coordination remain unresolved. So, the question
becomes, if vertical information sharing is unfeasible and social media analysis does not resolve the problem, what kind of information sharing is both feasible for disaster relief and would enable information sharing between aid agencies? In the subsequent section, a hypothetical information sharing scenario described here as “horizontal information sharing” that is unavailable to the private sector is proposed. There are some similarities and differences with “horizontal information sharing” and similar terms in the existing literature, which are explained in the Discussion chapter (pp. 167-191).

4.2.3. **Horizontal information sharing as an alternative model**

Instead of vertical information sharing across a single supply chain, information can be shared horizontally between retailers across different supply chains. In the private sector, this might be considered the illegal behaviour of a cartel operating as a monopoly (EU, 2011), but in the absence of commercial competition, it may be considered both legal and desirable in the humanitarian sector. In many ways, horizontal information sharing is more representative of downstream supply chains for disaster relief than any other information sharing scenario even now, despite the limited and ad hoc information sharing that occurs. The difference between what exists now in disaster relief and what is being proposed as the third scenario for horizontal information sharing are vastly increased scalability and efficiency. Instead of ad hoc agreements that are limited in scope, full horizontal information sharing proposes an automated process for sharing all information at the retailer level constantly and at intervals approaching real time.

Each aid agency has an incomplete and often distorted operating picture of the needs of the affected population, which are influenced by the location of their personnel within the disaster zone and adjacent refugee camps, as well as the clarity and time delay of coordination within each aid agency at different levels of their organisational hierarchies.
Each piece of information an aid agency possesses is not just immediate information that can be used, but with sparse accurate and usable information, is often used for extrapolation or estimates as if they were representative of the affected population’s needs. If the information each aid agency can see is aggregated across aid agencies at the lowest level, this should hypothetically increase information visibility. Once information is visible, it can be shared. If information is visible and shared, it should hypothetically increase supply chain performance.

Conceptually, the relationship between vertical and horizontal information sharing used in this thesis for supply chain coordination is like vertical and horizontal integration (e.g. Markham & Westbrook, 2001) in business integration, but information sharing does not necessarily involve business integration. Only information is being shared, whereas business integration involves interfacing/interconnecting business processes across organisations and represents a much closer relationship that is more likely to be a strategic long-term partnership involving significant process engineering and virtual integration (e.g. Gunasekaran & Ngai, 2004), than a short-term, transactional, or ad hoc relationship. That does not mean that the two cannot coexist, but this thesis only suggests information sharing in a transactional relationship towards short-term objectives, such as would be found in disaster relief.

4.2.4. Summary of descriptions for information sharing scenarios

The descriptions/definitions for different information sharing scenarios used throughout this thesis are given in Table 4.1 (p. 108) below.
<table>
<thead>
<tr>
<th>Information Sharing Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No information sharing</td>
<td>There is no information sharing between organisations within or across supply chains. Each organisation gives orders to the next echelon of their respective supply chains without consultation with any other organisation.</td>
</tr>
<tr>
<td>2. Vertical information sharing</td>
<td>There is information sharing across each organisation’s supply chains. Each echelon of the supply chain communicates their demand information and ordering information to higher echelons. Otherwise, there is no additional information sharing.</td>
</tr>
<tr>
<td>3. Horizontal information sharing</td>
<td>There is information sharing between different supply chains between retailers at the lowest downstream level. Otherwise, there is no additional information sharing.</td>
</tr>
<tr>
<td>4. Horizontal and vertical information sharing</td>
<td>There is information sharing across each organisation’s supply chains, and between each retailer. Each echelon of the supply chain communicates their demand information and ordering information to higher echelons. Additionally, retailers share demand and ordering information between one another.</td>
</tr>
</tbody>
</table>

Table 4.1: Descriptions of information sharing scenarios

4.3. **Stock and flow diagrams for simulations**

Before embarking on the design science process for system development, the theoretical value of the system must be established. There is a wealth of research proving the value of information sharing in a supply chain (Lee, Padmanabhan, & Whang, 1997; Lee & Whang, 2000; Francis, 2008), which can be described as “horizontal information sharing” (i.e. between supply chain partners). Previously, vertical and horizontal information sharing were described. Four different information sharing scenarios in disaster relief supply chains can be derived from these approaches: (1) No information sharing at all, (2) Vertical information sharing across a single supply chain, (3) Horizontal information sharing across downstream supply chains and (4) Vertical and horizontal information sharing simultaneously. (Social media analysis will not be simulated, since it is difficult to draw a line of cause and effect between social media insights and aid agencies’ operations, and in any event, it does not address information sharing between aid agencies.) From the perspective of system dynamics, enabling greater downstream information visibility, which
can be termed “horizontal information sharing” (i.e. between retailers), would reduce the
time taken to collect demand information, as well as allowing for a far greater detection of
existing demand, which hypothetically should reduce supply chain volatility. Key
considerations of creating system dynamics simulations using stock and flow diagrams will
be explained in this section.

4.3.1. Purpose of the simulations

The hypothetical effect of implementing the eventual practical artefact to be produced must
be simulated to prove its utility before embarking on the rest of the design science process.
Multiple information sharing scenarios are tested and benchmarked against one another to
measure the value of each scenario and whether design science development could
continue, or whether the problem solving approach of enabling vertical information sharing
is fundamentally flawed. This is a significant challenge because the disaster relief
environment is heavily risk-averse (Thomas & Fritz, 2006) and no practitioner would allow
a new solution to be adopted without first testing it outside of a disaster relief environment.
This is further complicated by the lack of time humanitarian logisticians generally have,
which means a complete field experiment is out of the question as there are simply no
available or willing participants.

To prove the hypothetical value of the artefact, its effect on interorganisational and
intraorganisational performance can be simulated by adapting existing models of order
fulfilment and modifying it to include different types of information sharing, then
comparing the results. We can simulate the effects of having and not having the system in a
highly decentralised, chaotic, and dynamic situation, such as the disaster relief
environment, by using system dynamics (Forrester, 1961), allowing the exploration of
nonlinear relationships in a system using a holistic view (Sterman, 2000).
The system dynamics process consists of the following elements (Sterman, 2000): (1) Articulating the problem, (2) Developing a hypothesis, (3) Developing a simulation model, (4) Testing that model and (5) Designing and evaluating policy. Barlas (1996, p. 185) identifies six major stages in the system dynamics process: (1) Identifying the problem, (2) Conceptualising the problem as a model, (3) Formulating the model, (4) Analysing and validating the model, (5) Designing and analysing policy from the model and (6) Implementing the modelled policy. In subsequent chapters, a system dynamics model of a generic order fulfilment process along a supply chain is adapted to include various means of information sharing. Nevertheless, even though it is a minor adjustment of an existing model (Borshchev & Filippov, 2004; Kirkwood, 1998), the model must be slightly reconceptualised and reformulated (Barlas, 1996, p. 185). Afterwards, the model can be analysed. Andersen, Richardson and Vennix (1997, p. 187) state, “Model building is... more art than science.”

The structural validity of the model (Barlas, 1996, p. 189) is unambiguous, as it is simply an extension of the existing model’s information sharing along a supply chain to include information sharing across different supply chains at a single point. The exact process of information sharing within each aid agency is not being tested because it is not relevant at this point. The general flow of information between each aid agency and their respective supply chains is being simulated. The resulting model is a high level model of generic information sharing. Ultimately, the simulations are concerned with supply chain dynamics in general, not the accurate quantification of any specific aid agency’s supply chain operations.
4.3.2. Underlying assumptions

Beyond the resource, personnel, and trust issues inhibiting information sharing and interagency coordination from the Literature review chapter (pp. 21-73) that serve as the impetus for carrying out simulations, there are several assumptions that do not come with supporting research that are required for building the simulations. These assumptions are summarised in Table 4.2 (p. 111) below.

<table>
<thead>
<tr>
<th>Simulation Assumption</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumption 1</td>
<td>Aid agencies’ own operations are visible to themselves, even if there is a substantial time delay in information from downstream operations filtering up to higher level headquarters.</td>
</tr>
<tr>
<td>Assumption 2</td>
<td>Aid agencies’ information on their own operations are accurate.</td>
</tr>
<tr>
<td>Assumption 3</td>
<td>Aid agencies’ that have heterogeneous data/information standards nevertheless are similar enough to be comparable.</td>
</tr>
<tr>
<td>Assumption 4</td>
<td>Aid agencies are willing and able to share relevant information according to each information sharing scenario. (Obviously, this is barring the scenario with no information sharing.)</td>
</tr>
<tr>
<td>Assumption 5</td>
<td>For each information sharing scenario, there is full adoption by all organisations across all supply chains.</td>
</tr>
<tr>
<td>Assumption 6</td>
<td>There is a negligible time delay for each echelon in the supply chain when detecting their own demand data.</td>
</tr>
<tr>
<td>Assumption 7</td>
<td>There is only one organisation within each echelon of each supply chain.</td>
</tr>
<tr>
<td>Assumption 8</td>
<td>No exogenous variables are considered.</td>
</tr>
</tbody>
</table>

Table 4.2: Assumptions for supply chain simulation

Simulation assumptions 5, 6, 7, and 8 make modelling significantly easier but also less representative. However, by simplifying the disaster relief environment it has also been artificially rendered less dynamic, which reduces supply chain performance improvements from information sharing scenarios. Mathematically, this makes it significantly harder for horizontal information sharing to show performance increases under these simulation parameters. Given that each disaster relief operation is unique and that an indeterminate number of aid agencies may be involved with hastily formed supply chains, the full extent
of the benefits of various forms of information sharing will be significantly understated by these simulations.

4.3.3. Conceptual models of different information sharing scenarios

To artificially reproduce (Min & Zhou, 2002) what happens within a single organisation when the artefact is introduced, as purely an illustrative example of the dynamic relationships, a simplified version of a standard system dynamics model (Borshchev & Filippov, 2004) of the beer game was adapted (Kirkwood, 1998), substituting three supply chains in place of one, and substituting the Vensim equations in the appendices to represent the following the information sharing scenarios defined above in Figure 4.1 (p. 113) below, Figure 4.2 (p. 114) below, and Figure 4.3 (p. 115) below. The most important change in the original parameters were the introduction of highly volatile retailer demand, which is more representative of disaster relief volatility. The scenarios are simulated using dummy parameters. Given the lack of available data from disaster relief operations not only within, but across organisations, substituting real values into the model is a desirable but impossible fantasy.
Figure 4.1: Conceptual model of supply chain simulation for scenarios 1 and 2
(adapted from Taylor & Arthanari, 2018a, p. 6)
Figure 4.2: Conceptual model of supply chain simulation for scenario 3
(adapted from Taylor & Arthanari, 2018a, p. 7)
The order fulfilment process involves the twin flows of supplies moving downstream (i.e. towards the retailer) and demand information moving upstream (i.e. towards the supplier). Backlogs measure the total performance of an organisation in meeting demand, which in the context of disaster relief would directly represent deprivation costs, or the cost of the affected population being deprived of the necessities of survival. Backlogs are of special importance in disaster relief, as deprivation costs (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012) are the fundamental measure (Holguín-Veras, Perez, Jaller, Destro, & Wachtendorf, 2010) by which disaster relief supply
chain performance is measured. Ultimately, lower backlogs decrease the number of deaths over disaster relief effort, which is measured by the crude mortality rate. Disaster relief does not have disappearing demand due to business sales that were not capitalised in time, as the affected population will always need the necessities of life. Unless there is a mass mortality incidence during the relief effort, backlogs do not disappear over time, but instead continually pile up.

4.3.4. Hypotheses

The purpose of the simulation is to experiment with different information sharing scenarios and see if they reduce supply chain volatility in backlog levels. Backlogs represent deprivation costs for the affected population as they are deprived of the necessities of life, compromising their survival. Minimising backlogs will therefore maximise the chances of survival for the affected population. The null hypothesis for the value of vertical information sharing will not be given or tested, since there is an academic and professional consensus that vertical information sharing minimises the "bullwhip effect" (i.e. supply chain volatility in inventory levels), as intuited by Forrester (1961) over 50 years ago and mathematically formulated by Lee, Padmanabhan, & Whang (1997) over 20 years. Although ad hoc agreements between aid agencies is already a form of information sharing across aid agencies near and at the last mile of distribution, horizontal information sharing is tested to see if information sharing across aid agencies was scalable and efficient would actually minimise backlogs. We will only know whether horizontal information sharing offers any tangible benefits when it is tested. Additionally, as a curiosity a combination of vertical and horizontal information sharing is explored to see whether there is any combined benefit. The hypotheses in Table 4.3 (p. 117) below were formulated and tested:
### Table 4.3: Hypotheses for supply chain simulations

<table>
<thead>
<tr>
<th>Hypotheses</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_0$</td>
<td>Horizontal information sharing does not reduce backlogs sufficiently to be a viable alternative to vertical information sharing (i.e. null hypothesis).</td>
</tr>
<tr>
<td>$H_1$</td>
<td>Vertical information sharing reduces backlogs more than horizontal information sharing.</td>
</tr>
<tr>
<td>$H_2$</td>
<td>Horizontal information sharing reduces backlogs almost as much as vertical information sharing.</td>
</tr>
<tr>
<td>$H_3$</td>
<td>Using vertical and horizontal information sharing simultaneously reduces backlogs more than using vertical or horizontal information sharing alone.</td>
</tr>
</tbody>
</table>

#### 4.3.5. Stock and flow diagrams in Vensim

To build the supply chain simulation, stock and flow diagrams for each scenario are built in the Vensim computer application using the equations in the appendices. Translating the diagrams for each supply chain simulation scenario above results in the Vensim diagrams below. Figure 4.4 (p. 118) below for scenarios 1 and 2 is identical, but use different equations. Figure 4.5 (p. 119) below for scenarios 3 and 4 involves an information link between retailers, which requires a different diagram. Very briefly, the diagrams can be described as follows: Each organisation within a supply chain has an ordering point ("Order"), which is connected to their incoming supplies ("SupplyL") from the echelon above. Any demand short of the incoming supplies is entered in the backlog ("Backlog"). The ordering point is affected by various variables that introduce a time delay between demand data being received and orders being made ("$\alpha$, $\beta$, and "SmoothTime"). Different numbers after each component in the diagrams indicate that they are unique to a specific organisation in a specific supply chain: only one number indicates the supply chain it belongs to, while with two numbers the first indicates the supply chain and the second number indicates the echelon going from left to right (e.g. [variable]23 = supply chain 2 and echelon 3).
Note: Mathematically there is no difference in simulating multiple supply chains compared to simulating just one supply chain, since they do not interact, even when serving a common pool of demand. The second and third supply chains have been removed for the sake of simplicity.

Figure 4.4: Vensim model of supply chain simulation scenarios 1 and 2

(Taylor & Arthanari, 2018a, p. 8)
Finally, Figure 4.4 (p. 118) above and Figure 4.5 (p. 119) above utilise the same feedback diagram for calculating inventory levels (“EffInv”) and inventory costs (“Cost”) from existing inventory levels (“Inventory”) and backlogs (“Backlog”), which is shown in Figure 4.6 (p. 120) below.
Figure 4.6: Vensim diagram for inventory costs

(Taylor & Arthanari, 2018a, pp. 8-9)
In the following section, the findings of each simulation are shown, compared, and their implications interpreted.

4.4. Findings

Figure 4.7 (p. 123) below and Figure 4.8 (p. 123) below show the backlogs of Retailer 1 in one of the supply chains. Since all organisations and supply chains are homogeneous, the results are virtually identical. Crucially, volatility in backlogs do not travel up to higher echelons of the supply chain with any form of information sharing and volatility is similar for all echelons across a supply chain. Information sharing scenarios 2, 3, and 4 involve some form of information sharing, and all three show vast improvements over scenario 1 with no information sharing of any kind. Therefore, the null hypothesis ("H0") is false. The vertical information sharing in scenario 2 results in the best performance with no backlog, while the horizontal information sharing in scenario 3 results in almost no backlog outside of an initial demand spike lasting around 18 days. The reason for this initial demand spike is that while horizontal information sharing has immediate information sharing between retailers, it takes around 18 days for the demand and ordering information to filter upstream to suppliers. This is consistent with initial disaster response conditions, which is generally geared towards an enormous ‘push’ or allocation approach from the top-down until demand information starts to be collected from the downstream retailer (USAID, 2011). Therefore, the hypotheses H2 and H3 are true.

Unexpectedly, the dynamics show that vertical information sharing in scenario 2 already yields maximum performance, which means that combining vertical and horizontal information sharing in scenario 4 do not result in any additional benefits to backlog reduction. Altering the parameters affecting time delays and demand levels does not seem to have any significant impact on this, indicating that vertical information sharing with
perfect demand visibility by retailers has the best performance in minimising backlogs. Therefore, hypothesis H3 is false. As mentioned in the first half of this chapter, this is an impossible fantasy in disaster relief. Now that the hypothetical utility of vertical information sharing has been confirmed in a simulation, the design science research process can begin architecting and prototyping. The implications and limitations of these findings are discussed in the Discussion chapter (pp. 167-191).
Figure 4.7: Retailer 1’s backlogs from day 0 to 50
(adapted from Taylor & Arthanari, 2018a, p. 10)

Figure 4.8: Retailer 1’s backlogs from day 50-100
(adapted from Taylor & Arthanari, 2018a, p. 10)
4.5. Conclusion

To simulate the effects of different information sharing models in supply chains for disaster relief, a simplified system dynamics stock and flow model of the beer game was adapted to disaster relief with different information linkages and highly volatile retailer demand. Each simulation was run to test the effects of four different information sharing models on minimising retailer backlogs, representing deprivation costs for the affected population in disaster relief: (1) No information sharing, (2) Vertical information sharing, (3) Horizontal information sharing and (4) Both vertical and horizontal information sharing. The results show that vertical information sharing eliminates all backlogs but requires perfect demand visibility from the retailer and is unfeasible, while combining vertical and horizontal information sharing is both unfeasible (as it includes the unfeasible vertical information sharing) and offers no additional benefits (compared to only using vertical information sharing). Horizontal information sharing shows significant promise in eliminating backlogs entirely, but only after suffering a spike in backlogs from the initial response stage of the disaster effort. This is less significant, because early disaster response generally uses a mass ‘push’ or allocation model for determining order quantities from the top-down, and only after the response develops does the orientation of orders increasing move towards ‘pull’ or requisition models from the bottom-up. Now that the hypothetical value of horizontal information sharing has been established, the next stage of the design science research process is to develop a prototype to deliver that capability. The Conceptual model chapter (pp. 125-139) outlines a conceptual framework as a strategy for delivering horizontal information sharing in a lateral way, while the System architecture chapter instantiates this framework as a practical artefact.
5. Conceptual model

5.1. Introduction

Any systems architecture seeking to deliver information visibility and supply chain coordination to humanitarian logistics must fulfil several criteria. It must have a topology or interorganisational process that operates in harmony with the decentralised and ad hoc structure of disaster relief, as well as enable information sharing within and outside an organisation. An artificial experiment using horizontal information sharing in a highly volatile demand environment confirmed that the information sharing approach is at least of possible benefit. However, it is unfeasible to implement horizontal information sharing directly. This chapter defines a technology and process integration strategy that enables horizontal information sharing in a lateral way, where the solution is automated, and few resources and no business integration are required.

5.2. Central argument

From the previous literature support, the following argument justifies the research problem and research statement in this thesis. Whether it is termed supply chain collaboration, supply chain coordination, or interagency coordination, coordination across organisations is a primary determinant of supply chain performance in disaster relief (Tomasini & Van Wassenhove, 2009). Information sharing is the most basic means of interagency coordination and is the main enabler for all other forms of coordination. However, most information is not visible and aid agencies can often only see environmental information within their immediate field of view and information on their own operations, and what most information aid agencies can see is not accurate and is often contradictory (Day,
Junglas, & Silva, 2009). The limited information aid agencies possess are shared in a highly limited and ad hoc manner, often using manual processes that are personnel and time-intensive in an environment that has no personnel, time, or resources to spare (Fritz Institute, 2005). Additionally, aid agencies do not trust each other or outsiders beyond what is necessary to complete their immediate tasks. Consequently, information sharing is poor and interagency coordination is highly limited.

What is considered a high level of information sharing and interagency coordination is contextual to disaster relief. Aid agencies frequently claim they do perform significant information sharing and interagency coordination, yet when their operations are examined by outsiders the truth is revealed to be the opposite (Thomas & Kopczak, 2005), perhaps because their expectations are tempered by what has been historically achievable in disaster relief. In highly volatile situations where coordination is the primary determinant of success (e.g. fast fashion in Cachon & Swinney, 2011), the levels of information sharing, and supply chain collaboration seen in disaster relief would be considered unacceptable in the private sector.

Now that the central problem has been defined, the question becomes, “How can information visibility and information sharing to support interagency coordination be enabled in a low trust, high risk environment that has virtually no resources for implementing and/or supporting a solution?” The most obvious problem solving technique is to invert the conditions of the problem. The solution proposed in this chapter enables information visibility and information sharing in a secure, anonymous, and decentralised way that requires very little trust amongst participants and even the organisation or individual providing the network. It requires almost no resources in procurement, training, operation, maintenance, and repair.
Figure 5.1 (p. 128) below shows the progression of development from existing mechanisms in the Literature review chapter (see Figure 2.2 above, p. 67, and Table 2.10 above, p. 69) were developed into the operationalised, integrated solutions chosen for this thesis, a conceptual framework of requirements from those chosen solutions, and the system architecture requirements for implementing them.
M1: Standardised information processes.\(^a\)\(^b\)\(^c\)
M2: Digitised information processes.\(^a\)\(^c\)
M3: Standardised automated information processes.\(^a\)\(^c\)
M4: Automated data collection.\(^a\)\(^c\)
M5: Automated data anonymisation for security and privacy.\(^a\)\(^c\)
M6: Automated data analysis.\(^a\)\(^c\)
M7: Automated analysis reporting.\(^a\)\(^c\)
M8: Common information space for interagency coordination.\(^a\)\(^c\)
M9: Swift trust between NGOs to handle critical, time-sensitive issues.\(^b\)\(^c\)
O1: Horizontal information sharing between NGOs at last-mile distribution level.\(^b\)\(^c\)
O2: Lateral information sharing as adaptation of horizontal information sharing.\(^b\)\(^c\)
O3: Information sharing process that approximates horizontal process integration.\(^b\)\(^c\)
F1: Encapsulating all necessary functions in each cluster of users, controlled by NGO-users.\(^a\)\(^c\)
F2: One-way integration with NGO-users’ existing information processes.\(^a\)\(^c\)
F3: Anonymisation to clean data for NGO-user security and privacy.\(^c\)
F4: Information pipeline to centralised analytics database.\(^c\)
A1: Networking and messaging-related process encapsulated in single platform that exists and is controlled at NGO-user level.\(^a\)\(^c\)
A2: Automated process for information collection and anonymisation, with one-way integration with NGO-user information systems (e.g. ERP systems) and digitised documents (e.g. e-mail messages and attachments, PDF reports, MS Word reports, MS Excel spreadsheets).\(^a\)\(^c\)
A3: Centralised database for processing data and reporting insights from data analysis.\(^a\)\(^b\)\(^c\)
\(^a\): Perspective from resource-based view, or RBV.
\(^b\): Perspective from knowledge-based view, or KBV.
\(^c\): Perspective from transaction cost theory, or TCT.

Figure 5.1: Developing existing mechanisms into a system architecture
5.2.1. Organisational information flow

To enable information visibility and information sharing in disaster relief supply chains at downstream echelons, an information management process must be architected and instantiated to facilitate and automate this capability. The Harvard Humanitarian Initiative (2010), a partnership between the United Nations, humanitarian logisticians, and academics, produced a seminal report called “Disaster relief 2.0: The future of information sharing in humanitarian emergencies”, which was one of the many official calls to action for humanitarians to embrace digitisation, automation, and big data to enhance interagency coordination.

Taking the objectives and opportunities from those calls to action, the automation and information sharing mechanisms from practitioner solutions (see p. 51 for an overview of current solutions) already deployed in the field were extended to meet the problems, issues, and requirements from the Literature review chapter (pp. 21-72). This section presents the organisational information flow as a business process. The subsequent System architecture chapter (pp. 140-166) will present the system architecture and the technological information flow used to instantiate the organisational information flow, as well as how all three elements are connected. Informal talks between several humanitarian logisticians were held at various stages of the research and have informed the design of the solution.

A process flow is a process of events and decision points connected by logical operators, which is used to orient resources to achieve some objective. An information flow

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3 By leveraging my experience and connections with the NGO community, I secured some discussions with current and former humanitarian logisticians. By discussing things informally and off-the-record, humanitarian logisticians felt at ease to discuss more controversial aspects of interagency coordination, as well as relate specific experiences without fear of fallout. Additionally, I explained that without ethics approval and explicit human participant consent, none of what was discussed could be reproduced or attributed to them, or I would be expelled from the university. Since there was no ethics approval, they could feel at ease to say anything.
is a process flow that only considers the movement of information within a system. This thesis refers to two types of information flows: (1) Organisational information flow and (2) Technological information flow. Organisational information flows view information from the perspective of a business flow for information, where organisational events and decision points connected by logical operators are more important than technological facilitators, where much of the operation is automated. This is a higher level view of the information management relationship and serves as the blueprint for how the business process should be instantiated in the system architecture. Technological information flows view information from the perspective of the technological capabilities used to implement the organisational information flow, mapping the movement of digital information between different parts of a system architecture.

To enable horizontal information sharing without any of its traditional requirements, namely high levels of trust and business integration, Figure 5.2 (p. 131) below presents the envisioned organisational information flow as an automated process that sits above organisations without directly coupling or interfacing into their decision-making processes. Data is collected, aggregated, and securely anonymised at each aid agency’s chosen collection points within their own computer networks, then passed onto a central server and analysed. The results of the analysis are published and are accessible to all participants of the network. Now, the challenge is to design a conceptual framework in this chapter that can implement the organisational information flow as a system architecture in the next chapter.
5.3. Developing the conceptual framework

In order to enable the organisational information flow outlined above, a conceptual framework must be designed, then instantiated as a system architecture with a technological information flow. A conceptual framework serves as an abstract blueprint for combining various technologies and capabilities into a cohesive system. The design science research process is generally highly iterative at this stage and there is substantial flux and co-evolution between the conceptual framework [overall design strategy], system architecture [configuration of components], and technological information flow [how the design functions]. The design process keeps cycling back and forth until the technological information flow performs well with reasonable stability. In this chapter, only the final iterations are presented. This section briefly covers the conceptual framework, while the subsequent section covers the instantiated system architecture in detail.
5.3.1. **Basic design approach**

To build a conceptual framework, the basic needs to enable the capability as the objective of the design must be consistent with environmental and technological constraints. The organisational information flow has defined the capability to be built. The environmental and technological constraints were identified and explained in-depth in the *Literature review* chapter (pp. 21-73) as operational problems, and are summarised here as resulting technological problems. After settling on an overall design approach meeting capabilities and constraints, the conceptual model can be developed into a system architecture and prototyping can begin, which is covered in the subsequent *System architecture* section.

The disaster relief environment is highly fragmented, decentralised (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012), and ad hoc (Day, Junglas, & Silva, 2009). Solutions relying on centralisation (e.g. Akhtar, Marr, & Garnevska, 2012) have struggled to gain traction. Disaster relief needs a solution that allows both *intra-* organisational (e.g. van der Laan, de Brito, van Fenema, & Vermaesen, 2009) and *inter-* organisational (e.g. Jahre & Jensen, 2010) interagency coordination. The most important issue is the ability for highly heterogeneous organisations with highly heterogeneous data standards to coordinate their efforts across a decentralised platform that is automated.

It would be unreasonable to expect the thousands of aid agencies that may turn up at any given disaster (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012), with different languages and customs (Fabbe-Costes & Jahre, 2015), non-interoperable technologies and standards (Tatham & Houghton, 2011), with different levels of funding and different objective scopes (Kovács & Spens, 2007), to suddenly drop everything they know and migrate all their existing systems and data onto a centralised system. Such a migration of data and the creation of new inter organisational business processes would
take an enormous amount of time, resources, and personnel that aid agencies simply do not have, which seriously brings into question its feasibility before even considering issues of adoption consent (Pettit & Beresford, 2009). A decentralised solution that leaves information and network control in the hands of its original owners is a more practical solution.

5.3.2. Conceptual framework

The question remains, what kind of technological configuration would enable almost entirely automated “horizontal information sharing” in a supply chain suitable for disaster relief? In this section, Figure 5.3 (p. 134) below shows a vision of a conceptual framework to enable this capability. The framework is a system of largely homogeneous network nodes, built using either the same or interoperable development platforms and wireless communications standards. All its dependencies are encapsulated, meaning all software dependencies are either included in each network nodes’ firmware or are provided as a single installation file. Its entire operation is automated, including node configuration, network configuration, data collection, data analysis, maintenance, and repair. The only exception is that users must physically place devices and turn them on by flipping a switch, but from that point onward everything is handled automatically by the system without the need for human input.
5.3.3. **Autonomous modules**

Every node within the conceptual framework has six basic autonomous modules programmed within them: (1) Configuration, (2) Network, (3) Routing, (4) Messaging, (5) Data capture and (6) Analytics. Each of these modules will now be explained. The *configuration* module is an autonomous setup procedure that is triggered whenever the device is turned on, causing the device to update its software from the rest of the network, broadcast its location, receive the locations of other nodes, and becomes ready to receive and transmit messages. Additionally, the configuration module automatically broadcasts...
software updates and each node propagates the updates through their individual connections in the network. The *network* module consists of the technical components and procedures for message transmission and reception within a network. The *routing* module determines the order of the message queue and their transmission route through the network to maximise efficiency. Additionally, the routing module includes the ability to create a self-healing (i.e. autonomously (re)routing) mesh network, meaning if any network nodes stop responding for any reason (e.g. nodes are damaged, or signals interference has made compromised an existing connection), the rest of the network will find paths around it using the remaining network nodes that are still responding.

The *messaging* module autonomously handles all messaging functions that allow nodes to communicate with one another. This includes message (dis)assembly using a message structure to include relevant metadata (e.g. code words, sequence of a multi-frame messages, origin, and destination). The *data capture* module automatically performs data collection at individual user devices or user-selected collection points within their own networks, anonymises the data, then uploads them as metadata to the analytics module for analysis. Additionally, the data capture module allows users to configure what and how information can be collected and shared. (Warning: Owing to significant security, privacy, and legal issues, the design of this module must be very specific and is covered in its own section in the next chapter.)

The *analytics* module autonomously retrieves information from agencies at each node, further anonymises information, and then aggregates individual metadata to create aggregate metadata to describe environmental conditions. The results of this analysis are accessible by all users on the entire network, allowing users to identify areas of logistics needs, logistics activity, and logistics congestion, as well as imply but not confirm the existence of surpluses and shortages, allowing organisations to identify who to contact to
seek closer arrangements while also giving them plausible deniability. Inevitably, there will be compatibility issues going outside of common data standards, which is why there should be a generic middleware systems architecture. Jrad and Sundaram (2016) have defined just such an architecture.

Together, these modules represent all the necessary capabilities and components for developing an anonymised horizontal information sharing process that operates in a low trust and high risk environment, which is built into an autonomous mesh network. Additionally, as better telecommunications networks are available as telecommunications infrastructure is repaired, replaced and/or augmented, the system allows migration away from the mesh network towards more traditional high speed and capacity networks while still retaining its information sharing capability.

5.3.4. Theory used for conceptual framework

Supply chain and strategic management theory were used to inform the design of the conceptual model. The literature implies a set of design requirements for the network. Figure 5.4 (p. 138) below outlines the major sources from the academic literature directly used to develop the problem solving approach in the conceptual framework; major abstract theoretical lenses (e.g. theories of the firm from strategic management theory). Minor sources used indirectly are not included in Figure 5.4 (p. 138) below. Literature that has been extensively covered elsewhere in the thesis and is used for clearly obvious reasons is not explained below, such as the bullwhip effect and importance of information sharing, which was covered extensively in the Literature review chapter (pp. 21-73) and Supply chain simulation chapter (pp. 103-124).

To enable horizontal information sharing (Lee & Whang, 2000), a common decentralised platform of largely homogenous nodes is used so that there are minimal
technological barriers to information sharing (cf. Day, Junglas, & Silva, 2009). To enable supply chain collaboration (Akhtar, Marr, & Garnevksa, 2012) in an environment where trust (Perry, 2007) and information sharing is a major issue (Day, Junglas, & Silva, 2009), a solution tailored to unique aspects of disaster relief is required. This platform is built into an autonomous mesh network for its telecommunications capability, but also a software application for data collection and analysis that can migrate away from the original network towards more powerful networks as they become available. There is no network or vendor lock-in of any kind in this system: each aid agency is the sole determining authority in controlling and owning their data and their respective parts of the network.

The conceptual framework describes a system that uses user devices, information systems, and telecommunications networks to autonomously capture, analyse, and disseminate insights through data analytics using generalised and anonymised metadata. The anonymisation component is essential to preserving privacy and security (Stallings & Tahiliani, 2014). For example, if too many metadata details are known it is possible to deduce its origin (Lassila, 1998), which could potentially lead to media ‘witch hunts’ (Büscher, Easton, Kuhnert, Wietfeld, Ahlsén, Pottebaum, & Van Veelen, 2014).

Data analytics are performed on the metadata and made available to every user through a common portal. Insights creation must be automated to ensure even those delivering or operating the network do not know the original sources of data being transmitted through the network. This would enable the aid agencies to simultaneously coordinate their efforts and compete for donor funding amongst themselves (Bakshi & Kleindorfer, 2009), while also providing enough plausible deniability to shield them from external scrutiny and legal liability. By targeting the challenges and impediments to horizontal cooperation (Cruijssen, Cools, & Dullaert, 2007) and incorporating previous theories, a lateral information sharing is enabled.
5.4. Conclusion

The simulations in the previous chapter show that horizontal cooperation that extends to information sharing minimises backlogs almost as effectively as traditional vertical
information sharing, but this approach requires heavy adaptation to handle the constraints in the disaster relief environment. This chapter outlines the initial phase of prototyping in the design science research process, developing a conceptual framework that serves as an abstract strategy blueprint for integrating technologies, processes, and standards into an integrated and automated solution. The framework intends to enable information sharing between aid agencies that do not trust each other but still want interagency coordination. Given the lateral approach to integrating data management and information sharing, this new approach is described as lateral information sharing.
6. **System architecture**

6.1. **Introduction**

The conceptual framework in the previous chapter is only a strategy blueprint, not a discrete artefact. Here, the framework is developed into a generic system architecture, which is then instantiated with a prototype as an illustrated example. How each part of the conceptual framework was developed into the system architecture is explained. The technologies used for the instantiation are briefly described, while the critical security and privacy strategy is outlined. Finally, the practical artefact’s lateral information sharing approach is compared to other existing approaches to highlight key differences.

6.2. **Developing the systems architecture**

Once the conceptual framework has been designed, a system architecture can be developed to implement the information visibility and information sharing capability outlined in the organisational information flow at the beginning of this chapter. The system architecture diagram details a generic blueprint for integrating any technology that fulfils its generic functions, as well as an instantiation using specific technology. This section is split into three subsections. First, the system architecture is presented and explained. Then the exact relationship showing how each part of the conceptual framework was developed into the system architecture is explained. Finally, the technological information flow showing how the system architecture functions in practice is shown as the instantiation of the organisational information flow presented at the beginning of this chapter.
6.2.1. System architecture

Owing to the nature of design science, the system architecture is quite technical, but its configuration and operation are explained in terms that the layperson can easily understand. The more obscure technical details that are required for the system to function but would only serve to confuse readers who are not technical experts in information systems and electronics programming, has been moved to the appendices at the end of the thesis. Screenshots of the prototype in operations are also provided, though they lack a graphical user interface. The system architecture is shown in Figure 6.1 (p. 143) below. In this section we briefly describe the components and their connections. The overall structure of the system architecture can essentially be described as a network of user devices (e.g. laptops), which are connected to an autonomous mesh network by attaching a physical network device (e.g. USB dongle) to a user device. This mesh network automatically assembles itself and connects user devices together with a central analytics database. Various subcomponents of this overall structure are described below in subsections.

This mesh network can be extended by nesting mesh networks inside larger mesh networks. For example, if an aid agency operates 20 laptops and designates one of the them as the entry/exit node, they can have complete control and ownership over their own network of at least 20 nodes while using of one those nodes as the entry/exit connection to a larger public network with hundreds or possibly thousands of nodes. Through logical deductions of how network effects operate, it is probably impractical to have more than three levels of nesting (e.g. aid agency network inside an aid agency alliance network inside a public network) without sacrificing flexibility.

Within the network device’s memory, is a data capture computer application that must be installed separately. The data capture application is walled off from the rest of the
network and only the specific user device’s user can control it, for reasons that will become obvious; network providers cannot interface with it. The application automatically searches for certain designated locations and file formats on the user device for logistics and environmental-related information, aggregates the data into aggregate data, anonymises it, repeatedly tries to deanonymise it, and increasingly removes specific data that allows it to be deanonymised. This process repeats until deanonymisation fails and the aggregate data is considered secure and anonymous. Then, there is a single exit point in the application that allows data that cannot be deanonymised to be periodically forwarded to the rest of the network and make its way to the central analytics server. Once the data is collected, the central server performs automated data analytics, including automated data preparation, data transformation, selection of statistical techniques, and interpretation. After data analysis, the analytics server produces reports of statistical insights, which are made available to all network users through a portal.
Notes: Instantiated components are given in brackets, otherwise components are generic.

Figure 6.1: Generic and instantiated system architecture
(Taylor & Arthanari, 2018b, p. 6)

Figure 6.2 (p. 144) below shows exactly how the conceptual framework was developed into the system architecture. Components across both diagrams are colour-coded so its origins are obvious to readers. The middleware layer from the conceptual model is abstract and is found in various places throughout the instantiated system architecture. Through the design science research process, the analytics module was moved from being inside an individual network node in a separate section to being merged into the database component of a network’s user-defined data collection points in a designated network node. It was simply easier to do it this way through the instantiation, but it is entirely
possible to have the data capture application form the data analytics module operate in each network node.

Notes: The components of the conceptual framework are colour-coded to show how they were developed into the system architecture. The middleware layer in the conceptual framework is abstract and is found in many places throughout the system architecture.

Figure 6.2: Developing the conceptual framework into the system architecture (adapted from Taylor & Arthanari, 2017, p. 6; Taylor & Arthanari, 2018b, p. 6)

6.2.2. Technology used in instantiation

The choice of technologies used to instantiate the generic system architecture in Figure 6.1 (p. 143) above is representative of enterprise-level solutions designed for high volume, high stress environments. The exception is the Raspberry Pi as the user device in the prototype, and the reasons for this are covered in its own subsection below. However, these are not
the only solutions. The instantiated systems architecture is provided as an illustrated example only to prove hypotheses and theories created before and during the design science process; it does not claim to be the only solution, or even the best solution. By using the generic systems architecture, other researchers can develop technologies that enable the same functionality at similar or better performance levels, though other implementations will inevitably face their own unique design challenges (e.g. Wi-Fi having no native mesh support).

The choice of the universally used CSV file format (comma-separated values) for importing and exporting databases as spreadsheets enables easy integration into existing information systems, such as other databases and enterprise resource planning systems. The network is built entirely using free and open source software, and commercial open source hardware. Commercial open source products allow others to prototype using them and develop their own solutions that no longer rely on proprietary components. “Open source” is a term from software engineering that indicates the source code (i.e. core programming), blueprints, and documentation for a piece of technology which is fully publicly available, but open source does not indicate it is necessarily free or unlicensed.

By using extremely inexpensive components, producing and operating the entire system is very inexpensive. Each network node is cheaper to procure than a low-end smart phone. As for its operation, all it takes for a user device (e.g. Raspberry Pi, laptop, desktop) to join the network is to plug in a small dongle containing the ZigBee node into its USB port, switch the device on, then click on a button in a pop-up window to install the data capture application on the user device. Everything else is handled by the programming.

The generic system architecture is not specific to any wireless communications standard, and the structure is designed to be extensible and modular to allow integrating additional standards into the same network (e.g. Wi-Fi, GSM, satellite internet), but these
would have to exist in their own network topologies. The implications are important, because it would allow user devices with native support for the wireless communications standard to connect to the network without any network device, such as a mobile phone downloading a mobile application that allows it to connect with the network.

Many development shields already exist with interconnecting pins and sockets that fit onto existing development boards, which enable an enormous variety of new technologies from environmental sensors to satellite internet. Shields in electronics programming are electronics components that enable new capabilities with an existing interface with a base development board. These operate much like LEGO pieces and simply snap together. The development environment already includes programming to connect the shield to the base board. Interoperability between information systems and wireless communications standards is essential to enabling information visibility. For supply chain coordination, applications can be implemented to facilitate interagency communications (e.g. BBS forums, text chat rooms, voice chat rooms). A key difference between the system architecture presented in this thesis and other solutions is that it is entirely autonomous and does not require human input.

### 6.2.2.1. Mesh network: ZigBee

ZigBee is a short range wireless communications standard based on the IEEE 802.15.4 standard. It was designed for creating wireless sensor networks, which are networks of environmental sensors for monitoring temperature, moisture, light, and water levels for industrial purposes. This thesis turns ZigBee on its head and uses it as a specialised communications network for passing logistics-related information. ZigBee uses a mesh topology, meaning every node can connect to every other node if they are in range, and transmits at a frequency of 2.4 GHz. ZigBee has a data rate of 250 KBps (0.25 Mbps) and a
physical omnidirectional transmission range of 100 metres, but this can be boosted by a larger and more complex antenna at the expense of significantly higher power consumption to a range of up to 4,000 metres (Engineer Live, 2013). More powerful antennae are usually only used to fill gaps in network coverage or to serve as an information highway to connect the network of short range nodes to another network that is a long distance away.

The prototype in the Technical annex (pp. 241-270) uses the XBee S2 Wire Antenna Shield as shown in Figure 6.3 (p. 147) below, which is a ZigBee device. This antenna only has a range of 100 metres and this small antenna was chosen to make prototyping and testing easier.

![Figure 6.3: XBee S2 Wire Antenna Shield](SparkFun, n.d.a)

In order to use the ZigBee antenna, it has to be attached to a carrier board. The prototype uses the Grove XBee Carrier as shown in Figure 6.4 (p. 148) below. When assembled together, the ZigBee node device using the components above is roughly the size of $62 \times 44 \times 10$ millimetres and weighs 17 grams, so it can fit in the palm of your hand and weighs slightly more than two $1$ New Zealand Dollar coins. For long range antenna that can reach thousands of metres, large, bulky amplifiers are required, which can increase the size of a ZigBee node to something as large as a show box. Many commercial
implementations of ZigBee settle on a compromise between transmission range, power consumption, data rate speeds, and electronic complexity, and usually have a range of 1,000 metres.

The basic structure of a ZigBee mesh is shown in Figure 6.5 (p. 150) below. Basically, there are three types of nodes: (1) Coordinators, (2) Routers and (3) Sensors. In each network, there is only one coordinator node, which is a router node that has been promoted to handling the routing table that determines how messages move across the network. As soon as the coordinator becomes non-responsive, the network shuts down and the role of coordinator is moved to another router node. Router nodes serve as connection points in a wireless sensor network. The sensor nodes are the true purpose of a traditional wireless sensor network, because they serve as environmental sensors that pass data up to routers. Sensor nodes can only transmit data to the network but cannot receive data. The configuration in this thesis includes no sensor nodes and cannot be considered a wireless sensor network. Normally, a ZigBee network is configured to power itself on and off during
publishing cycles to minimise power consumption, but here the nodes are on and ready for transmission all the time.

Periodically, each node in the network is preconfigured to broadcast its location in all directions. Every other node in range will pick up this information and pass it on, until the location and range information of all nodes is passed onto the coordinator node. ZigBee can be self-healing and that is the way it has been configured in the prototype, but it is not configured that way by default. The advantages of a self-healing mesh topology are that non-responsive nodes will not shut down the network, as there are many redundant nodes representing redundant paths for messages to be transmitted. Origin nodes that are out of direct range of their intended destination will automatically use a multi-hop (i.e. routing transmissions through other nodes). As each hop requires information about previous hops, there is a maximum 16 hops that are practical for large messages.

Because the routing table communicated to the coordinator only selects the most efficient route by the lowest number of hops according to the capacity of each node, adding additional nodes does not affect the network connection nor does it overload the network structure. This also means that non-responsive nodes will be automatically routed around instead of a network connection breaking down. Each node can store the port information of up to 240 other nodes (after excluding reserved ports) and there is a practical maximum network size of several thousand nodes. These advantages mean that ZigBee mesh networks can handle a heavy amount of constant network traffic, however at a low data rate.
The disadvantages of a mesh topology are that it requires many network nodes, which may be cost-prohibitive, and that there is a practical limit to network size. ZigBee devices are so inexpensive (e.g. approximately US $35.00 per device) that this is not an issue. Regarding security, ZigBee has the native capability for end-to-end encryption using the AES 128-bit standard, which has yet to be broken. When broken in the future, other encryption standards can be used, such as those not based on factoring prime numbers.

6.2.2.2. User device: Raspberry Pi

The Raspberry Pi is a single board computer, meaning it is an entire computer on a single electronics chip. It can do everything a laptop does but is much slower and lacks a display screen and keyboard, so users need to connect to it using a wired or wireless network connection and control it from another computer possessing a display screen and keyboard. A Raspberry Pi is extremely small, weighs under 100 grams with an external protective case, and fits in the palm of your hand. The Raspberry Pi is only used to serve as a stand-in for a user’s laptop for testing. Afterall, it is far cheaper and more practical to have a dozen Raspberry Pi’s on a network during the prototyping stage than it is to buy or rent a dozen
consumer laptops. Additionally, if the system architecture can operate perfectly fine using such low powered computers, they will run on practically anything, including consumer laptops released 15 years ago and still running Windows XP.

When this thesis started, I used the Raspberry Pi 1 Model B+ as shown in Figure 6.6 (p. 151) below, but many newer models have since been released with additional functionality and more processing power. The Raspberry Pi 1 Model B+ has a 700 MHz processor with 512 Mb of memory, which is more than enough for running the native Raspbian Linux operating system and performing maintenance functions. This means that the computer is significantly less powerful than an entry-level consumer smart phone available from your local supermarket. This model of Raspberry Pi does not have native wireless communications of any sort and must be connected to a ZigBee dongle/device to connect to the ZigBee mesh network.

Figure 6.6: Raspberry Pi 1 Model B+
(Raspberry Pi Foundation, n.d.)
6.2.2.3. **Message broker: Mosquitto and MQTT**

The number of incoming messages entering a network node will often exceed its capacity to immediately transmit them, which means there must be a system for queueing messages above immediate transmission capacity and a method for determining the order in which they should be transmitted. Mosquitto is an industrial-grade message broker used for queueing the transmission of messages using the “Message Queuing Telemetry Transport” (MQTT) standard. It has seen widespread adoption (e.g. Amazon Web Services, Facebook Messenger, Microsoft Azure) and is considered one of the industry’s ‘gold standards’ for message queuing solutions for big data applications. Mosquitto prioritises message traffic to achieve a user-defined “quality of service”, which refers to network transmission performance such as the reliability and stability of transmission (e.g. latency, jitter, delay).

6.2.2.4. **Database: MySQL**

At different points the data collected must be stored somehow so that it can be used later. The central data analytics server requires a database, as does the ZigBee coordinator node to manage the queue of messages. MySQL is an industrial-grade open source database used for storing data in a relational format. Specifically, it is what is called a “relational management database system” (RMDBS), which records data in tables which can be connected through a relationship to other tables. These relationships can be created and/or modified without affecting the underlying tables. MySQL has seen widespread adoption (e.g. Facebook, Google, YouTube) and is considered the industry ‘gold standard’ for all forms of database management, small and large.
6.2.2.5. Server access: Nginx and PageKite

To control and configure the network and access the database through a portal, a server needs to serve as an access point for users. Nginx is a free and open source high performance HTTP server. PageKite is a localhost tunnelling service that is used to connect to the server. Together, a graphical user interface is hosted on the server that is accessed through a web browser, which allows users to interact with the network. Additionally, provided at least one of the network nodes has an internet connection, it can connect the ZigBee mesh network to the internet.

6.2.3. Technological information flow

The organisational information flow presented in the beginning of this chapter manifests itself as the technological information flow shown in Figure 6.7 (p. 154) below. End users have user devices with a data capture application installed on them, which connects to the messaging server on a nearby router node through the ZigBee network. The router node determines how the messages are read and queued using Mosquitto, then passes the forwards aggregate data from each user to the analytics database to form higher level aggregate data. How the data capture application and central data analytics server function works is covered in subsequent subsections.
6.3. Security and privacy strategy

There are obvious security and privacy concerns with collecting data autonomously. This section describes the basic security and privacy requirements for the application for data capture in lateral information sharing, such as anonymisation processes and network restrictions. Data collection operates on simple trawling according to a whitelist and/or blacklist of keywords and/or data locations according to default settings, which must be made easily configurable by users. When the application has been started, a pop-up should ask the users to either configure their own settings or choose the default settings to obtain explicit user consent. Obviously, any part of data collection and anonymisation can be made much more sophisticated and computationally efficient, but it is enough to show that these capabilities already exist, are mature, and are not controversial in the least.
6.3.1. **Source code available on request**

The source code data capture application must be made available in full to aid agencies for independent auditing, both as a sign of good faith that the application is safe for them to use, as well as a practical matter for ensuring information security to avoid data leaks. Intuitively, the easiest and cheapest way to allow external auditing is to keep the application entirely open source and published on a public repository such as GitHub, which means that anybody can audit it at any time. Each new version of the application needs to be internally audited before being released, while each major application update needs to be externally audited. If the application’s source code is not made available for external auditing, whether by making it open source or releasing it to a reputable third party on request, it risks becoming a “black box”, or an unknown process. It would be unreasonable to expect any aid agency to trust a black box application that could not be audited, and it would be reasonable for anyone to assume that such bad faith behaviour indicates that the application is literal spyware.

6.3.2. **Encrypted sandbox**

The entire technological information flow relies on the use of a data capture module to automatically search user devices for logistics-related data, to collect, anonymise, and aggregate the data, then forward the securely anonymised aggregate data to a central server for network-wide analytics to be performed. The analytics produce statistical insights that inform users about network and environmental conditions, such as the probable location and levels of demand, surpluses, shortages, and bottlenecks. Obviously, the exact design and configuration of the data capture module is extremely sensitive, otherwise it amounts to what is essentially called “spyware” in information security, which
is software that gathers and communicates information about the user to external parties without the user’s full knowledge or consent. As any information security expert intuitively understands, any computer application that automatically gathers information has the potential to be turned into spyware, whether it is something that was originally intended to be innocuous and useful, or deliberately designed to track user activity far beyond activities immediately relevant to an organisation’s legitimate operations.

While creating such an application is known about and does not constitute original research content, it is nevertheless important to briefly cover this topic. Creating the data capture application relies heavily on information security competence. Firstly, the programming team involved must have extensive experience in information security programming, because the slightest mistake can leave a vulnerability for hackers to exploit. Secondly, the application must be periodically audited by its programmers to test it against emerging vulnerabilities from new hacking applications and methods.

These security elements exist in major security applications available to consumers at inexpensive prices already, but they need to be integrated into the data capture application to be a single application that requires no user configuration to setup and start using—it is unreasonable to expect humanitarian logisticians to become information security experts. The data capture application needs to be put into a jail-type sandbox (i.e. extremely restricted network access with rules-based execution on what and how an application can run inside it) and encrypted, with its encryption key deleted immediately, so no one can tamper with the process. Sandboxie is an example of a popular sandboxing application used by consumers and enterprises, but it lacks encryption.

VeraCrypt is an example of one of the best encryption applications available, but it is not integrated with sandboxing because its purpose is to help users protect their data, not protect users from an application’s own programmers. AES-256 is considered the ‘gold
standard’ for encryption and is widely used for internet banking and business transactions. In practice, the encryption standard is usually strong enough that the vulnerabilities lie elsewhere, since hackers will attack an application or network at its weakest point, not its strongest.

6.3.3. Data anonymisation

Figure 6.8 (p. 158) below defines a generic data management process with sub-processes that are covered in subsequent figures, which is required for lateral information sharing to be accepted by participants. The main process operates according to a publishing period (e.g. upload data every 12 hours). Figure 6.8 (p. 158) below shows the main process and how different subprocesses feed into each other. Figure 6.9 (p. 159) below shows the data collection process, where logistics-related data is searched and collected in a temporary repository. Then Figure 6.10 (p. 160) below shows the data being transformed into aggregate data when the publishing period has been reached, before becoming anonymised, with a machine learning process to test whether anonymisation was successful. If deanonymisation was successful, the data has not been made safe to share and must be anonymised again, until deanonymisation attempts fail. Afterwards, Figure 6.11 (p. 161) below shows the data being uploaded to the central data analytics server, as well as downloading data ‘variable distribution’ information that has been uploaded by every other participant. This variable distribution information will be used to test whether the data can be reverse-engineered/deanonymised during the sub-process for data anonymisation in Figure 6.10 (p. 160) below in subsequent runs.

There are existing data anonymisation techniques (e.g. \( k \)-anonymity and \( k \)-Optimize, \( t \)-closeness, \( l \)-diversity) that are highly robust and mathematically proven (e.g. Samarati & Sweeney, 1998). Aggregation of data into defined group sizes already contains
some form of anonymity, however aggregate data that is too unique or contains too many dimensions is easily deanonymised. By combining some form of random process to progressively stripping out more data until anonymity reaches a certain level of plausible deniability, data is made far more private and secure. For example, a strong pseudo-random number generator can be used to randomly select amongst the most unique dimensions of the aggregate data, then randomly determining whether to remove them or replace them with a more generic description (e.g. date of birth in medical data can be switched to age group). Every publishing period the process undergoes, the distribution and range of data of values in variables are saved in a generic way, but the values of those variables are not saved. This variable distribution allows anonymity testing of new aggregate data against the distribution of variable values from all previous publishing periods.

Figure 6.8: Overview of main process for generic data management
Figure 6.9: Sub-process for data collection
Figure 6.10: Sub-process for data anonymisation
6.3.4. Updates and patches

The only way the process should be modifiable is through the configuration settings, which should only be accessible by the user operating their user device in the user organisation. For updating the application, either there needs to be a secure patch management system, which is very difficult and rigorous to implement, or the software must be manually
updated by users downloading new versions. New updates are only needed to patch bugs and security exploits, but the software should otherwise be kept as rudimentary as possible to keep auditing quick and simple. Each new version can potentially introduce new vulnerabilities, as well as sneaky changes in the programming and terms of service made by unscrupulous service providers.

6.4. Comparison with existing solutions

The heart of the practical artefact for implementing lateral information sharing is a process-centric solution that is facilitated by technology. Many of the constituent components and approaches are not new, but the way they have been put together is novel, and the intended purpose of the artefact is also novel. The characteristics of different supply chain strategies and coordination mechanisms, telecommunications networks, and information systems, have already been extensively covered in the Literature review chapter (pp. 33-56). This section only covers the main differences between this approach and existing approaches.

The mesh topology (e.g. Yang & Deng, 2011) is not new and neither is the repurposing of wireless sensor networks for telecommunications (e.g. Wang, Zhang, & Lu, 2008), though the implementation in this chapter is somewhat unusual. Nor is the use of ad hoc mesh networks (e.g. Malan, 2004). The main differences between the system architecture in this chapter and other existing approaches are as follows: (1) Autonomous operation, requiring virtually no personnel, time, or resources, (2) Scalability, by minimising transaction costs of coordination to negligible levels, and (3) Automated analytics, where other approaches do not integrate data collection and information sharing processes, information systems, and telecommunications networks into a cohesive solution. The existing telecommunications solutions are missing an analytics component because they are ostensibly for enabling telecommunications, not providing supply chain visibility
and coordination. To coordinate and make visible supply chain activity into a telecommunications system is not enough, other supporting infrastructure is required.

An obvious question results from the architecture, “Given that existing solutions are just means of connectivity, could supporting capabilities like analytics be communicated through those networks?” The answer is an emphatic “yes” and is the reason why the system architecture has been provided as a generic with an instantiation. The generic blueprint can be used to integrate any technology that fulfils those generic functions. In truth, the system architecture defined in this thesis could be fully instantiated with most of the existing technology covered in the Literature review chapter (pp. 51-56), but with additional automation and self-healing mesh networking characteristics. The problem is that nobody has done this yet for disaster relief.

Throughout this thesis, I have mentioned that the practical artefact has not been fully instantiated. Readers may be wondering about the kinds of statistical techniques that allow aggregating heterogeneous data at a lower level, which then becomes anonymised, and yet can still produce useful statistical insights. These kinds of techniques have been used for many years, such as census data for demographic records, innumerable hospitals and health boards for medical records, etc. Cormode and Srivastava (2009) provide a comprehensive primer on anonymisation models and issues. Crowcroft & Gascón (2018) write about the issue of anonymisation, which strips out identifying data, yet still maintains enough context for the data to be useful for analytics. The operative word is *plausible deniability*, so identifying the origin of a part of aggregate data to a confidence of 90% is still far too low to blame someone for it. As for the analytics themselves, there are many analytics frameworks out there, but most follow a standard playbook (e.g. mostly machine learning for data preparation and dimension reduction applied to a clustering, classification,
regression, or hybrid techniques), with the variations in squeezing out as much incremental computational efficiency and predictive accuracy as possible.

New telecommunications and information systems solutions are emerging every day. There are increasingly robust temporary telecommunications that can be transported in a small package and installed quickly (e.g. HERMES network in Perry, 2018). Perhaps, the introduction of low earth orbit telecommunications satellites in the near-future will finally deliver ubiquitous high speed, high capacity telecommunications to everyone (e.g. SpaceX in Mack, 2018), assuming the power consumption or battery issues with user devices can be resolved. However, rapidly deployable cellular towers that were introduced several decades ago have already removed data throughput as a major bottleneck in interagency coordination. What has emerged is a different problem. The scalability of coordination mechanisms across a decentralised and ad hoc environment has become the primary constraint that limits humanitarian logistics performance. Meanwhile, there are emerging artificial intelligence and information systems solutions that address automated risk analysis (e.g. GDACS in Bjerge, Clark, Fisker, & Raju, 2016) and automated heat maps for identifying places of high activity (e.g. Azure Maps in Seto, 2018).

The greatest challenge to interagency coordination remains extreme heterogeneity in organisations, internal processes, and the technology that facilitates those processes. This lack of interoperability leaves no inherent point of contact to easily interface with an aid agency’s operations, and no number of widespread telecommunications and information systems support will resolve this issue. The problem is fundamentally an issue of combining heterogeneous processes and information standards (Day, Junglas, & Silva, 2009). Simply gathering and sharing more data without the ability to contextualise it and turn it into useable information means interagency coordination issues will be exacerbated. Instead of being a benefit, the introduction of new capabilities to increase information
throughput may end up drowning aid agencies in a data deluge. A lack of data throughput was never the problem; it was always a lack of usable and relevant information for decision-making that could be easily shared across aid agencies.

As is often seen in the design science research process, there is no prescription for a solution and researchers/designers do not know where the iterative design process will end up. Admittedly, lateral information sharing is a very unusual solution. But without the resources, personnel, or technology to implement industrial solutions, creativity and resourcefulness must be used instead. The practical artefact is designed to be as simple and rudimentary as possible while still addressing the main problem. It costs virtually nothing to run, can operate on the most rudimentary entry-level laptops purchased over 10 years ago, requires a very low data rate for uploading aggregate data to the central server, and it requires no oversight or personnel to operate. However, it cannot control or influence how aid agencies use their information, but that was never a realistic prospect.

6.5. Conclusion

The conceptual framework presented in the previous chapter was developed into a system architecture, complete with technical specifications and an instantiated prototype. Technical details of the instantiation have mostly been moved to the appendices. The system architecture shows how telecommunications networks with a decentralised mesh topology can be developed to include self-healing and autonomous characteristics, which can then be used to facilitate a data collection and information sharing application to deliver lateral information sharing. Privacy and security are critical issues in all data collection contexts, so a security and privacy strategy are given outlining the minimum standards that would allow lateral information sharing to be safe in a low trust, high risk environment. Anything below that standard is unlikely to be acceptable and extremely high
risk. This unusual problem solving approach to improving interagency coordination is briefly compared to other approaches. The findings, implications, and limitations of the approach are covered in detail in the Discussion chapter.
7. Discussion

7.1. Introduction

Although previous chapters have presented raw findings, this chapter describes and contextualises those findings. Each finding builds on previous research artefacts used to answer the research question, which are then generalised to become main contributions. The literature synthesis interpreted poor interagency coordination as a process issue and wicked problem. By manipulating and bypassing constraints, a novel form of horizontal information sharing can be enabled. A system dynamics simulation was conducted to see if horizontal information sharing delivered any benefits. Once the benefits were confirmed, a lateral form of information sharing was defined, then instantiated as a system architecture. The implication of these contributions is the creation of a new supply chain coordination mechanism/strategy called “lateral information sharing”. This theory is defined and situated in the literature alongside existing supply chain approaches on a spectrum. The limitations of any solution to interagency coordination is constrained by its nature as a wicked problem, especially one that is highly cross-disciplinary and multi-faceted. As a methodology, design science is about the process of designing a solution in a rigorous way, but it does not specify whether the design itself is good or bad. Nor does it specify the ‘proper’ choice of technologies, mechanisms, or means of implementation. The principles underlying good design, as opposed to a good design process, is under design research in engineering and not design science research in information systems. Supply chain simulations that have not been validated to field data can generalise to a broad explanatory level, but not a predictive level, regardless of whether system dynamics or another
modelling approach was used. Finally, there are trust issues around precisely how lateral information sharing is implemented.

7.2. Findings

Before being able to answer the research question in the Introduction chapter, it was necessary to identify the literature gap.

7.2.1. Identifying the literature gap

Surveying, comparing, and synthesising the existing academic and practitioner literature, as well as novel emerging solutions from the private sector, on both challenges, solutions, and unresolved problem. The supply chain strategies of agile, leagile, and quick response were compared to characteristics of the disaster relief environment (see Table 2.2, p. 48, Table 2.3, p. 48; Table 2.4, p. 49; Table 2.5, p. 49). Conflicts and interactions between them were resolved by existing academic and practitioner solutions from disaster relief and traditional supply chain theory, which were included in a series of tables showing the current state of practitioner solutions to addressing problems with uncertainty and demand volatility (see Table 2.6, p. 50; and Table 2.7, p. 51). Not only were some of the solutions lacking in performance, there were some problem areas that were currently without solutions.

There were also various information systems that represent the state of the art in practitioner solutions (see Table 2.8 and Table 2.9, p. 55), but they do not address the issue of information sharing processes across aid agencies. The strengths and limitations of practitioners’ and academic solutions were presented as a literature gap and capability gap (pp. 38-56), where both sectors offer centralised coordination mechanisms with unrealistic assumptions of heavily centralised authority (see Table 2.8, p. 54, and Table 2.9, p. 55)
and/or high degrees of information visibility (pp. 33-56), whereas the disaster relief environment is heavily ad hoc and decentralised (p. 21).

Beyond direct solutions to interagency coordination problems, a unified taxonomy was created in the Technical annex (see Table B.1 below, p. 242) to compare telecommunications networks solutions used to facilitate information (see Table B.2, p. 244; Table B.3, p. 244; Table B.6, p. 248; and Table B.7, p. 249). What emerged was that there are ample telecommunications solutions to handle logistics data. A lack of telecommunications connectivity or capacity is not the constraint holding back interagency coordination. The limited scalability of coordination mechanisms across a large number of heterogeneous aid agencies in a highly decentralised and ad hoc environment is the main problem. The literature describing the state of humanitarian logistics theory and practice for interagency coordination problems was interpreted and synthesised to answer the research question.

7.2.2. Main contributions from the answering the research question

Research question below is the principal focus of this thesis, which was answered in the Conceptual framework chapter (pp. 125-139) and System architecture chapter (pp. 140-166).

Research question: How can a solution to problems in interagency coordination in disaster relief be developed that integrates multiple disciplines, to address problems that are simultaneously related to technology, process, culture, and politics?
By approaching information sharing in a lateral direction, the traditional requirements of needing some level of business integration, high degrees of trust, strategic partnerships, and high degrees of information visibility are all bypassed. True, this is a suboptimal solution compared to professionalising the entire humanitarian sector’s humanitarian logistics and their associated processes, implementing common information sharing standards across all aid agencies, and developing robust and scalable technological facilitators to information sharing processes, but that was never a realistic prospect.

Chronic underfunding is a defining characteristic of disaster relief. This approach, which has been tentatively called “lateral information sharing”, may be the best that can be achieved with such few resources available.

Since the organisational information sharing process does not directly integrate with aid agencies’ internal decision-making processes, it can be useful across extremely heterogeneous organisations. Interagency coordination is indirectly influenced by offering better quality logistics information to aid agencies, such as information about the demand of the affected population and how it interacts with environmental constraints. However, because there is no direct business integration of organisational processes, very few resources are required to implement the solution and it involves virtually zero overhead to operate.

The process of answering the research question involves a direct progression from the original research problems to subsequent research artefacts. Those artefacts directly answer the literature gap and the research question. To develop research artefacts into main contributions, the artefacts need to be interpreted and generalised back in the direction of the original research problems. The research problems at the beginning of this investigation were as follows: (1) How can (near) real time demand information be captured
in disaster response efforts and (2) How can logistics data be shared across aid agencies in disaster response efforts?

Research artefacts 1, 2, 3, and 4 were created to answer identify the literature gap, which creates the following ‘conditional’ main contributions: (1) The problem of poor interagency coordination is viewed as a wicked problem and its nature is interpreted by synthesising the literature and practitioner solutions that are currently used, then (2) lateral information sharing is proposed and experimented with to develop an alternative information sharing approach that is scalable and robust, yet does not require high degrees, high degrees of information visibility, any business integration, or strategic partnerships while still receiving most of the benefits of traditional vertical information sharing. These contributions are ‘contingent’ because they require an instantiation of the problem solving approach, otherwise they never become main contributions and remain purely hypothetical.

Finally, research artefacts 4 and 5 were created to instantiate the problem solving approach, becoming proof that lateral information sharing is possible by providing a feasible technology and process integration strategy, and therefore becoming the final main contribution. Once the third main contribution is made, it transforms previous main contributions from their previous ‘conditional’ status to being proper main contributions.

7.3. **Implications**

Design science has clear limitations about what it can and cannot prove, which is covered in detail in the *Limitations* section below. However, if I were to generalise the problem solving approach used in the practical artefact to create an additional research artefact, I could tentatively view things from the perspective of supply chain coordination mechanisms and create two new theories: (1) Identifying a new and unusual form of
information sharing as a supply chain coordination mechanism, which can be situated in a (2) Spectrum of information sharing, going from no information sharing to total information sharing.

7.3.1. **Lateral information sharing as an information sharing strategy**

While the system dynamics simulation presented in the *Supply chain simulation* chapter (pp. 103-124) was described as horizontal information sharing, or information sharing only between retailers across supply chains, the way in which it is implemented through the system architecture is an unusual approach. The practical artefact goes far beyond horizontal information sharing and approaches information sharing in a lateral way, using anonymised data shared between retailers that do not trust each other. At the risk of coining an awful neologism and looking like a fool, I tentatively call this problem solving approach ”lateral information sharing”, which can be described as follows:

**Lateral information sharing** is a form of information sharing, intended for low trust and high risk environments as a supply chain coordination mechanism, to synchronise demand and ordering information to improve supply chain performance. It works by sharing information across multiple competing supply chains instead of along a single supply chain, where information is collected and securely anonymised at each organisation, then aggregated at a central repository made available to all participating organisations. While the environment is accurately described by aggregate data, individual operations are only implied, preserving organisations’ privacy through plausible deniability. Due to low trust and lack of integration the participants only have a transactional relationship, but the capability enables a level of coordination that is usually indicative of a strategic relationship. It does not necessarily require any business integration (e.g. vertical, horizontal, and/or virtual integration) and does not integrate with participants’ business processes. However, it can be combined with integration, or migrated away from, to move towards more strategic partnerships if participants want to develop their relationship further.
7.3.2. **Implications for practitioners**

The original contributions are also of practical importance. The implementation framework in the *System architecture* chapter (see Figure 6.1 above, p. 143) gives practitioners a strategy for how to integrate multiple capabilities to deliver lateral information sharing. As shown in the *Supply chain simulation* chapter (see p. 121, above), lateral information sharing can minimise backlogs and therefore deprivation costs by sharing information at the point of the local warehouse and last-mile distribution.

Although there is a partial prototype given in the *Technical annex* (pp. 241-270, below) in the appendices, this framework is generic and can incorporate different technologies and be extended to include other useful and related capabilities. For example, once information sharing exists laterally, trigger-and-alert systems or decision support systems could be integrated using the new sources of information, which can be made dynamic.

Additionally, performance measurement of an aid agency’s efficiency in meeting the needs of the affect population may be able to be benchmarked against a hypothetical ideal or even other aid agencies, depending on how much information is available and whether the participating aid agencies are willing. Finally, lateral information sharing can be used as a ‘stepping-stone’ to move towards closer, more formal partnerships.

7.3.3. **Spectrum of information sharing in supply chain coordination**

The types of information sharing in a supply chain can be viewed as a spectrum, going from ad hoc information sharing to total omni-directional, cross-functional information sharing across all competitors and supply chain echelons, as well as the miscellaneous category of ‘none’. This spectrum is summarised in Table 7.1 (p. 174) below. Obviously,
combinations of these can exist to complement each other, and transition and migration between levels can occur.

<table>
<thead>
<tr>
<th>Maturity of Information Sharing</th>
<th>Closeness of Relationship</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Omni-directional (most mature)</td>
<td>Strategic</td>
<td>Information is shared between all organisations in an industry/sector/alliance with near complete transparency. Unless permitted by commercial law, this is usually illegal anti-competitive cartel behaviour.</td>
<td>–</td>
</tr>
<tr>
<td>2. Multi-directional (e.g. horizontal and vertical)</td>
<td>Strategic</td>
<td>Information is shared between and across supply chains in multiple lanes, but not every organisation in the industry/sector/alliance is sharing with absolutely everyone else.</td>
<td>(Note: Merely a combination between Levels 2 and 3.)</td>
</tr>
<tr>
<td>3. Uni-directional (e.g. horizontal or vertical)</td>
<td>Strategic</td>
<td>Information is shared either between organisations in a single echelon of the supply chain (e.g. between retailers), or across organisations along a single supply chain.</td>
<td>Lee &amp; Whang, 2000; Li, 2002; Taylor &amp; Arthanari, 2018a</td>
</tr>
<tr>
<td>4. Lateral</td>
<td>Transactional</td>
<td>Information is shared in an anonymised and aggregate way to preserve each participant’s privacy when they do not trust one another.</td>
<td>Taylor, 2019</td>
</tr>
<tr>
<td>5. Ad hoc (least mature)</td>
<td>Transactional</td>
<td>Information is shared in an ad hoc manner with no formal or long-term agreements, usually operating on swift trust (i.e. trust now, verify later).</td>
<td>Day et al., 2009; Holguín-Veras et al., 2012</td>
</tr>
<tr>
<td>None</td>
<td>None</td>
<td>No information is shared.</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 7.1: Spectrum of information sharing in supply chain

Lateral information sharing is in the lower end of these scenarios, but it does provide an intermediate step between ad hoc and vertical or horizontal information sharing. Once participating organisations see the benefits of information sharing and develop closer relationships, they can use lateral information sharing as a springboard for closer relationships, though closer supply chain relationships may never develop. It merely remains an option to interested parties. Aid agencies that specialise in disaster relief and have operations with an international reach may find themselves repeatedly working
together in disaster relief across different disaster events, and having an intermediate step may help foster trust and help aid agencies see opportunities that were not considered before seeing the direct benefits of some form of information sharing under lateral information sharing.

7.3.4. Comparison with related concepts

To see if there were any existing or related concepts, a thorough search was made in Google Scholar for “horizontal information sharing”, “vertical information sharing”, and “lateral information sharing” using various synonyms and their combinations with “logistics”, “supply chain”, “channel coordination”, and “disaster relief”. The search results included a lot of miscellaneous and unrelated material that initially sounded relevant, but after reading the full article it became clear that they were very misleading. Often titles and abstracts in academic literature do not even resemble what was written in the body of the text.

For various reasons, very limited horizontal information sharing is an existing concept called “horizontal cooperation”, however it is usually limited to highly competitive contexts and sharing supply cost information (e.g. Simatupang & Sridharan, 2002; Cruijssen, Dullaert, & Fleuren, 2007; Krajewska, Kopfer, Laporte, Ropke, & Zaccour, 2008). Obviously, decentralised supply chains also exist in the commercial sector, but many of their most robust and effective decentralised coordination mechanisms are not appropriate for disaster relief, with techniques such as transfer pricing, shortage reimbursement, and backlog penalties (Lee & Whang, 1999). When the operative principle is saving and sustaining lives in the humanitarian sector, rather than maximising profits in the private sector, these traditional coordination mechanisms that involve heavy punitive measures and unfair sharing of the burdens no longer remain relevant.
By comparison, the ‘horizontal information sharing’ scenario presented in the Supply chain simulation chapter (pp. 103-124) with full information sharing between retailers (Taylor & Arthanari, 2018a) has not been tried yet, probably because outside of disaster relief it would run afoul of competition laws. Lateral information sharing is not an existing concept and does not seem to have any parallels, possibly because traditional supply chain research mostly deals with the private sector.

7.4. Limitations

There are limitations to the findings summarised above. The cross-disciplinary nature of the problem makes literature reviews difficult. The design science methodology is as much a creative endeavour as it is a technological enterprise, meaning the frameworks tend to lack a clearly defined and strictly procedural direction to problem solving, while practical artefacts created using design science are restricted in what they can and cannot prove. The lateral information sharing approach may have limited generalisability in the private sector due to competition laws, as well as trust issues around its implementation in any context. Finally, there are practical issues around adoption and usage that affect all proposed solutions, where it will remain a mere technical curiosity if no one chooses to use it.

7.4.1. Research topic currently lacks predictive maturity

The subject matter of this thesis is highly cross-disciplinary, involving supply chain management, operations management, information systems, electronics engineering, and computer science, amongst other secondary fields. This is a thesis for a doctorate in supply chain management, not information systems or any branch of engineering. With that in mind, the core literature review is structured around humanitarian logistics as the setting, and supply chain management as the theoretical foundation. Design science research from
information systems is used only as the methodology, while the electronics engineering and computer science elements are but a means to an end, and their design is derived from a design science approach that is heavily informed by supply chain theory to adapt it to this setting. Across these different disciplines, the lack of information visibility and archival research in interagency coordination issues has created a situation where there are plenty of descriptive models, obtained from interviews and surveys, a few explanatory models, mostly obtained from a synthesis of the former, and no predictive models (see p. 183 for a more in-depth explanation of the maturity of models).

This research takes the constructionism approach (Kafai & Resnick, 1996) to proving supply chain theory, where the creation of implementable artefacts allows for theory to be tested and validated or falsified. The importance of information visibility and supply chain collaboration is central to the argument that humanitarian logistics lacks coordination because, at least in part, it lacks information visibility and information sharing (Holguín-Veras, Jaller, Van Wassenhove, Pérez, & Wachtendorf, 2012). However, given the complex socio-political context of disaster relief, there may be hidden underlying factors inhibiting information sharing (e.g. Day, Junglas, & Silva, 2009) beyond the lack of information visibility and lack of resources.

Unfortunately, with operational secrecy around humanitarian logistics it may be impossible to discern these factors until the researcher is in the disaster relief setting. However, finding willing participants for action research or case study research on-the-record in this area will be extraordinarily difficult, as issues of politics, crime, corruption, and/or incompetence (Hancock, 1992; Whybark, 2007, pp. 231-232) are likely present and extremely relevant. Therefore, any literature review on humanitarian logistics conditions are going to be limited by an imperfect lens, which is something a researcher is just going to have to accept as an inevitability until enterprising researchers manage to carry out
research on those highly sensitive topics somehow, likely using an approach that heavily involves diplomacy, making social connections, and dealing with tense political issues.

Additionally, the research problem is mostly concerned with capabilities to produce empirical quantitative evidence of supply chain phenomena to a sufficient level to produce validated mathematical models. There is plenty of mathematical modelling that has been published, but no research has been proven to be able to quantify interagency coordination outside of a laboratory scenario. The solution offered in this thesis at least provides a pathway to empirical research for humanitarian logistics outside of very generic case study research and opinion polling. Obviously, this will require some enterprising researcher at an academic institution or an official within an aid agency to persuade the rest of the users of this solution to allow aggregate findings to be published in a public forum. As a side note, the academic researcher who achieves and publishes first will find a veritable gold mine of empirical research that is detailed and specific, which would be the first of its kind in humanitarian logistics.

7.4.2. No design specifics in design science

As a methodology, design science uses a development process that requires the creation of certain research artefacts throughout sequential stages of learning and prototype development, which eventually results in a practical artefact that is technological and/or process-related. Throughout this process, hypotheses are created about the nature of the research problem and requirements for feasible solutions. Once the solution is built it can be validated, which if successful becomes proof that the problem can be solved using this specific approach from a positive philosophical perspective (Prat, Comyn-Wattiau, & Akoka, 2014), even though the act of creating the solution is interpretivist and constructivist.
This process is iterative, experiential and empirical by nature. All that design science can ever achieve is to prove that a theory is true through experimentation. It cannot prove that a theory is false, merely that a researcher/designer is insufficiently capable of solving the problem themselves, nor does it necessarily confirm why the solution failed validation. It also cannot prove that a theory that is true is necessarily the 'best' theory without benchmarking each approach alongside another, which is a task so arduous and onerous that it is almost never carried out by a single research group. Generic benchmarking techniques from computer science, information systems, and/or operations management are better suited to evaluating competing systems than is design science, which is primarily focused on creating solutions instead of evaluating them.

Even then, the solutions are specific to their configuration, so a theory that is proven false in its current configuration may nevertheless involve subcomponents that are correct in isolation or are useful when separated from the rest of the system. In a very real sense, the development process is a learning process that teaches lessons, and even abject failures can contain some form of learning, so failures can be 'rolled upwards' to future alternative solutions or other development projects to achieve eventual success.

Design science is inherently a creative endeavour, which makes it constructivist, interpretivist, and positivist simultaneously. Depending on the researcher, any of those three philosophical assumptions can be considered more important than the others. Though design science produces artefacts based on positivist capabilities in a technological or process-related system, the creation of any solution to a problem is heavily influenced by the biases and preferences of the designers involved. This does not make a theory proven using design science any less true, but it does directly affect the project management risk associated with researchers less qualified or less experienced in the problem area.
The only meaningful proof of whether an artefact produced through the design science process is fit-for-purpose is whether it has been successfully implemented. Helpfully, all of the mechanisms identified and extended are based on known solutions that are currently in use by aid agencies (see Figure 2.2 above, p. 67, Table 2.10 above, p. 69, Figure 5.1 above, p. 128). By extending these solutions to achieve the capabilities practitioners have already said that they want (Harvard Humanitarian Initiative, 2010), while also knowing how these mechanisms interact with the environment based on prior experience, it is already known whether the system architecture is feasible. In other words, much of the leg-work has been done by the domain already, but the information from practitioners have never been combined in such a way as the system architecture in this thesis.

Fundamentally, a practical artefact produced as a solution from the design science research process is manifestation of an integrated theory of how a problem operates in an environment and how the researcher’s solution resolves that problem. This integrated theory can only be considered holistically in design science (Prat, Comyn-Wattiau, & Akoka, 2014), rather than as its separate components. If certain components are mature and proven elsewhere and were therefore excluded from the process in a research project, then only their ability to integrate with the researcher’s solution needs to be proven.

7.4.3. Difficulties in modelling complex social activity

There is a common difficulty in using mathematical modelling to predict high level social phenomena, regardless of whether a researcher is using discrete event simulations, agent based models, or system dynamics, or using operations research. This is a limitation that not only restricts the generalisability and validity of the system dynamics simulation used in this thesis, but virtually all mathematical models for social environments. Here I deduce
the reasons for this difficulty with an interpretation rooted in an analogy of open loop systems versus closed loop systems and the nature of knowledge.

When looking at low level phenomena that is largely procedural and clearly-defined, mathematical models excel at uncovering and predicting relationships between variables. However, higher level phenomena in social systems are incredibly complex and dynamic and are difficult to accurately explain and predict moving from bottom up. Usually higher level phenomena are more than just the sum of lower level phenomena, including some bizarre and unforeseen dynamics between existing lower level phenomena, as well as including relationships that do not emerge until observing mid to higher level phenomena.

The problems with mathematical modelling methods applied to higher level social phenomena are that almost all they can reveal are dynamics, rather than becoming predictive. Searching through the entire archive of the proceedings for the International Conference of the System Dynamics Society will easily verify that claim for system dynamics. This is a fundamental problem with model validation in mathematical models. This is my personal interpretation of why this problem exists, which I will tentatively describe as the ‘Mona Lisa interpretation’ from the analogy used.

It is very easy for experts with experience to identify important variables and their relationships, but it is very difficult for those same experts to then quantify those relationships and turn them into an accurate prediction. Incidentally, this is also the greatest limitation in the Delphi method and developing theories from opinion polling (e.g. factor analysis, structural equation modelling, and multiple regression applied to opinion polls of experts) that are so much in vogue these days in the operations management and supply chain management literature. It is far easier for an expert to build a rationalist model from empirical observations and achieve construct validity in the formulation of relationships, than it is to make any model accurate enough for prediction.
I think this represents a fundamental logical relationship that is seen everywhere in the environment. It stems from the relationship between open loop and closed loop systems and the nature of the information required to create and operate each system competently. In an open loop system looking from the top-down, middle-up, or middle-down, only a small slice of information about a system is required to accurately assess its aggregate effects and broad relationships. By comparison, in a close loop system complete knowledge is required, including knowing every variable and its relationships. Moving from open loop to closed loop systems requires significantly more knowledge. When a closed loop system is then exposed to an open loop environment, the closed loop system can be updated to match the interactions with the wider environment, but so much time and effort has been invested in understanding the entirety of the closed loop system that little investment has been put into wider systems thinking.

In a sense, this is also the fundamental problem with technocratic systems such as the Soviet Union, where the assumption existed that technical experts in a field require such high intelligence and skill, that they are assumed to be highly transferrable to things such as wider organisational strategy and management, that technocrats are assumed to always make superior decisions and achieve superior outcomes compared to managerial experts. However, the relationship goes the other way and managerial experts are generally very poor at determining technical matters. To explain the generic difficulties of mathematical modelling of complex, high level social phenomena, I offer the following corollary:

It is far easier to competently judge something than it is to competently create something; it is far easier to judge and enjoy the Mona Lisa than it is to paint it.
7.4.4. Supply chain simulation is explanatory, not predictive

In the Supply chain simulation chapter (pp. 103-124), the system dynamics methodology was used to produce a supply chain model of how retailer backlogs would change in the order fulfilment process under different information sharing scenarios. This model was a highly simplified scenario of a very complex phenomenon, often involving hastily formed partnerships and involving many supply partners at each echelon. The meaning of the simulation’s findings is discussed here, from the context of the different categories of models used for their purposes and the validity of underlying assumptions.

Broadly speaking, there are three categories of models intended to represent observable phenomena: (1) Descriptive models, which describe the characteristics of phenomena well enough, so others can identify and classify phenomena, (2) Explanatory models, which outline constituent variables, their relationships, and the direction of those relationships within phenomena, and (3) Predictive models, which quantify the relationships within explanatory models well enough to accurately predict outcomes. Starting from descriptive models, models that meet successive categories generally require the model to meet previous categories as well.

As a minor addendum, there are some models using powerful statistical and machine learning techniques that are primarily predictive, but only weakly explanatory (e.g. random forest, gradient boosted trees, artificial neural networks). These approaches rest on the assumption that certain related phenomena will continue to have an effect, which are perhaps too latent, nebulous, or unobservable to capture directly. These predictive approaches are more likely to capture the dynamics of phenomena in an open loop environment, but they often suffer from difficulties in informing researchers how to
manipulate variables that affect the outcome because of the lack of full explanatory power. These techniques will not be discussed.

The stock and flow model used in the Supply chain simulation chapter (pp. 103-124) is an explanatory model, not a predictive model, which means the model is at best a partial representation of supply chain behaviour. The model has quantitative equations determining the relationships, but while the variable constructs are valid, and the formulation of relationships are logical, the lack of empirical quantification means any exploration of how variables interact can only identify dynamic relationships. Nor can any empirical data be gathered, since widespread information visibility is not currently present in disaster relief. It cannot be used to definitively confirm that certain information sharing approaches will always be effective. The most an explanatory model can achieve is strongly suggest an approach that will be effective.

The inherent risk of an explanatory model for analysing dynamics is that any relationship that is not included in the model may overpower any relationship within the model. There are usually implicit underlying assumptions that are considered so obvious to a researcher they are not explicitly included. An example is the assumption in many humanitarian logistics models of supply chain volatility that it is not necessary to include subsequent disasters, which assumes that the disaster event has occurred and has no aftereffects (e.g. post-earthquake tremors, liquification destroying roads, etc.).

To unambiguously state the sole purpose of the model: to serve as an illustrated example of what effect different types of information sharing would have on inventory levels in a simplified scenario. The general dynamic is that the more heterogeneous and larger the number of aid agencies, the more chaos and supply chain volatility will be in the system, and therefore the more drastic the reductions in backlog volatility will be when any
information sharing scenario is introduced. In other words, this simplified system dynamics model significantly understates the benefits of all information sharing scenarios.

However, the information sharing scenarios do not consider partial adoption, assuming full adoption. This is because we are interested in the dynamics of information sharing as an explanatory model, rather than producing a predictive model with complete visibility of relief operations. The most likely scenario with any information sharing scenario implementation is partial adoption by aid agencies, or even adoption of aid agencies but under different networks and different sharing agreements. If the model cannot deliver hypothetical value in even these conditions, the design approach used in this thesis to solve the research problems is faulty and/or the simulation is faulty. If this point of the design science research process fails, the model must be analysed for its validity, and/or another design approach must be used, tested, and pass testing.

These simulation scenarios only consider demand information as the single dimension of information visibility, since it is one of the most sought-after forms of information in disaster relief (Sheu, 2007b), the full effects of high information visibility and information sharing are possibly even more pronounced than the simulation results suggest. Thus, these results provide a viable benefit for horizontal information sharing, even if it is hypothetical. This may possibly provide enough hypothetical potential for humanitarian logisticians to at least trial the artefact in a simulated scenario, but more importantly for this thesis it provides the impetus for continuing the design science process.

Because this model is not empirically quantified, it should be considered a synthetic, rationalist model that includes many artificial assumptions, such as perfect information visibility for each echelon’s immediate demand, perfect information sharing, and no multiples of suppliers and customers at each echelon of the supply chain. It does not
consider exogenous variables (e.g. Langley, Paich, & Sterman, 1998), instead focusing on the
delays (Diehl & Sterman, 1995) and the strength of feedback loops (Diehl, 1989). The most
unlikely assumptions to be true within the simulations are as follows: (1) All organisations
in the supply network are homogeneous instead of heterogeneous (cf. Balcik, Beamon,
Krejci, Muramatsu, & Ramirez, 2010) and (2) There are only twelve organisations in the
disaster relief effort instead of literally thousands (cf. Jaller, Van Wassenhove, Pérez, &
Wachtendorf, 2012).

In the Literature review chapter (pp. 21-56), I criticised the much of the corpus of
current academic solutions as being almost entirely rationalist, yet in a seeming
contradiction the simulation used here is itself a generic and synthetic model. The
important distinctions that separate this preliminary work from the rest of the literature are
as follows: (1) I recognise that empirical quantification is currently impossible as there is no
data collection or analysis, for the reasons outlined in the Introduction chapter (pp. 10-20)
and Literature review chapter (pp. 21-73), (2) The simulation is only used as a ‘litmus test’
(i.e. an inexpensive, quick test used as the first stage of confirmation) to discover if there is
any hypothetical value to the prototype’s problem solving approach before continuing with
the design science research process, and most importantly (3) This thesis offers a solution
to solving the lack of data collection and analysis in the subsequent process solution
outlined in the System architecture chapter (pp. 140-166), instead of leaving it permanently
unresolved as with the rest of the literature. Therefore, the purpose of the simulation is
completely different from the claims made by other research using rationalist approaches.

7.4.5. Trust issues around lateral information sharing

The question remains, is lateral information sharing feasible outside of a laboratory setting?
Without attempting actual implementation, any argument for or against will be
hypothetical at best. While Day, Junglas, and Silva’s (2009) paper remains the best study on the subject, there is currently little research on how trust issues between NGOs manifest. There are lingering questions about how willing NGOs are willing to trust and coordinate with each other as they compete for media attention, getting credit for performance, and donor funding.

While lateral information sharing is set up so that participants do not need to trust each other, they still need to place their trust in three things: (1) Whoever is providing the information sharing capability is competent and has integrity, but this can be readily mitigated by allowing independent audits by releasing the source code and designing appropriate information security mechanisms, (2) the anonymisation process must be statistically rigorous and sound, though this has largely been solved in data science, and (3) that other participants do not try to ‘game the system’ by planting false information to distort aggregate statistics for private gain.

While planting false information is a risk with all information sharing agreements, there are some differences in lateral information sharing: (1) Transactional nature of relationships can increase risks, (2) It is difficult to sabotage the system with false information and still use the aggregate analytics by trying to reverse engineer the sabotage with an organisation’s private data, (3) the larger the network of participants and more transparent the environment, the larger the number of sabotaging organisations required to make the analytics useless, and (4) Sabotaging the network would literally indirectly kill people in disaster relief, and aid agencies are more interested in saving and sustaining lives in the moment than competing for major donor funding long after the disaster response.

Data anonymisation is largely a solved matter in statistics (e.g. Samarati & Sweeney, 1998), but it is rarely implemented rigorously because either it is too computationally inefficient across datasets with many dimensions and/or it makes the data less valuable (e.g.}
Crowcroft & Gascón, 2018). Most of the advances in this area are incremental increases in computational efficiency. Generally, the more anonymous the data becomes, the less specific the information becomes. If an information sharing provider wants to own their customers’ data and lock them into vendor contracts to eliminate competition and preserve monopoly power, effective anonymisation is the last thing they want because it makes the data less valuable and more difficult to sell to third parties (Schreieck, Hein, Wiesche, & Krcmar, 2018). Lateral information sharing is diametrically opposed to data science approaches such as those espoused by Facebook and Cambridge Analytica, who perform blanket surveillance on their customers and sell data to third parties (Fuchs, 2017, pp. 183-216). If the organisation providing the lateral information sharing capability cannot be trusted and has questionable integrity, this approach becomes impossible.

In the System architecture chapter (pp. 140-166), an implementation strategy was given alongside anonymisation in the data capture application. Briefly, it involves compartmentalising the application that performs data collection and anonymisation to a user’s computer and securing it against manipulation by the user and provider of the application. The user is in full control of the application and can change its settings for what data can be gathered, but no one can tamper with the anonymisation programming, not even the programmers themselves. The source code should be made available to anyone wanting to do an independent audit or made open source entirely. Updates/patches require new audits and the application should not be allowed to automatically update under any circumstances—automatic updates should never be programmed into the application. This largely eliminates the need to trust the provider of the application.
7.4.6. Practical issues around adoption

I once described the solution presented in this thesis to an information systems expert, who immediately brought up the issue of how to convince aid agencies to install what basically amounted to spyware on their computers and would not stop repeating it throughout the conversation, regardless of what I said. Unfortunately, this individual did not really understand the approach, but this kind of alarmist reaction is completely understandable and far more likely to occur than not. A central component of the solution is in how the data collection is configured. Trust and power need to remain in the process, which needs to be controlled by aid agencies themselves. It can never be allowed to fall into the hands of the person or organisation providing the solution or data analytics. This thesis has produced a practical artefact that can enable information visibility and information sharing across aid agencies in downstream supply chains in disaster relief. The theories associated with the design science development process were proven true, but what was never addressed was the adoption approach.

Extensive literature has already been written on this research topic and the adoption of new information systems in extremely risk-averse and resource constrained organisations is sufficiently complicated to constitute an entirely separate Doctor of Philosophy degree in the field of information systems. To put it as unambiguously as possible, this thesis only proves that information visibility and information sharing can be enabled in disaster relief whereas previously there were no viable solutions, but it does not offer any pathway to navigating the political issues of adoption. Using a common colloquialism, I imagine that convincing the first aid agency to adopt the solution would need one hell of a sales pitch. There have been seminal papers on implementing horizontal cooperation. For example, Verstrepen, Cools, Cruijssen, and Dullaert (2009) provide an
extensive framework for navigating implementation issues in the commercial sector, but it is also completely useless for disaster relief because it involves a heavy amount of trust, process engineering, and virtual integration. The implementation difficulties in disaster relief are unique and there is limited generalisability of existing studies.

The need to use an application that is independently audited for its security and anonymity creates an interesting challenge in maintaining and improving the application, because newer versions must encapsulate all the dependencies of older versions and there must be perfect cross-functionality between versions—obviously except for features that have not been introduced to a specific version yet. The best solution may be to offer multiple security and anonymity policies to aid agencies and allow them to manually choose the one that suits them best, otherwise it defaults to the most secure and anonymous option. This also means that if only a small fraction of the overall disaster relief effort adopts the solution, the application will not work because there are too few data points and too few sources for aid agencies to hide in, which leads to the application stripping out so much information it makes the data useless.

Alternatively, as a practical issue the data collection points can be recalibrated to other parts of the network (e.g. at specified and monitored collection points within each aid agencies own private networks). They can be reprogrammed to only collect certain types of data from certain repositories, which can operate on a user-defined blacklist (i.e. users indicate what is to be excluded, otherwise it will be included) or whitelist (i.e. users indicate what is to be included, otherwise it will be excluded). From a pure process engineering perspective, these are inferior approaches because they result in drastically lower network efficiency, while they also do not resolve the issue of security and anonymity. This pushes the burden of configuring the system onto aid agencies, which are not equipped for
analysing which kinds of information are safe to share. Nevertheless, it can be done if requested by an aid agency.

7.4.7. Practical issues around usage

Because the solution attempts to bypass political and legal issues by giving all control and power to users, while also bypassing resource and personnel issues through complete automation, the resulting solution ‘floats’ on top of aid agencies’ decision making processes without directly integrating with any of them. The insights published from data analytics are given as is, so there is no guarantee how aid agencies should, would, or even will use it. The untested assumption throughout this thesis is that more accurate and complete logistics information of demand data and environmental data affecting supply chain operations will be used by aid agencies because they have a natural incentive. I honestly have no idea if this is true. It is very possible that I am unaware of critical political elements that would see humanitarian logisticians ignore statistical insights that are politically inconvenient.
8. Conclusion

8.1. Introduction

The investigation explored the nature of poor interagency coordination in disaster relief supply chains and the solutions to the problem using improving supply chain coordination mechanisms and technological facilitators. This problem is seemingly insoluble and sufficient solutions have evaded humanitarian logisticians for decades. Interagency coordination is truly a wicked problem, combining multiple classes of wicked problems across an extremely heterogeneous, decentralised, and ad hoc environment. Disaster relief is also extremely resource-constrained and chronically underfunded. Together, these elements seem to preclude any viable solutions because the usual problem solving approaches for different classes of wicked problems are incompatible and contradict one another. To solve this problem, a strategy of information sharing called “lateral information sharing” was developed, using a technologically-facilitated process that shares information indirectly and anonymously. This approach was instantiated as a system architecture, which implemented data collection, anonymisation, and processing processes with telecommunications technology. The thesis research is summarised by identifying the main original contributions and limitations, as well as postulating future research directions.

8.2. Summary of research

This investigation is summarised by affirming the following: (1) The method of framing interagency coordination problems as wicked problems with causal problems [distal causes], issues [proximal causes], and requirements [constraints] to understand its nature is shown, (2) explaining how that framework was developed into a hypothetical information
This investigation began with the research questions: How can logistics data be shared across aid agencies in disaster response efforts? After exploring the literature across several fields, the following research questions were developed from these two problems: (1) What are the seminal academic papers and practitioner reports on problems in interagency coordination in disaster relief, (2) What are the strengths and limitations of current technological, process, and operational solutions in interagency coordination in disaster relief, (3) Is there a capability gap between practitioners’ solutions and academic proposals that do not adequately address problems in interagency coordination in disaster relief; (4) Are there existing supply chain theories and related techniques that lead to solutions to problems in interagency coordination in disaster relief, and (5) How can a solution to problems in interagency coordination in disaster relief be developed that integrates multiple disciplines, to address problems that are simultaneously related to technology, process, culture, and politics?

This thesis surveyed, synthesised, and interpreted the problems affecting interagency coordination in disaster relief supply chains as information sharing problems from a process-perspective to answer the research question. By categorising elements of the problem area and establishing the causality between them, the problem’s constraints emerge and can be stated explicitly and unambiguously. The characteristics of the volatile disaster relief environment were compared to standard supply chain approaches to mitigate volatility. The supply chain strategies of agile, leagile, and quick response were synthesised to identify common antecedents. Then these antecedents were compared to the disaster relief environment. The interactions between environmental characteristics inhibiting
supply chain strategy antecedents were analysed for common solutions from the humanitarian sector and comparable solutions from the private sector to identify the literature gap. This revealed that some solutions are insufficient, while others are unresolved and have no solutions.

This literature synthesis revealed that interagency coordination problems are all three classes of wicked problems, where they have areas of dispersed and concentrated power/authority; and areas of contested and uncontested power/authority. The general problem solving approaches for each class of wicked problem contradicts the others, yet this problem has to be solved concurrently and holistically. The lack of resources ultimately leads to information sharing processes that are not scalable. It is not possible to reduce the problem by dividing it into smaller, more soluble problems. This led to an unusual dilemma: “How do you enable interagency coordination while virtually using almost no resources?”

Instinctively, it seemed that horizontal information sharing had potential and could identify part of the literature gap. Horizontal cooperation is a highly limited form of information sharing found in the private sector. It is usually heavily regulated because the information sharing is occurring between competitors, where too much coordination would result in illegal cartel behaviour. However, disaster relief is not necessarily a profit-seeking enterprise and most aid agencies are non-profit organisations.

To test whether or not direct horizontal information sharing would minimise deprivation costs, a system dynamics simulation was used to test out different information sharing scenarios across three supply chains with four echelons each. The experiment showed that after the initial delay stabilises, as the first few batches of orders filters upstream to the supplier, horizontal information sharing [sharing across competing retailers in separate supply chains] is just as effective as vertical information sharing [sharing between partnered retailers and suppliers in a single supply chain]. However,
what we are left with is what would be considered an illegal approach in the private sector when done directly. Now a hypothetical but unfeasible solution has been proven, and the mission became to turn it into something feasible.

A conceptual model was created to implement a generic information flow across organisation that enables a lateral form of horizontal information sharing called “lateral information sharing”. Under this approach, information is aggregated and anonymised using an automated process, before being uploaded to a central server and then aggregated and analysed to reveal statistical insights. It does not require that participants trust each other or the programmers of the data management application. It also does not allow perfect coordination because the information sharing is imperfect and anonymous, so there will always be doubt that provides plausible deniability on the precise origins of data that is collected using this process. Educated guesses can be made about the origins of data, but no one can be absolutely certain. Now a hypothetical approach has been defined and the task becomes how to implement it as an instantiation to prove it is more than just hypothetical.

By viewing supply chain theory from strategic management perspectives, namely theories of the firm, and integrating them as design principles in an adapted design science research process, a generic system architecture was defined. It was then instantiated using ZigBee as the mesh network, various industrial applications for handling messaging such as Mosquitto, and various industrial data handling applications such as MySQL databases, all with associated middleware to integrate components. This involved integrating multiple technologies, functions, and processes into an automated process solution. A data capture application would run on each participating aid agency’s laptop and collect specific data that users permitted it to gather. Then the data would be securely anonymised and uploaded to a central server. The server would process the data and disseminate insights by publishing them on a web-page in a central repository. The programming of the data
capture application must be made available to all aid agencies requesting a security audit by independent information security firms to ensure the application is free from tampering and truly respects the privacy, security, and anonymity of its users.

By creating the instantiated system architecture, we now know that lateral information sharing is technically possible, which validates the literature synthesis used to frame the wicked problem, the horizontal information sharing scenario used in the supply chain simulation, and the problem solving approach in the conceptual model. This instantiation feeds back into the beginning of the research statement to address those two original research problems to create original main contributions, which are discussed in the section below.

8.3. Contributions

The research artefacts can be seen as original minor contributions, which were used to directly answer the research question that were generated from the process in the research statement. By interpreting and generalising these minor contributions, the major original contributions are revealed. The two original research problems were two facets of the same problem: poor interagency coordination in disaster relief supply chains. The first major contribution is the problem of poor interagency coordination can be viewed as a wicked problem from a process-perspective, which can then be explored and synthesised into a problem solving approach that overcomes the limitations of using a generic approach for a single category of wicked problem.

The second major contribution is the proposal of lateral information sharing as a lateral, indirect implementation of horizontal information sharing that does not contradict the environmental constraints identified in the first major contribution. Lateral information sharing seeks to allow information sharing across participants that are reluctant to trust
one another in a way that is scalable, robust, and does not require a heavy amount of investment or process engineering. The intended outcome is to gain almost all the benefits of traditional information sharing agreements under strategic partnerships without any investment or integration, and while still remaining in a transactional relationship.

The third major contribution instantiated lateral information sharing as a system architecture, which defined various technological and process functions that were required, along with suitable technologies that possess those functions and can integrate with one another. Through instantiation, the third major contribution transforms the second major contribution from a problem solving approach into a viable theory as a new form of supply chain coordination mechanism and/or strategy. Finally, as a series of practical contributions, the implementation strategy in the system architecture can be extended to incorporate related and useful capabilities, as well as be used as an interim solution for moving towards closer and more formal interagency coordination with trusted partners.

8.4. Limitations

There are fundamental limits to what is knowable, which become more restrictive as time and resources become more constrained. This section identifies the major limitations of this investigation’s choices and uses of methodologies and the generalisability of its findings.

The nature of interagency coordination problems as wicked problems complicates the literature review, because the problem has many interrelated facets straddling many different fields, and it is not obvious where certain phenomena begin and where they end. In wicked problems, there is no right or wrong answer, only comparatively better and worse solutions. This makes a very broad literature review an inescapable requirement for understanding the problem, which comes at the expense of depth. The mathematical formulations of information sharing scenarios were not explored, nor were socio-political
issues that affect human interactions. By viewing poor interagency coordination as primarily a process issue, it intentionally does not consider political issues.

The choice of design science is unusual for supply chain research and it is rarely seen. Most supply chain research in the topic of supply chain coordination mechanisms and strategies are based on operations research models that are heavily influenced by economic theory. The unique challenges of adapting supply chain theories to disaster relief have led to this approach being used, but there is no inherent direction in the design science research process. An operations research model entails certain solutions, whereas design science is about constructing solutions to enable capabilities, which is a creative enterprise that can only imply a solution approach. The quality of the solution is entirely up to the researcher/designer of the practical artefact.

There are trust issues around the exact implementation of security policies in lateral information sharing. The data anonymisation process must be secure and the applications used to facilitate them must not allow non-users from outside aid agencies to compromise the security, privacy, and anonymity of participating aid agencies. The trust is effectively built into the programming, but if the programming is not made available to participants on request for auditing, then prospective participants will never adopt lateral information sharing.

8.5. Publications from thesis

The investigation created several publications that were released in academic outlets, which relate to certain research artefacts from various chapters. A summary of all published original research from the thesis is given in Table 8.1 (p. 199) below.
Table 8.1: Summary of publications from thesis

Each publication corresponds to certain research artefacts and chapters in this thesis, which are summarised in Table 8.2 (p. 200) below. As can be seen, research artefact 2 was never published. This is because the design science research process inherently requires producing these kinds of frameworks as part of the learning process, which are highly specific to the objectives and problem solving approaches of each research project. While the lessons learned from producing adapted frameworks are useful and design principles can be derived across the creation of many adapted frameworks after seeing their successful implementation, individual adapted frameworks such as research artefact 2 are usually very limited in generalisability and of limited interest to the academic community.
<table>
<thead>
<tr>
<th>Publications</th>
<th>Research Artefacts</th>
<th>Thesis Chapters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper 1: Literature review and conceptual model</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Paper 2: Supply chain simulation</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Paper 3: System architecture</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Notes:

- **Research artefact 1:** The academic and practitioner literature on interagency coordination issues stemming from characteristics of disaster relief is synthesised into several tables, which provide a cross-section of disaster relief challenges but also serves to highlight capability and literature gaps.

- **Research artefact 2:** A design science framework is adapted to supply chain theory to address interagency coordination issues. This new framework exemplifies how different theoretical perspectives can serve as design principles and approaches during the design science development process.

- **Research artefact 3:** A simplified supply chain simulation using stock and flow diagrams from system dynamics is produced, illustrating the effects of different information sharing scenarios. This serves as a litmus test for whether it is at least hypothetically worthwhile to develop the practical artefact.

- **Research artefact 4:** A system architecture is defined for integrating multiple generic technologies into a technologically-supported process solution for automated data collection, analysis, and dissemination to support interagency coordination in disaster relief.

- **Research artefact 5:** An instantiation/implementation of the system architecture is defined, with specific technologies serving as constituent components in an integrated solution.

Table 8.2: Summary of publications, and their research artefacts and thesis chapters

### 8.6. Future research directions

The most obvious future research direction is to complete the missing components to fully instantiate the system architecture in preparation for field deployment. When the system architecture has been fully instantiated as a fully working prototype, there are several ways to prove its ability to improve interagency coordination.

Firstly, building an *operations research model* of the capability being enabled would present the theory in a format that the rest of the traditional supply chain literature would find acceptable, which is a rationalist mathematical model much like what the rest of the supply chain and humanitarian logistics literature relies on. The construct validity and realism of these kinds of models are always highly suspect. All these models rely on the assumption of perfectly rational and capable economic agents, which originated in
economics and has been derided by the rest of academia as the fictional and hyper-idealised ‘homo economicus’. The dynamism of human behaviour in complex social activities such as disaster relief can be crudely simulated by integrating stochastic elements into a deterministic model. The exact way in which coopetition manifests during interagency coordination needs to be explored, where cooperation and competition occur simultaneously between rivals. Coopetition models in economics, and interview and case study research with practitioners are potential starting points.

Secondly, creating a conflict simulation with human participants (Herman, Frost, & Kurz, 2009) would allow the exploration of unintentional and complex emergent social dynamics as users interact with the system. This is frequently called a “war game” by the private, public, and military sector, but usually does not involve any military-related activity. Sometimes it goes by the term “conflict simulation” to describe its adversarial nature. A simulation with human participants assigns roles to human participants and confines human behaviour to predefined rules, but it does not specify exactly how they can use those rules. Strategies and behaviour that emerge often diverge from what game moderators would expect from ‘homo economicus’. A crucial concept is the “red team”, which serve as adversaries/rivals. Simulations can be cooperative, with the adversary as an environment. These kinds of simulations are excellent at uncovering political and strategic dynamics but are generally poor at quantifying relationships. One of the most common forms of these games are “matrix games”, which involve no quantification at all.

Thirdly, expert validation should be conducted, where domain experts with experience in disaster relief from NGOs of varying sizes, local government officials, national government officials, and military personnel should examine the system architecture to see if they find it acceptable. Finally, some form of field deployment, whether it is a small pilot study or a large scale implementation, would allow case study
research and put lateral information sharing to the ultimate test. For reasons outlined repeatedly throughout this thesis, this is very difficult for an academic researcher or even a private company to achieve, though this is a primarily a ‘business case’ rather than a research case.

Briefly, aid agencies have few resources and are very risk-averse, making them extremely hesitant to implement anything that has not been thoroughly tested and proven, such as being ported from the private sector. If the system architecture is deployed in the field in the future, for the first time historical statistics for a disaster relief operation can be collected and analysed, which means that quantitative empiricism can be brought to the study of humanitarian logistics, provided aid agencies permit publishing aggregate results and exercise some editorial control. This fundamentally means that there will either be less reliance on rationalist models, or that those models can now be validated against historical practice. The potential applications from gaining access to such information are vast, such as empirical theory development, but the path to full instantiation and implementation is probably a long one.
9. Bibliography

9.1. Main references

This section covers all the references, except the literature search for novel and emerging solutions on interagency coordination issues, and non-academic websites for general information, which are covered in separate sections.


Conference on Information Systems (ACIS) (pp. 1-10). Australasian Association for Information Systems (AAIS).


Oh, E. S. (2003). Information and communication technology in the service of disaster mitigation and humanitarian relief. In *Proceedings of the 9th Asia-Pacific Conference on Communications (APCC)* (pp. 730-733). Institute of Electrical and Electronics Engineers (IEEE).


Pallotta, D. (2013). *The way we think about charity is dead wrong* [Video File]. Retrieved from


<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Journal/Conference</th>
</tr>
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<tbody>
<tr>
<td>Tapia, A. H., Bajpai, K.,</td>
<td>Seeking the trustworthy tweet: Can microblogged data fit the information needs of disaster response and humanitarian relief organizations.</td>
<td><em>Proceedings of the 8th International Conference on Information Systems for Crisis Response and Management (ISCRAM) (pp.1-10). ISCRAM.</em></td>
</tr>
<tr>
<td>Jansen, B. J., Yen, J.,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp; Giles, L.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tatham, P., Spens, K., &amp; Kovács, G.</td>
<td>The humanitarian common logistic operating picture: A solution to the inter-agency coordination challenge.</td>
<td><em>Disasters, 41</em>(1), 77-100.</td>
</tr>
</tbody>
</table>


9.2. **Search for emerging solutions**

This section covers the literature search for novel and emerging solutions to interagency coordination issues that can be applied to disaster relief but have not yet been adopted. These come from a variety of sources, from academic research to patents and start-up companies.

9.2.1. **Conference proceedings**


software defined networks. In *Proceedings of the 3rd GENI Research and Educational Experiment Workshop (GREE)* (pp. 1-8). Institute of Electrical and Electronics Engineers (IEEE).

Meissner, A., Luckenbach, T., Risse, T., Kirste, T., & Kirchner, H. (2002). Design challenges for an integrated disaster management communication and information system. In *Proceedings of the 1st IEEE Workshop on Disaster Recovery Networks* (pp. 1-7). Institute of Electrical and Electronics Engineers (IEEE).


9.2.2. Journal and magazine articles


9.2.3. Patents


### 9.2.4. Company websites


### 9.2.5. Miscellaneous


9.3. Further Reading

This section suggests some useful resources for learning more about telecommunications and networking technology.

9.3.1. Telecommunications standards


9.3.2. Guides for telecommunications networking


9.3.3. Guides for building wireless sensor networks


9.3.4. Data anonymisation

Appendix A: Vensim equations

The stock and flow models used for the supply chain simulations of information sharing scenarios in the Supply Chain Simulations chapter (pp. 108-120) were built using the Vensim application. The equations below detail the connections between nodes and equations within nodes necessary to reproduce the simulation.

A1. Scenario 1: No information sharing

The no information sharing scenario represents no information sharing along a supply chain. Each node/echelon makes its own ordering decisions without consulting or informing other nodes/echelons. It is used to illustrate the “bullwhip effect” and serves as a benchmark for information sharing scenarios that include some form of information sharing.
(030) Cost3 = INTEG(CostIncrease3, 0)
(031) CostIncrease1 = 1 * (Backlog11 + Backlog12 + Backlog13 + Backlog14) + 0.5 * (Inventory11 + Inventory12 + Inventory13 + Inventory14)
(032) CostIncrease2 = 1 * (Backlog22 + Backlog23 + Backlog24 + Backlog21) + 0.5 * (Inventory22 + Inventory23 + Inventory24 + Inventory21)
(033) CostIncrease3 = 1 * (Backlog32 + Backlog33 + Backlog34 + Backlog31) + 0.5 * (Inventory32 + Inventory33 + Inventory34 + Inventory31)
(034) EffEnv11 = Inventory11 - Backlog11
(035) EffEnv12 = Inventory12 - Backlog12
(036) EffEnv13 = Inventory13 - Backlog13
(037) EffEnv14 = Inventory14 - Backlog14
(038) EffEnv21 = Inventory21 - Backlog21
(039) EffEnv22 = Inventory22 - Backlog22
(040) EffEnv23 = Inventory23 - Backlog23
(041) EffEnv24 = Inventory24 - Backlog24
(042) EffEnv31 = Inventory31 - Backlog31
(043) EffEnv32 = Inventory32 - Backlog32
(044) EffEnv33 = Inventory33 - Backlog33
(045) EffEnv34 = Inventory34 - Backlog34
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(050) In14 = DELAY FIXED(Coming1, 2, 4)
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(073) Order2 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)
(074) Order3 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)
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(076) Ordered12 = DELAY FIXED(Placed12, 1, 4)
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(082) Ordered24 = DELAY FIXED(Placed24, 1, 4)
(083) Ordered31 = DELAY FIXED(Placed31, 1, 4)
(084) Ordered32 = DELAY FIXED(Placed32, 1, 4)
(085) Ordered33 = DELAY FIXED(Placed33, 1, 4)
(086) Ordered34 = DELAY FIXED(Placed34, 1, 4)
(087) Placed11 = MAX0, SMOOTH(Order1, SmoothTime1) + a1 * (12 - (Inventory11 - Backlog11) - B1 * SupplyL11)
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(089) Placed13 = MAX0, SMOOTH(Ordered13, SmoothTime1) + a1 * (12 - (Inventory13 - Backlog13) - B1 * SupplyL13)
(090) Placed14 = MAX0, SMOOTH(Ordered14, SmoothTime1) + a1 * (12 - (Inventory14 - Backlog14) - B1 * SupplyL14)
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(093) Placed23 = MAX0, SMOOTH(Ordered22, SmoothTime2) + a2 * (12 - (Inventory23 - Backlog23) - B2 * SupplyL23)
(094) Placed24 = MAX0, SMOOTH(Ordered23, SmoothTime2) + a2 * (12 - (Inventory24 - Backlog24) - B2 * SupplyL24)
A2. Scenario 2: Vertical information sharing

The vertical information sharing scenario represents traditional information sharing in supply chain theory, where starting from downstream retailers, each node/echelon shares their demand and ordering information up to the next node/echelon.
Backlog11 = INTEG(bFlow11, 0)
Backlog12 = INTEG(bFlow12, 0)
Backlog13 = INTEG(bFlow13, 0)
Backlog14 = INTEG(bFlow14, 0)
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Backlog22 = INTEG(bFlow22, 0)
Backlog23 = INTEG(bFlow23, 0)
Backlog24 = INTEG(bFlow24, 0)
Backlog31 = INTEG(bFlow31, 0)
Backlog32 = INTEG(bFlow32, 0)
Backlog33 = INTEG(bFlow33, 0)
Backlog34 = INTEG(bFlow34, 0)
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bFlow12 = Ordered11 - Sold12
bFlow13 = Order12 - Sold13
bFlow14 = Order13 - Sold14
bFlow21 = Order21 - Sold21
bFlow22 = Order22 - Sold22
bFlow23 = Order23 - Sold23
bFlow24 = Order24 - Sold24
bFlow31 = Order31 - Sold31
bFlow32 = Order32 - Sold32
bFlow33 = Order33 - Sold33
bFlow34 = Order34 - Sold34
Coming1 = Order14
Coming2 = Order24
Coming3 = Order34
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Cost2 = INTEG(CostIncrease2, 0)
Cost3 = INTEG(CostIncrease3, 0)
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(Inventory11 + Inventory12 + Inventory13 + Inventory14)
CostIncrease2 = 1 * (Backlog22 + Backlog23 + Backlog24 + Backlog21) + 0.5 *
(Inventory22 + Inventory23 + Inventory24 + Inventory21)
CostIncrease3 = 1 * (Backlog32 + Backlog33 + Backlog34 + Backlog31) + 0.5 *
(Inventory32 + Inventory33 + Inventory34 + Inventory31)
EffEnv11 = Inventory11 - Backlog11
EffEnv12 = Inventory12 - Backlog12
EffEnv13 = Inventory13 - Backlog13
EffEnv14 = Inventory14 - Backlog14
EffEnv21 = Inventory21 - Backlog21
EffEnv22 = Inventory22 - Backlog22
EffEnv23 = Inventory23 - Backlog23
EffEnv24 = Inventory24 - Backlog24
EffEnv31 = Inventory31 - Backlog31
EffEnv32 = Inventory32 - Backlog32
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In21 = Sold22
In22 = Sold23
In23 = Sold24
In24 = Coming2
In31 = Sold32
In32 = Sold33
In33 = Sold34
In34 = Coming3
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Inventory12 = INTEG(In12 - Sold12, 12)
Inventory13 = INTEG(In13 - Sold13, 12)
Inventory14 = INTEG(In14 - Sold14, 12)
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Inventory32 = INTEG(In32 - Sold32, 12)
Inventory33 = INTEG(In33 - Sold33, 12)
Inventory34 = INTEG(In34 - Sold34, 12)
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Order2 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)
Order3 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)
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Ordered21 = Placed21
Ordered22 = Placed22
Ordered23 = Placed23
Ordered24 = Placed24
Ordered31 = Placed31
Ordered32 = Placed32
Ordered33 = Placed33
Ordered34 = Placed34
Order1 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)
Order2 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)
Order3 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)

Placed11 = MAX(0, SMOOTH(Order1, SmoothTime1) + α1 * (12 - (Inventory11 - Backlog11) - β1 * SupplyL11))
Placed12 = MAX(0, SMOOTH(Ordered11, SmoothTime1) + α1 * (12 - (Inventory12 - Backlog12) - β1 * SupplyL12))
Placed13 = MAX(0, SMOOTH(Ordered12, SmoothTime1) + α1 * (12 - (Inventory13 - Backlog13) - β1 * SupplyL13))
Placed14 = MAX(0, SMOOTH(Ordered13, SmoothTime1) + α1 * (12 - (Inventory14 - Backlog14) - β1 * SupplyL14))
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Placed22 = MAX(0, SMOOTH(Ordered21, SmoothTime2) + α2 * (12 - (Inventory22 - Backlog22) - β2 * SupplyL22))
Placed23 = MAX(0, SMOOTH(Ordered22, SmoothTime2) + α2 * (12 - (Inventory23 - Backlog23) - β2 * SupplyL23))
Placed24 = MAX(0, SMOOTH(Ordered23, SmoothTime2) + α2 * (12 - (Inventory24 - Backlog24) - β2 * SupplyL24))
Placed31 = MAX(0, SMOOTH(Order3, SmoothTime3) + α3 * (12 - (Inventory31 - Backlog31) - β3 * SupplyL31))
Placed32 = MAX(0, SMOOTH(Ordered31, SmoothTime3) + α3 * (12 - (Inventory32 - Backlog32) - β3 * SupplyL32))
Placed33 = MAX(0, SMOOTH(Ordered32, SmoothTime3) + α3 * (12 - (Inventory33 - Backlog33) - β3 * SupplyL33))
Placed34 = MAX(0, SMOOTH(Ordered33, SmoothTime3) + α3 * (12 - (Inventory34 - Backlog34) - β3 * SupplyL34))

SAVEPER = TIME STEP
sFlow11 = Placed11 - In11
sFlow12 = Placed12 - In12
sFlow13 = Placed13 - In13
sFlow14 = Placed14 - In14
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sFlow22 = Placed22 - In22
sFlow23 = Placed23 - In23
sFlow24 = Placed24 - In24
sFlow31 = Placed31 - In31
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Sold12 = MIN(Inventory12 + In12, Order11 + Backlog12)
Sold13 = MIN(Inventory13 + In13, Order12 + Backlog13)
Sold14 = MIN(Inventory14 + In14, Order13 + Backlog14)
Sold21 = MIN(Inventory21 + In21, Order2 + Backlog21)
Sold22 = MIN(Inventory22 + In22, Order21 + Backlog22)
Sold23 = MIN(Inventory23 + In23, Order22 + Backlog23)
Sold24 = MIN(Inventory24 + In24, Order23 + Backlog24)
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Sold32 = MIN(Inventory32 + In32, Order31 + Backlog32)
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Sold34 = MIN(Inventory34 + In34, Order33 + Backlog34)
SupplyL11 = INTEG(sFlow11, 0)
SupplyL12 = INTEG(sFlow12, 0)
SupplyL13 = INTEG(sFlow13, 0)
SupplyL14 = INTEG(sFlow14, 0)
SupplyL21 = INTEG(sFlow21, 0)
SupplyL22 = INTEG(sFlow22, 0)
A3. Scenario 3: Horizontal information sharing

In the horizontal information sharing scenario, instead of sharing demand and ordering information upstream a single supply chain, information sharing is confined to downstream retailers across multiple supply chains. Here there is no information sharing between retailers and their supply chain partners in higher nodes/echelons. This is a peculiar scenario for industry, since it means competing retailers are coordinating their operations without involving other supply chain partners. However, this is the kind of scenario that is found in disaster relief humanitarian logistics, where aid agencies help one another, and their supply chains are frequently not tightly integrated.
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(027) Coming3 = Ordered34
(028) Cost1 = INTEG (CostIncrease1, 0)
(029) Cost2 = INTEG (CostIncrease2, 0)
(030) Cost3 = INTEG (CostIncrease3, 0)
(031) CostIncrease1 = 1 * (Backlog11 + Backlog12 + Backlog13 + Backlog14) + 0.5 * (Inventory11 + Inventory12 + Inventory13 + Inventory14)
(032) CostIncrease2 = 1 * (Backlog22 + Backlog23 + Backlog24 + Backlog21) + 0.5 * (Inventory22 + Inventory23 + Inventory24 + Inventory21)
(033) CostIncrease3 = 1 * (Backlog32 + Backlog33 + Backlog34 + Backlog31) + 0.5 * (Inventory32 + Inventory33 + Inventory34 + Inventory31)
(034) EffEnv11 = Inventory11 - Backlog11
(035) EffEnv12 = Inventory12 - Backlog12
(036) EffEnv13 = Inventory13 - Backlog13
(037) EffEnv14 = Inventory14 - Backlog14
(038) EffEnv21 = Inventory21 - Backlog21
(039) EffEnv22 = Inventory22 - Backlog22
(040) EffEnv23 = Inventory23 - Backlog23
(041) EffEnv24 = Inventory24 - Backlog24
(042) EffEnv31 = Inventory31 - Backlog31
(043) EffEnv32 = Inventory32 - Backlog32
(044) EffEnv33 = Inventory33 - Backlog33
(045) EffEnv34 = Inventory34 - Backlog34
(046) FINAL TIME = 100
(047) In11 = DELAY FIXED(Sold12, 2, 4)
(048) In12 = DELAY FIXED(Sold13, 2, 4)
(049) In13 = DELAY FIXED(Sold14, 2, 4)
(050) In14 = DELAY FIXED(Coming1, 2, 4)
(051) In21 = DELAY FIXED(Sold22, 2, 4)
(052) In22 = DELAY FIXED(Sold23, 2, 4)
(053) In23 = DELAY FIXED(Sold24, 2, 4)
(054) In24 = DELAY FIXED(Coming2, 2, 4)
(055) In31 = DELAY FIXED(Sold32, 2, 4)
(056) In32 = DELAY FIXED(Sold33, 2, 4)
(057) In33 = DELAY FIXED(Sold34, 2, 4)
(058) In34 = DELAY FIXED(Coming3, 2, 4)
(059) INITIAL TIME = 0
(060) Inventory11 = INTEG(In11 - Sold11, 12)
(061) Inventory12 = INTEG(In12 - Sold12, 12)
(062) Inventory13 = INTEG(In13 - Sold13, 12)
(063) Inventory14 = INTEG(In14 - Sold14, 12)
(064) Inventory21 = INTEG(In21 - Sold21, 12)
(065) Inventory22 = INTEG(In22 - Sold22, 12)
(066) Inventory23 = INTEG(In23 - Sold23, 12)
(067) Inventory24 = INTEG(In24 - Sold24, 12)
(068) Inventory31 = INTEG(In31 - Sold31, 12)
(069) Inventory32 = INTEG(In32 - Sold32, 12)
(070) Inventory33 = INTEG(In33 - Sold33, 12)
(071) Inventory34 = INTEG(In34 - Sold34, 12)
(072) Ordered11 = DELAY FIXED(Placed11, 1, 4)
(073) Ordered12 = DELAY FIXED(Placed12, 1, 4)
(074) Ordered13 = DELAY FIXED(Placed13, 1, 4)
(075) Ordered14 = DELAY FIXED(Placed14, 1, 4)
(076) Ordered21 = DELAY FIXED(Placed21, 1, 4)
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(082) Ordered33 = DELAY FIXED(Placed33, 1, 4)
(083) Ordered34 = DELAY FIXED(Placed34, 1, 4)
(084) Orders1 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)
(085) Orders2 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)
(086) Orders3 = 100 + RANDOM NORMAL(1, 50, 25, 3, 0)
(087) Placed11 = MAX(0, SMOOTH(TotalOrders, SmoothTime1) + a1 * (12 - (Inventory11 - Backlog11) - b1 * SupplyL11))
(088) Placed12 = MAX(0, SMOOTH(Ordered11, SmoothTime1) + a1 * (12 - (Inventory12 - Backlog12) - b1 * SupplyL12))
(089) Placed13 = MAX(0, SMOOTH(Ordered12, SmoothTime1) + a1 * (12 - (Inventory13 - Backlog13) - b1 * SupplyL13))
(090) Placed14 = MAX(0, SMOOTH(Ordered13, SmoothTime1) + a1 * (12 - (Inventory14 - Backlog14) - b1 * SupplyL14))
(091) Placed21 = MAX(0, SMOOTH(TotalOrders, SmoothTime2) + a2 * (12 - (Inventory21 - Backlog21) - b2 * SupplyL21))
(092) Placed22 = MAX(0, SMOOTH(Ordered21, SmoothTime2) + a2 * (12 - (Inventory22 -
Backlog22) - B2 * SupplyL22))

Placed23 = MAX(0, SMOOTH(Ordered22, SmoothTime2) + α2 * (12 - (Inventory23 - Backlog23) - B2 * SupplyL22))

Placed24 = MAX(0, SMOOTH(Ordered23, SmoothTime2) + α2 * (12 - (Inventory24 - Backlog24) - B2 * SupplyL24))

Placed31 = MAX(0, SMOOTH(TotalOrders, SmoothTime3) + α3 * (12 - (Inventory31 - Backlog31) - B3 * SupplyL31))

Placed32 = MAX(0, SMOOTH(Ordered31, SmoothTime3) + α3 * (12 - (Inventory32 - Backlog32) - B3 * SupplyL32))

Placed33 = MAX(0, SMOOTH(Ordered32, SmoothTime3) + α3 * (12 - (Inventory33 - Backlog33) - B3 * SupplyL33))

Placed34 = MAX(0, SMOOTH(Ordered33, SmoothTime3) + α3 * (12 - (Inventory34 - Backlog34) - B3 * SupplyL34))

SAVEPER = TIME STEP

sFlow11 = Placed11 - In11

sFlow12 = Placed12 - In12

sFlow13 = Placed13 - In13

sFlow14 = Placed14 - In14

sFlow21 = Placed21 - In21

sFlow22 = Placed22 - In22

sFlow23 = Placed23 - In23

sFlow24 = Placed24 - In24

sFlow31 = Placed31 - In31

sFlow32 = Placed32 - In32

sFlow33 = Placed33 - In33

sFlow34 = Placed34 - In34

SmoothTime1 = 1

SmoothTime2 = 1

SmoothTime3 = 1

Sold11 = MIN(Inventory11 + In11, Orders1 + Backlog11)

Sold12 = MIN(Inventory12 + In12, Ordered11 + Backlog12)

Sold13 = MIN(Inventory13 + In13, Ordered12 + Backlog13)

Sold14 = MIN(Inventory14 + In14, Ordered13 + Backlog14)

Sold21 = MIN(Inventory21 + In21, Orders2 + Backlog21)

Sold22 = MIN(Inventory22 + In22, Ordered21 + Backlog22)

Sold23 = MIN(Inventory23 + In23, Ordered22 + Backlog23)

Sold24 = MIN(Inventory24 + In24, Ordered23 + Backlog24)

Sold31 = MIN(Inventory31 + In31, Orders3 + Backlog31)

Sold32 = MIN(Inventory32 + In32, Ordered31 + Backlog32)

Sold33 = MIN(Inventory33 + In33, Ordered32 + Backlog33)

Sold34 = MIN(Inventory34 + In34, Ordered33 + Backlog34)

SupplyL11 = INTEG (sFlow11, 0)

SupplyL12 = INTEG (sFlow12, 0)

SupplyL13 = INTEG (sFlow13, 0)

SupplyL14 = INTEG (sFlow14, 0)

SupplyL21 = INTEG (sFlow21, 0)

SupplyL22 = INTEG (sFlow22, 0)

SupplyL23 = INTEG (sFlow23, 0)

SupplyL24 = INTEG (sFlow24, 0)

SupplyL31 = INTEG (sFlow31, 0)

SupplyL32 = INTEG (sFlow32, 0)

SupplyL33 = INTEG (sFlow33, 0)

SupplyL34 = INTEG (sFlow34, 0)

β1 = 0.33

β2 = 0.33

β3 = 0.33

TIME STEP = 1

TotalOrders = Orders1 + Orders2 + Orders3

α1 = 0.25

α2 = 0.25

α3 = 0.25
Scenario 4: Vertical and horizontal information sharing

The simultaneous vertical and horizontal information sharing scenario is simply a combination of the previous vertical information sharing scenario and horizontal information sharing scenario.

(001) $\text{Backlog}_{11} = \text{INTEG}(\text{bFlow}_{11}, 0)$
(002) $\text{Backlog}_{12} = \text{INTEG}(\text{bFlow}_{12}, 0)$
(003) $\text{Backlog}_{13} = \text{INTEG}(\text{bFlow}_{13}, 0)$
(004) $\text{Backlog}_{14} = \text{INTEG}(\text{bFlow}_{14}, 0)$
(005) $\text{Backlog}_{21} = \text{INTEG}(\text{bFlow}_{21}, 0)$
(006) $\text{Backlog}_{22} = \text{INTEG}(\text{bFlow}_{22}, 0)$
(007) $\text{Backlog}_{23} = \text{INTEG}(\text{bFlow}_{23}, 0)$
(008) $\text{Backlog}_{24} = \text{INTEG}(\text{bFlow}_{24}, 0)$
(009) $\text{Backlog}_{31} = \text{INTEG}(\text{bFlow}_{31}, 0)$
(010) $\text{Backlog}_{32} = \text{INTEG}(\text{bFlow}_{32}, 0)$
(011) $\text{Backlog}_{33} = \text{INTEG}(\text{bFlow}_{33}, 0)$
(012) $\text{Backlog}_{34} = \text{INTEG}(\text{bFlow}_{34}, 0)$
(013) $\text{bFlow}_{11} = \text{Orders}_{1} - \text{Sold}_{11}$
(014) $\text{bFlow}_{12} = \text{Ordered}_{11} - \text{Sold}_{12}$
(015) $\text{bFlow}_{13} = \text{Ordered}_{12} - \text{Sold}_{13}$
(016) $\text{bFlow}_{14} = \text{Ordered}_{13} - \text{Sold}_{14}$
(017) $\text{bFlow}_{21} = \text{Orders}_{2} - \text{Sold}_{21}$
(018) $\text{bFlow}_{22} = \text{Ordered}_{21} - \text{sold}_{22}$
(019) $\text{bFlow}_{23} = \text{Ordered}_{22} - \text{Sold}_{23}$
(020) $\text{bFlow}_{24} = \text{Ordered}_{23} - \text{Sold}_{24}$
(021) $\text{bFlow}_{31} = \text{Orders}_{3} - \text{Sold}_{31}$
(022) $\text{bFlow}_{32} = \text{Ordered}_{31} - \text{Sold}_{32}$
(023) $\text{bFlow}_{33} = \text{Ordered}_{32} - \text{Sold}_{33}$
(024) $\text{bFlow}_{34} = \text{Ordered}_{33} - \text{Sold}_{34}$
(025) $\text{Coming}_{1} = \text{Ordered}_{14}$
(026) $\text{Coming}_{2} = \text{Ordered}_{24}$
(027) $\text{Coming}_{3} = \text{Ordered}_{34}$
(028) $\text{Cost}_{1} = \text{INTEG} (\text{CostIncrease}_{1}, 0)$
(029) $\text{Cost}_{2} = \text{INTEG} (\text{CostIncrease}_{2}, 0)$
(030) $\text{Cost}_{3} = \text{INTEG} (\text{CostIncrease}_{3}, 0)$
(031) $\text{CostIncrease}_{1} = 1 * (\text{Backlog}_{11} + \text{Backlog}_{12} + \text{Backlog}_{13} + \text{Backlog}_{14}) + 0.5 * (\text{Inventory}_{11} + \text{Inventory}_{12} + \text{Inventory}_{13} + \text{Inventory}_{14})$
(032) $\text{CostIncrease}_{2} = 1 * (\text{Backlog}_{22} + \text{Backlog}_{23} + \text{Backlog}_{24} + \text{Backlog}_{21}) + 0.5 * (\text{Inventory}_{22} + \text{Inventory}_{23} + \text{Inventory}_{24} + \text{Inventory}_{21})$
(033) $\text{CostIncrease}_{3} = 1 * (\text{Backlog}_{32} + \text{Backlog}_{33} + \text{Backlog}_{34} + \text{Backlog}_{31}) + 0.5 * (\text{Inventory}_{32} + \text{Inventory}_{33} + \text{Inventory}_{34} + \text{Inventory}_{31})$
(034) $\text{EffInv}_{11} = \text{Inventory}_{11} - \text{Backlog}_{11}$
(035) $\text{EffInv}_{12} = \text{Inventory}_{12} - \text{Backlog}_{12}$
(036) $\text{EffInv}_{13} = \text{Inventory}_{13} - \text{Backlog}_{13}$
(037) $\text{EffInv}_{14} = \text{Inventory}_{14} - \text{Backlog}_{14}$
(038) $\text{EffInv}_{21} = \text{Inventory}_{21} - \text{Backlog}_{21}$
(039) $\text{EffInv}_{22} = \text{Inventory}_{22} - \text{Backlog}_{22}$
(040) $\text{EffInv}_{23} = \text{Inventory}_{23} - \text{Backlog}_{23}$
(041) $\text{EffInv}_{24} = \text{Inventory}_{24} - \text{Backlog}_{24}$
(042) $\text{EffInv}_{31} = \text{Inventory}_{31} - \text{Backlog}_{31}$
(043) $\text{EffInv}_{32} = \text{Inventory}_{32} - \text{Backlog}_{32}$
(044) $\text{EffInv}_{33} = \text{Inventory}_{33} - \text{Backlog}_{33}$
(045) $\text{EffInv}_{34} = \text{Inventory}_{34} - \text{Backlog}_{34}$
(046) $\text{FINAL TIME} = 100$
(047) $\text{In}_{11} = \text{Sold}_{12}$
(048) $\text{In}_{12} = \text{Sold}_{13}$
(049) $\text{In}_{13} = \text{Sold}_{14}$
(050) $\text{In}_{14} = \text{Coming}_{1}$
(051) $\text{In}_{21} = \text{Sold}_{22}$
(052) $\text{In}_{22} = \text{Sold}_{23}$
\( \text{In}23 = \text{Sold}24 \)
\( \text{In}24 = \text{Coming}2 \)
\( \text{In}31 = \text{Sold}32 \)
\( \text{In}32 = \text{Sold}33 \)
\( \text{In}33 = \text{Sold}34 \)
\( \text{In}34 = \text{Coming}3 \)

\( \text{INITIAL TIME} = 0 \)

\( \text{Inventory}_{11} = \text{INTEG}(\text{In}_{11} - \text{Sold}_{11}, 12) \)
\( \text{Inventory}_{12} = \text{INTEG}(\text{In}_{12} - \text{Sold}_{12}, 12) \)
\( \text{Inventory}_{13} = \text{INTEG}(\text{In}_{13} - \text{Sold}_{13}, 12) \)
\( \text{Inventory}_{14} = \text{INTEG}(\text{In}_{14} - \text{Sold}_{14}, 12) \)
\( \text{Inventory}_{21} = \text{INTEG}(\text{In}_{21} - \text{Sold}_{21}, 12) \)
\( \text{Inventory}_{22} = \text{INTEG}(\text{In}_{22} - \text{Sold}_{22}, 12) \)
\( \text{Inventory}_{23} = \text{INTEG}(\text{In}_{23} - \text{Sold}_{23}, 12) \)
\( \text{Inventory}_{24} = \text{INTEG}(\text{In}_{24} - \text{Sold}_{24}, 12) \)
\( \text{Inventory}_{31} = \text{INTEG}(\text{In}_{31} - \text{Sold}_{31}, 12) \)
\( \text{Inventory}_{32} = \text{INTEG}(\text{In}_{32} - \text{Sold}_{32}, 12) \)
\( \text{Inventory}_{33} = \text{INTEG}(\text{In}_{33} - \text{Sold}_{33}, 12) \)
\( \text{Inventory}_{34} = \text{INTEG}(\text{In}_{34} - \text{Sold}_{34}, 12) \)

\( \text{Ordered}_{11} = \text{Placed}_{11} \)
\( \text{Ordered}_{12} = \text{Placed}_{12} \)
\( \text{Ordered}_{13} = \text{Placed}_{13} \)
\( \text{Ordered}_{14} = \text{Placed}_{14} \)
\( \text{Ordered}_{21} = \text{Placed}_{21} \)
\( \text{Ordered}_{22} = \text{Placed}_{22} \)
\( \text{Ordered}_{23} = \text{Placed}_{23} \)
\( \text{Ordered}_{24} = \text{Placed}_{24} \)
\( \text{Ordered}_{31} = \text{Placed}_{31} \)
\( \text{Ordered}_{32} = \text{Placed}_{32} \)
\( \text{Ordered}_{33} = \text{Placed}_{33} \)
\( \text{Ordered}_{34} = \text{Placed}_{34} \)

\( \text{Orders}_{1} = 100 + \text{RANDOM NORMAL}(1, 50, 25, 3, 0) \)
\( \text{Orders}_{2} = 100 + \text{RANDOM NORMAL}(1, 50, 25, 3, 0) \)
\( \text{Orders}_{3} = 100 + \text{RANDOM NORMAL}(1, 50, 25, 3, 0) \)

\( \text{Placed}_{11} = \text{MAX}(0, \text{SMOOTH}(\text{TotalOrders}, \text{SmoothTime}1) + a1 \times (12 - (\text{Inventory}_{11} - \text{Backlog}_{11}) - b1 \times \text{SupplyL}_{11})) \)
\( \text{Placed}_{12} = \text{MAX}(0, \text{SMOOTH}(\text{Ordered}_{11}, \text{SmoothTime}1) + a1 \times (12 - (\text{Inventory}_{12} - \text{Backlog}_{12}) - b1 \times \text{SupplyL}_{12})) \)
\( \text{Placed}_{13} = \text{MAX}(0, \text{SMOOTH}(\text{Ordered}_{12}, \text{SmoothTime}1) + a1 \times (12 - (\text{Inventory}_{13} - \text{Backlog}_{13}) - b1 \times \text{SupplyL}_{13})) \)
\( \text{Placed}_{14} = \text{MAX}(0, \text{SMOOTH}(\text{Ordered}_{13}, \text{SmoothTime}1) + a1 \times (12 - (\text{Inventory}_{14} - \text{Backlog}_{14}) - b1 \times \text{SupplyL}_{14})) \)
\( \text{Placed}_{21} = \text{MAX}(0, \text{SMOOTH}(\text{TotalOrders}, \text{SmoothTime}2) + a2 \times (12 - (\text{Inventory}_{21} - \text{Backlog}_{21}) - b2 \times \text{SupplyL}_{21})) \)
\( \text{Placed}_{22} = \text{MAX}(0, \text{SMOOTH}(\text{Ordered}_{21}, \text{SmoothTime}2) + a2 \times (12 - (\text{Inventory}_{22} - \text{Backlog}_{22}) - b2 \times \text{SupplyL}_{22})) \)
\( \text{Placed}_{23} = \text{MAX}(0, \text{SMOOTH}(\text{Ordered}_{22}, \text{SmoothTime}2) + a2 \times (12 - (\text{Inventory}_{23} - \text{Backlog}_{23}) - b2 \times \text{SupplyL}_{23})) \)
\( \text{Placed}_{24} = \text{MAX}(0, \text{SMOOTH}(\text{Ordered}_{23}, \text{SmoothTime}2) + a2 \times (12 - (\text{Inventory}_{24} - \text{Backlog}_{24}) - b2 \times \text{SupplyL}_{24})) \)
\( \text{Placed}_{31} = \text{MAX}(0, \text{SMOOTH}(\text{TotalOrders}, \text{SmoothTime}3) + a3 \times (12 - (\text{Inventory}_{31} - \text{Backlog}_{31}) - b3 \times \text{SupplyL}_{31})) \)
\( \text{Placed}_{32} = \text{MAX}(0, \text{SMOOTH}(\text{Ordered}_{31}, \text{SmoothTime}3) + a3 \times (12 - (\text{Inventory}_{32} - \text{Backlog}_{32}) - b3 \times \text{SupplyL}_{32})) \)
\( \text{Placed}_{33} = \text{MAX}(0, \text{SMOOTH}(\text{Ordered}_{32}, \text{SmoothTime}3) + a3 \times (12 - (\text{Inventory}_{33} - \text{Backlog}_{33}) - b3 \times \text{SupplyL}_{33})) \)
\( \text{Placed}_{34} = \text{MAX}(0, \text{SMOOTH}(\text{Ordered}_{33}, \text{SmoothTime}3) + a3 \times (12 - (\text{Inventory}_{34} - \text{Backlog}_{34}) - b3 \times \text{SupplyL}_{34})) \)

\( \text{SAVEPER} = \text{TIME STEP} \)
\( \text{sFlow}_{11} = \text{Placed}_{11} - \text{In}_{11} \)
\( \text{sFlow}_{12} = \text{Placed}_{12} - \text{In}_{12} \)
\( \text{sFlow}_{13} = \text{Placed}_{13} - \text{In}_{13} \)
\( \text{sFlow}_{14} = \text{Placed}_{14} - \text{In}_{14} \)
\( \text{sFlow}_{21} = \text{Placed}_{21} - \text{In}_{21} \)
\( \text{Sflow}_{22} = \text{Placed}_{22} - \text{In}_{22} \)
\( \text{Sflow}_{23} = \text{Placed}_{23} - \text{In}_{23} \)
\( \text{Sflow}_{24} = \text{Placed}_{24} - \text{In}_{24} \)
\( \text{Sflow}_{31} = \text{Placed}_{31} - \text{In}_{31} \)
\( \text{Sflow}_{32} = \text{Placed}_{32} - \text{In}_{32} \)
\( \text{Sflow}_{33} = \text{Placed}_{33} - \text{In}_{33} \)
\( \text{Sflow}_{34} = \text{Placed}_{34} - \text{In}_{34} \)

\( \text{SmoothTime}_{1} = 1 \)
\( \text{SmoothTime}_{2} = 1 \)
\( \text{SmoothTime}_{3} = 1 \)

\( \text{Sold}_{11} = \text{MIN}(\text{Inventory}_{11} + \text{In}_{11}, \text{Orders}_{1} + \text{Backlog}_{11}) \)
\( \text{Sold12} = \text{MIN}(\text{Inventory12} + \text{In12}, \text{Ordered11} + \text{Backlog12}) \)
\( \text{Sold13} = \text{MIN}(\text{Inventory13} + \text{In13}, \text{Ordered12} + \text{Backlog13}) \)
\( \text{Sold14} = \text{MIN}(\text{Inventory14} + \text{In14}, \text{Ordered13} + \text{Backlog14}) \)
\( \text{Sold21} = \text{MIN}(\text{Inventory21} + \text{In21}, \text{Orders2} + \text{Backlog21}) \)
\( \text{Sold22} = \text{MIN}(\text{Inventory22} + \text{In22}, \text{Ordered21} + \text{Backlog22}) \)
\( \text{Sold23} = \text{MIN}(\text{Inventory23} + \text{In23}, \text{Ordered22} + \text{Backlog23}) \)
\( \text{Sold24} = \text{MIN}(\text{Inventory24} + \text{In24}, \text{Ordered23} + \text{Backlog24}) \)
\( \text{Sold31} = \text{MIN}(\text{Inventory31} + \text{In31}, \text{Orders3} + \text{Backlog31}) \)
\( \text{Sold32} = \text{MIN}(\text{Inventory32} + \text{In32}, \text{Ordered31} + \text{Backlog32}) \)
\( \text{Sold33} = \text{MIN}(\text{Inventory33} + \text{In33}, \text{Ordered32} + \text{Backlog33}) \)
\( \text{Sold34} = \text{MIN}(\text{Inventory34} + \text{In34}, \text{Ordered33} + \text{Backlog34}) \)
\( \text{SupplyL11} = \text{INTEG}(\text{sFlow11}, 0) \)
\( \text{SupplyL12} = \text{INTEG}(\text{sFlow12}, 0) \)
\( \text{SupplyL13} = \text{INTEG}(\text{sFlow13}, 0) \)
\( \text{SupplyL14} = \text{INTEG}(\text{sFlow14}, 0) \)
\( \text{SupplyL21} = \text{INTEG}(\text{sFlow21}, 0) \)
\( \text{SupplyL22} = \text{INTEG}(\text{sFlow22}, 0) \)
\( \text{SupplyL23} = \text{INTEG}(\text{sFlow23}, 0) \)
\( \text{SupplyL24} = \text{INTEG}(\text{sFlow24}, 0) \)
\( \text{SupplyL31} = \text{INTEG}(\text{sFlow31}, 0) \)
\( \text{SupplyL32} = \text{INTEG}(\text{sFlow32}, 0) \)
\( \text{SupplyL33} = \text{INTEG}(\text{sFlow33}, 0) \)
\( \text{SupplyL34} = \text{INTEG}(\text{sFlow34}, 0) \)
\( \beta_1 = 0.33 \)
\( \beta_2 = 0.33 \)
\( \beta_3 = 0.33 \)
\( \text{TIME STEP} = 1 \)
\( \text{TotalOrders} = \text{Orders1} + \text{Orders2} + \text{Orders3} \)
\( \alpha_1 = 0.25 \)
\( \alpha_2 = 0.25 \)
\( \alpha_3 = 0.25 \)
Appendix B: Technical annex

Disclaimer:
The primary contribution of this thesis is to develop a framework to enable lateral information sharing as a new information sharing approach. This thesis does not involve developing a fully instantiated prototype that is ready for field deployment. Parts of the practical artefact described in the System architecture chapter (pp. 141-154) have been instantiated, and the electronics assembly, source code, and operating instructions are included below ‘for your information’ only. This is intended to be useful for researchers and programmers replicating the existing prototype and for designing their own implementations of the system architecture. To develop a fully working prototype ready for field deployment and implement it in a disaster relief operation as a case study would be the culmination of a career’s work, involving many co-researchers, rather than being the start of a research career, which is what a doctorate represents. This is not a thesis for a doctorate in information systems, software engineering, or electronics engineering.

B1. Overview of telecommunications networks

Telecommunications used in disaster relief are often called “disaster communications” in the humanitarian sector. For the last three decades, purportedly novel wireless disaster communications networks have emerged from academia and the private sector, but these have not been widely adopted by aid agencies. These solutions tend to be experimental, theoretical, or implemented but not yet widely utilised. These disaster communications solutions tend to be published most frequently in conference proceedings and patents, although they are also seen infrequently in academic journal and trade magazine articles.

The information systems solutions will be limited only by the underlying means of information transmission, so it is important to identify the capabilities and structure of disaster communications networks. Disaster communications can be categorised by
common taxonomies of wireless communications standards and network capabilities. These taxonomies are combined into a single taxonomy in Table B.1 (p. 242) below, allowing easy cross-comparison of network capabilities.

<table>
<thead>
<tr>
<th>Network Characteristics</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>ITU, 2005; Horak, 2007</td>
</tr>
<tr>
<td>Frequency, Protocol, or Standard</td>
<td>Cheekiralla, 2005; ITU, 2005; Liu et al., 2008</td>
</tr>
<tr>
<td>Data Rate</td>
<td>ITU, 2005; Horak, 2007; Mac Ruairí et al., 2008; Pereira, 2011</td>
</tr>
<tr>
<td>Response Time</td>
<td>ITU, 2005; Horak, 2007; Mac Ruairí et al., 2008</td>
</tr>
<tr>
<td>Topology</td>
<td>ITU, 2005; Mac Ruairí et al., 2008; Anjum et al., 2015</td>
</tr>
<tr>
<td>Infrastructure Requirements</td>
<td>ITU, 2005; Anjum et al., 2015</td>
</tr>
<tr>
<td>Mobility of Setup</td>
<td>ITU, 2005; Horak, 2007; Mac Ruairí et al., 2008</td>
</tr>
<tr>
<td>Mobility of Nodes</td>
<td>Pereira, 2011</td>
</tr>
<tr>
<td>Power Profile</td>
<td>Cheekiralla, 2005; ITU, 2005; Liu et al., 2008</td>
</tr>
<tr>
<td>Reliability</td>
<td>ITU, 2005; Mac Ruairí et al., 2008; Pereira, 2011</td>
</tr>
<tr>
<td>Scalability</td>
<td>Anjum et al., 2015</td>
</tr>
<tr>
<td>Interoperability</td>
<td>ITU, 2005</td>
</tr>
<tr>
<td>Maintainability</td>
<td>ITU, 2005</td>
</tr>
<tr>
<td>Cost</td>
<td>Cheekiralla, 2005; Horak, 2007; Liu et al., 2008</td>
</tr>
</tbody>
</table>

Table B.1: Taxonomy of telecommunications network characteristics

Existing disaster communications technologies are compared in the tables below, listing their capabilities across their main performance dimensions and network characteristics. Existing solutions are usually rapidly deployed versions of conventional wireless telecommunications or are low power or short range wireless networks using different wireless communications standards. Rapidly deployable versions of traditional telecommunications and traditional radio networks are the most widely used, because of the widespread availability of compatible user devices (e.g. mobile phones in Sheller, 2012, p.13), robust reliability in a volatile and resource-constrained environment (e.g. walkie-talkie), and/or their high data capacity. Additionally, many alternative networks come with serious limitations, such as low data rates and/or requiring users to maintain complex networks (ITU, 2005, p.70).
Established technologies for wireless disaster communications are largely covered in the International Telecommunication Union’s (2005) *Handbook on Emergency Communications*. Briefly, these will be summarised here using the previous works’ taxonomy (ITU, 2005). Public communication networks include cellular networks (e.g. GSM) and satellite phones. The internet includes Wi-Fi (i.e. using radio waves) and WiMAX (i.e. using microwaves). Private networks include land mobile radio and the maritime radio service. Amateur radio is categorised by range rather than by technologies used into short, medium, and long-range. Huang & Lien, (2012, p. 4) identify the key performance attributes for any disaster communications system and compare established telecommunications technologies. These telecommunications technologies only facilitate information sharing, but they lack any inherent ability to direct how information is shared.
Table B.2: Comparison of telecommunications networks used in disaster relief (Part 1)
(Huang & Lien, 2012, p. 4)

<table>
<thead>
<tr>
<th>Communications Network</th>
<th>Practicability</th>
<th>Popularity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost</td>
<td>Construction</td>
</tr>
<tr>
<td>Walkie-Talkie</td>
<td>Low</td>
<td>No Need</td>
</tr>
<tr>
<td>Amateur Radio</td>
<td>Middle</td>
<td>Need Professionals</td>
</tr>
<tr>
<td>Satellite</td>
<td>Extremely High</td>
<td>Existing System</td>
</tr>
<tr>
<td>Trunking Radio</td>
<td>High (few devices)</td>
<td>Easy</td>
</tr>
<tr>
<td>Cell on Wheels</td>
<td>High (few devices)</td>
<td>Easy</td>
</tr>
<tr>
<td>MANET</td>
<td>Low</td>
<td>Need Professionals</td>
</tr>
<tr>
<td>BSNET</td>
<td>High</td>
<td>Need Professionals</td>
</tr>
<tr>
<td>Hybrid Mesh</td>
<td>High</td>
<td>Need Professionals</td>
</tr>
</tbody>
</table>

Table B.3: Comparison of telecommunications networks used in disaster relief (Part 2)
(Huang & Lien, 2012, p. 4)

<table>
<thead>
<tr>
<th>Communications Network</th>
<th>Usability</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mobility</td>
<td>Quality</td>
</tr>
<tr>
<td>Walkie-Talkie</td>
<td>High</td>
<td>Middle</td>
</tr>
<tr>
<td>Amateur Radio</td>
<td>Low</td>
<td>Middle</td>
</tr>
<tr>
<td>Satellite</td>
<td>High</td>
<td>Middle</td>
</tr>
<tr>
<td>Trunking Radio</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cell on Wheels</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>MANET</td>
<td>Middle</td>
<td>Low</td>
</tr>
<tr>
<td>BSNET</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Hybrid Mesh</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Technical Capabilities</td>
<td>LoRaWAN</td>
<td>Neul</td>
</tr>
<tr>
<td>------------------------</td>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>Range (km/m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 km</td>
<td>10 km</td>
</tr>
<tr>
<td></td>
<td>Urban; 15 km Suburban; 45 km Rural</td>
<td></td>
</tr>
<tr>
<td>Deep Indoor Performance</td>
<td>Yes</td>
<td>ISM</td>
</tr>
<tr>
<td>Frequency Band</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Varies, Sub-GHz</td>
<td>Yes</td>
</tr>
<tr>
<td>ISM</td>
<td>Yes</td>
<td>ISM</td>
</tr>
<tr>
<td>Fully Bi-Directional</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes, Depends</td>
<td>ISM</td>
</tr>
<tr>
<td>Data Rate</td>
<td>0.3-50 KBps Adaptive</td>
<td>Low</td>
</tr>
<tr>
<td>Power Profile</td>
<td>Low</td>
<td>100 Bps</td>
</tr>
<tr>
<td>Authentication</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>End-to-End Encryption</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Over the Air Software Upgrades</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Supports Moving Sensors</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Location Aware</td>
<td>Yes</td>
<td>—</td>
</tr>
<tr>
<td>Operational Model</td>
<td>Public or Private</td>
<td>—</td>
</tr>
<tr>
<td>Standard</td>
<td>LoRaWAN</td>
<td>Weightless</td>
</tr>
<tr>
<td>Scalability</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table B.4: Comparison of low power telecommunications networks

(OpenSensors, n.d.)
<table>
<thead>
<tr>
<th>Technical Capabilities</th>
<th>BLE</th>
<th>Wi-Fi</th>
<th>Thread</th>
<th>ZigBee</th>
<th>Z-Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (km/m)</td>
<td>80 m</td>
<td>50 m</td>
<td>Mesh</td>
<td>100 m/Mesh</td>
<td>30 m/Mesh</td>
</tr>
<tr>
<td>Deep Indoor Performance</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>ISM</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Fully Bi-Directional</td>
<td>Yes</td>
<td>Yes</td>
<td>—</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Data Rate</td>
<td>&lt; 1 Mbps</td>
<td>600 Mbps max.</td>
<td>—</td>
<td>250 KBps</td>
<td>10-100 KBps</td>
</tr>
<tr>
<td>Power Profile</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Authentication</td>
<td>Trusted Devices Problematic</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>End-to-End Encryption</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Over the Air Software Upgrades</td>
<td>Yes</td>
<td>Yes</td>
<td>—</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Supports Moving Sensors</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes, Mesh Based</td>
<td>Yes, Mesh Based</td>
</tr>
<tr>
<td>Location Aware</td>
<td>No</td>
<td>Yes</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Operational Model</td>
<td>No</td>
<td>Yes</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Standard</td>
<td>Bluetooth 4.0</td>
<td>IEEE 802.11</td>
<td>Thread Based on 6LoWPAN IEEE 802.11</td>
<td>ZigBee</td>
<td>Z-Wave</td>
</tr>
<tr>
<td>Scalability</td>
<td>Yes</td>
<td>—</td>
<td>Yes</td>
<td>Yes</td>
<td>Limited</td>
</tr>
</tbody>
</table>

Table B.5: Comparison of short-range telecommunications networks

(OpenSensors, n.d.)

In addition to established disaster communications networks, there are emerging network technologies that show some promise. To search for emerging disaster communications solutions, the search terms “disaster communications”, “emergency communications”, and “rapidly deployable communications” were entered in Google Scholar and Google, including various synonyms and combinations, to look for academic references, patents, and private companies with existing deployable prototypes. After a cursory examination of each search result, it appeared that approximately 500 search results were relevant. To be considered relevant, the search had to propose or detail a physical wireless communications device and/or a software application utilising a wireless communications device for the use of disaster communications. In other words, the search is for full-fledged telecommunications systems, which excludes inventions such as
emergency alerts. Upon manually examining the abstracts of those 500 results, many redundant and fantastical solutions with no prototypes were pruned, and the relevant results were narrowed down to around 40 entries. The results were not examined for verification of novelty or originality. For contemporaneity, the search is limited to the last 20 years.

The characteristics of emerging disaster communications are categorised by the previous taxonomy. To avoid confusion with the rest of the citations used in this thesis, the references for search findings are included in a separate section in the Bibliography and are categorised by type of document. In many of the solutions, such as with most of the patents and a few of the conference proceedings, a highly generic systems architecture (e.g. Klein, 2008) is proposed without any real details as to how it can be implemented, and they do not provide any practical artefacts, indicating that the solution is purely hypothetical.

The use of wireless sensor networks (WSN), mobile ad hoc networks (MANET), satellite technology, flexible two-way radio networks, and air-delivered network nodes for disaster communications are clearly not new concepts, though they are novel in that they have not seen widespread deployment. The primary outstanding issues with existing novel solutions are: (1) Reliability, (2) Scalability, (3) Interoperability, (4) Maintainability and (5) Cost. While each solution provides optimal performance on some of the network characteristics, no solution provides a comprehensive answer. It is impossible for any single network to deliver maximum performance across all dimensions, and individual solutions only contribute to the overall mix of disaster communications to complement each other’s strengths and weaknesses, instead of becoming a monolithic universal standard. Due to the lack of interoperability between anything but Wi-Fi, outside of a permissive, stable environment, it is currently impossible to connect these networks together to provide a comprehensive solution without creating new middleware. Wi-Fi has a short transmission
range and high power consumption, but an incredibly high data rate, which makes it more suitable for business and consumer applications than for disaster communications.

<table>
<thead>
<tr>
<th>Themes</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ad Hoc Networks</td>
<td>Di Felice et al., 2013; Durresi et al., 2007; Illand &amp; Belding, 2014; Kanchanasut et al., 2007; Knopp et al., 2004; Malan, 2004; Park et al., 2010; Shao et al., 2011; Souryal et al., 2009; Wang et al., 2008</td>
</tr>
<tr>
<td>Quick-to-Deploy Versions of Traditional Telecommunications</td>
<td>Bai et al., 2010; Bostian et al., 2004; Bupe, 2015; Dervin et al., 2009; Jalihal et al., 2012; Klein, 2008; Mathur, 2005; Midkiff &amp; Bostian, 2002; Okada et al., 2012; Reynaud &amp; Rasheed, 2012; Sánchez, et al., 1998; Sun &amp; Chowdhury, 2014; Tachwali et al., 2010</td>
</tr>
<tr>
<td>Optimising Traditional Telecommunications</td>
<td>Aiache et al., 2009; Bing-Lin, 2009; Deaton, 2008; Elliott et al., 2006; He et al., 2010; Jang et al., 2009; Lien et al., 2010; Madey et al., 2007; Manic et al., 2014; Meissner et al., 2002; Muehleisen &amp; Muehleisen, 2005; Salahshour et al., 2008; Wang et al., 2007</td>
</tr>
<tr>
<td>Other</td>
<td>Jenkins, 2008 (physical communication device); Kedar &amp; Arnon, 2004 (optical wireless); O’Connor &amp; Ayoub, 2007 (remote access individuals’ phones); Truesdale &amp; McDermott, 2005 (tracking using cellular); Yang &amp; Deng, 2011 (internet of things)</td>
</tr>
</tbody>
</table>

Table B.6: Characteristics of telecommunications networks used in disaster relief (Part 1)
<table>
<thead>
<tr>
<th>Network Characteristics</th>
<th>Ad Hoc Networks</th>
<th>Quick-to-Deploy Versions of Traditional Telecommunications</th>
<th>Optimising Traditional Telecommunications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>Limited by Number of Devices</td>
<td>Moderate to Extensive</td>
<td>Extensive</td>
</tr>
<tr>
<td>Standard</td>
<td>Wi-Fi, Cellular, ZigBee</td>
<td>Various</td>
<td>Various</td>
</tr>
<tr>
<td>Data Rate</td>
<td>Low (e.g. ZigBee) to High (e.g. Wi-Fi)</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Response Time</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Topology</td>
<td>Star or Mesh</td>
<td>Star or Point-to-Point</td>
<td>Star or Point-to-Point</td>
</tr>
<tr>
<td>Infrastructure Requirements</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Mobility of Setup</td>
<td>Very High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Mobility of Nodes</td>
<td>None to High</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Power Profile</td>
<td>Low (e.g. GSM, ZigBee) to High (e.g. Wi-Fi)</td>
<td>Moderate (e.g. Two-Way Radio) to High (e.g. Wi-Fi)</td>
<td>Moderate (e.g. Two-Way Radio) to High (e.g. Wi-Fi)</td>
</tr>
<tr>
<td>Reliability (in a Disaster)</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Scalability</td>
<td>Very High</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Interoperability</td>
<td>Low to None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Maintainability</td>
<td>Low Maintenance</td>
<td>High Maintenance</td>
<td>Very High Maintenance</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Very High to High</td>
<td>Very High</td>
</tr>
<tr>
<td>Security and Privacy</td>
<td>Encryption and Authentication Possible</td>
<td>Encryption and Authentication Possible</td>
<td>Encryption and Authentication Possible</td>
</tr>
</tbody>
</table>

Table B.7: Characteristics of telecommunications networks used in disaster relief (Part 2)

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>Transmission Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (&lt; 1 Mbps)</td>
<td>LoraWAN, Neul, Nwave, Open Garden, SigFox, Weightless-N, Weightless-P, ZigBee</td>
</tr>
<tr>
<td>Moderate (1-5 Mbps)</td>
<td>BLE, Thread, ZigBee, Z-Wave</td>
</tr>
<tr>
<td>High (&gt; 5 Mbps)</td>
<td>Wi-Fi</td>
</tr>
</tbody>
</table>

Note: Classification in this table only uses the most common configuration of each technology, but range can often be extended through various means.

Table B.8: Wireless telecommunications technologies by speed and range

Beyond the search criteria above, an effort was made to find novel emerging disaster communications systems and computer applications for information visibility from industry and humanitarian logisticians. Open Garden (n.d.) is a mesh network built on
mobile phones, which saw widespread use during the 2014 Hong Kong protest movement Occupy Central. The most promising telecommunications solutions are Sonnet (n.d.), GOTOKY (n.d.), and goTenna (n.d.). These solutions come from their respective start-up companies. All three solutions are highly similar ad hoc mesh networks, designed with a low power consumption profile and long range. However, these networks are not autonomous and require manual configuration to connect to one another, and they are not interoperable outside of Wi-Fi. It remains to be seen whether any of these novel solutions from the private sector are widely adopted for disaster communications.

B2. Software dependencies

The practical artefact described in the System architecture chapter (pp. 141-154) has various dependencies, which must be setup in a very strict sequential process. Some legacy versions of software dependencies are required, because newer versions remove components that are dependencies for other dependencies.

B2.1. Overview of the solution

The instantiation of the system architecture can be viewed as a solution stack in Figure 9.1 (p. 251) below, showing the hierarchy of dependencies for each component; higher level components are built on top of lower level components. Note that since we are only interested in the networking capabilities of the mesh rather than field deployment, the antennae chosen was the smallest and had the lowest range to test broken and non-responding nodes by simply moving the nodes out of range of one another, or by placing a tin can on top to act as a faraday cage to block the signal. The hardware stack consists of just two components. An XBee Series 2 Shield 2mW Wire Antenna shown in Figure 6.3 (p. 147) above, which is mounted on a Grove XBee Carrier Board shown in Figure 6.4 (p. 148)
above. The XBee Shield provides the telecommunications capabilities and antenna, while either carrier board contains the internal logic required to operate the telecommunications and interface with other programs. Each of these three electronics chips are shown in the photos below.

![Diagram of solution stack](image)

**Figure 9.1: Solution stack**

### B2.2. Software dependencies

To enable disparate elements to communicate with each other, the following dependencies in Table B.9 (p. 253) below must be met. It is critically important that dependencies are be
installed in the specific sequence in Table B.10 (p. 254) below, because while these are the overall dependencies for the system, individual dependencies have their own dependencies during installation. Unless specified, all software applications are running on either Windows 7 or Windows 8.1 operating systems.

Visual C++ redistributable is a dependency of some of the main components in the practical artefact. The Python 2.7 programming language is used as the middleware programming for connecting the ZigBee messages, the MQTT message broker Mosquitto, MySQL database, and Nginx web interface. Bottle is a web framework for Python. MySQL-Python enables MySQL to be operated through a Python interface for programming purposes. PySerial provides a serial port and serves as a back-end access point for Windows and Linux operating systems.

Visual C++ Runtime for Python is a compiler for the programming language C++ to convert Python code into executable C++ code. The FTDI Windows Drivers and Visual C++ Runtime file “VCRunTime140.dll” and necessary dependencies for the XBee implementation of ZigBee. XBee python package contains all the programming required to operate the ZigBee nodes, while XCTU is the configuration application for changing the ZigBee nodes’ firmware.

Eclipse Paho is an implementation of Message Queueing Telemetry Transport (MQTT), a standard for transmitting and handling messages, while Mosquitto is the message broker application that utilises Eclipse Paho to manage message queues. MySQL is a relational database for storing messaging data and metadata for the analytics module. MySQL-Python provides a Python interface to operating MySQL, so middleware can be programmed using Python and it will be able to interface with the MySQL database. SQLyog Community is a user interface for the MySQL database.
OpenSSL is an implementation for the Transport Layer Security (TLS) and Secure Sockets Layer (SSL) protocols for transmitting data securely over a network, whereby it is encrypted to scramble the contents to everyone but the intended recipient with the decryption key, authenticated to verify where it came from, and checked for file integrity to see if there are missing parts of the file. Although readers can implement their own web interface, the author has chosen to use Nginx as the server, PageKite to connect the local computer to the internet server, and PuTTY as the means to remotely connect to the central computer serving as the Coordinator node in the ZigBee mesh.

<table>
<thead>
<tr>
<th>Main Components</th>
<th>Software Dependencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Python 2.7 (Windows)</td>
<td>2. Bottle (v0.13)</td>
</tr>
<tr>
<td></td>
<td>3. MySQL-Python (v1.2.5)</td>
</tr>
<tr>
<td></td>
<td>4. PySerial (v3.4)</td>
</tr>
<tr>
<td></td>
<td>5. Python (v2.7.12)</td>
</tr>
<tr>
<td></td>
<td>6. Visual C++ Runtime (v9.0) for Python</td>
</tr>
<tr>
<td>ZigBee/XBee</td>
<td>7. FTDI CDM Windows Drivers (v2.12.28.2)</td>
</tr>
<tr>
<td></td>
<td>8. Visual C++ Runtime VCRuntime140.dll</td>
</tr>
<tr>
<td></td>
<td>9. XBee Python Package (v2.3.1)</td>
</tr>
<tr>
<td></td>
<td>10. XCTU (v6.3.10)</td>
</tr>
<tr>
<td>MQTT</td>
<td>11. Eclipse Paho (v1.3.0)</td>
</tr>
<tr>
<td></td>
<td>12. Mosquitto (v1.4.14)</td>
</tr>
<tr>
<td></td>
<td>13. OpenSSL (v1.0.2)</td>
</tr>
<tr>
<td>MySQL</td>
<td>14. MySQL (v5.7.20)</td>
</tr>
<tr>
<td></td>
<td>15. MySQL-Python (v1.2.5)</td>
</tr>
<tr>
<td></td>
<td>16. SQLite (v3.21.0)</td>
</tr>
<tr>
<td></td>
<td>17. SQLyog Community (v12.5)</td>
</tr>
<tr>
<td>Web Interface</td>
<td>18. NGINX (v1.12.2)</td>
</tr>
<tr>
<td></td>
<td>19. PageKite (v0.5.9)</td>
</tr>
<tr>
<td></td>
<td>20. PuTTY (v0.7.0)</td>
</tr>
</tbody>
</table>

Table B.9: Summary of software dependencies

B2.3. Software installation guide

The software must be installed in the following sequence. (Warning: Do not skip any of these steps, or the practical artefact will not function.) Pip (9.0.1) should be used for the installation of Python packages (e.g. XBee Python Package, Bottle, PySerial). The practical
artefact is only designed to work with these specific versions of software applications and there is no guarantee that anything will work with newer versions (e.g. Python 3 and anything other than OpenSSL 1.0.2 are unsupported by XBee) (Exception: For packages installed using Pip, always use the latest version). Nginx is a paid software-as-a-service server solution and does not need to be installed.

<table>
<thead>
<tr>
<th>Install Sequence</th>
<th>Download Website</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. FTDI CDM Windows Drivers (v2.12.28.2)</td>
<td><a href="http://www.ftdichip.com/Drivers/CDM/CDM21228_Setup.zip">http://www.ftdichip.com/Drivers/CDM/CDM21228_Setup.zip</a></td>
</tr>
<tr>
<td>4. OpenSSL Light (v1.0.2)</td>
<td><a href="http://slproweb.com/download/Win32OpenSSL_Light-1_0_2m.exe">http://slproweb.com/download/Win32OpenSSL_Light-1_0_2m.exe</a></td>
</tr>
<tr>
<td>7. Visual C++ Runtime (9.0) for Python</td>
<td><a href="http://aka.ms/vcpython27">http://aka.ms/vcpython27</a></td>
</tr>
<tr>
<td>10. Bottle (v0.13)</td>
<td>Use Pip to install with the following command: pip install bottle</td>
</tr>
<tr>
<td>11. PySerial (v3.4)</td>
<td>Use Pip to install with the following command: pip install pyserial</td>
</tr>
<tr>
<td>12. XBee Python Package (v2.3.1)</td>
<td>Use Pip to install with the following command: pip install xbee</td>
</tr>
<tr>
<td>13. Eclipse Paho (v1.3.0)</td>
<td>Use Pip to install with the following command: pip install paho-mqtt</td>
</tr>
<tr>
<td>14. MySQL-Python (v1.2.5)</td>
<td><a href="https://www.fld.ucd.ie/~gohlke/pythonlibs/#mysql-python">https://www.fld.ucd.ie/~gohlke/pythonlibs/#mysql-python</a></td>
</tr>
<tr>
<td>15. MySQL (v5.7.20)</td>
<td><a href="https://dev.mysql.com/downloads/windows/installer/5.7.html">https://dev.mysql.com/downloads/windows/installer/5.7.html</a></td>
</tr>
<tr>
<td>16. SQLite (v3.21.0)</td>
<td><a href="https://sqlite.org/download.html">https://sqlite.org/download.html</a></td>
</tr>
<tr>
<td>18. PageKite (v0.5.9)</td>
<td><a href="https://pagekite.net/pk/pagekite.py">https://pagekite.net/pk/pagekite.py</a></td>
</tr>
<tr>
<td>19. PuTTY (v0.7.0)</td>
<td><a href="https://www.chiark.greenend.org.uk/~sgtatham/putty/latest.html">https://www.chiark.greenend.org.uk/~sgtatham/putty/latest.html</a></td>
</tr>
</tbody>
</table>

Table B.10: Installation sequence for software dependencies

B3. Hardware assembly

XBee is Digi’s implementation of the open source standard for ZigBee. XBee devices and add-on components are designed around shields, which snap certain pins into compatible sockets like children’s toy LEGO blocks. The XBee Shield is designed to be used with
certain carrier boards. Insert the XBee Shield’s pins into either the Grove XBee Carrier Board’s or SparkFun Explorer Carrier Board’s sockets. Make sure the XBee Shield is oriented the correct way up with the carrier board. (Note: There should be a white outline on the carrier board indicating which way the narrow end of the XBee should be facing.) It is obvious which pins fit into which sockets, since the electronic boards are designed so they can only fit together from one direction.

B3.1. Instructions for manually reset

If any intractable difficulties are encountered, such as erratic performance or the device becoming non-responsive, the device can be reset by using a piece of electrical wire or a jumper wire, with one end placed into the reset pinhole tagged “RST” or “RESET”, and the other end of the wire into the ground pinhole tagged “GND”. (Warning: Do not mistake the “RES” pinhole for the “RST” pinhole—they are not the same.) After leaving both ends of the wire in those pinholes for 2 seconds, remove the wire. What has happened is that the circuit has been completed and an electrical current has been established between the two pinholes, triggering the reset. The device will now reset. (Warning: Do not insert the electrical wire into other pinholes by mistake.) Figure 9.2 (p. 256) below indicates where the pinholes are on the Grove XBee carrier board. Obviously, a finalised instantiation should program the all-purpose button on the board to cause a reset instead of requiring users manually reset non-responsive nodes.
Figure 9.2: Location of manual reset pins for Grove XBee Carrier board
B4. Source code

The solution’s practical artefact presented in the System architecture chapter (pp. 140-166) is written in the Python 2.7 programming language. This appendix covers the source code required to recreate or modify the solution. Below are snippets of code needed to run operate the network. The code refers to Python files with certain filenames, so it is important that developers save these snippets of code using the specified filenames only.

B4.1. ZigBee node settings

Save this code in a file called “NETWORK_LOCALS”. This configures the basic settings for the ZigBee chip.

```python
# --- BEGIN ---
# LOCAL CONFIG VALUES
# Used for variables specific to a running machine
#
# --- XBee COM Port ---
USB   = "COM5"
# --- ZigBee Settings ---
# Use escaped mode API=1
ZB_API_ESC = True
ZB_BAUD_BASE = 9600
ZB_BAUD_MESH = 38400
#
if __name__ == "__main__":
    print "Test mode of file."
quit()
# --- END ---
```

B4.2. ZigBee application

Save this code in a file called “xbdmesg.py”. This is the main network application that allows the ZigBee network to function.
from xbee import ZigBee
from xbee.python2to3 import byteToInt, intToByte
import datetime, time
import serial
import Queue
import binascii
import NetworkGLOBALS
import NetworkLOCALS as EL

def debug_print(mystring):
    if dbgout:
        print mystring
    return

def string2hex(s):
    #hexy = s.decode("hex")
    hexy = binascii.hexlify(s)
    return hexy

def hex2string(hexstring):
    return ''.join(["%02X" % ord(x) for x in hexstring])

def timestamp():
    now = time.time()
    localtime = time.localtime(now)
    milliseconds = '%03d' % int((now - int(now)) * 1000)
    return time.strftime('%Y%m%d:%H%M%S') + '.' + milliseconds

def zb_getBAUD():
    # Get the baud rate of the XBee chip
    ATcmd = 'BD'
    try:
        zb.at(frame_id='\x01', command=ATcmd, parameter=None)
    except:
        raise
    return byteToInt(zb.wait_read_frame().get('frmc1')) / 16
```python
def debug_print(data):
    if (data['id'] == 'at_response') and (data['command'] == ATcmd):
        myBAUD = NetworkGLOBALS.hex2string(data['parameter'])
    else:
        if dbgout: print ATfail, data
    except:
        myBAUD = '\n'
    print 'BAUD=', myBAUD
    return myBAUD

def zb_getID():
    # Get the Node ID of the ZigBee device
    ATcmd = 'NI'
    myNodeID = '\n'
    try:
        zb.at(frame_id=\"x01\", command=ATcmd, parameter=None)
        data = zb.wait_read_frame()
        debug_print(data)
        if (data['id'] == 'at_response') and (data['command'] == ATcmd):
            myNodeID = (data['parameter'])
        else:
            print ATfail, data
    except:
        myNodeID = 'UNKNOWN'
    print 'NodeID=' + myNodeID
    return myNodeID

def zb_getADDR():
    # Get the Node Address (low part) for the Zigbee device
    ATcmd = 'SL'
    myNodeSL = '\n'
    try:
        zb.at(frame_id=\"x01\", command=ATcmd, parameter=None)
        data = zb.wait_read_frame()
        debug_print(data)
        if (data['id'] == 'at_response') and (data['command'] == ATcmd):
            myNodeSL = NetworkGLOBALS.hex2string(data['parameter'])
        else:
            print ATfail, data
    except:
        myNodeSL = 'UNKNOWN'
    print 'Local Long Addr(SL)= ', myNodeSL
    return myNodeSL

def zb_getPAN():
    # Get the PAN ID of XBee network
    ATcmd = 'OP'
    myPAN = '\n'
    try:
        zb.at(frame_id=\"x01\", command=ATcmd, parameter=None)
        data = zb.wait_read_frame()
        debug_print(data)
        if (data['id'] == 'at_response') and (data['command'] == ATcmd):
            myPAN = NetworkGLOBALS.hex2string(data['parameter'])
        else:
            print ATfail, data
    except:
        myPAN = ''
    print 'PANID=', myPAN
    return myPAN

def zb_wakeup():
    # Wake up XBee node and get identifying data from local chip
    PAN = zb_getPAN()
    if (PAN < 1):
        print 'Not connected to ZigBee PAN'
        return 99
```
else:
    zb_getBAUD()
    zb_getID()
    # zb_getADDR()
    return 0

def zb_setPAN(panid):
    debug_print('Set PANID: ' + panid)
    # TODO convert a string to hex
    zb.at( frame_id='\x01',command='ID',parameter=panid)
    try:
        data = zb.wait_read_frame()
        print data
    except KeyboardInterrupt:
        pass
    finally:
        print 'Continue....'
    return

def message_received(data):
    packets.put(data, block=False)
    # print 'recv packet', data

def zbsendPacket(targetlong, payload):
    print('longaddr = ' + targetlong)
    longaddr = string2hex(targetlong)
    longaddr = bytearray.fromhex(targetlong)
    # print binascii.a2b_qp(targetlong)
    frametype = '10'
    frameid = '07'
    frameoptsbcast = '0000'
    datalength = 14 + len(payload)  # preamble(packed) + payload(unpacked)
    print datalength
    # import pdb; pdb.set_trace()
    # '7E 0018 10 07 0013A20040C8F0A FFFE 00 00 42656520746F20426565 1A'
    framestring = '7E00{:2}{:2}{:2}{:16}FFFE{:4}'.format(
        str(hex(datalength))[-2:], frametype, frameid, targetlong, frameoptsbcast)
    framestring += (str(string2hex(payload)))
    print 'frame source (no chksum) ', framestring
    fb = bytearray.fromhex(framestring)
    # fb.extend(str(string2hex(payload)))
    print 'frame bytearray ', fb
    # Calculate checksum byte
    fb.append(0xFF - (sum(fb[3:]) & 0xFF))
    print 'frame bytearray + chksum ', fb
    # print 'outgoing frame ', fb
    # write the serial bytearray
    ss = ser.write(fb)
    print ss
    r = 0
    respType = 'tx_status'
    respDel0K = '\\x00'
    sendOK = False
    sendRetry = True
    while (sendRetry == True):
        print r
        time.sleep(0.1)
        ss = ser.write(fb)
        print 'send serial status ', ss
data = zb.wait_read_frame()
    print data
    debug_print(data)
    if (data['id'] == respType):
if (data['deliver_status'] == respDelOK):
    sendRetry = False
    sendOK = True
else:
    sendRetry = True
    sendOK = False

    # Max retries is set to 20 to force a break
    r += 1
    if (r > 20):
        sendRetry = False

# End of while

if (sendOK == True):
    print 'sent packet:
	' + payload + '
'
    print 'to address:
	' + targetlong + ' 
'
else:
    print 'Failed to send after ' + str(r) + ' retries.'

return sendOK

def zbsendQueryPacket():
    print 'sending query packet'
    zbsendPacket(BROADCAST, UNKNOWN, '?\r')

# Another thread has caught the packet from the XBee network,
# placed it in the queue, this process has taken it out of the
# queue and passed it into this routine, now we can take it apart
# to see what is going on

def zbhandlePacket(data):
    print 'In handlePacket: ',
    retlst = []
    print data['id'],
    if data['id'] == 'tx_status':
        retlst.append(Network_GLOBALS.hex2string((data['frame_id'])))
        retlst.append(Network_GLOBALS.hex2string((data['deliver_status'])))
        retlst.append(Network_GLOBALS.hex2string((data['dest_addr'])))
    else:
        print 'Unimplemented frame type'

    # print data

    print retlst

    return

def finish():
    # halt() must be called before closing the serial
    # port in order to ensure proper thread shutdown

    zb.halt()
    ser.close()

    print '<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<'

    return

# --- Main ---

print 'Connect local ......'
res = zb_wakeup()
print res
if (res > 0):
    print 'Closing now. Setup issues on mesh.'
    runproc = False
else:
    runproc = True

# Do other stuff in the main thread
while runproc:

    print """""""""""""""""""""""""""""""
    try:
        msg2send = raw_input('Type your message: ')
msg2send = 'Angry Bees' #"Bee to Bee"
sendTime = b'00132A004C8CF0A'
print 'zbSend.....'
sentMsg = zbsendPacket(sendTo, msg2send)
print 'send outcome ', sentMsg
except KeyboardInterrupt:
    runproc = False
    #runproc = False # stop after sending
time.sleep(1)
finish()
quit()

B4.3. Connecting MySQL to SQLite

Save this code in a file called "db2db.py". This connects the SQLite database to MySQL database. SQLite does not have a server, so MySQL is needed.
# Retrieve data from SQLite table and insert into MySQL table.

```python
for row in lite_cur.execute("SELECT * FROM zbq"):  
    print row[1]  
    mypayload = row[1]  
    mysq_Ins = "insert into xbdata (xbpayload) VALUES ('\%s')" % (mypayload)  
    print mysq_Ins  
    mysq_cur.execute(mysq_Ins)

    mysql_con.commit()  
    print "%d rows were inserted" % mysq_cur.rowcount

lite_con.close()  
mysql_con.close()  
quit()

print " --- END ---"
```

## B4.4. Web portal

Save this code in a file named “eWeb.py”. This sets up the web-based user interface for users to interact with the network.

```python
from bottle import SimpleTemplate, template
from bottle import route, run
from bottle import get, post, request
import MySQLdb
import sqlite3
from xbee import ZigBee
import datetime, time
from time import sleep as time_sleep
from time import time  as time_time
import serial
import Queue
import Network_GLOBALS

global hBR
hBR = "<BR>"
global myXBnet
myXBnet = {}

eh = """
  <head>
    <title>(Unnamed Practical Artefact)</title>
    <meta name="viewport" content="width=device-width, initial-scale=1" />
    <h2>Prototype Network for Lateral Information Sharing</h2>
    <br>
    <br>
  </head>
  <form action="/Network/menu" >
    <input type="submit" value="Menu" />
  </form>

```

ef = ""
<footer>
```
<form action="/Network/home" >
  <input type="submit" value="Home" />
</form>

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```python
@route('/
@route('/Network/home')
def home():
    menumsg = "Home ."
    content = eh + menumsg + ef
    return template(content)

@route('/Network/menu')
def menu():
    menuForm = ""
        <a href="/Network/send">Send some data</a> <BR>
        <a href="/Network/cast">Broadcast over mesh</a> <BR>
        <a href="/Network/info">System info</a> <BR>
        <a href="/Network/mesh">Data from mesh</a> <BR>
        <a href="/Network/data">Central data warehouse</a> <BR>
        <a href="/Network/keyw">Keywords</a> <BR>
        <a href="/Network/TBD">TBD</a> <BR>
    ""
    return eh + menuForm + ef

#--- Send a Specific Command ---
@get('/Network/send')
def menuSend():
    sendForm = ""
        <form action="/Network/send" method="post">
        <br>
        command: <input name="cmdtext" type="text" />
        <input name="sendbtn" value="Send" type="submit" />
        <BR>
        </form>
    ""
    content = eh + sendForm + ef
    return content

@post('/Network/send')
def menuSend():
    content = eh
    c = request.forms.get('cmdtext')
    b = request.forms.get('sendbtn')
    print c, b
    if b == "Send":
        content += ' Data: ' + c + ' sent at: ' + timestamp() + '<br>'
    content += ef
    return content

#--- Broadcast Over Mesh Network ---
@get('/Network/cast')
def menuCast():
    sendForm = ""
        <form action="/Network/cast" method="post">
        <br>
        content: <input name="cmdtext" type="text" size="50" maxlength="80" />
        <input name="castbtn" value="Cast" type="submit" />
        <BR>
        </form>
    ""
    content = eh + sendForm + ef
    return content

@post('/Network/cast')
def menuCast():
```
content = eh

b = request.forms.get('castbtn')
if b != "Cast":  
    content += "Error. Please try again." + ef 
return content

port = Network_GLOBALS.USB1
content += 'Broadcast using port: ' + port + '<br>

broadcastLONG = Network_GLOBALS.XB_BROADCAST 
C1ID = Network_GLOBALS.XB_CONTROL_ID
C1LONG = Network_GLOBALS.XB_C1_LONG
print b, port, c
try:
    ser = serial.Serial(port, Network_GLOBALS.ZB_BAUD_BASE)
zb = ZigBee(ser, escaped = Network_GLOBALS.ZB_API_ESC)
zb.send('tx', 
    frame_id = '\x01',
    dest_addr_long = broadcastLONG,
    dest_addr = '\x00\x00',
    data = c
)
zb.halt()
ser.close()
content += 'Broadcast completed of:' + '<br>' + c + '<br>at:<br>' + timestamp() + '<br>'
except:
    content += 'Unable to broadcast.'
    content += ef 
return content

--- Callback for ZigBee Frames Async ---

def getNDdata(zbdata):
    print zbdata
    nodeID = str( (zbdata['parameter'])['node_identifier'])
    nodeType = str( (zbdata['parameter'])['device_type'])
    pretty_value = ','.join(':02X'.format(ord(c)) for c in nodeType)
    print nodeID, pretty_value
    dictNodeTypes = {'00':'coordinator','01':'router', '02':'endpoint'}
    myXBnet[nodeID] = dictNodeTypes[pretty_value]
    print myXBnet
    return

--- System Information ---
@route('/Network/info')
def menuInfo():
    content = eh + "Server info:<br>
    thisIP = request.environ.get('REMOTE_ADDR')
    thisSW = request.environ.get('SERVER_SOFTWARE')
    thisWV = request.environ.get('wsgi.version')
    content += ''.join(map(str,thisIP)) + '<br>
    content += ''.join(map(str,thisSW)) + '<br>
    content += ''.join(map(str,thisWV)) + '<br>

--- Node ID of Locally Attached XBee Device ... ---
@route('/Network/info')
def menuInfo():
    content = eh + "Server info:<br>
    thisIP = request.environ.get('REMOTE_ADDR')
    thisSW = request.environ.get('SERVER_SOFTWARE')
    thisWV = request.environ.get('wsgi.version')
    content += ''.join(map(str,thisIP)) + '<br>
    content += ''.join(map(str,thisSW)) + '<br>
    content += ''.join(map(str,thisWV)) + '<br>

try:
    ser = serial.Serial(port, Network_GLOBALS.ZB_BAUD_BASE)
zb = ZigBee(ser, escaped = Network_GLOBALS.ZB_API_ESC)
zb.at(command='NI')
niFrame = zb.wait_read_frame()
nodeID = str( niFrame['parameter'] )
zb.halt()
ser.close()
content += "<br>" + "Connected port: " + port + " has Node ID: " + nodeID
except:
try:
    ser = serial.Serial(port, Network_GLOBALS.ZB_BAUD_BASE)
    zb = ZigBee(ser, escaped=True, callback=getNDdata)
    NDstart = time.time()
    print NDstart
    zb.at(command='ND')
    while True:
        try:
            time.sleep(0.1)
            if ((time.time() - NDstart) > NDtime):
                print "time expired"
                break
            except KeyboardInterrupt:
                break
        except:
            content += hBR + "Unable to discover mesh nodes." + hBR + hBR
            print "Finished Node Discovery."
            content += hBR + "Node, Type" + hBR
            for mynode,mytype in myXBnet.items():
                content += str(mynode) + " , " + str(mytype) + hBR
            content += ef + hBR + timestamp() + hBR
            return content

#--- Storing Data in MySQL ---
@route('/Network/data')
def menuData():
    content = eh

    db = MySQLdb.connect(Network_GLOBALS.MYSQL_SERVER, Network_GLOBALS.MYSQL_USER,
                          Network_GLOBALS.MYSQL_PASS, Network_GLOBALS.MYSQL_DB)
    #db = MySQLdb.connect("localhost", "networkuser", "networkpass", "test")

    s = "SELECT * from xbdata  WHERE id > 0 "

    try:
        # Execute the SQL command
        cursor.execute(s)
        # Fetch all the rows
        rowset = cursor.fetchall()
        content += "<th>XBee data (MySQL)</th>
        content += "<table>
        print content
        for row in rowset:
            seq = str(row[0])
            pload = str(row[1])
            # Now print fetched result
            print seq, pload
            content += "<tr>
            content += "<td/"" + seq + "<td/>"" + pload + "<td/>""
            content += "</tr>"
        content += "</table><br>End of data.<br>"
        except:
            content += "<br>Error: unable to fetch data<br>"
    except:
        content += "<br>Error: unable to fetch data<br>"

    db.close()
    content += ef
    return content

#--- Keyword Data in MySQL ---
@route('/Network/keyw')
def menuKeyWords():
    menumsg = "Analyse payload keywords in data warehouse"
    content = eh + menumsg

    # Uses keywords to search the data from mesh.
    # Outputs stats about keywords found
    try:
        with open('./KeywordsList.txt') as wordfile:
            kw_list = wordfile.read().splitlines()
        except:
            content = 
            "<br><br>    Unable to open keywords file.<br>"
        content = ef
        return content
        kw_dict = {}
        kw_dict = kw_dict.fromkeys(kw_list,0)
        print kw_list
        db = MySQLdb.connect(Network_GLOBALS.MYSQL_SERVER, Network_GLOBALS.MYSQL_USER,
                                  Network_GLOBALS.MYSQL_PASS, Network_GLOBALS.MYSQL_DB)
        cursor = db.cursor()
        s = "SELECT * from xbdata WHERE id > 0 "
        try:
            # Execute the SQL command
            cursor.execute(s)
            # Fetch all the rows
            rowset = cursor.fetchall()
            rc = cursor.rowcount
        except:
            content = 
            "<br><br>    Unable to retrieve data.<br>"
        db.close()
        content = ef
        return content
        if rc > 2:
            try:
                print "%d rows of data were found." % rowset.rowcount
                #process each row for any keywords
                for row in rowset:
                    rowid = row[0]
                    s = row[1]
                    for k in kw_list:
                        # create a regular expression from the keyword
                        g = re.search('{}'.format(k),s,re.IGNORECASE)
                        if g:
                            #print string.upper(g.group(0))
                            kw_dict[k] = kw_dict[k]+1
                            for word in kw_dict:
                                occurs = int(kw_dict[word])
                                #print occurs
                                if occurs > 0:
                                    grafline = str(string.ljust('', occurs, '*'))
                                    content = "<tr>"
                                    content += ""<td/>"" + word + ""<td/>"" + occurs + ""<td/>"" + grafline
                                    content += ""</tr>"
                                    #print '{:<15}{:6} {:<}'.format(word, occurs, grafline)
                                content += "</table><br>End of keywords.<br>"
                            except:
                                content += ""<br><br>    Error: unable to fetch data<br>"
                            if rc < 2:
                                content += ""<br><br>    No data in server (" + Network_GLOBALS.MYSQL_SERVER + ")
                                for database (" + Network_GLOBALS.MYSQL_DB + ")<br>"
                            db.close()
                            content = ef
                            return content
        content = ef
        return content
--- Moving Data from SQLite to MySQL ---
def menuLoad():
    menumsg = "Load data from SQLite to MySQL"
    content = eh + menumsg + ef
    return content

--- Show Mesh Network Data Logged in SQLite ---
@route('/Network/mesh')
def menuMesh():
    menumsg = "Show the ZB mesh raw data from SQLite."
    content = eh
    con = None
    try:
        con = sqlite3.connect('zbdata.db')
        cursor = con.cursor()
        cursor.execute('SELECT * FROM zbq')
        rowset = cursor.fetchall()
        content += '<th>ZB data (SQLite)</th><table>
        for row in rowset:
            content += "<tr">
            content += '"td/" + str(row[0]) + "<td/">" + str(row[1]) + ""td/""
            print str(row[0]), str(row[1])
            content += "</tr>"
        content += "</table><br>End of data.<br>"
    except sqlite3.Error, e:
        print "Error %s:" % e.args[0]
    if con:
        con.close()
    content += ef
    return content

--- Reserved Space for Future Use ---
@route('/Network/TBD')
def menuUndef():
    menumsg = "Watch this space."
    content = eh + menumsg + ef
    return content

def timestamp():
    now = time.time()
    localtime = time.localtime(now)
    milliseconds = '%03d' % int((now - int(now)) * 1000)
    return time.strftime('%Y%m%d:%H%M%S') + '.' + milliseconds
    s = datetime.datetime.now().strftime("%Y-%m-%d %H:%M:%S")
    return s

---

# Reloader will autoreload when changes are made
# Debug is for verbose console output
# Host is the localhost for development, but it’s set to IP address 0.0.0.0 for internet use
# Port is the webserver serving port
bottleport = 8066
bottledev = 'localhost'
bottlerun = '0.0.0.0'
run(host=bottlerun, port=bottleport, debug=True, reloader=True)
quit()

B5. Sample screenshots

If everything is running correctly, the user should see screenshots like those in the following sections.
B5.1. ZigBee messaging within console

The console output in Figure 9.3 (p. 269) below shows an example what the identification, sending, and receiving of ZigBee data packets using secure shell (SSH) looks like.

![Figure 9.3: Example of console output](image)

B5.2. ZigBee messaging within XCTU

In addition to Figure 9.3 (p. 269) above, the output within the XCTU application in Figure 9.4 (p. 270) below should also show the identification, sending, and receiving of ZigBee data packets.
Figure 9.4: Example of XCTU output