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Towards a hyperconnected humanitarian supply chain

Manon Grest

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Université Fédérale



Toulouse Midi-Pyrénées

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Manon GREST

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INTRODUCTION

A very warm welcome to you dear reader, I hope you're prepared for the journey ahead because when I started this PhD from the very first day, I discovered a world that I thought I knew, or at least had a rough idea of, and ended up somewhere I never expected to go. Please have a seat, grasp something warm to drink and let me tell you a story...

This is the story of my PhD journey that started in January 2019 and today, three years later, makes it possible for me to write these lines and share with you the discoveries, the learning, the decisions and the achievements that marked my way. You have to be aware that I was not totally alone in this. Indeed, a bit like the Fellowship of the Ring, I have been mentored, guided, helped when the path seemed blocked to me and accompanied by PhD fellow adventurers for a short or long period. Still, in the end, when I look back, I realize every step was mine and I'm grateful and pleased to share all of this with you.

Everything started on a cold day, in early January 2019 with a colleague who became a friend who welcomed me, provided me with a computer and helped me settle down in my new office in the Industrial Engineering lab at IMT Mines Albi (France). I remember sitting on my chair and asking myself where this 3-years adventure would lead me. I thought I should start with the start and read again the short thesis proposal I was provided by my supervisors before I signed up for the PhD. Basically, the title was the same as today "*Towards a Hyperconnected Humanitarian Supply Chain (HHSC)*" and it was a question of Humanitarian Supply Chain (HSC) challenges that could be overcome with a Physical Internet (PI) approach. The topic drew my attention for the social-related aspects and met my wish to work on something useful that could maybe one day bring some additional comfort to someone during a disaster situation. Besides, I was slightly acquainted with the PI and curious to discover more.

Part I - The discovery of the Humanitarian Supply Chain Universe

Consequently, a long phase began of exploration and investigation into the different fields. First, I familiarized myself with the humanitarian world, its Supply Chain (SC) specificities compared to the commercial sector, the challenges encountered and the particular context. To strengthen and broaden my knowledge not only with academic reading, but I also had the chance to travel to Malaysia and Indonesia to meet International Federation of Red Cross and Red Crescent Societies (IFRC) and Indonesian Red Cross logistics teams to conduct interviews and warehouse visits. At this time, I fully measured why aid delivery was not straightforward and efficient enough, as had been highlighted by newspaper headlines and reports after major disaster events. There were clearly numerous challenges, uncertainties and a lack of resources. However, the interest and involvement such people demonstrated in doing

their work reinforced my motivation and my role, even if I remained aware that the project I was part of was a very long-term one. During this time, I documented a lot on humanitarian relief operation management by examining the academic body of knowledge that currently, emphasises the need for more relevant research to support practitioners. I also collected data and compiled disaster statistics to understand the growing trend in humanitarian needs as well as the widening gap with the funding provided. I reviewed existing contributions and solutions to help Humanitarian Organization (HO)s in performing better at the SC and logistics management level, which is recognized as a key part of the success of a relief operation. In parallel, I investigated in more detail the PI and its main components. The applicative opportunities and potential benefits became more obvious the more I learned about the concept. I also identified a huge exploratory research opportunity to investigate such an original association. So, I ended this period with a defined problem to address and the intention of an experiment-based research project to assess the relevance of the application of PI principles to the humanitarian sector. All of this reflection process and associated details can be found in the first Chapter 1 of this manuscript which constitutes a kind of proof of value.

Part II - The ideation phase regarding the future of Humanitarian Supply Chains

From there, followed a second phase dedicated to the design of the HSCs of the future. The novelty of the topic and the small amount of research into it leaves a large space for being creative. However, where to start? And how make the proposals relevant? Such questions led me, beforehand, to investigate the key components or levers of SCs and HSCs more specifically to understand their relationship on performance. Since the final objective is to improve the performance and *in fine* the well-being of the affected population, this is where I started. In light of current practices for each identified lever, I brainstormed with other creative brains on the subject of new PI-oriented practices. A part of this creative phase happened when I was in the PI lab, which I'm also part of, within the buildings of Georgia Institute of Technology University (USA). Some suggestions for organizational reforms were presented to some practitioners who showed positive curiosity and interest. After that, a qualitative study, relying on a simple case study, constituted a first attempt to test the concept and reinforced our convictions to pursue our research with a qualitative assessment. This imaginative process, on PI-oriented proposals and the qualitative benefits detected for the future of HSCs are described in the second Chapter 2.

Part III - The design phase of a quantitative experiment about the Humanitarian Supply Chain

The intention to conduct an experiment was known since the end of the first phase of the PhD. However, how to correctly measure the PI impacts on HSC performance was something else. Even more so, as no experiment has been performed before on the topic. Again, the exploratory avenue was wide open. To secure the conclusion to be drawn from this experiment, I spent a long phase just thinking and designing this experiment. We rapidly agreed with my supervisors that a simulation approach

was suitable for such exploratory studies. From there, I found the need to learn about simulation, modeling and experiment design in general. The knowledge gained allowed me to develop a functional framework (i.e. a methodology) to frame the simulation development and ensure the proper alignment with the objective of the initial experiment. In addition, I developed a sort of simulation-oriented test bench to carry out the experiment. This required a long design period to build a new model of HSCs in a holistic perspective, something I was not able to find in the literature. All of these experimental elements and details are available in Chapter 3 if you wish to read more about them.

Part IV - The test phase of the Hyperconnected Humanitarian Supply Chain paradigm in situation

The previous phase was about the design of the experiment only. This new phase focused on the conduct of the experiment to generate results and an analysis period to draw conclusions. However, before this, a case study had to be built to fill the two frameworks, which are essentially architectures with substance. So, once we decided to use Indonesia and the SC organization of the Indonesian Red Cross as a source of inspiration, a long period was spent building a case study with a representative model. Several workshop sessions were organized with practitioners to ensure the validity of the model we developed and our understanding of the operational decisions taken during relief operations. In parallel, the model was coded and implemented in a simulation-adapted software. The development took some months to be completed and finally provide results. From there, the journey was close to the end but an analysis phase was still required. Descriptive analysis was used to measure the effect of PI proposals tested on performance and to identify effective combinations as a form of scenario. Your curiosity about the proof of their impacts will hopefully be satisfied if you pay a visit to Chapter 4.

Thank you for having followed so far. However, I hope you are still curious to learn more because this was just the introduction. It is now time for me to let you spend some time on your own to explore, question or, at least, learn something you did not know before by reading these pages. I made this map 1 to help you find your way around. I'll see you again at the conclusion. By then, I hope you will have enjoyed it.

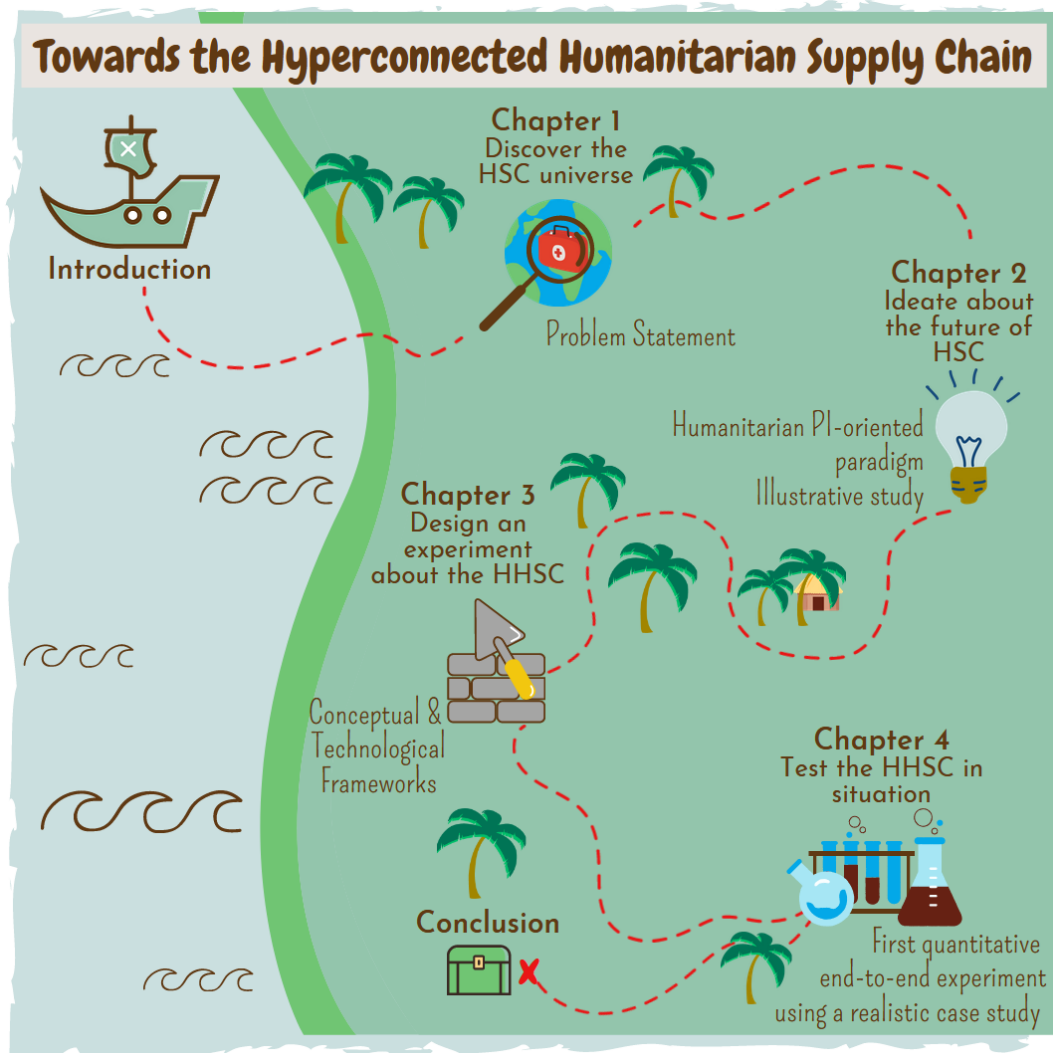


Figure 1: Towards the Hyperconnected Humanitarian Supply Chain (HHSC)

DISCOVER THE HUMANITARIAN SUPPLY CHAIN UNIVERSE

Why could not advantage be taken of a time of relative calm and quiet to investigate and try to solve a question of such immense and worldwide importance, both from the humane and Christian stand-point?

– Henry Dunant, *A Memory of Solferino*, (1862)

1.1 Research context: What is Humanitarian aid?

This section aims to provide the reader with fundamental concepts and introductory details related to humanitarian aid and its context through four dedicated sub sections: a brief history to trace the development of aid, details about humanitarian crises and expected trends and finally, an overview of humanitarian operations and their associated context.

1.1.1 History of the humanitarian aid

According to [Davey et al. \[2013\]](#), the history of the humanitarian aid system can be divided into 4 major periods beginning the 19th century: the mid 19th century to the end of the World War I (1918), the interwar period, the Cold War and the post Cold War period until now (see figure 1.1).

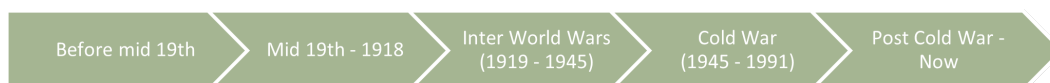


Figure 1.1: Humanitarian aid history timeline

1.1.1.1 Before mid 19th

“Humanitarian” actions in a broad sense have taken place throughout history and across the globe. Closer to charity rather than aid, in fact, these voluntary actions were motivated by religious beliefs and the laws of war [[Davey et al., 2013](#)]. As early as the Vth century, the Christian Church developed aid activities for destitute people and built schools, hospitals and orphanages [[Bioforce, 2012](#)]. Charitable gestures were also encouraged in other religions, such as Islam, which encouraged assistance to others. The laws of war also framed soldiers’ scope of action to avoid unacceptable

behaviour that regularly occurred during battles. Such considerations first appeared at the ancient Greek and Roman period, then were reworked by Sun Tzu in the Art of War and promoted by Saladin in the 1100s and by Gustavus Adolphus in the 1600s [Davey et al., 2013].

1.1.1.2 Mid-19th century to the end of World War I (1918)

The origins of the modern humanitarian system really took root during the 19th century with a succession of military conflicts. The main event that marks its emergence is probably the creation of the International Committee of the Red Cross (ICRC) in 1863. Shocked by the lack of relief aid support to injured soldiers during the battle of Solferino, Henry Dunant imagined an aid system based on national societies and an international treaty to protect civilian and military victims [Dunant, 1986]. During the same period, the development of technologies and means of communication, along with innovations in military medicine (practice of triage or medical transportation...) initiated humanitarian efforts at a local and national scale [Davey et al., 2013]. Subsequently, international aid was fostered by the Geneva Convention in 1864 [Davey et al., 2013]. Established to improve the situation of injured soldiers during battles, the text mentions the necessity that all warring parties agree upon the neutrality of relief facilities and should treat them with respect [Dunant, 1986]. After that, some natural disasters in the late 19th and early 20th century led to international aid efforts. As an illustration, in 1907 after the Kingston earthquake in Jamaica, British, French and US assistance and medical support was provided and funds came from around the British Empire [Davey et al., 2013]). Areas under colonial rule also saw the emergence of humanitarian actions to face famine, poverty and poor health conditions even though the main beneficiaries were the Europeans [Davey et al., 2013].

1.1.1.3 The inter-war period

Despite the improvement of skills in the relief domain, the First World War raised large humanitarian issues since the needs it caused greatly exceeded the available resources. To overcome this situation, the ICRC and religious associations and communities had to join forces [Davey et al., 2013]. After the First World War, considerable food security and diseases issues as well as mass displacements due to conflicts such as the Bolshevik Revolution (1917) or the Nazi regime (1933-1945) had to be managed. This inter-war period is marked by a major reform after WWI, the Treaty of Versailles in 1919. This treaty, among other things, led to the creation of the first permanent international organization to address humanitarian issues and maintain peace in the world: The League of Nations, which would later become the United Nations (UN). After that, an additional institution following the same philosophy was created: The League of Red Cross Societies (LRCS) in 1919 (former name of the current International Federation of Red Cross and Red Crescent Societies (IFRC)). During this period, humanitarian efforts were concentrated outside Europe, due to colonial expansion and the East Asia conflicts. The creation of the UN in 1945 was accompanied by some legal changes such as the Universal Declaration of Human Rights (UDHR), which ensures that “*everyone has the right to life, liberty and security*” [Nations, 1948]. This revealed the new international concern for the protection of human rights [Davey et al., 2013]. In terms of specialization, the UN encompasses various agencies such as the United Nations Children’s Fund (UNICEF),

the Food and Agriculture Organisation (FAO), the World Health Organisation (WHO) and the International Refugee Organisation (IRO, replaced by the United Nations High Commissioner for Refugees (UNHCR) in 1951) [Davey et al., 2013].

1.1.1.4 The cold war (1945-1991)

During the cold war period, humanitarian needs concentrated around poverty and inequality and the period is marked by a shift in the beneficiaries from Europeans to all people in need. Indeed, while Europe was recovering and undergoing reconstruction after WWII, leaders of less developed countries also claimed the right to international attention regarding their delay in development. In response to the request, up to 200 Non-Governmental Organization (NGO)s flourished between 1945 and 1949, mostly in the United States, to support economic and social development. These bodies were not so different in term of structure from the current humanitarian agencies known today. However, as highlighted by criticism directed at some experiences during this period, the mobilizations that took place demonstrated coordination issues in the humanitarian network, as well as inefficiencies and dialog difficulties with impacted governments. From there, on 19 December 1991, resolution 46/182 adopted by the UN, started building what is today's international humanitarian system. It mainly aimed to centralize funds with the creation of the Central Emergency Response Fund (CERF) creation and to coordinate and frame the humanitarian response through the creation of the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) [OCHA, 2016]. Besides, after major famines in Africa, humanitarian agencies also realized the importance of anticipating food crises [Davey et al., 2013].

1.1.1.5 The post-cold war until now

After the cold war, humanitarian actors introduced the concept of “complex emergencies” to deal with the situations they were now facing. This term can be defined as *“a humanitarian crisis in a country, region or society where there is a total or considerable breakdown of authority resulting from internal or external conflict, and which requires an international response that goes beyond the mandate or capacity of any single agency and/or the ongoing UN country program”*. Such an emergency may present the following characteristics: a large number of victims with a demand exceeding the capacity of local agencies and requiring international assistance which may be prevented by parties to the conflict [UNHCR, 2001]. Such circumstances highlighted the potential for international agencies to sometime overpass government consent if human rights are jeopardized. In 2005, after some major events such as the Indian Ocean tsunami in 2004, a major humanitarian coordination reform was initiated, called the Humanitarian Reform Agenda. It was developed with the objective of enhancing the quality of the aid delivered, ensuring accountability and strengthening partnerships among the different aid agencies. Feedback on the ground had shown that some sectors were given little attention compared to others. Recognizing this, the Inter-Agency Standing Committee (IASC) created a “cluster” system for humanitarian emergencies, counting today eleven areas of activities (food security, logistics, education, shelter, camp management, emergency telecommunications, health, nutrition, early recovery, protection and water, hygiene and sanitation) [IASC, 2006]. Other areas have been added recently, as the scope of aid action has widened to cover, for instance, the oppression of ethnic or other minorities (children, woman or even LGBT people) [Davey et al., 2013]. Clusters

1. DISCOVER the Humanitarian Supply Chain Universe

Table 1.1: Main characteristics of the history of humanitarian aid by period

Period	Mid-19th - WWI (1850 - 1918)	WWI - WWII (1918 - 1945)	Cold War (1946 - 1991)	Post-Cold War - Now (1992 - now)
Relief focus	Military conflicts	Food, disease & mass displacement	Poverty & Inequalities	Complex emergencies
Key events	Geneva Convention (1864) ICRC creation (1863)	1 st international HO (UN)	General Assembly Resolution 46/182	Humanitarian Reform Agenda
Main beneficiaries	Europeans	Europeans in colonies East Asia	European & developing countries	All people in need

are a means of regrouping actors mandated in the same sector, under the overall supervision of a UN coordinating unit [IASC, 2006].

1.1.2 Humanitarian crisis

To understand the humanitarian context, it is also necessary to investigate the whole scope revolving around it. When assistance is brought to people in need, it is generally in the aftermath of a disaster. The UN defines a humanitarian crisis as “an event or series of events that represents a critical threat to the health, safety, security, or wellbeing of a community or other large group of people, usually over a wider area” [Jeong and Yeo, 2017]. A humanitarian emergency occurs when a natural disaster, a man-made natural disaster, a man-made crisis, or a combination of all three, overwhelms the affected population’s ability to handle the situation. Humanitarian emergencies may develop gradually or occur suddenly.

In the following sections, the emphasis is on disaster characteristics and trends that create challenging and numerous environments for humanitarian operations.

1.1.2.1 Disaster classification

A large variety of disasters exist, which are generally characterized by their origin, speed of onset and predictability [Kara and Savaşer, 2017] (see figure 1.2). Also, the location of the disaster [Duran et al., 2013], the severity of its impact and eventual recurrence can all define its features [Glade and E. Alexander, 2013].

Disaster origin

With regard to its origin, a disaster can be the result of hazardous forces of nature or it can be man-made. According to CRED [2009] disaster classification, natural disasters can be geophysical (earthquake, mass movement due to drought or volcanic eruption), meteorological (extreme temperature, fog or storm), hydrological (flood, landslide or wave action), climatological (drought, glacial lake outburst or wildfire), biological (epidemic, insect infestation or animal accident) or extra-terrestrial (impact or space weather). Man-made disasters are generally related to a conflict (terrorist attack, political crisis) or can be technological (industrial, transport or miscellaneous accidents). Wars are not considered as a man-made disaster and have their own category [Van Wassenhove, 2006].

Disaster speed of onset & duration

The speed of onset and duration of a disaster are closely correlated in the form of two classifications: slow onset and sudden onset. Slow onset disasters occur gradually and last for a long period (e.g. famine or drought), whereas sudden onset disasters occur during a short time frame and appear suddenly (e.g. earthquake or tsunami) [Duran et al., 2013].

Disaster predictability

Disasters present large variation in terms of predictability. As an illustration, some tsunamis are triggered abruptly by the fast displacement of a water column in the ocean. However, the time taken for long distances tsunamis to travel allows them to be monitored and their route anticipated. The problem is when the time slot between the detection and striking of a disaster represents only a few minutes and prevents people being evacuated, which happens with earthquakes or volcanic activities [Glade and E. Alexander, 2013].

Disaster location

One other specificity of disasters is that they may hit a localized zone or, on the contrary, several areas that may be dispersed over a region [Duran et al., 2013].

Disaster impact severity

Disaster impact severity is characterized according to the scope of the emergency. Four types of emergencies have been identified: incidents, major incidents, disasters and catastrophes [Glade and E. Alexander, 2013].

1. Incidents are very localized and require local efforts and resources.
2. Major incidents generally take place in larger local areas like a region, where local and neighbourhood assistance is required.
3. Disasters demand intergovernmental assistance and the raising of attention from the public. They pose major challenges.
4. Finally, catastrophes present an extremely wide impact and require a major international response. In this last situation, local resources are overwhelmed and generate massive challenges and large public involvement

Disaster recurrence

In the disaster classification, recurrence or regularity vary according to the nature of the disaster. Many man-made events are non-recurrent (ex: transportation crashes) whereas most extreme natural phenomena are repetitive. Among them, meteorological and hydrological disaster types are the most cyclical due to their seasonality. As an illustration, it is well known that from April to September in the south of Asia, there is the monsoon period characterized by heavy rains and thus, floods [Glade and E. Alexander, 2013].

Disaster characteristics and challenges

Obviously, it is difficult to make a perfect characterization of disasters since each emergency situation is unique [Beamon and Balcik, 2008]. Besides, there are plenty of examples where, in a short period of time, one type of disaster triggered another

one. A recent illustration is probably the tsunami that struck Japan in 2011 and then generated the Fukushima nuclear disaster. On the contrary, “complex emergencies” are usually man-made, by an armed conflict for example, and followed by loss of life, destruction, displacements, family separation or loss of education issues. Current examples of complex emergencies can be found in Afghanistan, Iraq or Libya.

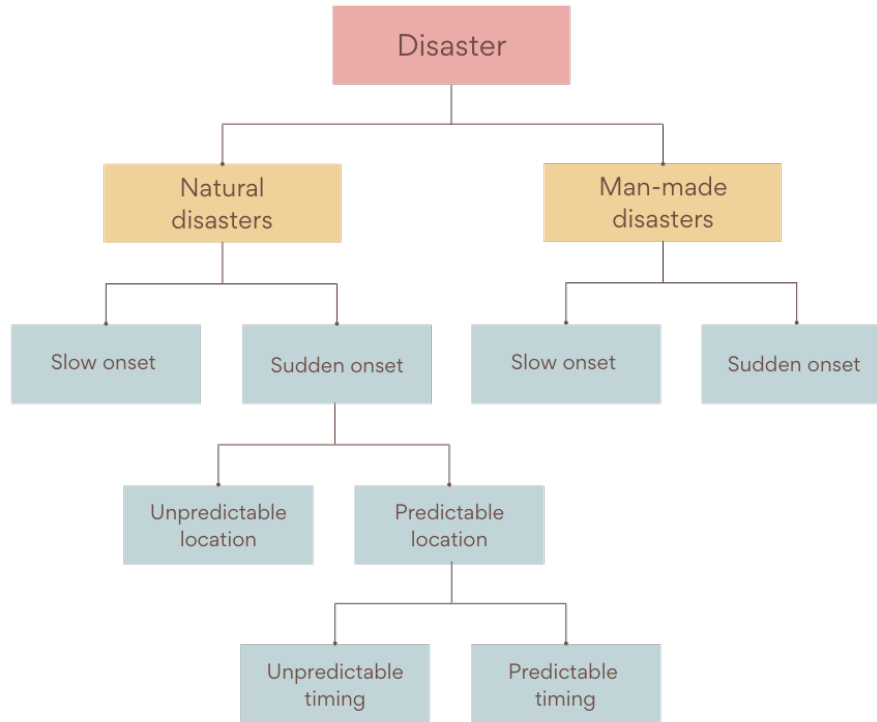


Figure 1.2: Disaster classification adapted [Kara and Savaşer, 2017]

1.1.2.2 Disaster statistics and trends

On average natural disasters are responsible for the death of 60,000 people per year, which represents 0.1% of total deaths in the world over the past decade [Ritchie and Roser, 2014]. Such a percentage presents a high variability, from 0.01% to 0.4% from year to year and relies heavily on the number and severity of the disasters that may occur each year.

Disaster occurrence

From 1960 to 2019, the number of natural disasters has been multiplied by 10, reaching 396 recorded incidents. A peak was observed in 2005 with 442 events [GCSP et al., 2020] (See Figure 1.3). This significant increase may also be explained by the fact that disaster monitoring is relatively recent and gathers officially registered occurrences. Indeed, all are not recorded as some criteria have to be met. As an illustration, Emergency Events Database (EM-DAT), one of the most famous event databases, was created in 1988 with the support of the WHO and Belgian government but counts disasters from 1900 to the present day. Besides, the main information sources are the humanitarian organizations, depending on the type of

disasters covered [CREED et al., 2018]. This may partially explain the recent increase in incidents over this period or the extent of data concerning Europe.

The top 3 of disasters in terms of the number of events from 1990 to 2019 are floods, which represents 41.5%, storms with 29.6% and earthquakes with 8.2%. Cumulatively, floods and storms account for more than 70% of the disasters occurring during these past 30 years [GCSP et al., 2020].

Now, geographically over the past 30 years, the Asia-Pacific region was the main scene of natural disasters with 2,845 events, or 29% of the total number of disasters (9,924). Europe and sub-Saharan Africa are respectively the second and third scenes, both being hit by around 13% of the total [GCSP et al., 2020].

The impact of each disaster also needs to be considered, even more than the number of occurrences, since a large number of low intensity disasters may not be as dramatic as a catastrophic one.



Figure 1.3: Trend in the number of natural disasters (1900-2019) [Ritchie and Roser, 2014] Note: Includes drought, earthquakes, volcanic activity, mass movement (dry), storms, floods, landslides, wildfire and extreme temperature.

Disaster impacts

To be considered as a disaster, a hazard that is a severe occurrence of an event has to damage livelihoods and cause deaths. EM-DAT records a disaster when it meets at least one of the following criteria: ten or more people killed, one hundred or more people reported affected, declaration of a state of emergency or call for international assistance [CREED and UNDRR, 2020]. The criteria or indicators may vary from one disaster database to another. However, the measures always consider the human and economic impacts.

Human impacts

The first impact indicator from disasters considered is generally the mortality rate. The top 3 in the number of deaths among the different natural disaster types are earthquakes, floods and droughts. Over time the trend shows a decline in the number of deaths generated by all types of natural disasters, except for earthquakes and extreme weather [Ritchie and Roser, 2014].

Now, the mortality rate does not cover all the human impacts generated by disasters. Other indicators, such as the number of people injured, homeless, displaced and affected help capture the global impacts and generally appear in database records. While injuries and homelessness indicators are meaningful, it is not that clear what constitutes being “affected”. It seems there is no consensus on the definition of this term but we base ours on the following definition: “People requiring immediate

assistance during a period of emergency, i.e. requiring basic survival needs such as food, water, shelter, sanitation and immediate medical assistance” [Ritchie and Roser, 2014].

Economic impacts

Not only does disaster cause loss of human lives but also severe destruction, which is captured as economic impacts. These represent the amount of damage to property, crops and livestock. Such information has been under-reported for a long time. Indeed, data only exist for 37% of disaster records over the 1998 to 2017 period [CRED et al., 2018].

From what is available, the top 3 countries in terms of absolute losses are in this ranking order: the USA (944.8 billion US\$), China (492.2 billion US\$) and Japan (376.3 billion US\$). However, those are developed countries with high incomes and absolute losses hide the real burden faced by low-income countries. Indeed, by considering losses as an average percentage of the Gross Domestic Product (GDP) then, the ranking appears differently.

The top ten countries in terms of average annual percentage losses relative to GDP includes 80% of low income and lower-middle income countries compared to a 10% representation in the absolute losses ranking. The top 3 is then, Haiti (17.5 %), Puerto Rico (12.2 %) and Korea D.P.R (7.4%) in terms of losses relative to GDP [CRED et al., 2018].

As an illustration of the difference revealed by these two indicators, one of the top 10 storm disasters between 1998 and 2017 with the most significant economic losses is Hurricane Ivan in September 2004. It hit the USA, Caribbean Islands and Venezuela and total damage was estimated to be 29.9 billion US\$ as absolute losses. However, it appears that for the same event, part of the top ten countries affected regarding losses as a percentage of GDP are Grenada and Cayman Islands, with respectively 148 and 129 % GDP [CRED et al., 2018].

In terms of disaster patterns, these are difficult to assess, as there is continuous variability over the years and some major events occurred unpredictably and quite randomly. Unfortunately, along with global warming and significant demographic growth, we can expect an increase in disaster occurrence and potential damage. Rising waters, weather extremes and wildfires are more and more threatening. However, we know, total damage as human impacts is mainly correlated to the territory vulnerability and income level. So, efforts have to concentrate on the protection of the most vulnerable and on risk reduction, as well as improving the resilience of territories. This is crucial and encouraged by the logic of sustainable development.

1.1.3 Humanitarian aid characteristics

Never more than today has the world experienced so many serious humanitarian crises simultaneously. In addition to natural disasters (e.g. in 2019 the wildfires in Australia, hurricanes Harvey, Irma & Maria in 2017), there are many armed conflicts. The crises in Iraq and Syria alone have affected more than 12 million people, and the number of refugees from this region has reached 6 million. In addition, the COVID-19 pandemic has exacerbated current humanitarian crisis needs, with more people affected.

Humanitarian action revolves around some key components that make it specific and unique on any occasion. To describe such a particular context, we will rely on the

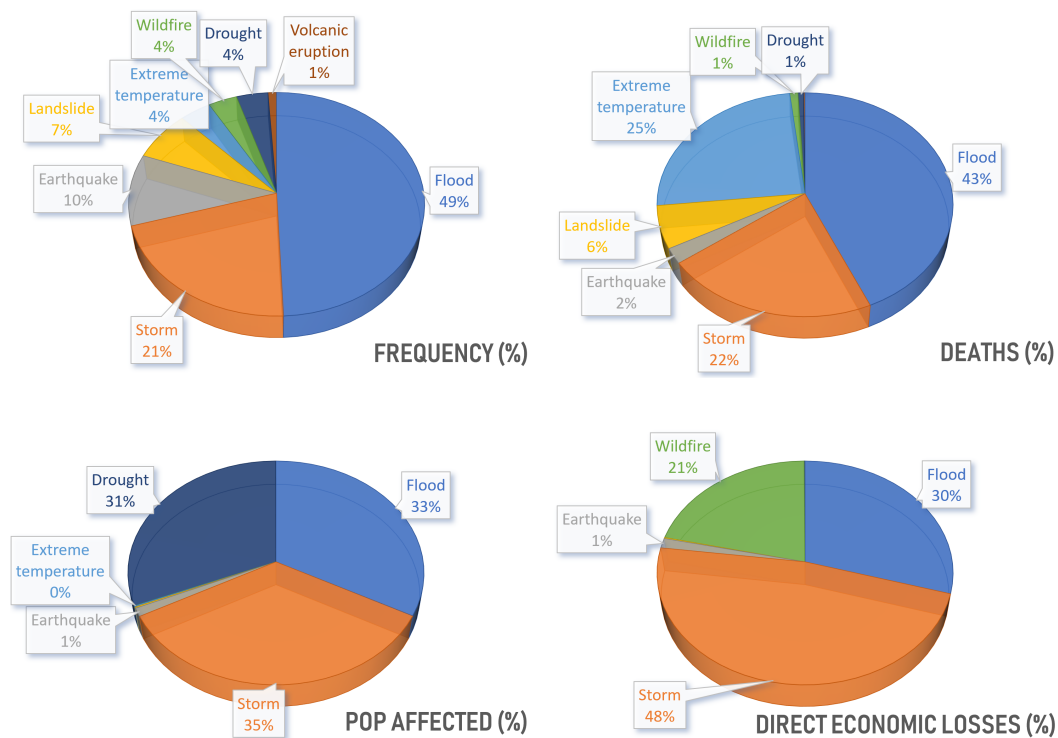


Figure 1.4: Disaster type breakdown regarding frequency and losses in 2019 [NDRCC et al., 2020]

characteristics identified by Charles and Lauras [2011] that need to be known: the humanitarian operation life cycle, the funding & donations system, the humanitarian ethical space and the panel of actors. Others categories are more logistics related, such as flow management and the dynamics and complexity of the environment. These will be discussed later on, respectively in sections 1.3.1 and 1.3.2.1.

1.1.3.1 The humanitarian operation life cycle

Driven by the need to meet growing human needs, numerous Humanitarian Organization (HO)s have flourished in the past and continue to do so today. Whatever the emergency context, the primary objective of HOs is to save lives, alleviate suffering, and maintain human dignity [Gutierrez Salgado et al., 2017]. Consequently, attention is directly focused on the reduction of human mortality and suffering through effective life-saving activities.

Basically, managing a disaster consists in planning actions, mobilizing resources and coordinating activities and actors to meet emergency needs. Activities and type of operations will differ depending on the phase of the disaster under consideration. The disaster life cycle is generally composed of three parts: preparedness before the disaster, response when the disaster occurs, and finally the rehabilitation phase [Kusumastuti et al., 2010].

During normal times, before any event, there is the mitigation phase well ahead the disaster and the preparation phase just before. Mitigation is a continuous process aimed at reducing or eliminating risk. It includes risk identification, analysis and assessment, as well as risk reduction through land-use planning, technical and public measures, public awareness and education. Preparedness focus on the planning of

how to respond to hazardous events. It includes emergency planning and training, as well as the installation of monitoring systems, forecasting and early warning systems to alert the population. The idea is to be prepared for a possible disaster and its impact on the population.

When the disaster strikes, the response phase is activated. In such urgent situations where victims' livelihood perspectives decrease with time, humanitarian operations focus firstly on saving lives with activities like search and rescue or evacuation and secondly on maintaining human dignity by meeting basic needs like providing water and food, shelter and sanitation services during the first weeks [Beamon and Balcik, 2008]. Such actions leave room to rehabilitation activities, after a few months, to help affected communities recover and get back to their previous level of development. They include reconstructions activities or risk mitigation actions.

For slow onsets, which are more stable contexts, the phasing is the same but the duration is spread out over a longer period of time (see figure 1.5). In such contexts, humanitarian organization conduct actions that are part of development programs (from 1 to several years) aiming to help poor or vulnerable communities facing systemic issues by enhancing their economic or social development [Beamon and Balcik, 2008]. Projects take various forms and focus on health promotion with vaccine campaigns, or on social aspects with gender equality actions, for instance, or the distribution of educational material.

The temporal limit between the different emergency, rehabilitation and development aid phases is often blurred. One reason for this is the increasing number of complex disasters where areas that are subject to armed conflicts, for instance, are also the scene of a natural disaster (drought, famine etc.).

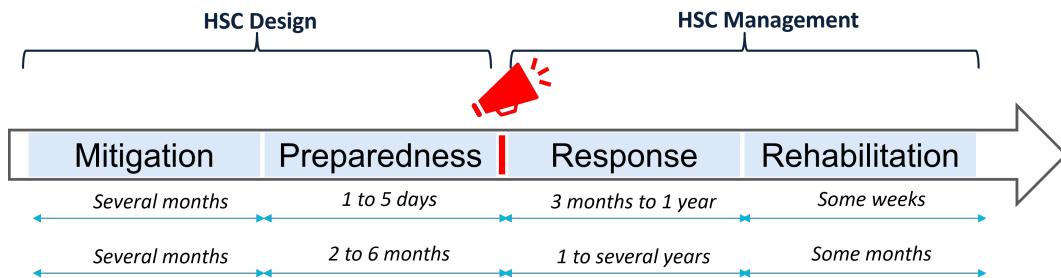


Figure 1.5: The humanitarian operations life cycle adapted from [Charles and Lauras, 2011]

1.1.3.2 Funding & Donations system to support the humanitarian aid requirements

Unlike commercial companies that generate income by selling services or products to clients, HOs do not benefit from the aid provided to beneficiaries, as theirs is a social and non-lucrative mission. However, to continue field operations and achieve their goals, the humanitarian system heavily relies on funding and donations.

Whether for preparedness, disaster response or socio-economic development projects, HOs regularly organize funding appeals. To do so, they formulate and publish an operational project with motivations, a list of requirements, estimated budgets and goals to achieve. From there, donors make promises and the provisioning

is organized. In return for these donations, HOs have to ensure and respect the accountability rules defined in agreement with those funding them. Generally, this consists in justifying expenses and reporting the level of achievement regarding the expected objectives []. Also, the donor may constrain the allocation of its donations to a relief operation or country for instance. These are called earmarked donations [Van Wassenhove, 2006]. Donations can take the form of money, products (referred to as in-kind donations), sending personnel to intervene on site or strengthening local actors.

Different types of donors exist, including private, institutional (i.e. other HOs) or public sources. Governments represent the main contributors by providing 70% of the funds while the private sector contributed up to 22% and miscellaneous contributors up to 2.5 billion US dollars. There is a real challenge in tracking how funding is disseminated beyond first-level recipients. However, from what is known, in 2019, governments prioritized support for NGOs, Red Cross and Red Crescent (RCRC) and the public sector while private donors mainly focused on NGOs. The largest three donors in volume over the same period were the US (US\$8.9 billion), Germany (US\$3.7 billion) and the EU (US\$2.6 billion) [Rouyer, 2021].

Today, trends show (2016 - 2020) that donors prefer earmarked donations, which represent 83% of funding, while cash and voucher assistance is increasingly being considered and beginning to reverse the domination of in-kind donations. Direct funding to local and national actors still remains low (3% in average) [Rouyer, 2021].

1.1.3.3 Humanitarian ethical space

Humanitarian aid and operations are guided by a set of ethical codes and standards. The range of these standards is wide but the most commonly accepted were originally defined by Henry Dunant to protect soldier rights and are the four following principles [Marshall, 2018]:

- **Humanity**, in all conditions any person should be treated respectfully and deserve assistance,
- **Impartiality**, the right to humanitarian assistance is the same whatever the person's origin, race, religion or personal beliefs, and is driven only by need,
- **Independence**, HO's decisions should be autonomous and only in the interest of providing aid,
- **Neutrality**, HO must remain neutral, and not take sides.

These fundamental principles are at the core of numerous standards and guidelines forming a body of international humanitarian law that notably include the four Geneva Conventions of 1949, UN conventions and the "*Responsibility to Protect*". The latter emphasises that states have the primary responsibility for protecting their population, while the international community has a duty to encourage and assist States in fulfilling this responsibility. If a State is failing in its duty of protection, the international community can take collective action in accordance with international humanitarian law [Marshall, 2018].

Adhering to such a regulatory framework ensures operational effectiveness to beneficiaries and the perennity of humanitarian action [Schenkenberg et al., 2014].

1.1.3.4 The humanitarian actor system

In the aftermath of a disaster it is not rare to see a wide diversity of actors taking actions and contributing to the relief organization. The main actors are the government and related bodies, HOs that mostly involve the UN, the RCRC movement and NGOs, the public sector and finally the general public & local communities, which may even count aid recipients amongst them.

Governmental entities

First in all, disaster management is the responsibility of the affected state's government. In charge of civil protection, it is expected to work on risk prevention during normal times and to take actions in the aftermath of a disaster. When the level of damage exceed local capacity, the government can request and/or accept external assistance from a large variety of HOs to support disaster preparedness and/or response. These include the UN agencies, the RCRC Movement, regional intergovernmental organizations, NGOs, assisting Governments, foreign militaries, and the private sector. Some of them, such as national or regional governments, the military, local businesses or some NGOs are locally based while others, located outside the affected region, are larger actors managing relief operations in several territories in parallel [Kovacs and Spens, 2007]. Examples include the UN or the IFRC part of the RCRC Movement.

Depending on the state administrative organization, regional government entities, military or government departments may mobilize resources and efforts to provide help in one or several humanitarian sector needs. For instance, in Indonesia, the Ministry of Social Welfare and Health provide support respectively in maintaining central warehouses used for supplies, food and tents deliveries and in providing medical services through allocated crisis centers. In parallel, the Ministry of Public Works takes care of the transport and communication infrastructures by clearing and repairing them [Kusumastuti et al., 2010]. As for the military, it play significant roles such as protecting civilians, distributing relief items or mobilizing aircraft for the transport of resources.

At a larger scale, governments from different countries may join forces to form regional humanitarian organizations or intergovernmental forums. For instance in Asia, Association of Southeast Asian Nations (ASEAN) brings together Indonesia, Cambodia, Brunei Darussalam, the PDR of Laos, Malaysia, Myanmar, The Philippines, Singapore, Vietnam and Thailand. The aim is to develop peace, security, economic growth and socio-cultural aspects in this region [Regional Office for Asia and the Pacific (ROAP)]. Also in Asia, there is the South Asia Association for Regional Cooperation (SAARC), the Pacific Islands Forum (PIF) and the East Asia Summit (EAS).

UN

The United Nations (UN) is an International Governmental Organisation (IGO) currently comprising 193 member states. It was established on 24 October 1945. It replaced the League of Nations.

The primary objective of this organization is the maintenance of international peace and security. To achieve this objective, it promotes the protection of human rights, provides humanitarian aid, supports sustainable development, guarantees international law and can impose international sanctions or organize military interventions.

The main specialised UN agencies with humanitarian mandates include the Food and Agriculture Organization (FAO), the International Organization for Migration (IOM), the United Nations Development Programme (UNDP), the United Nations Populations Fund (UNFPA), the UN Refugee Agency (UNHCR), UN-Habitat, the United Nations Children’s Fund (UNICEF), UN Women, the World Food Programme (WFP) and the World Health Organization (WHO).

Each of these entities is an independent organisation with its own management, budget and Member States working with the UN. However, they are committed to working in accordance with the established UN coordination mechanisms and report to the UN Member States [Nations].

RCRC Movement

The International RCRC Movement is the world’s largest humanitarian network working to help people affected by disasters, armed conflict, health and social issues. The Movement comprises the ICRC, the IFRC and 191 National Red Cross and Red Crescent Societies [ICRC, 2014].

The ICRC specializes in the protection and assistance of victims of armed conflict and other situations of violence, in providing humanitarian aid in emergency situations, and promoting respect for international humanitarian law and its integration into national legislation [ICRC, 2014].

As for the IFRC, it focuses on alleviating and preventing human suffering after disasters, reducing climate change related risks, assisting migrants and displaced people, promoting gender inclusion and education and finally, supporting the development of national societies by reinforcing their humanitarian action capacities.

Unlike the ICRC and the IFRC, which are international agencies, the 192 National Red Cross or Red Crescent Societies are based in almost every country in the world. They represent local actors whose activities differ from one country to another, but all strive to relieve suffering.

As regards the coordination mechanisms of the RCRC movement, national societies are usually the first to take action locally while the IFRC or the ICRC help in coordinating and supporting national societies’ activities [IFRC].

NGO

NGOs are national and community-based non-governmental organizations functioning within the border of a country. They partner with UN agencies or International Non-Governmental Organization (INGO)s. The latter include humanitarian and multi-mandated organizations that work independently. Médecins Sans Frontières (MSF), *Oxfam International* and *Save the Children Alliance* were part of the largest INGOs in the world in 2015 [Regional Office for Asia and the Pacific (ROAP)]. Such agencies and other related groups are non-profit associations of public interest that do not need to report to a state or an international institution [Beamon and Balcik, 2008]. They support emergency preparedness and response activities of communities and national governments.

They play an important role in the global amount of aid delivered, which accounts for 60 to 80% of operations [Schenkenberg et al., 2014]. Some of these organizations direct their actions towards specific sectors (only food/nutrition, such as *Action contre la Faim* or medical care like *Médecins Sans Frontières*, for instance). Others cover several sectors such as *Cooperative for Assistance and Relief Everywhere (CARE)*

which focuses on economic empowerment, risk reduction, food & nutrition, health, education, water and sanitation [Beamon and Balcik, 2008].

Private Sector

The private sector including large or small companies in various sectors, from retail to banks, plays an active role in supporting various humanitarian operations. The private sector generally provides support as a service (logistics, telecommunication, etc.) or in the form of in-kind or cash-based donations. Humanitarian actors also rely on them for innovative support by developing the use of new technology or new organizational approaches [Marshall, 2018].

Public & Communities

The public, in addition, can be regarded as a humanitarian actor as they have an influence on the aid provided. Their first lever is by making donations to any HO of their choice. This source of funding allows aid agencies to have funds available rapidly in order to react after a crisis. In other cases they rely on public funds that are slow to be released and may take weeks to become available. Their second lever is through public opinion, which may influence public policy by drawing attention to under-publicized crises.

As for communities, whether they are formal or informal in nature, they are locally based and represent the first real responders to take action. Religious communities are one example of formal communities while informal communities may be citizens volunteering and organizing spontaneously on the basis of need. These communities are acknowledged in their contributions but difficult to integrate and coordinate into disaster management mechanisms [Batard, 2017].

Last but not least, the beneficiaries of humanitarian aid can be viewed as humanitarian actors. This is a new vision of their role. So far, they were only seen as passive aid recipients. Today, their involvement may also be to contribute, as they are best placed to know what their needs or their local capacities are. Studies currently analysing their new empowerment envision the simplification of decision-making opportunities and better fitting demand by placing beneficiaries as a pseudo-consumer with customized needs and desires [Altay et al., 2018].

1.1.4 Current capacity of Humanitarian aid

Rouyer [2021] take stock of humanitarian aid. Given the current number of crises in the world, humanitarian needs are growing: 243.8 million people in 75 countries were assessed as needing humanitarian assistance in 2020. Worse still, the COVID-19 pandemic is exacerbating existing needs and creating additional humanitarian crises. Poverty in the world is rising along with the vulnerability of various populations, which consequently increases their exposure to hazard damage. In 2020, the number of displaced people increased for the ninth consecutive year to 82.1 million (a 3.4% rise). Climate change effects are visible and threatening and food insecurity is increasing substantially [Rouyer, 2021]. Griffiths [2021] estimates that, in 2022, 274 million of people in 63 countries will need humanitarian aid and protection.

While in 2020 the world's humanitarian needs grew faster than ever, the growth of humanitarian aid has stalled over the last few years. It did increase from 2012, reaching 31,3 billion US\$ in 2018. but has stagnated since then. In any case and for a long time, the funding has never been able to meet demand, with an average of

40% of total requirements unmet (see figure 1.6). In 2020, most government donors increased their contributions, but significant reductions from a few key donors led to stagnation in the value of total aid. Globally, countries received less funding than in 2019, especially if we do not consider funding related to COVID-19 [Rouyer, 2021].

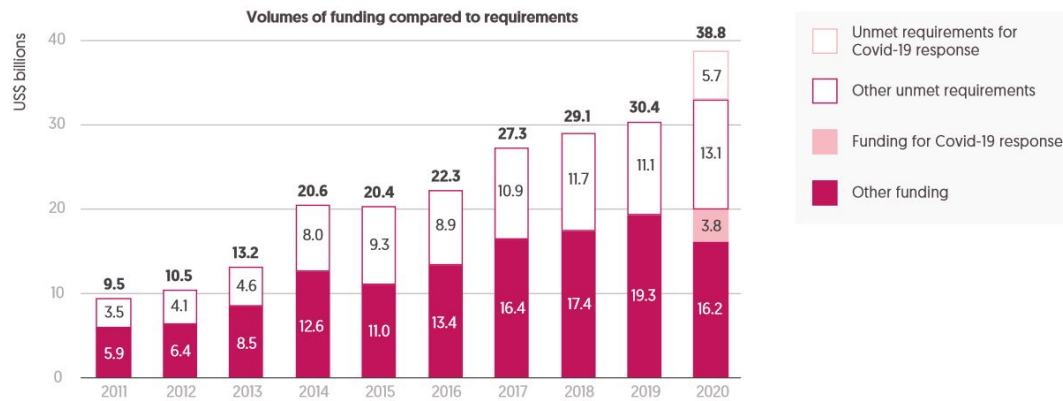


Figure 1.6: Funding and unmet requirements, UN-coordinated appeals (2011 – 2020) [Rouyer, 2021]

In the light of this concerning perspective, research motivation cannot possibly rely on reducing the number of disasters (although this is a real topic) but on the improvement in people’s living conditions when affected by natural disasters. To do so, we will focus on the relief operating procedures and mechanisms of HOs for delivering aid.

1.2 Methodology for defining the Research Problem Statement

In the research process, after choosing an interesting topic and showing its relevance for study, comes the time to define the research problem to be studied and to position it within the relevant state of the art. This phase ends with the problem statement, which requires putting the problem into context, describing the issues to address, showing the relevance of the problem and setting the objectives to pursue. Practically, a research problem is an anticipated or currently-faced issue that does not have an obvious solution. Therefore, it requires a good understanding through a refined exploration, before even considering proposing solutions.

To come up with an effective problem statement a series of steps need to be completed beforehand. In this sense, a methodology has been developed, inspired by [Bairagi and Munot, 2019, Mukherjee, 2019, Scribbr, 2019], which will be described in this section. The next section (See section 1.3), develops the methodology and defines the problem addressed in this study.

The methodology aims to frame the exploration related to the area of interest and the selection of sub-domains of interest which are then refined to address a specific problem. It comprises two major investigations (of the problem area and the research problem) and three key decisions before being able to take a position on the problem statement. Basically, the methodology works through iterative logic sequencing: repeating the actions of decision, then information collection and finally analysis.

First of all, the methodology consists in selecting a *problem area* to investigate within the existing available literature. By investigating we mean: becoming acquainted with the topic and the existing body of knowledge. This is achieved through the literature survey. In addition, it means examining the existing contributions/findings. This is achieved by performing the literature review. This work is a pre-requisite and provides strong background and context elements, which need to be kept in mind even when the problem has been narrowed down. At the end, the researcher should have a good understanding of the domain and be aware of the trends, main problem areas discussed and research gaps. More specifically, the researcher should have become acquainted with main keywords and vocabulary terms, names and work of major contributors, important historical dates and events relating to the work carried out and the interest of studying this topic. To do so, physical books, reports or articles, or queries on academic databases (e.g. Google scholar, Web of Science (WoS), SCOPUS...) are recommended [Bairagi and Munot, 2019].

Once the problem area has been scoured, a *research problem* needs to be chosen among the interest from the interesting topics of the domain and checked for relevance and feasibility with experts. A clear definition of the research problem helps in pursuing the research work and concentrates efforts, while an ill-defined project may generate difficulties and a loss of time. To ensure a clear definition, questions regarding the problem limitations, the data needed and existing methods need to be answered. In this perspective, new exploratory work has to be carried out similar to the problem area approach used. A literature survey has to be undertaken to get a good understanding of the problem characteristics and the components that revolve around them. An analysis of findings should allow similar problems related to the research subject to be identified. Also, the environment or context of the

problem is key and may lead to different outcomes [Bairagi and Munot, 2019]. Many parameters affect the problem to be studied and this is why there is a contextualizing step to define the situation and limit the perimeter in which the research problem is studied. Also, an exploration of existing contributions to address this research problem is required, and this should go beyond the defined context. The idea is to get an overview of the approaches used so far to identify gaps, to draw parallels, to explore the possibilities for simplification or the potential to relax assumptions so as to come up with a new interpretation or approach angle to investigate the topic [Mukherjee, 2019].

At this stage, the researcher normally has all the elements to clearly define the *problem statement*. In practice, an effective problem statement should address the following aspects [Bairagi and Munot, 2019]:

1. Context of the problem regarding the causes and consequences, the direct or indirect stakeholders, the geographic or temporal perimeter and whether or not these elements are debated in the the literature,
2. Relevance of the problem to present the interest of such study and the potential gains associated. Also, the gaps in debating or addressing the research problem and thus the novelty of the contribution,
3. Objectives/Approach to address the problem and define what outcomes are expected from the research work. Once defined, this leads to the definition of the research questions.
4. Feasibility of such an approach regarding the available resources, skills and time constraints.

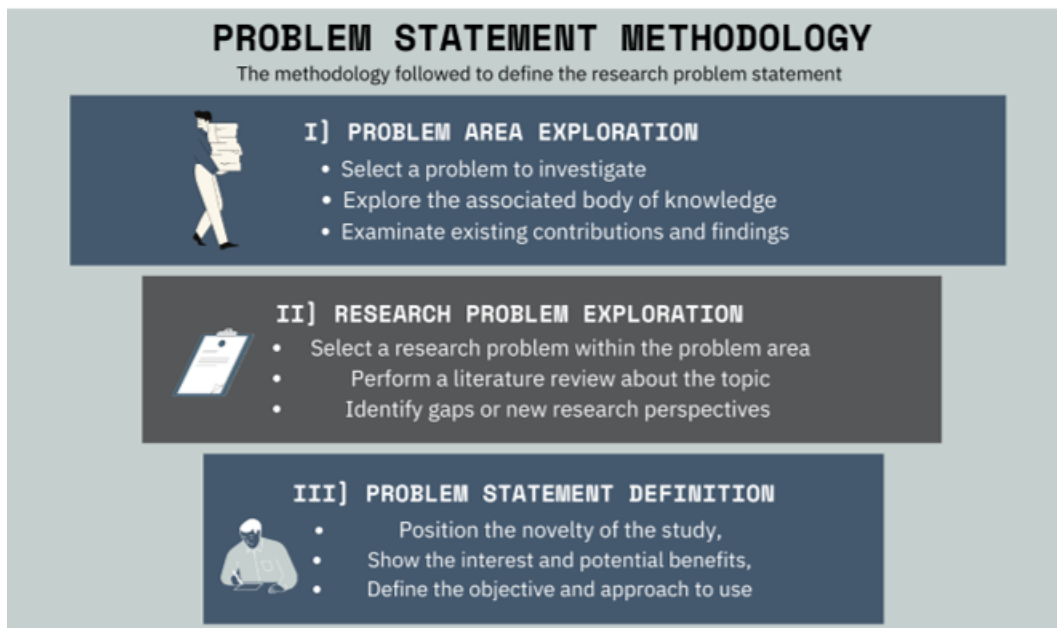


Figure 1.7: Research Problem Statement Methodology, inspired from [Bairagi and Munot, 2019]

1.3 Application of the Research Problem Statement Definition Methodology

As previously mentioned, the relief management by HOs plays a crucial role on the livelihood perspectives of victims in the aftermath of natural disasters. Among the variety of aid actions, it has been recognized in the literature that 80% of relief activities are in fact logistics efforts [Van Wassenhove, 2006] and, by extension, come about through Supply Chain Management (SCM). Specifically, these are support activities related to *“the design, planning, execution, control, and monitoring of Supply Chain (SC) activities with the objective of creating net value, building a competitive infrastructure, leveraging world-wide logistics, synchronizing supply with demand, and measuring performance globally”*, according to the Pittman and Atwater [2016] definition of SCM in a business oriented context.

Consequently, research attention has been drawn towards the improvement of the Humanitarian Supply Chain (HSC), sharing similarities with commercial SCs yet different [Kunz et al., 2017]. Consequently, this is the problem area explored and the starting point of this section.

Through a proper methodology (See Section 1.2) supporting the investigation of the topic, the next section (1.3.1) represents the first step in the application of the methodology, and will provide an overview of the academic state of the art and the concerns of its practitioners, and conclude with a review of currently debated research problems. Then, a second section (1.3.2) will discuss the performance in the humanitarian domain as a research problem. Indeed, since the ambition is to improve relief performance results, it appears obvious to spend time on this theme to understand the mechanics behind it. Focusing on the second step of the methodology, the discussion will evolve around how practitioners operate, academic data and related challenges. Finally, the problem statement (1.4) will be described in an additional section giving details about the research work undertaken.

1.3.1 Step 1 – HSC problem area investigation

1.3.1.1 HSC background

Humanitarian Supply Chain Management (HSCM) is defined as *“the planning and management of all activities related to material, information and financial flows in disaster relief. Importantly, it also includes co-ordination and collaboration with supply chain members, third party service providers, and across humanitarian organizations. Possible synonyms is: relief supply chain management”* [Kovacs and Spens, 2012].

In terms of physical flows, HSCs have to deal with materials (food, relief items, equipment, etc.) and humans (doctors, experts, volunteers, etc.). Depending on the needs, these have to be mobilized from various sources and locations and sent to the place they are expected to be. This is not possible without information and communication exchanges among the SC members, such as order transmission, transport position updates, stock movements or coordination indications. To support this structure and make the mobilization possible, money is involved [Charles and Luras, 2011]. Mostly, the financial flow comes from donors to HOs, however, new

forms of aid are appearing, such as cash transfers instead of providing relief items to beneficiaries [Altay et al., 2018].

A proper presentation and more details about HSC is provided in the second Chapter (See 2.2.2).

1.3.1.2 HSC Research domain trends

The field of SCM has been researched in depth by various studies, while its humanitarian aspects have been exhaustively discussed by only a handful of researchers.

From a global perspective, the field of humanitarian logistics and SCM has gained an increasing attention in research by academia and practitioners. Since it is a quite recently studied topic, explored for just twenty years, it is only recently gaining attention from practitioners, who are now recognizing its importance [Behl and Dutta, 2018]. Unlike the SCM domain for the business sector, which has been covered in depth by various studies, its role for managing disasters has received limited contributions in comparison. The main reasons why it counts a smaller researchers community is that research work is generally financed by own funds, and HOs cannot afford to invest in research as their means are already limited.

To identify appropriate keywords for this domain, Professor Peter Tatham (one of the top 3 contributors [Fosso Wamba, 2020] with Van Wassenhove L. N and Kovacs G) has made available his bibliography of humanitarian logistics research from the Hanken School of Economics website (Last update: 07/01/2021). A word cloud analysis using TagCrow website showing the top 50 words of referenced publications with a 10 words minimum frequency has highlighted that, in decreasing order, “humanitarian”, “logistics”, “supply chain”, “management”, “disaster” and finally “relief” are the most commonly employed words for titles.

From there, a database query using WoS over the past 20 years with the following keywords: (Humanit* AND (logisti* OR “supply chain”)) OR (“disaster relief”) generated 1,522 results from the WoS Core Collection. The following graph (see 1.8) count the records and shows the number of papers published over the years that are related to HSC. At first glance, the research domain demonstrates an increasing number of publications over time and a stepwise evolution. This evolution can be broken down into 4 main phases.

Behl and Dutta [2018] highlighted the possibility of dividing the academic work related to HSC into three major periods: Before 2005, 2005 - 2009 and 2011 onward. Our analysis led us to distinguish a fourth starting around 2015/2017.

Early stages phase

First of all, what we called the “early stages” period of the domain, includes a small amount of articles published before 2005. These works were mainly focusing on specific topics like major disaster events and associated SC strategies to respond to them [Behl and Dutta, 2018]. An illustration is the paper from Leungbootnak et al. [2005]: “*Post-tsunami disaster reconstruction management: a case study of Thailand*”.

Growth phase

Then the “growth” phase started with central articles such as [Van Wassenhove, 2006] or [Kovacs and Spens, 2007] laying the groundwork in the field. This period can itself be divided into two parts whose breaking point is at the launch of the first dedicated journal in 2011 named *Journal of Humanitarian Logistics and*

Supply Chain Management (JHLSCM). Before that period, logistics management discussions were at their early stages and the work was sparse and specific [Behl and Dutta, 2018]. Discussions were mainly focused on planning and procedures, transportation [Overstreet et al., 2011], the use of information and technologies [Fuad et al., 2006] and collaboration [Tomasini and Wassenhove, 2009] to enhance performance effectiveness [Lu et al., 2006, Davidson, 2006].

The journal’s launch, in 2011, marked a shift in the publication dynamic in the HSC field. Indeed, no longer limited by the special issue themes offered by journals willing to discuss humanitarian logistics, the work became more varied and versatile [Behl and Dutta, 2018]. At this period, humanitarian logistics was still regarded as an emerging field and interest turned towards how commercial and HSCs could benefit one another [Kovács and Spens, 2011].

Maturity phase

Finally, the current phase that probably started around 2015/2017, with this key paper from Kunz et al. [2017], can be regarded as a “mature” phase and advocates a research that is more relevant and practitioner-oriented. As highlighted at a very early stage by Kovács and Spens [2011] in 2011, there is a lack of empirical and relevant research led in association with practitioners. Indeed, even with an increased number of papers published, so few had an impact on practice and were judged to be unadapted due to, among other things, a lack of in-depth knowledge of the reality on the ground [Kunz et al., 2017]. Furthermore, there was also growing consideration for the role of the beneficiaries of aid, as the principal interested parties and those best placed to be involved in the decision-making process. Also in 2011, with this article, Kovács and Spens [2011] concluded that: “Humanitarian logistics research needs to rediscover its aim to serve beneficiaries” [Kovács and Spens, 2011]. Allowing beneficiary to take on a role has only recently and infrequently been discussed [Altay et al., 2018],[Cardoso et al., 2021].

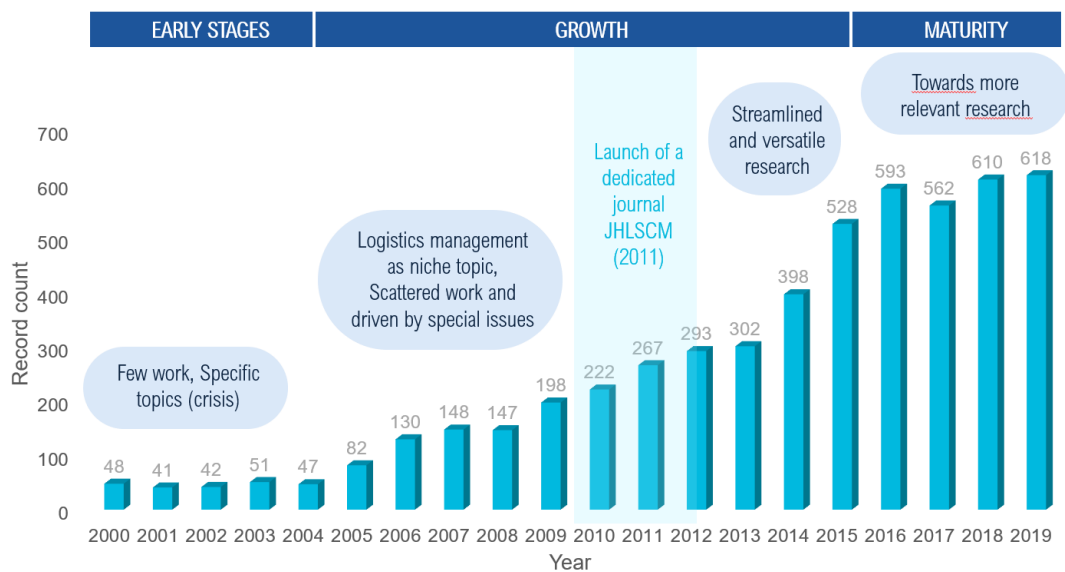


Figure 1.8: HSC domain and publication years record counting from WoS Core Collection query (2000-2019) and based on [Kunz et al., 2017, Behl and Dutta, 2018]

1.3.1.3 Mapping of knowledge structure within the HSC research domain

In order to position this research work in relation to the existing scientific literature, an exploration of recent literature reviews related to HSC was performed. To highlight topics currently discussed and research gaps, six papers held our attention: Banomyong et al. [2017], Kunz et al. [2017], Chiappetta Jabbour et al. [2017], Behl and Dutta [2018], Altay et al. [2018], Fosso Wamba [2020],

A review of these papers highlighted three major dimensions which were used to classify research articles into groups. Other possible dimensions, considered only in Chiappetta Jabbour et al. [2017], were the economic context, the type of disaster, the type of humanitarian organization, the region of authorship and the region of the disaster.

Stream Dimension

The first dimension is the stream, i.e. what is the theme of the article. This was employed in Banomyong et al. [2017], Chiappetta Jabbour et al. [2017], Behl and Dutta [2018], Altay et al. [2018] to group together publications. Behl and Dutta [2018] identified, for instance, Information & Technology related studies, performance evaluation and logistics as topics. We observed that the range of thematic discussion topics is not commonly shared and varies according to the collected papers. A list of all the themes addressed in Banomyong et al. [2017], Chiappetta Jabbour et al. [2017], Behl and Dutta [2018], Altay et al. [2018] highlighted the recurrence of certain terms among the studies. After that, secondary terms compared to big thematic terms were included. For instance, “*Big data*” was included in the Information & Technology topic. Also, topics referring to research methods were removed as part of another dimension. Five major topics have thus been distinguished:

- **Knowledge management** [Banomyong et al., 2017, Altay et al., 2018] where main stakes are related to local knowledge integration to better address the needs [Kunz et al., 2017] and enhance the quality of the reporting to capitalize upon lessons learned [Behl and Dutta, 2018]
- **Information & Technology** [Banomyong et al., 2017, Behl and Dutta, 2018, Altay et al., 2018] where main stakes are about processes standardization [Altay et al., 2018], faster the information availability and dissemination as well as speeding up the various flows using advanced technology [Leiras et al., 2014],
- **Logistics & Operations** [Banomyong et al., 2017, Behl and Dutta, 2018, Altay et al., 2018] where main stakes are about long term actions and consideration [Banomyong et al., 2017] and better preparing to accelerate the response time and quality [Behl and Dutta, 2018],
- **Integration & Collaboration** [Banomyong et al., 2017, Chiappetta Jabbour et al., 2017, Altay et al., 2018] where main stakes are about developing trust [Tatham and Kovács, 2010] and enhancing cooperation between the various actors to get over current pressures and competition slowing down the relief operations [Fathalikhani et al., 2020],
- **Performance Measurement** [Chiappetta Jabbour et al., 2017, Behl and Dutta, 2018, Altay et al., 2018] where main stakes are about long term considerations [Banomyong et al., 2017] and better monitoring performance [Kunz et al., 2017] towards the enhancement of the quality of the aid delivered.

Disaster Life Cycle Dimension

The second dimension is the positioning through the disaster life cycle. Indeed, studies can address one or several of these four categories: 1) Mitigation, 2) Preparedness, 3) Response and 4) Recovery phase. As a result, most researchers focused on the response (35%), 31% of studies gave priority to the upstream phase of the disaster and 24% to a mix between multiple phases, while the rate studying recovery (10%) is the lowest [Chiappetta Jabbour et al., 2017]. On the contrary, Banomyong et al. [2017] observed more articles dealing with mitigation and preparedness as the first studied areas but agrees that recovery is the least investigated.

Research Method Dimension

Finally, articles were classified according to the research method used, which represents the third dimension, in [Banomyong et al., 2017] and [Chiappetta Jabbour et al., 2017] only. Many research methods are possible and include qualitative, quantitative and more specifically conceptual, modelling, survey, interviews or even mixed methodologies. Chiappetta Jabbour et al. [2017] reported that the majority of articles are using qualitative methods while quantitative methods or a mix of the two are few. On the contrary, Behl and Dutta [2018] indicates that most of publications used case studies, empirical validation, simulations and mathematical modeling.

1.3.2 Step 2 – Performance as a research problem for HSCs

1.3.2.1 Practitioners' operating challenges

The humanitarian domain encounters many challenges that affect its performance and raise the question of a review of its SC.

Indeed, the location impacted by the disaster becomes an adverse environment which limits the scope of the humanitarian relief. The growing number of people on earth and the development of territories increase the complexity of disasters and their impacts. The urgency context pushes aid workers to work under pressure, responding as fast as possible, since the first 72 hours are critical to saving lives [İlhan, 2011]. Besides, the presence of a politicized environment makes humanitarian relief decisions delicate and subject to outside pressures. As an illustration, the space dedicated to humanitarian operations is often chosen by the government or military and can be limited for security or political reasons [Tomasini and Wassenhove, 2009]. Then, the high uncertainty regarding the disaster occurrence, location and damage makes it difficult to assess and anticipate resource requirements [Kovacs and Spens, 2007]. Furthermore, the fact that information systems are not well established induces a lack of data accuracy and reliability [Beamon and Balcik, 2008]. Consequently, agents are often sent into the field to evaluate the situation and waste precious time [Thomas, 2008]. Limited resource availability is another big challenge for aid agencies. When a crisis occurs, the transport network and infrastructure are often unusable or temporarily under-equipped [Wood et al., 1995]. There is also a lack of skilled and available human resources to join the aid forces [İlhan, 2011]. In addition, HOs regularly lack financial resources to perform their mission and need to wait for donations. Moreover, donation utilization is restricted by contributors' decisions and is regularly unsolicited [Ado et al., 2014]. Public opinion is also another factor to consider in raising funds. In this perspective, the media is a key player since the attention focused on a disaster has a real influence on the amount raised [Seaman,

1999]. The public image of aid agencies is also precious in order to maintain and attract donations. This has led to the creation of marketing departments within HOs [Dobiecki, 2007]. The convergence of numerous and various players on the disaster location is probably the main challenge that organizations have to deal with. The diversity in objectives, equipment and methods poses coordination and last-mile issues [Ado et al., 2014] and thus, reduces operational effectiveness [Stephenson, 2005]. Besides, the absence of regulations defining the roles of stakeholders creates confusion about the objectives of the organization and generates operational redundancies or shortcomings [Seaman, 1999]. Beyond the connection between HOs, it is also, at the core, within aid agencies' organization themselves that there are challenges to overcome. Basically, the current way operations management is performed has limitations in terms of effectiveness, efficiency and sustainability. Limited knowledge transfer [Tomasini and Wassenhove, 2009], performance measurement [Blecken, 2010] and control of distribution [Ado et al., 2014], as well as long-term considerations that are often ignored, and a neglect of environmental impacts [Eng-Larsson and Vega, 2011] are the source of mismanagement of resources and high costs. Besides, the firefighting approach, defined as "*situations where people rush from one crisis to one another without fixing each of them properly and clogging them*" [Tomasini and Wassenhove, 2009], mainly seen during the response phase, generates a lot of waste and causes optimization considerations to be neglected.

Finally, the emergency context, the destabilized transport network and the novelty of the downstream part of the supply network all make logistics efforts inefficient and under-exploited. For example, regarding transport, impracticable roads limiting access to the crisis areas [Ado et al., 2014] while the unavailability of transportation and long procedures slow down the reception of goods at the point of demand [Balcik et al., 2010]. Furthermore, the variety of the physical flow (food, tools and equipment), the different packaging formats and storage conditions required by specific items, all conspire to complicate flow management and regularly generate less-than-truckload transport [Ado et al., 2014]. In addition, often inappropriate and/or unsolicited donations provoke the underuse of products or create waste, which then requires additional operations and resources to be mobilized [Ado et al., 2014]. Relief items and donations benefit from limited monitoring along the chain while funders' expectations of better accountability are growing [Beamon and Balcik, 2008]. Finally, the unsuitability of warehouses, plus their insufficiency for humanitarian needs [Ado et al., 2014] generate under-utilization of storage facilities and increased lead times. Clearly, the humanitarian sector faces many and diverse challenges that affect its performance. Recently, logistics and SC have been recognized as concentrating most of disaster-relief efforts [Tomasini and Wassenhove, 2009] where related activities are determining factors in the success of an operation [Van Wassenhove, 2006]. This fact alone indicates that improvement in the SC is required to address most of the issues facing HSCs.

A summary of the challenges just discussed is provided in the form of an illustration (see figure 1.9).

The main objective of HOs is and will remain to save lives and alleviate human suffering. Until the end of the 20th century, the performance focus was on the operation's effectiveness (i.e. achieving the intended results) and especially on speed, as this is a determining component when lives are at stake [Tomasini and Wassenhove,

1. DISCOVER the Humanitarian Supply Chain Universe

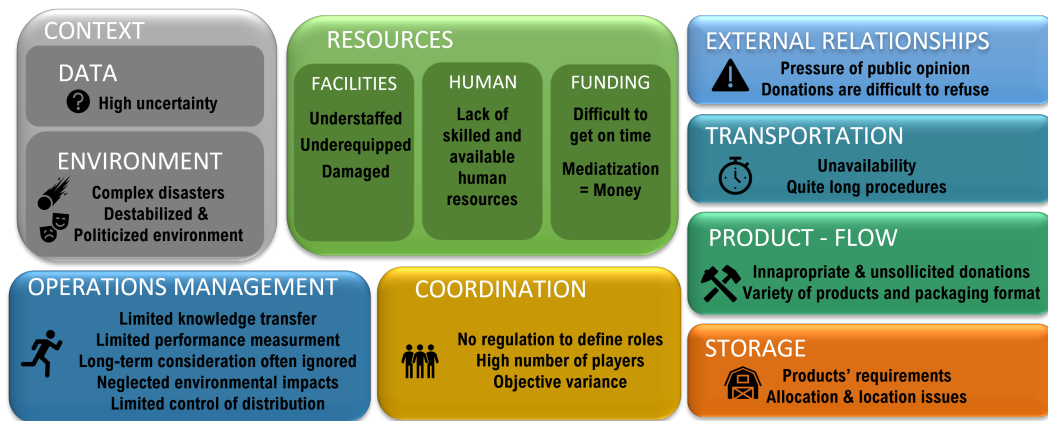


Figure 1.9: Humanitarian operation main challenges [Kovacs and Spens, 2007, Tomasini and Wassenhove, 2009]

2009]. Attention was focused on the delivery of the aid, so urgency led to a firefighting response.

A series of factors at the start of the millennium, such as (i) concerns over the scarcity of resources, (ii) increased pressure from donors requesting HOs to be more transparent and to show impactful and qualitative actions, plus (iii) the growing number of disasters, forced HOs to give a central role to performance and to monitor activities with a view to responding both efficiently and effectively [Beamon and Balcik, 2008]. In other words, they needed to perform in the best possible manner with the least waste of time and effort. At the same time, they needed to resist economically and to attract the interest of donors, given the growing competition for funding among them [Salvadó and Lauras, 2017] (see figure 1.10).

Nowadays, the increasing awareness of environment emergencies cannot be ignored, with public opinion getting more and more sensitive to this issue (see figure 1.10). As an illustration, the Sphere Handbook, a manual of humanitarian standards developed through consensus and best practices, included in its last 2018 edition a section related to the reduction of the environmental impacts of humanitarian operations. Such efforts not only support climate change but recognize that they can reduce future damage while providing an effective response [Project, 2018].

1.3.2.2 Academic challenges

Before going into the details of the literature, an etymology investigation of the term “*performance*” may be useful. According to the Online Etymology Dictionary the term originates from *parfornir* which gathers *par-* (i.e. “completely”) and *fornir* (i.e. “to provide”). Then it became *performen*: “*carry into effect, fulfill, discharge, carry out what is demanded or required*”. As for its antonym *non-performance*, it is defined as “*failure or neglect to perform*”. Of course, this term does not have the same meaning when it comes to the art domain, for instance, where it is synonymous of a stage representation [Dictionary, 2022]. All of these elements, seem to highlight three main characteristics to the idea of Performance: first, it depends of a context, which generally implies an objective. For example, in a race competition the objective is to rank the candidates and decide the winner. Secondly, to achieve such an objective, a set of specific indicators have to be chosen and measured. In our example, this would

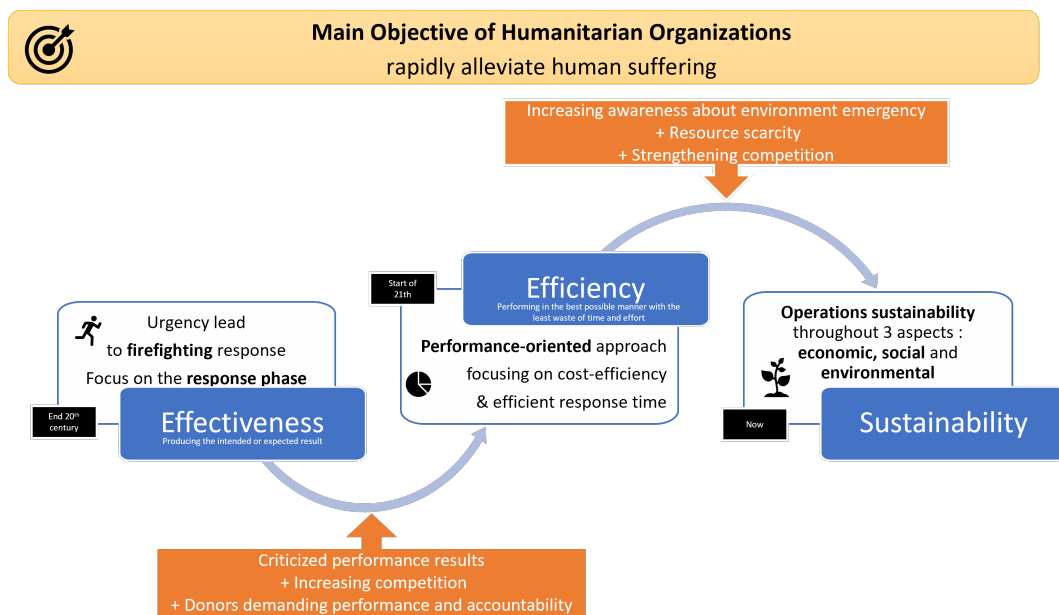


Figure 1.10: Humanitarian actors objectives evolution [Beamon and Balciik, 2008, Salvadó and Lauras, 2017]

be speed. The runners' shoe size could also be a possible measurement but it does not make sense in this situation. Finally, it involves an evaluation i.e. a comparison of the results. Indeed, we generally speak about a performance as an achievement, or we talk about a below-average performance, which necessarily means that there is a comparison with a reference.

With this in mind, a literature survey was undertaken in order to clarify, in the context of HSC:

Literature Question 1 How is the performance defined in the HSC context?

Literature Question 2 How should performance be measured in HSC?

Literature Question 3 How has performance evaluation been done so far?

The area of performance measurement and management in HSC has been investigated by researchers since 2006 in the wake of big events like the Indian Ocean Tsunami in 2004. Before that period, a few references exist but these were scattered [Abidi et al., 2014]. Until 2014, research work mostly concentrated on the definition and measurement of success, on the management of performance and the challenges impacting it [Abidi et al., 2014]. Nowadays, this field is still relatively rare in studies related to the performance evaluation of HOs [Cardoso et al., 2021].

HSC Performance definition

Humanitarian performance is defined by Ramalingam et al. [2009b] as: *“the effective collective performance of a complex system of international, national and locally-based organizations, which works to save lives, alleviate suffering and maintain human dignity both during and in the aftermath of man-made crises and natural disasters, as well working to prevent and strengthen preparedness for the occurrence of such situations”*. In addition *“effective performance means undertaking work in ways that are consistent with humanitarian principles, mobilizing and deploying sufficient*

financial, material and human resources in ways that are relevant, well-managed, accountable, impartial, durable and ensure good quality”.

In the context of HSCs, such a definition recalls the fact that HOs aim to save lives by providing aid in the aftermath of a disaster or before it strikes. The definition also explains how to be “*performant*” by using the term “*efficient*” and this, according to the definition, can be achieved basically through a smart use of resources. Surprisingly, and similarly for other definitions, it seems that humanitarian performance can be achieved by the smart use of means, while it is not totally or directly related to the objective of saving lives. In fact, this perspective is not often considered and the final results and impact on societies are often overlooked [Haavisto and Kovacs, 2012]. The potential reasons for this are the difficulties in assessing the impact on societies as they involve evaluating qualitative factors, plus the lack of access to real-time information. This said, this concern has been taken seriously in recent years and is, for instance, part of The European Parliament reflections on how to provide more effective humanitarian action [Muguruza, 2015].

HSC Performance indicators

First of all, what has been observed and recognized in the literature is that even with some close similarities to the commercial sector, humanitarian logistics is different in nature, and so performance can not be managed in the same way [Dubey et al., 2014]. The use of traditional performance indicators would be irrelevant and misleading [Abidi et al., 2014].

Consequently, our attention was drawn to the concept of Critical Success Factor (CSF), which are parameters defining success in HSC [Behl and Dutta, 2018]. Various key terms are used in publications such as, obviously, Effectiveness and Efficiency [Gizaw and Gumus, 2016] but also Agility [Kabra and Ramesh, 2016, Charles et al., 2010], Responsiveness, Flexibility [Kabra and Ramesh, 2016], Sustainability [Gizaw and Gumus, 2016, Laguna-Salvadó et al., 2019], Adaptability [Kabra and Ramesh, 2016], Alignment, Resilience and Readiness [Apte, 2020]; These concepts are also considered in the traditional SC. This overview has highlighted that there is no real shared vision about the CSF although a large number have been identified. Overall, however, little attention has been paid to the identification of CSF in the literature [Kabra and Ramesh, 2016]. Besides, such terms are vague in their definition (e.g. Resilience *reflects how quickly original state can be regained and normalcy can be retained* [Dubey et al., 2014]) and are difficult to measure as such. It is also recognized by the humanitarian community that there is a lack of clear and measurable performance indicators [Apte, 2020].

HSC Performance measurement systems

Measuring performance is recognized as being beneficial to organizations that take the time to do it [Abidi et al., 2014]. Indeed, it is clearly useful to assess a current organization or operating procedure and be able to make corrections if the outcomes do not tend to the desired level of performance. In other words, it informs decision-makers and helps in achieving strategic goals [Abidi et al., 2014]. Besides, it is of interest not only to managers but also to donors and partners that are pressuring HOs to demonstrate their effectiveness [Haavisto and Goentzel, 2015].

While it is well-known and perceived as useful by practitioners, the majority do not monitor their SC's outcomes [Blecken, 2010]. Abidi et al. [2013] identified that the main reasons for this are a lack of motivation, limited information technology

and real-time data, potential negative media exposure, conflict between goals and a non-recognition of the value of the SCM.

Research on SC performance evaluation uses various techniques from simple methods to multi-criteria decision-making tools and modeling techniques [Gizaw and Gumus, 2016]. Techniques have gained in complexity along with the development of technology. As of 2016, empirical analysis, fuzzy logic and multi-criteria decision-making methods have mostly been used [Gizaw and Gumus, 2016]. Least used were simulation, balanced score card, neural network and a combination of those. As for the analysis of HSC over the same period, not enough research has been done to permit any statistical analysis. Today, the methods employed are the Supply Chain Operations Reference (SCOR) [Gizaw and Gumus, 2016], [Davidson, 2006], the balanced score card [Gizaw and Gumus, 2016], [Davidson, 2006] and multi-criteria decision making [Gizaw and Gumus, 2016].

Clearly, performance measurement is required in order to increase effectiveness. It is not a simple matter and requires a system that monitors many indicators [Beamon and Balcik, 2008]. The literature review has revealed and highlighted different focuses or themes for monitoring humanitarian performance: Abidi et al. [2014] presents a performance framework from an organizational perspective to monitor the management, the network and the processes aspects. In [Schulz and Heigh, 2009] metrics are regrouped according to financial, time, customer service, innovation and volume aspects. Finally, Haavisto and Goentzel [2015] presents a metrics classification according to the efficiency, quality, reliability or accountability. The number, variety and level of detail in the metrics selection differ and has to be different from one organization to another depending on the objective(s) pursued.

1.4 Problem Statement

1.4.1 Context & Relevance

The threat and impact of climate change along with on-going wars, the increase in poverty and vulnerable people in the world as well as the COVID-19 pandemic, have all led to a growth in the number of disasters of different types and, as a consequence, of the number of affected people. Today, humanitarian needs have reached record levels and estimates in the following years are expected to be higher than the previous, affecting an estimated 274 million people in no less than 63 countries in 2022 [Griffiths, 2021].

Nevertheless, humanitarian aid has remained stagnant in terms of funding over the last few years and the gap in unmet requirements has increased [Rouyer, 2021]. In light of this trends, it is becoming urgent to rethink humanitarian aid as it is provided today and investigate how requirements can be met while reducing expenses.

As limiting disaster trends is unfortunately not within the scope of this research work, the research ambition instead is to contribute to improving the living conditions of people affected by natural disasters by accelerating the provision of basic necessities to victims. In parallel of doing so efficiently and sustainably. As we know, this can make a huge difference in survival rates among the population affected or later on regarding economical or social aspects at the recovery period.

In this research work, the focus is limited to major incidents and disasters characterized by a sudden onset according to the disaster classification previously defined (See section 1.1.2.1). The main reason for such a choice is our partnership with IFRC during this research work. We thus aligned with their relief operation speciality, which is natural disasters and mostly sudden onset disasters. Besides, we believe that if our work shows potential added value for this type of crisis, then it should be possible to extend it relatively easily to longer-term crises. Finally, incidents do not require any particular effort. On the contrary, catastrophes are chaotic environments, each time-unique, for which one cannot really try to propose repeatable organisational schemes. So we decided to focus mainly on major incidents and disasters.

In these situations, HOs are the main responders in assisting the population when a disaster occurs. However, given the many challenges faced by aid agencies in pursuing this mission and the poor performance in providing help, denounced after some recent major events [Thomas and Kopczak, 2005], it is legitimate to question the way they organize relief. Logistics and the SC are increasingly recognized as representing the major part of disaster-relief efforts [Tomasini and Wassenhove, 2009] and are determining factors for an operations' success [Van Wassenhove, 2006]. Factually, the management of HSC appears as the main area improvement required to address most of the issues in the delivery of aid. Besides, one activity, relief supplies distribution, is recognized as crucial [Shao et al., 2020], which is why the research perimeter includes this aspect in particular.

In this perspective, researchers have widely investigated the opportunities that the business sector could offer [Tomasini and Wassenhove, 2009]. Indeed, both sectors, humanitarian and business, show complementarities that may be of benefit to each other. For example the commercial SC is assessed as being efficient but not really agile (i.e. quickly reacting to rapid changes) whereas, for the humanitarian sector, agility is a prerequisite but there seems to be a lack of efficiency [İlhan, 2011]. There is a clear interest in cross-learning, but only targeting efficiency is restrictive since effectiveness and sustainability are also the new order qualifiers of today, and will require additional efforts in the near future [Abidi et al., 2013], . Besides, Montreuil [2011] demonstrates that logistics shows inefficiencies and symptoms of non-sustainability .For instance, the way logistics is organized and the way goods are produced, stored and displaced is about to compromise the Paris agreements regarding the reduction of gas emission. It is also non-viable from an economic and social perspective.

According to Van Wassenhove [2006], HOs are lagging behind the private sector and have taken a long time to realize the potential of effective SCM. Logically, a willingness to improve would suggest the humanitarian sector could catch up with the commercial sector, which nevertheless is not that efficient and presents many areas in need of improvement. By doing so, HSC could waste a lot of time, while by considering bypassing this gap and directly targeting a system that is more suitable to current issues, organizations would gain in efficiency and sustainability and also make savings.

Consequently, two routes are available to HOs willing to consider improving their SC:

1. Optimizing the existing system and edging toward the maturity of classical SCs. This is where most of the research is concentrated today.

2. Accepting the need to call into question some fundamentals. This is our position and one we intend to explore as a new perspective to think things differently.

Such a choice is supported by recent reports assessing current and future trends in humanitarian action and exploring opportunities [Griffiths, 2021, Rouyer, 2021]. Regarding the current situation, Rouyer [2021] highlights that COVID-19 has “*intensified the strain on a humanitarian system struggling to cope with existing challenges*” and that “*progress in reforming the delivery of humanitarian assistance needs to be consolidated and accelerated*”. Griffiths [2021] adds that “*Humanitarian action must adapt to the climate crisis*” and “*This is the moment to double down [...] and to take the kind of decisive action that is in everyone’s interests*”. Development initiatives should be directed toward better inter-agency coordination [Griffiths, 2021] and more effective deliveries [Rouyer, 2021, Griffiths, 2021].

To sum-up, while the performance target should be directed towards the improvement of the capabilities of HOs in mobilizing logistical resources in an effective, efficient and sustainable manner, as it is a viability issue for HOs today, the question of how to achieve this goal appears less obvious.

1.4.2 Vision & Objectives

To meet these requirements, our investigation of solutions has led to the discovery of the Physical Internet (PI), a new logistics concept breaking with current practices, and which may be of interest [Montreuil, 2011].

The PI is an emergent and innovative concept of an interconnected logistics networks capitalizing on the opportunity of sharing assets and capabilities [Montreuil et al., 2012b]. It has been defined as: “*[an] hyperconnected global logistics system enabling seamless open assets sharing and flow consolidation through standardized encapsulation, modularization, protocols and interfaces*” [Montreuil, 2017]. As highlighted by the definition, the PI completely remodels the foundations of logistics.

The term “*hyperconnected*” refers to the tight and intensive connection between the actors and the physical components of the network. This rapprochement operates through multiple layers i.e. at digital, physical, operational, business, legal and personal levels thanks to an optimization of the various containers and the standardization of the exchanges [Montreuil et al., 2012b].

The second core aspect of the PI lies in the desire to open up logistics networks and sharing their assets. Nowadays, companies are part of a specific and stable network and possess or have mostly their own warehouses or fleets. The concept takes the opposite view and proposes that access to these assets and their services be openly shared to all the users that are part of this global network and used on the basis of need. Also, the PI as “the network of logistics networks” would increase the visibility of, and opportunity for new partnerships. This concept of PI appears as a result of the realization that only a new logistics organization will enable us to meet the new environmental and service requirement challenges.

The current logistics system shows too many unsustainable symptoms and is participating in compromising the objectives of the Paris agreement [Ballot and Montreuil, 2014]. Before it is too late, the PI has been designed to offer a more resilient, efficient, sustainable and adaptable logistics service to its users by changing the way physical objects are handled along the network [Montreuil et al., 2012b].

Thus far, using the the PI concepts to rethink current humanitarian practices has received scant attention from researchers. The state of the art related to the Hyperconnected Humanitarian Supply Chain (HHSC), using the combination of key words such as “*Physical Internet*” or “*Hyperconnected*” and “*Humanitarian*”, has brought up very few results. A possible explanation lies in the fact that the PI is a recent concept and although it is increasing its visibility in the commercial sector, it appears plausible few applications in other domains have been investigated yet.

In this perspective, the research will be based on the main assumption that the PI has a lot to offer to the humanitarian universe in transforming HSC practices. Consequently, research efforts will be concentrated on answering three main questions:

RQ1 What are the avenues for change in practices, at the HSC level, by taking advantage of PI concepts to improve the performance of humanitarian relief?

RQ2 How can the application of PI concepts to HSC levers be assessed in terms of its impact on performance?

RQ3 How can decision-makers be supported in a relevant way and what are the consequences of such a major structural change?

These questions will each be answered respectively through the three following chapters and remains at the core of our study.

IDEATE ABOUT THE FUTURE OF HUMANITARIAN SUPPLY CHAINS

If I had asked people what they wanted, they would have said faster horses.
– Henry Ford, *American manufacturer*, (1863-1947)

The chapter’s main materials have been originally published as part of the papers entitled “Toward Humanitarian Supply Chains Enhancement by Using Physical Internet Principles” in the proceedings of the 2019 International Conference on Industrial Engineering and Systems Management (IESM), ©2019, IEEE and “Toward Assessing Physical Internet Potential Benefits for Humanitarian Supply Chains” of the Information Systems, Logistics and Supply Chain (ILS), 2020.

2.1 Context, Objectives and Methodology

I really like this quotation from Henry Ford that ironically illustrate that a client may be aware of his or her need (here, to go faster) but often go wrong on the right way to meet it. Visionaries like Henry Ford, who thought out of the box and apprehend things differently, have allowed huge progress in our daily life. Today, if we ask humanitarians what they want, they would majoritarily answer that they want to “*respond to urgent need wherever it arises*” and *respond more effectively to the needs of people affected by crisis* [Rouyer, 2021]. While they know what they want, they do not really mention how to undertake such a change. In this regard, the present research work is committed to a specific vision of the future of Humanitarian Supply Chain (HSC)s. Inspired by the Physical Internet (PI) approach, we intend to explore how to build a relief system that would meet the requirements of current humanitarian actors and even go beyond them anticipating future needs and being compliant with the issue of global warming. In this perspective, this chapter aims to provide elements to answer the following research question:

RQ1 What are the avenues for change in practices, at the HSC level, by taking advantage of PI concepts to improve performance in relief operations?

To answer this question, we based our approach on the philosophy of a mathematical equation or a process. In theory, we know that output(s) of a system are related to input factors, and that this can be written as $y = f(x_1, x_2, \dots)$. We consider HSCs as our system of interest and the outputs of such a system as the performance. Then to improve the performance, we have work on the input factors and how they relate.

However, for such a complex system as HSCs, what are the factors that influence the performance? Among them, which are the critical ones?

With this mindset, we explored the literature related to Supply Chain (SC)s in general, as HSCs are particular types of SC. Then we examined the literature related specifically to HSC, to draw out the key success factors identified by researchers. After that, we investigated the PI and associated concepts to get better acquainted with the topic. Eventually, we explored what has already been done and what is currently debated around the future of HSCs inspired from PI concepts. We shall name this hybrid paradigm between HSC and PI the *Hyperconnected Humanitarian Supply Chain (HHSC)*. All these explorations have allowed us to identify avenues or places that would benefit from the PI approach to be characterized and eventually ideated with new practices, since this original association has not really been studied so far. This sequencing was our approach to answer the previous research question. It also structures this chapter with a first section dedicated to the literature investigations, which is followed by an ideation about the HHSC and which ends with a section using a simple case study to illustrate and highlight the first perspectives of a new HSC paradigm. The chapter concludes with elements regarding the benefits and obstacles of such a change and the efforts that need to be considered.



Figure 2.1: Towards the Hyperconnected Humanitarian Supply Chain - Ideation Methodology

2.2 Literature Investigations

2.2.1 Supply chain overview and key levers

A SC is defined first and foremost as a network of organizations. These can be of various types such as suppliers, plants, distributors, clients or third party logistics (3PL)s. These SC members associate to create value in the perspective of selling a product or service to targeted clients. Each of them represents a key element of the

chain and may be in charge of various activities such as production, delivery or sales. For the chain to operate properly and to get the final product or service ready at the end to meet the demand, its members may exchange materials, information or money [Le Moigne, 2013].

According to the Council of Supply Chain Management Professionals (CSCMP) glossary, Supply Chain Management (SCM) “*encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers, and customers. In essence, SCM integrates supply and demand management within and across companies*” [CSCMP, 2013]. Put another way, SCM intends to integrate and align business processes and functions within and between organizations according to a coherent strategy. If the term SCM is widely used, it remains confusing for many. Indeed, the term has evolved since its creation and today about a dozen different definitions exist. Some orient the term towards a set of processes whereas others prefer to view it as a management principle [Le Moigne, 2013]. There is also one well known definition that presents SCM as an objective: “*to deliver the right product, in the right quantity and the right condition, to the right place at the right time for the right customer at the right price*” [swa, 2000]. Besides, terms similar to SCM are also used and may be confusing, like *materials management, demand chain, value chain* [Le Moigne, 2013] or *logistics management*. The latter is said to be “*that part of SCM that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers’ requirements*” [CSCMP, 2013]. Logistics management itself also suffers from different definitions and the absence of a common and shared definition leads to considerable confusion, which organizations like the CSCMP have tried to standardize. According to Lambert and Cooper [2000], the usual swapping between logistics and SC is probably due to the confusion between logistics as a function within an organization and the management of the physical and information flows across the SC. In a similar way, marketing cannot be managed only by the dedicated department but perceived as a bigger concept towards which all activities must align.

As highlighted by the definitions, managing a SC is challenging due to its high degree of complexity. It incorporates a large range of activities (planning, monitoring, logistics, etc.), various members (partners, suppliers, customers, etc.) and types of connection (information, physical and financial flows). Lambert and Cooper [2000] characterize the SCM in a framework that consists of three interconnected components: the SC Network structure, the SC Business processes and the SC Management components (See Fig 2.2).

2.2.1.1 The Supply Chain Network Structure

In general networks are usually associated with the communications network used in the Digital Internet (DI). In such a context, a network is defined as a collection of interlinked nodes that exchange information. A node is thus an element of the network and may be a user or a computer, while a link is the connection between two nodes [Baran, 1964].

The most fundamental network structures defined by Baran [1964] are the centralized, decentralized and the distributed networks (see figure 2.3). The centralized

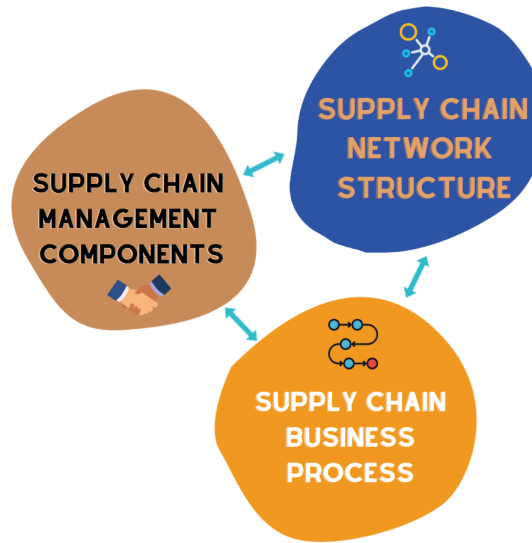


Figure 2.2: SCM framework: elements and key decisions [Lambert and Cooper, 2000]

network has a unique and central node gathering all the queries from the nodes and dispatching them to the intended nodes. It is a one-to-one form of communication. The distributed network integrates the notion of “servers” that are nodes connected to a large amount of nodes. Consequently, information transits from a sourcing node via servers offering the shortest path until reaching the destination node. In such a network, all the nodes are not all connected to one another but there are several server options for the flow routing, while in the decentralized network a node relies only on one server to transmit information. This last structure is an hybrid of the centralized and distributed network and can be characterized as a distributed network of centralized networks [Baran, 1964]. The distributed network concept is the proposed digital data communication system designed by Baran [1964] that forms the basis of the DI.

In a SC network, nodes are business members and the connection between them authorizes the exchange of physical, information and financial flows. A typical representation of the SC would show a focal company and associated members forming a network. Key configuration variables of the network structure are: (1) the number of members, as this increases management complexity, and their criticality i.e. are they contributing to the value-adding activities or supporting them by providing the means to produce outputs, (2) structural dimensions, which may be horizontal or vertical, and relate to the actors’ role in the same activity branch (horizontal) or in providing other services (vertical) and (3) the type of process link i.e. the value of the connection as well as the authority structure [Lambert and Cooper, 2000, Horling and Lesser, 2004]. Configuring the network is recognized as a strategic challenge that has a major influence on the total performance of the SC [Pishvae et al., 2009, Horling and Lesser, 2004].

2.2.1.2 The Supply Chain Business Processes

SC business processes are structured activities designed and organized to create the product or service expected by the end customer. Successful SCM and business process unification should rely on a dynamic management of products, information, cash,

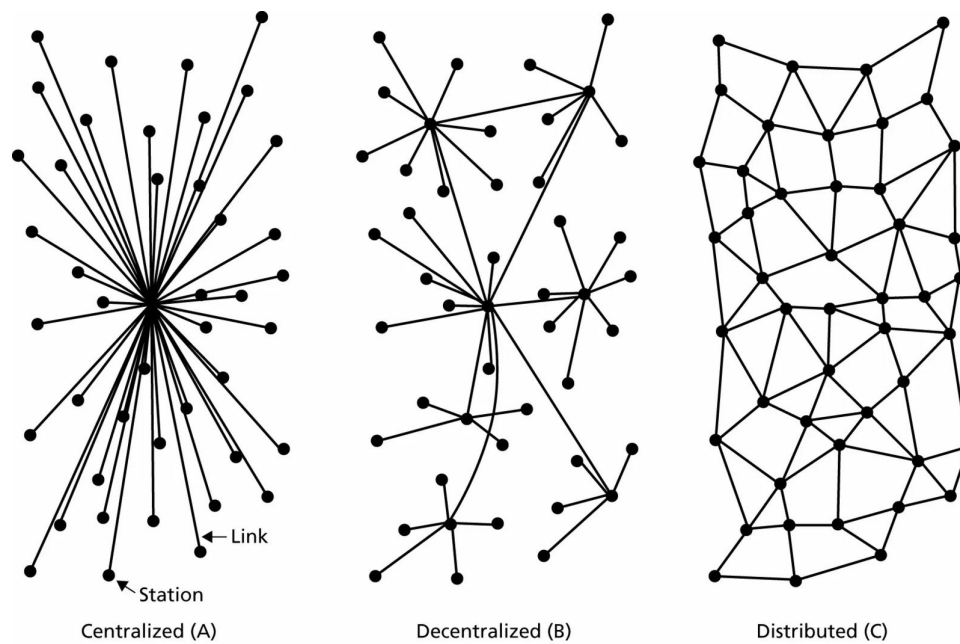


Figure 2.3: Centralized, decentralized and distributed network models by [Baran \[1964\]](#)

knowledge, and/or idea flows to induce the intended output(s). The end customer should remain central in decisions and change in demand should be monitored as well as processes and members' performance to enhance SC effectiveness [[Lambert and Cooper, 2000](#)]. Empirical research by Håkansson and Snehota has highlighted that, whether within or especially across organizations, processes are critical and directly influence the performance of the SC [[Lambert and Cooper, 2000](#)].

The APICS defines six management processes at the SC level destined to satisfy customer demand, which are available in the Supply Chain Operations Reference (SCOR) model, namely: Plan, Source, Make, Deliver, Return and Enable. Other processes exist, such as Research and Development (R&D), but appear in others APICS frameworks as they are not related to SCM directly.

Plan concerns processes aiming at planning and organizing the requirements to meet the demand,

Source processes focus on procuring goods and services,

Make processes ensure the production of goods,

Deliver processes enable the transport or accessibility of finished products or service,

Return processes are about the back management of the product for retreatment, and include after-sales services,

Enable processes that support the previously defined processes and may include the management of business rules, performance, data, resources or risks. [[Lawrence and Spring, 2017](#)].

2.2.1.3 The Supply Chain Management Components

The SCM components make up the last dimension of the SCM framework defined by Lambert and Cooper [2000]. They comprise managerial variables supporting the integration and proper functioning of the processes and links within and across the SC. For successful SCMs Lambert and Cooper [2000] identified the key physical structure and technique components of an organization, such as the planning and control of operations, the work structure, the organization structure, the product flow facility structure and the information flow facility structure and management. Additionally corporate philosophy-oriented components were also identified, such as the management methods, the power and leadership structure, the risk and reward structure and the culture and attitude within the organization. The first group contains components that are more tangible and easier to change than the second group. The second group also direct the way first-group elements are managed. One has to understand that these components are very specific from one organization to another. What is key for a successful SCM is the effort made to integrate, connect and align each element to the network. In this sense, the information flow system structure is probably the most crucial, as communication between SC members is key to the efficiency of the chain Lambert and Cooper [2000].

Spitzer [2007] dedicated an entire book to emphasising performance measurement as a key to success. Often neglected and judged too complicated, measuring performance not only shows the current state of the business, but also highlights a need for improvement and indicates the directions to be followed in order to do so. While performance measurement is recognized as having an influence on business outcomes by most organization leaders, only one third are satisfied with their current systems. In fact, it is not really a question of analyzing numbers and trends but more about creating a context where performance is effectively used, by working, for instance, on the relevance of what is measured, the involvement of workers and perception of the tool as informative rather than simply for monitoring.

2.2.2 Humanitarian Supply Chain presentation & challenges

The HSC, also referred to as “humanitarian logistics”, encompasses all the operations required for Humanitarian Organization (HO)s to achieve the goals of alleviating human suffering [Kovacs and Spens, 2007] and minimizing casualties [Thomas, 2008]. This concern induces daily engagement over the long run as disasters regularly occur across the globe and are showing an upward trend [Cozzolino, 2012]. For a long time, HOs did not recognize supply-chain issues as a crucial activity affecting their performance. However, and especially since HOs are dealing with lives, it is mandatory for HSCs to be effective and efficient, as each minute matters. Although easy to affirm, these targets are not straightforward to meet. HOs evolve in a specific context with characteristics that vary from their counterparts in the business sector. To discuss this point, the section offers the reader with an overview of HSC characteristics through the three dimensions identified by [Lambert and Cooper, 2000] namely the SC network structure, the SC business processes and the SC management components (see figure 2.2). These features, referred to as factors, are listed in a summary table (See table 2.1).

2.2.2.1 Humanitarian Supply Chain Network

Basically, to forward emergency items to the affected location, a dedicated relief network is set up. One part, called the upstream chain, is generally already in place and strategically located to cover most of the world's regions [Salvadó and Lauras, 2017]. Usually, relief goods end up at the Regional/Worldwide warehouse, which acts as a buffer and a stock decoupling point. The second part, the downstream chain, takes place in the disaster area [Salvadó and Lauras, 2017]. It connects to the available infrastructure and participants and ends at the dispensing point, which may be a field hospital, a shelter site and/or a point of distribution. These are secured locations within or close to the impacted zone where affected people gather, who are regarded as beneficiaries by aid providers.

In this type of SC, relief supplies can come from outside the disaster area (upstream section mainly) or locally (downstream section) through donations or purchases from suppliers. An illustration of a typical international HSC is shown below (see figure 2.4). In this type of supply network, the global physical flow may typically come from a plane in a first response and a boat in a second phase. Once items enter the disaster area via the entry point of the impacted country/region (airport or seaport), products are transported by railway or trucks during long-haul trips before reaching the Regional/Worldwide warehouse. Whoever the global or local suppliers are, the financial flow goes from the warehouses to the vendors, while it goes in the opposite direction in the case of donations [Ílhan, 2011]. Within the downstream chain, the physical flow leaves the Regional/Worldwide storage area to reach local warehouses close to the dispensing points. The distance and size of the warehouses tend to get smaller the closer they are to the consumption points. Finally, local warehouses oversee the last mile delivery to supply relief items to recently set up shelters. They can use vehicles to ensure the delivery or may have to adapt to local transportation conditions and thus use animals, carts, amphibious crafts or helicopters [Stephenson, 1993].

More specifically, in terms of architecture, the most common structures in general are hierarchical structures or market structures [Moharana et al., 2012] while many of the humanitarian agencies are organized as federations or pools. According to the descriptions given by Horling and Lesser [2004], these structures are as follows:

Hierarchical network organization In a hierarchical network organization nodes are connected according to a tree structure. Nodes above have authority over, and more perspectives on, the nodes below. In such an organization, there are different possible levels of decision for each node, ranging from a centralized decision-making system to a decentralized system where the bottom nodes may take local decisions. The interest of such a structure lies in the clarity of the roles, the ease of control, and consequently a harmonious system. However, this set-up can lead to limited interactions, creating a rigid system prone to single point failure as well as latency in information sharing and consequently potential bottleneck effects.

Federation network structure In a federation network structure, a set of agents gather and transfer some autonomy to a representative acting as a delegate for communicating and interacting with other representatives. This delegate is their unique contact in the pool to which they belong. This system facilitates the decision-making process, especially within an heterogeneous group.

2. IDEATE about the future of Humanitarian Supply Chains

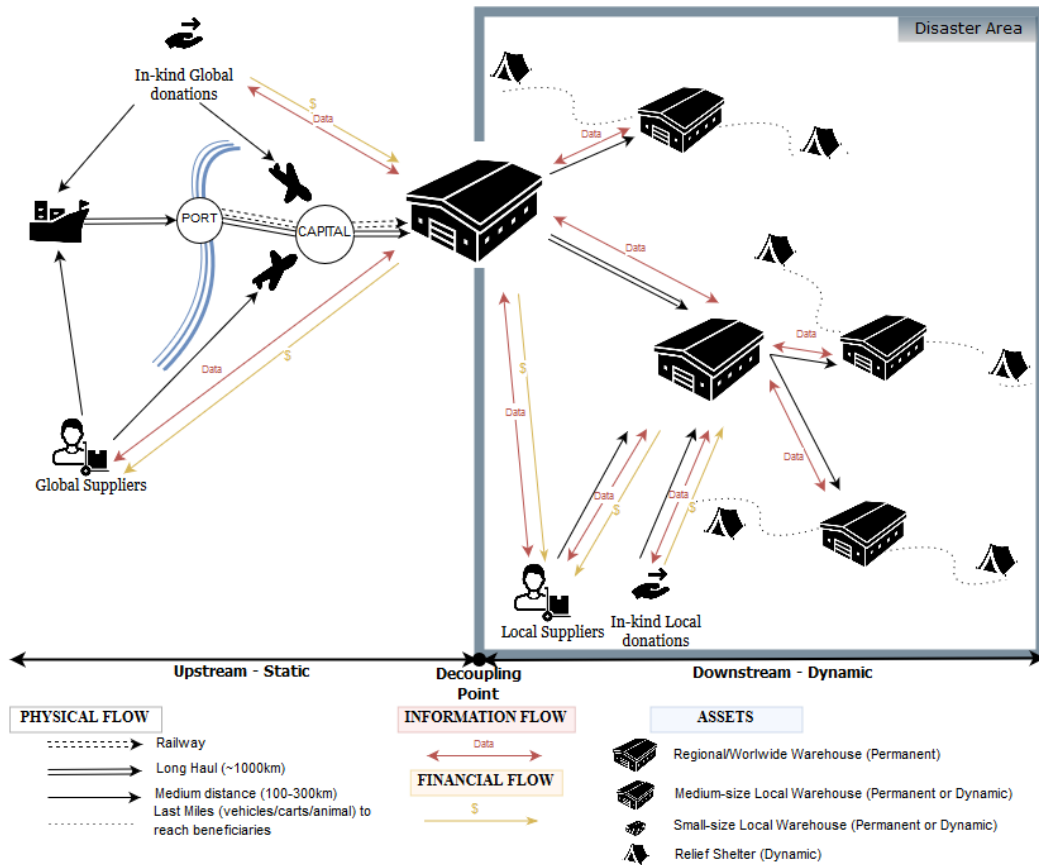


Figure 2.4: Illustration of a typical international humanitarian supply chain [Grest et al., 2019] ©2019 IEEE

Market network structure Market network structures are similar to federations in the sense that there is one or several elements responsible(s) for coordinating activities with the other participants. However, as opposed to federations, they do not transfer any authority and agents compete against each other.

In practice, HOs do not perfectly respect any one of the theoretical structures in particular. Even within the group, an organization's policies, structure and capacity may diverge. As an illustration, Save the Children Fund presents a centralized structure with standardized decision rules while Oxfam, which is rather more decentralized, operates with branches located in many countries and central offices [Dijkzeul and Moke, 2005].

An additional challenge, in a humanitarian context, as opposed to the commercial sector, is that each crisis requires the creation of a new SC, since numerous logistics nodes and linkages need to be created in addition to the existing structure [Salaun et al., 2015]. While the upstream part remains static, specific needs will vary and so, therefore, will the donors, suppliers and participating agencies. The downstream part will need to adapt to the crisis area, requiring new settings and partnerships. Consequently, the fresh connection between nodes is often fragile and subject to various challenges. The main reason for these challenges is the specificity and variety of the numerous HOs and the unclear role of the players, as well as the lack of regulations, which explains why aid agencies struggle to collaborate [Balcik et al.,

2010, Ado et al., 2014]. Nevertheless, collaboration and coordination are recognized as a key differentiator in logistics effectiveness in a disaster management context [Coppola, 2015].

2.2.2.2 Humanitarian Supply Chain Processes

When a disaster strikes, the government has to provide humanitarian assistance to its affected people, as its main responsibility is to be a first responder. As soon as the needs exceed government and local capacities, help from HOs is often requested [Weiss, 2016].

Just like any SC, HSCs aims to deliver the right products at the right place, quantity, quality and time. But unlike the commercial sector, which is relatively stable and performs moderately well at this, HSCs also have to deal with the different disaster phases and the related activities they require. Thus, each humanitarian operation and disaster phase leads to a mobilization of different resources and supply during, e.g. (i) the preparation phase, to limit potential negative effects, (ii) the immediate response phase after the strike, and (iii) the reconstruction phase to attempt to reach a stable and acceptable situation [Kovacs and Spens, 2007].

Moreover, since most disasters occur too suddenly to allow precise anticipation, humanitarians face many uncertainties regarding the disaster itself (occurrence and impacts) and the resources they are to rely on. Indeed, funding takes time to raise and liquidity is limited, volunteers are restricted due to a high turnover and finally, the infrastructure may be damaged or under-equipped [Tomasini and Wassenhove, 2009]. Consequently, HOs struggle to make plans [Charles and Lauras, 2011] and generally apply a firefighting approach [Tomasini and Wassenhove, 2009].

This context is challenging for the logistic function, since it must be ready to deploy at any moment, even though knowledge of the future needs and damage may be blurred. To be able to deliver products to beneficiaries, HSC management encompasses a range of operations related to material, information and financial flows [Kovacs and Spens, 2012]. However, unlike the business sector, it currently does not integrate any production operations. Consequently, the core functions remain supply, transport and distribution, which are critical in an emergency context [Long, 1997]. Regarding the supply operations, relief items are directly purchased from suppliers, gathered from pre-positioned stocks or provided by donors, either across borders or locally [Balcik et al., 2010]. Supplies arrive in the country via airport, seaport or land border points, and before entering the country they usually need to go through a relatively long customs clearance process. Then, the distribution proceeds in a cascading effect according to the principles of a hierarchical tree structure. Generally, once items cross the border of the affected country, they are sent to a primary hub, then to secondary warehouses, to finish at local-level depots to fulfil the needs of beneficiaries [Beamon and Balcik, 2008, Balcik et al., 2010, Laguna Salvadó et al., 2018]. The question of last-mile logistics related to delivery from local-level depots to beneficiaries is challenging and critical for equity reasons. This was highlighted as an area in need of improvement, along with the tracking and tracing of commodities to ensure accountability and human rights, in the recent *Outcome report: Shaping the Future for a Better Tomorrow* [Forum, 2021].

2.2.2.3 Humanitarian Supply Chain Management Components

The starting point of differences in approach is from the fact that humanitarian players do not share the same understanding of the importance of core humanitarian principles, namely, Neutrality, Impartiality, Independence & Humanity [Tomasini and Wassenhove, 2009]. Consequently, in the same situation, behaviors and approaches will vary and thus generate many coordination issues between the organizations [Slim, 1997]. To illustrate these differences of public policy, Dijkzeul and Moke [2005] categorized organizations according to their relationship with both victims and stakeholders. Based on this typology, the International Committee of the Red Cross (ICRC) and Médecins Sans Frontières (MSF) strongly value the impartiality principle i.e. providing aid without any discrimination, and maintaining their independence regarding their funding sources and their autonomy in decision-making. On the other hand, organizations such as World Food program (WFP) or Cooperative for Assistance and Relief Everywhere (CARE) give priority to their physical presence on the field (i.e. Solidarity) and support projects developed by governments (i.e. Subcontracting) [Dijkzeul and Moke, 2005].

Based on this vision, each agency differentiates itself and adopts a specific strategy that influences the structuring of its operating rules and network structure [Long and Wood, 1995]. This results in a culture and corporate attitude translating into policy choices at key decision levels, such as an approach based on location and the utilization of assets [Ado et al., 2014] or in terms of human resource management [Pettit and Beresford, 2009].

Consequently, these different operating approaches and work structures make coordination between the different actors very delicate, regardless of whether the aid agencies are within and outside the pool, or whether they are global or local. [Long and Wood, 1995]. In terms of collaboration, where partners are supposed to work jointly for a common objective [Moharana et al., 2012], successful outcomes have been rare, and inefficiencies common [Tomasini and Wassenhove, 2009, Stephenson, 2005]. Despite these failings, collaboration is recognized as a key differentiator in SC performance. In this perspective, information management and dissemination is crucial for effective relief management and coordination. Nonetheless, system compatibility, technology utilization and data management, while judged essential, are all areas of difficulty today. Collaboration also relies on trust and on valuing of relationships with other SC members [Pettit and Beresford, 2009].

It also requires performance measurement to ensure proper alignment with the strategy and with the accountability required by donors, which is vital for the organization's sustainability in the long run, as funding is scarce and competition increasing [Pettit and Beresford, 2009].

2.2.3 Physical Internet: objectives and issues

The PI (π) is an innovative concept that completely remodels the foundations of logistics, aiming to enable major improvement in the economic, environmental and societal sustainability of the way physical objects are moved, handled, stored, produced, supplied, designed and used through the world [Montreuil, 2011]. The symptoms of unsustainability abound. As an illustration, global demand for freight transportation is expected to triple by 2050, while induced CO₂ emissions are also projected to significantly increase and compromise Paris agreement targets

Table 2.1: Critical factors and key decision influencing HSC performance

Factor subdomain	Factor name	Factor description
Humanitarian Supply Chain Network [Abidi et al., 2014, Chopra, 2018, Spitzer, 2007, Lambert and Cooper, 2000]		
Network architecture [Lambert and Cooper, 2000, Chopra, 2018]		Members diversity, connections and leadership structure
	Logistics facilities [Le Moigne, 2013, Ado et al., 2014]	Logistics facility typology
Assets management [Le Moigne, 2013, Ado et al., 2014]	Warehouse location & allocation strategy [Ado et al., 2014]	Coverage strategy to anticipate needs
	Warehouse privacy strategy [Pettit and Beresford, 2009, Ado et al., 2014, ALICE-ETP, 2020]	Usufruct degree, accessibility, ownership
Humanitarian Supply Chain Processes [Abidi et al., 2014, Spitzer, 2007, Lambert and Cooper, 2000]		
Demand management [Pettit and Beresford, 2009]	Operational planning [Pettit and Beresford, 2009]	Operational task planning, demand assessment method
	Inventory pre-positioning [Pettit and Beresford, 2009, Ado et al., 2014, ALICE-ETP, 2020]	Demand anticipation measures related to the inventory
Inventory management [Pettit and Beresford, 2009, Ado et al., 2014, Abidi et al., 2013]	Product specification [Cross et al., 2012, Ado et al., 2014]	Type and diversity of relief item managed and provided
	Inventory policy [Pettit and Beresford, 2009, Le Moigne, 2013, Chopra, 2018]	Stock constitution rules and dimensioning
	Donations management	Organize donation promises and reception
Transport management [Pettit and Beresford, 2009, Ado et al., 2014]	Routing protocols [Le Moigne, 2013, Ado et al., 2014, L'Hermitte et al., 2018]	Routing decision to organize the transport journey
	Transportation privacy [Pettit and Beresford, 2009, Ado et al., 2014, ALICE-ETP, 2020]	Accessibility of transport opportunity
	Transport intermodality [Pettit and Beresford, 2009, ALICE-ETP, 2020]	Freight change
Warehousing management [Kılıcı et al., 2015, Pettit and Beresford, 2009]	Handling equipment [Pettit and Beresford, 2009, Ado et al., 2014]	Handling equipment for goods and packing unit manipulation
Supply management [Ado et al., 2014, Cross et al., 2012]		Replenishment method, supply sources possibilities
Distribution management [Ado et al., 2014, Le Moigne, 2013]	Last mile delivery [Forum, 2021]	Organization of the final part of the good journey from hub to final destination
	Goods track and trace [Ado et al., 2014, Forum, 2021]	Monitoring of good movement
Humanitarian Supply Chain Management Components [Abidi et al., 2014, Chopra, 2018, Spitzer, 2007, Abidi et al., 2013, Lambert and Cooper, 2000]		
Strategic planning [Pettit and Beresford, 2009, Lambert and Cooper, 2000]		Decision horizon, strategy, market analysis
Work and relationship structure [Lambert and Cooper, 2000, Abidi et al., 2013, Fertier, 2018]	Interfacing degree [Pettit and Beresford, 2009]	Communication degree between SC members
	Work standards & Protocols [Ado et al., 2014]	Operating procedures, collaboration and/or coordination degree
Continuous improvement [Pettit and Beresford, 2009]	Driving change [Pettit and Beresford, 2009, Altay et al., 2018]	Ability to change and upgrade
	Performance evaluation [Pettit and Beresford, 2009, Spitzer, 2007, Lambert and Cooper, 2000, Abidi et al., 2013]	Collecting, analyzing and/or reporting degree of information regarding the performance
Product flow facility [Pettit and Beresford, 2009, Kovacs and Spens, 2007]		Encapsulation system, packaging level and diversity
	Information transmission [Pettit and Beresford, 2009]	Capability and interest for communicating information to other players
Information flow facility [Pettit and Beresford, 2009, Kovacs and Spens, 2007]	Data collection management [Pettit and Beresford, 2009, Fertier, 2018]	Data granularity collected and processed
	Information and Communication system [Pettit and Beresford, 2009]	Technology system storing, processing and transmitting information in a digital form
Finanical flow facility [Kovacs and Spens, 2007]		Sized compared to requirements, obtention speed, complexity to manage
Corporate culture and attitude [Lambert and Cooper, 2000]		Trust, partnership degree with SC members
Human resource management [Pettit and Beresford, 2009]		Staff capacity, training, management

[[Forum International des Transports, 2019](#)]. Alongside these issues, studies show that transportation assets are underused, with 25% empty-truck travel and 10% carrying-space efficiency [[Ballot and Montreuil, 2014](#)]. In view of these observations, the PI proposes a restructuring of the current logistics system with new components and new management principles.

2.2.3.1 Physical Internet: main constituents

PI is inspired from the DI but instead of dealing with data, it deals with physical objects. In fact, while the DI is defined as “the network of computer networks”, similarly the PI is “the network of logistics networks” [[Sarraj et al., 2014](#)]. A rapid explanation of how the DI operates can help to better understand the parallel. Within the DI, when an email is sent, it is broken down into standardized data packets. Then, these packets transit to the recipient through different information networks connected to each other by routers. The role of routers is to orient data packets toward the next node until they reach their destination [[Sarraj et al., 2014](#)]. Similarly, within the PI, senders are mainly suppliers and receivers are mainly clients. The networks are logistics networks, the routers become logistics hubs, while the physical packets are standardized packaging, handling and transport containers (PI-containers) [[Sarraj et al., 2014](#)]. PI is based on the following building blocks: (1) unified set of standard modular containers; (2) containerized logistics equipment and technology; (3) standard logistics protocols; (4) certified open logistics facilities and ways; (5) global logistics monitoring systems; (6) open logistics decisional and transactional platforms; (7) smart data-driven analytics, optimization, simulation and artificial intelligence; and (8) certified open logistics service providers and users [[Montreuil et al., 2012b](#)].

New PI logistics containers, equipment and facilities paradigm

Facing the reality that most transporters are under-utilized and not optimally filled with goods, the PI addresses this issue with a new encapsulation paradigm. Currently, a large diversity of products can be packed into a large diversity of loading units, such as pallets, bags or crates. Then, these are more or less filled and put into transport units and/or transporters. Ultimately, this encapsulation system is not optimized, is costly and generates a significant loss of space while mobilizing more resources.

The PI, inspired by the principle of maritime containers, introduces the concept of standardized and modular containers that are easy to handle, store and transport, as well as being smart and eco-friendly. Similarly to the Russian doll, different levels of container, standardized in size, have been designed to fit optimally within each other. Ultimately, this would offer less variety compared to today but it would be more practical and adapted to logistics equipment for handling and facilitating storage. These PI-containers would also be connected using sensor technology such as Internet of Things (IoT) systems for tracking and tracing the movement of goods [[Ballot, 2017](#)].

This new encapsulation system would also require, by extension, a new generation of logistics equipment and facilities to be handled and deployed through the PI network. Designed to manipulate these standardized and easy-to-connect containers, handling equipment and facilities would enable a seamless, more sustainable and reliable flow of goods. Indeed, sustainability implies rethinking the way we consume and utilize resources. In this perspective, new logistics hubs will be introduced to

facilitate trans-shipments and multimodality, while private warehouses will become open PI-warehouses where non-utilized space will be available to anyone to rent. Additionally, PI transit hubs, similar to cross-docks, will organize the physical flow and consolidate shipments heading towards the same destination [Montreuil et al., 2010]. Consequently, trans-shipments will be facilitated and affordable, offering new multimodal opportunities such as the railway, which is currently underutilized while economically relevant.

New information tools and processes

To support and organize the proper deployment of goods through this PI network, communication and exchange systems have been revised. Today, communication and information exchange between businesses is fragmented and limited due to interoperability issues and lack of data-format standards. This is similar to people trading but not talking the same language, which does not facilitate the exchange, may create mistrust and thus limit coordination or collaboration opportunities. The PI intends to overcome this limitation by offering a structure and common communication language under the form of standardized protocols to facilitate the interconnection of actors. Inspired from the DI protocols, it requires to structure the flows of information (legal, customs, etc.), finance and goods (object or human). For this purpose an Open Logistics Interconnection (OLI) model has been developed. It deals with SCKey decisions on realization, distribution and mobility and is intended to be applicable to any business, location or maturity level [Montreuil et al., 2012a]. Different levels of decisions have to be integrated, but at the operational level, one example could be PI container assignment, with PI-means, shipment routing or consolidation of the containers. Such systems will also offer more visibility to all actors of the available capacities and opportunities for consolidating goods.

Hyperconnected/interconnected logistics

Nowadays, SCs mostly operate independently with dedicated assets (warehouses, equipment, trucks, etc.), sharing only the transportation infrastructure. This is clearly highlighted by looking at each organization's network and the connection between the plants, warehouses or delivery points, where we can see overlapping connections and the disconnection between the nodes (see figure 2.5). One reason lies in the interoperability and information transmission issues [Sarraj et al., 2014] which result in inefficiencies and symptoms of unsustainability in resource utilization, such as non-full trucks and empty return trips [Montreuil et al., 2012a].

Inspired from the DI, PI tempts to overturn this lack of connection with the idea of *“a hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols and interfaces to improve the efficiency and sustainability of fulfilling humanity's demand for physical object services”* [Montreuil et al., 2012b]. The PI is global as it spans the world at all scales, from within buildings and cities to across continents and the globe. It is hyperconnected in the way its components and actors are intensely interconnected on multiple layers, ultimately anytime, anywhere. Interconnectivity layers include digital, physical, operational, business, legal and personal aspects [Montreuil et al., 2012b], collectively easing PI nodes to exchange physical objects and support information and human transit. Technological platforms and tools will help in coordinating the whole system [Montreuil et al., 2012b]. It will also no longer be a question of only sharing the transport infrastructures, but rather the whole set

of logistics infrastructures. This shift towards interconnecting once private networks into an open logistics web will be accessible to any users and operated by certified and distinct parties. A new logistics paradigm such as this promises significant cost reduction and also lower CO₂ emissions [Montreuil et al., 2012a]. However, this transformation will rely on the proper functioning, and integration at a large scale, of standardized modular containers, PI logistics equipment and facilities, interfaces and protocols, as previously mentioned.

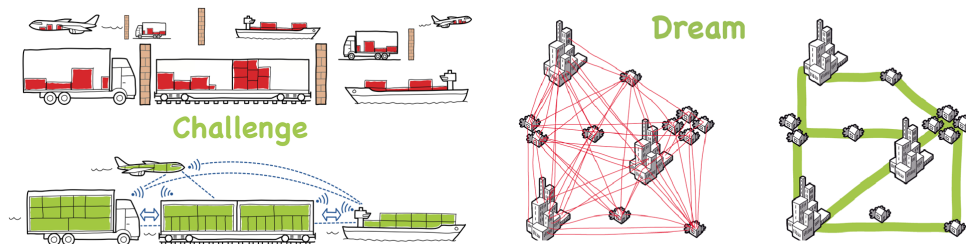


Figure 2.5: Physical Internet stakes & ambition [ALICE, 2016]

2.2.3.2 Physical Internet functionality

Based on these characteristics, the PI offers a more resilient, efficient, sustainable and adaptable logistics web service to its users [Montreuil et al., 2012b]. Indeed, by connecting nodes and creating a larger and open network, PI offers more routing opportunities and storage allocation availability [Ballot and Montreuil, 2014]. Consequently, unforeseen events, like the temporary loss of one or multiple nodes, would be easier to manage by rerouting or using other available facilities [Ballot and Montreuil, 2014]. Secondly, service levels would be improved by the gain in efficiency in the transport and warehousing domains. By mutualizing containers going to the same destination, transportation would be optimized using the appropriate combination of modes and parties, with a higher loading ratio and less empty travel [Ballot and Montreuil, 2014]. Besides, fewer vehicles would be required and thus, would lead to traffic disorgement, costs reduction and a reduction in green gas emissions [Ballot and Montreuil, 2014]. Additionally, the global design of all PI elements enables the smoothing out and speeding up physical flows, which would be noticeable in terms of delivery lead-time capacity [Ballot and Montreuil, 2014]. As regards warehousing, the possibility to share and use storage areas that, most of the time, are unsaturated [Montreuil, 2011], would allow optimization of the facilities and amortize the logistics costs, while enabling the deployment of stocks across numerous distributed facilities, near demand and across wide geomarkets [Ballot and Montreuil, 2014]. Finally, by the use of standardized protocols and contracts, the PI allows a high degree of open cooperation between the different types of actors [Montreuil et al., 2012b].

As an illustration of the concept, assume a client wants to order some products via the PI from different suppliers. Once they get the information, the items would be packed into adapted PI-containers. Then, they would transit node to node through the different logistics networks. The order's progress would be notified to both the suppliers and the client, since the containers are digitally connected. Each time a PI-hub receives some PI-containers, similar to what a digital router would do, these containers are sorted and reorganized with other PI-containers going to the same

destination [Sarraj et al., 2014]. Based on criteria like the targeted arrival date and destination as well as an assigned budget, the PI-containers are routed accordingly in the perspective of meeting these objectives [Montreuil et al., 2012b].

2.2.3.3 Physical Internet investigations & on going projects

The PI is an emerging concept that is gaining in attractiveness in both academia and the industrial domains. Indeed, even if most publications are conference papers and journals, commercial publications (project reports and white papers) account for 14% of the total number [Treiblmaier et al., 2020].

In academia, the number of research works show an increasing trend since 2011 and the number of publications is growing as well as the variety of themes addressed [Nguyen et al., 2022]. At the start, during the “incubation phase” (2008-2011), publications were not explicitly defining PI concepts but tended toward them. The “exploration phase”, identified between 2012 and 2014 emphasised PI principles and described the foundations of the concept. Publications were mostly conceptual and focused on proving feasibility and benefits. Since 2015, we are in the “expansion phase”, where topics tend to be more specialized, discussing the legal framework, transit centers, data exchange, cooperation, vehicle usage optimization and modular containers. The focus is now on the assessment of the proposed concepts and the first implementation project in industry. This trend is well illustrated by the research methodology used so far. Almost half of the papers produced have been conceptual, while one third have used quantitative methodology, including mostly simulation experiments, and the rest has taken the form of literature reviews, descriptive methods and non-quantitative simulation [Treiblmaier et al., 2020]. As for the gaps and perspectives identified, a lot remains to be explored and conceptualized via creative designs, engineering projects and simulation alongside practitioners. Also, the concepts need to be instrumented and implemented using pilots, prototypes and demonstrations to convince logistics users and make them part of the change [Montreuil et al., 2012b]. There is a real challenge with culture change, which has been identified as a major barrier to PI implementation. Indeed, today many show scepticism about the PI and expect more practical and operational explanations as well as proof of concept before they are convinced that it is worth adopting. Answers will have to address interoperability issues, container and equipment (re)design, technology usage, energy and investment requirements and reorganization efforts [Treiblmaier et al., 2020]. In this perspective, a roadmap, logically structured, has been developed to support the deployment of the PI in Europe from 2020 to 2040, with milestones and maturity levels to achieve. [ALICE-ETP, 2020]. One of these milestones is to have common and operational advanced pilots implemented in the industry by 2030. This is why PI related projects are flourishing today. The PI knowledge platform, which is the reference knowledge base for the PI powered by Alliance for Logistics Innovation through Collaboration in Europe (ALICE), currently registers fifty four ongoing projects. One of them, ICONET, is developing a cloud-based information and communication platform to support the collection, treatment and dissemination of information in future PI logistics. Several case studies and pilot projects are currently being tested to make the PI a reality.

2.2.4 Hyperconnected humanitarian supply chains

As regards the state of the art related to the HHSC, it appears that this domain has benefited from meagre attention compared to the PI ongoing discussions and objectives in the commercial context. Using the combination of key words such as “*Physical Internet*” or “*Hyperconnected*” and “*Humanitar**” has elicited few results on databases such as Web of Science (WoS), Google Scholar, and SCOPUS. A possible explanation is that the Physical Internet is a recent concept and although it is increasing its visibility in the commercial sector, it appears plausible few applications in other domains have been investigated. Nonetheless, two papers were found: [Ado et al. \[2014\]](#), [L’Hermitte et al. \[2018\]](#). Both attempt to conceptualize what being hyperconnected would mean in the humanitarian sector and highlight some early positive insights (see figure 2.6).

The paper published by [L’Hermitte et al. \[2018\]](#) explores the applicability of the PI to the humanitarian context. It confirms that such an original association has not been explored by academicians so far. For this reason, it takes a qualitative research approach in investigating the potential benefits of the PI within this sector. By crossing identified success factors from a crisis case study in New Zealand with core PI concepts, the study concludes that the PI has “the potential to enhance the speed, flexibility and reliability of emergency response”. The study also highlights the need for further investigations of the topic and above all in association with practitioners. It emphasizes that there is a need to bring strong evidence of the interest of the PI for the humanitarian sector. The suggested proposal is to use a quantitative research approach based on logistics data and to assess the current logistics performance inefficiencies, then simulate alternative responses integrating PI mechanisms to make the comparison.

The second paper, by [Ado et al. \[2014\]](#), with regard to humanitarian performance inefficiencies and challenges, investigates how PI can benefit humanitarian logistics in terms of greater efficiency and sustainability. By exploring the way operations are conducted, the authors propose what they call a global interconnected logistics system building on the interconnection of actors through a proposal of innovative information systems to manage the information flow and transactions as well as operational means such as PI-containers or PI-hubs to facilitate the transit of physical flows. The approach is similar to the previous paper as it is qualitative and focused firstly on investigating humanitarian challenges and identifying improvement areas and secondly on an exploration of PI to propose possible translations and define what they call the *humanitarian physical internet*. The authors also identify key avenues for change towards an interconnected humanitarian logistics system. The paper concludes that PI is a credible solution for overcoming humanitarian challenges. However, some additional investigation is expected, notably on the issues of coordination of humanitarian actions and knowledge management levels.

The present research work relies on the same observations as the two previous papers i.e. the humanitarian response inefficiencies and unsustainability in delivering aid and the potentiality of the PI to help overcome them. However, the methods used differ. Both the previous works start from the challenges faced by humanitarian actors and logisticians and investigate how the PI can address these inefficiencies, whereas we, for our part, decided to investigate the key factors having an influence on performance, essentially the root causes, and explored how current practices could be changed. In a sense, we consider a more holistic approach to the system. Besides,

Article	Observations	Method	Topics discussed	Conclusion(s)	Research perspective
L'hermitte et al. (2018)	<ul style="list-style-type: none"> • Applicability of the PI to the humanitarian context not discussed in the academic domain • Inefficiencies of the relief at the coordination, collaboration, use of resources, non-seamless transport flow, slow freight movement between transport modes and re-routing levels 	Qualitative research approach considering current inefficiencies and exploring PI applicability to overcome the challenges faced	<ul style="list-style-type: none"> • Standardised modular units • Open pool of hyperconnected operators & facilities • Widespread availability of real time information • Route optimisation supported by predictive & prescriptive analytics • Multi segment movements of goods 	<ul style="list-style-type: none"> • Expected outcomes in increased collaboration/coordination, optimisation of resources, efficient deliveries, rapid and well founded decisions • New paradigm not easy to implement 	<ul style="list-style-type: none"> • Inputs from practitioners • Evaluation of the logistics performance through the simulation of an alternative response based on PI principles • Avenues for conceptualisation and testing of a robust and comprehensive PI model
Ado et al. (2014)	<ul style="list-style-type: none"> • HOs use private logistics networks and partnership is limited • The logistics is neither efficient nor sustainable both economically, socially and environmentally 	Qualitative research approach considering current inefficiencies and exploring PI applicability to overcome the challenges faced	<ul style="list-style-type: none"> • Development of a humanitarian interconnected logistics system taking the opportunity of the pi-containers, humanitarian protocols and information platforms, interconnected transport, distribution and supply network • PI applicability along with the three phases of the disaster life cycle 	<ul style="list-style-type: none"> • PI is a suitable solution to improve the effectiveness and sustainability of humanitarian operations 	<ul style="list-style-type: none"> • Exploration of more coordinated humanitarian actions and knowledge management using PI potential • PI transition impacts at the regulation level of actors and stakeholders, decision support tool level and entry facilitation level of new players

Figure 2.6: HHSC Literature review of the two papers found

we also offer a slightly deeper qualitative approach which tends to be quantitative through a fictional case study to roughly assess the benefits of the PI in this specific sector. Our contribution is addressed in the following sections.

2.3 Towards the Hyperconnected Humanitarian Supply Chains (HHSC)

What we mean as HHSC is the new concept of HSC we have outlined with PI-oriented changes in practice. This new paradigm is a contribution of our research and will be detailed in the following sections, namely the HHSC network structure, HHSC business processes and HHSC management components. Our ideas have been formulated in relation to the list of factors identified as critical for HSC success, as previously discussed (See Table 2.1), which constitute the avenues for PI integration. A synthesis putting HSC current practices in perspective with suggested PI-oriented practices is available in table 2.2) as an extension of table 2.1.

2.3.1 HHSC Network Structure

According to [Pishvae et al. \[2009\]](#), the configuration of the logistics network has a real impact on the performance of the SC. According to [Lambert and Cooper \[2000\]](#), [Abidi et al. \[2013\]](#), what appear as central in the network organization performance is the way it gathers a range (in number and in variety) of members and the strength of the connection between them. Today, even within the same HO, such as the Red Cross or MSF, offices tend to be isolated and siloed from one another. Decisions are decentralized, using private means and working mostly on a need basis. There is also a trend to organize the network in a hierarchical tree or market structure [[Moharana et al., 2012](#), [Charles and Lauras, 2011](#)]. This leads to mostly unilateral exchanges and a limitation in the possible connections and service offers [[Ramalingam et al., 2009b](#)]. This approach may be explained by its ease of management and the better clarity it provides of each actor's role but it makes the network more vulnerable to disruptions.

The philosophy of the PI leads in the direction of the matrix type or multi-directional network. The connection will be vertically and horizontally authorized, thus improving the integration level of the nodes within the existing network. Besides, by increasing the level of shared information and visibility capacity of all the nodes, the HHSC offers the possibility to better exploit the resource network in local and, by extent, in global contexts.

Additionally, in the current relief network system, aid agencies also own dedicated warehouses or distribution centres to store products. These are generally permanently located, without consultation and seized on opportunity, nearby urban areas in correlation with the Gross Domestic Product (GDP) [[McGlynn Scanlon and Alawiyah, 2014](#)], which results in heterogeneous dispatch over the territory. With the PI, these will not be private anymore but accessible to any network user. As open and shared hubs, any HOs could pre-position inventory from those permanent assets and benefit from any available space opportunity. Thus, the flow from any organization could transit through the network and be deployed in a dynamic and agile manner according

to the anticipated or real demand and the state of the transport network [Ado et al., 2014]. Asset allocation and location would be dynamically adapted to predicted demand or to a change in demand, using stationary, transient or mobile PI-certified humanitarian warehouses. Assets would be managed optimally and deployed with agility, and it would be possible to consider associating with businesses as a strategic option to secure and/or pre-position inventory. Such a perspective would result in assets being reduced but more optimally positioned and thus, allow an increase in the range of coverage while limiting the risk of damage to the network. Besides, relief performance assessment would evaluate the global network organization as such, rather than just one agency organization, as is the case today. Indeed, as simply illustrated in Figure 2.7, if each colour represents one HO with a specific emergency product, according to the position, the delivery may take 1 to 4 units of time. With the open hub network, products would be stored in many hubs offering a faster and wider coverage. Furthermore, the agility offered by the PI philosophy would allow the deployment and positioning of temporary assets strategically and dynamically to support new or anticipated needs and shorten the delivery lead times.

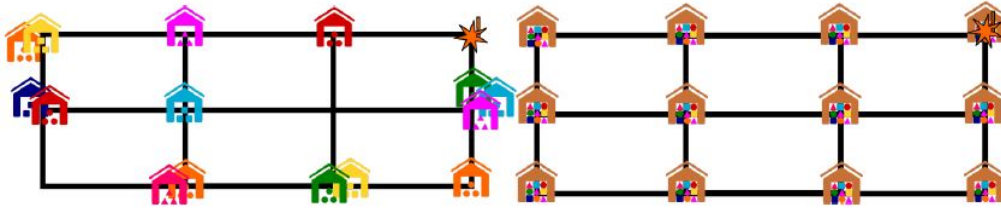


Figure 2.7: (on the left) AS-IS situation of dedicated distribution centers versus (on the right) an open-hub network with a reorganization of the assets and diversity of the stock origins increasing the coverage level and limiting the risk of damage [Grest et al., 2019] ©2019 IEEE

Finally, in the current HSCs network, formed by suppliers (vendors or donors), warehouses, ports or airports and beneficiaries, the physical flow essentially goes from one actor to another directly, on a one-to-one basis. The difference with a hyper-connected network is the addition of new node types, with the PI-hubs acting similarly to routers in the DI. With this type of node, the flow transits from an origin node and then from one hub to another before reaching its destination. As open and certified PI-hubs, they are not dedicated to a single organization and consequently, flows from different HOs going in the same direction can be re-organized and coordinated as is the case with cross-docking systems [Ballot et al., 2012] (see figure 2.8). The benefits should be notable in terms of cost and time efficiency.

2.3.2 HHSC Business Processes

Business processes or operational processes are the set of interrelated activities contributing to support an organization’s business goals. In the humanitarian context, we have identified demand management [Pettit and Beresford, 2009], inventory management [Pettit and Beresford, 2009, Ado et al., 2014, Abidi et al., 2013], transport management [Pettit and Beresford, 2009, Ado et al., 2014], warehouse and dispensing-point management [Kilci et al., 2015], supply management [Cross et al.,

2012, Ado et al., 2014] and distribution management [Ado et al., 2014, Le Moigne, 2013] as key activities in delivering aid in the form of relief items.

Prior to a disaster, humanitarian actors may have made a series of choices to anticipate the demand and prepare the response. For this, they may prepare ready-to-deploy key items, smartly pre-positioned in order to reduce delivery lead times [Pettit and Beresford, 2009, Ado et al., 2014, ALICE-ETP, 2020]. Today, pre-positioning is relatively non-existent at the local level but is more prevalent at the global level, with warehouses covering several countries, for instance [Ado et al., 2014]. There is also some anticipation of certain seasonal events like cyclones [Ado et al., 2014, Cross et al., 2012]. The elements provided are recurrently-needed items such as blankets or thematic items gathered into a family package (e.g. hygiene kits, kitchen sets, etc.) [Cross et al., 2012]. One advantage of kits is that they contain many small-sized and useful items in a package that is easy to transport, manipulate and distribute. However, they are difficult to prepare and assemble in emergency situations and it is often the case that their contents are bought or donated separately. Besides, the whole set is not always needed by recipients and kits are difficult to manage as the references do not have the same perishability date, leading to waste. As regards demand assessment, the quantity given may follow the Sphere of Standards, a set of standards and guidelines that specify the estimated needs by sectors and recipient [Project, 2018]. This system is not always followed by practitioners, as it is often not adapted to the disaster context and real needs vary according to the habits and customs of the affected region. Consequently, need estimation is generally based on experience with sector experts and only occasionally monitored [Hillson, 2001, Haight, 2012]. As regards the stock allocated, it is constituted only for recurrent items following a re-ordering point policy, and the rest is acquired on demand [Beamon and Balcik, 2008]. Besides, donations often flood the physical flow in an unsolicited and poorly-adapted manner, creating congestion, additional handling and waste [Tomasini and Wassenhove, 2009]. These donations are found to be difficult to refuse and need to be traced and reported to donors explaining their proper use [Ado et al., 2014].

The PI offers new perspectives for assessing demand by taking advantage of technology to gain access to real-time data, forecast the demand [Pettit and Beresford, 2009, Le Moigne, 2013] and monitor worldwide requirements [Ado et al., 2014]. Consequently, items can be located both nearer to the predicted areas of crisis and also secured from potential damage. The open network would offer a new opportunity for stock pre-positioning and make it possible to benefit from the available capacity of local business. Additionally, sourcing locally would be facilitated and lead to a more sustainable and adapted distribution, benefiting both local markets and recipients with a better fit in terms of needs. Organizing production closer to the point of consumption is another philosophy supported by the PI, where we may imagine that better needs estimates, sourcing offers or rapid production of equipment via 3D printing, for example, could allow customized kits to be rapidly assembled on demand. High-technology decision-support systems could help the purchasing department to anticipate purchases and local market trends while constituting stock inventory or building on partnerships to secure inventory. Finally, earmarked donations that are tagged donations to support relief operation(s) of the donors' choice, would be easier to manage and optimally used, with an increased visibility of available inventory, commitment and global requirements.

Although different from the circumstances faced by commercial organizations, the provision of transport and distribution is a challenging but essential requirement in the emergency context [Long, 1997, Ado et al., 2014]. Important aspects include the mode of transport, capacity utilization and scheduling to minimize the associated costs [Pettit and Beresford, 2009]. Regarding routing and transport mode shifts to satisfy change in demand or disruption, it is currently non-optimized, relying on information that could be captured beforehand by following main transport axes or nodes, leading to congestion due to a significant number of private and direct shipments [Blecken, 2010]. Moreover, trucks are not always full, sought to be mobilized from every node in a network [Kovacs and Spens, 2007] while there is limited availability of means of transportation, leading to competition and cost increases [Pettit and Beresford, 2009]. In addition, transport intermodality and freight change possibilities [Pettit and Beresford, 2009, L’Hermitte et al., 2018] are currently limited due to badly designed interfaces, which are judged to be cost and time inefficient and even risky [Montreuil, 2011]. Last-mile delivery organization is also really challenging [Forum, 2021] as it poses coordination issues [Kovacs and Spens, 2007] with the use of original means such as amphibious crafts or animals to access difficult and remote areas [Pettit and Beresford, 2009]. Furthermore, the tracking and tracing of transportation as well as the dispatch to recipient is neither egalitarian nor well controlled [Ado et al., 2014]. In light of these issues, the PI offers new perspectives to overcome them. First of all, there is an opportunity for opening and sharing transport opportunities between different organizations to organize the deliveries. Indeed, as illustrated by this figure 2.8, transport means can be coordinated, reduced in number and better fulfilled if transport consolidation is authorized and supported by efficient transmodal shift systems and an increased visibility regarding each actor’s delivery planning. The benefits should be significant in terms of efficiency. As an illustration, in the business sector, a reduction of transportation cost has been measured, with an improved fill rate from 65% to 85% and about a 60% reduction of greenhouse gas emissions and 15% of distance travelled [Ballot et al., 2012].

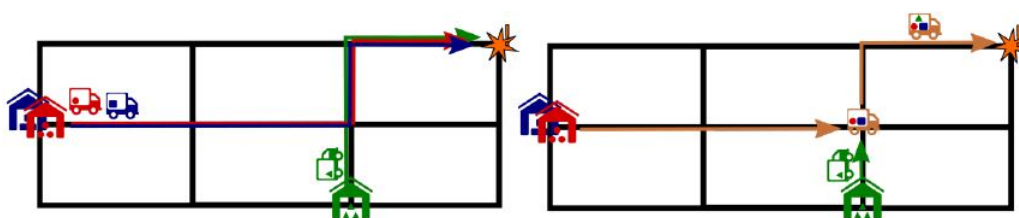


Figure 2.8: (on the left) AS-IS situation of one-to-one flows and dedicated transports versus (on the right) flow consolidation with open-hubs [Grest et al., 2019] ©2019 IEEE

PI also proposes encapsulating goods in PI-containers. Modular containers would be developed that are easy to handle, store and transport. They would also be smart, connected and eco-friendly to protect the encapsulated objects. These containers would be designed to easily snap together since the point is to maximize truck fulfillment or storage [Thomas, 2008]. Furthermore, if these boxes were unmarked they would become generic in terms of property (see figure 2.9, on the right). Imagine far and wide the perspectives, if inventory were not longer dedicated to one

organization, but represent a global and common stock for all aid agencies to avoid redundancies and better managing demand.

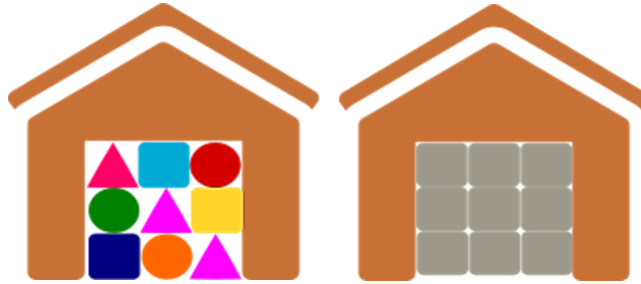


Figure 2.9: (on the left), optimization of storage capacity by mutualizing stock from different organizations (on the right), storage optimization using unmarked PI-containers [Grest et al., 2019] ©2019 IEEE

Besides, the use of IoT systems to monitor stocks would be beneficial to master lead-times and provide the accountability donors are expecting [Ballot and Montreuil, 2014]. Additionally, taking opportunity of easy transport change and innovation could increase access to new or customized means [Ado et al., 2014] such as drones or autonomous vehicles [Altay et al., 2018] as a solution to last-miles difficulties, or railway as a more sustainable approach than trucks [Montreuil, 2011]. Predictive and prescriptive analytics could support optimized routing, real-time adjustments and transport shifts in an effective, efficient and sustainable manner.

Last but not least, the supply process ensuring that the material and goods needed are available to support operational requirements and proper functioning [Blecken, 2010] is a central relief activity and source of expenditure [Le Moigne, 2013]. Decisions related to the supplier selection and mobilization strategy are fundamental in the process. Today, there is a trade-off and debate to consider between sourcing locally or globally, and both present advantages and disadvantages. Sourcing locally means reviving the local economy, reducing the delivery lead time and sourcing items that are adapted to the habits of the population. However, it tends to inflate prices, meaning goods become unaffordable for locals. Stock may be limited or not meet the quality requirements expected [Kusumastuti, Insanita, and Wibowo, 2010, Beamon and Balcik, 2008]. Sourcing globally (i.e. outside the affected region or country) may offer more sourcing possibilities and inventory availability to make large purchases and thus decrease costs. However, it involves time-consuming transport processes (long custom clearance procedures, competitive bidding) and large capacity requirements to send the shipments [Balcik et al., 2010, Kusumastuti et al., 2010]. The PI approach, as an open and interconnected network, would extend the sourcing panel options and capacity visibility to take better advantage of existing in-country sources of supply which are available in a short period of time. Furthermore, multi-sourcing would be facilitated to avoid drawing too many resources from some regions and provide better dispatching. Besides, it can be expected that better coordination between HOs in the actions undertaken would limit sourcing to what is strictly necessary and thus avoid waste. Finally, if the mobilization comes from pre-positioned storage units, convoys or material handling devices could be adapted to handle and organize PI-containers from various organizations and optimally prepare the shipments in an efficient way.

2.3.3 HHSC Management Components

Management components such as strategic planning, culture, work structure, continuous improvement procedures or external relations management have been identified as key aspects driving success in an organization [Abidi et al., 2014, Chopra, 2018, Spitzer, 2007, Abidi et al., 2013, Lambert and Cooper, 2000].

The strategy of a system is a sort of action plan defined to differentiate the organization from competitors and allow it to remain competitive in a specific marketplace and for a given period. Spitzer [2007] points out that any organization, even a non-profit one, should concentrate on the management of its activities and how to create value to remain competitive. To do so, *“value is created when the business model is properly leveraged through the effective execution of the strategy to produce the right operational performance”*. In other words, strategic priorities should be aligned with market demand and the performance measurement system consistent to them.

In the current humanitarian context, priorities should turn towards meeting the growing expectations of donors regarding transparency, or focus on the trends related to cash preference or giving priority to local resources. There is a real need to address the question of how to design the SC so that it is consistent with those it is assisting [Pettit and Beresford, 2009]. Also, Pettit and Beresford [2009] mentions the utility of strategic planning i.e. how to prepare the organization to respond to different disaster scenarios. Planning can be done at the resource level, via inventory pre-positioning approaches, securing capital or training volunteers for instance and differ according to the political or economic environment of the agency. Currently, although improvements are underway, strategic planning is often oriented towards short-term goals [Eng-Larsson and Vega, 2011], with a lack of preparation leading to firefighting responses [Pettit and Beresford, 2009] and sometimes denounced for causing more social or environmental damage than the disaster itself [Ado et al., 2014]. We imagine for the future HSC the possibility and capacity for organizations to consider both short-term and long-term goals, as well as multiple performance objectives. Also regarded as a success factor, performance measurement should be aligned with priorities [Abidi et al., 2013]. Priorities may evolve and need to be carefully selected, as they determine the efforts to make and consequently the results obtained [Spitzer, 2007]. In this perspective, it becomes important to consider not only effectiveness and efficiency but also sustainability, readiness or whatever indicator that is considered strategically important to adapt to value trends [Pettit and Beresford, 2009, Ado et al., 2014, Tohamy, 2017]. For this to be made possible will require a shift in technology utilization, data management and performance monitoring, all of which are recognized as key elements in determining the success of relief operations [Pettit and Beresford, 2009, Kovacs and Spens, 2007, Fertier, 2018]. Currently, data are collected in a fragmented manner via an ad hoc and basic set of tools, and generally not reliable due to a lack of resources [Pettit and Beresford, 2009, Ado et al., 2014, Laguna-Salvadó et al., 2019]. With the introduction of state-of-the-art tools and methods (e.g. pad technology, IoT systems, or sensors) as supported by the PI, real-time and reliable information will allow prescriptive analysis to recommend actions. An optimal use of resources and rapid change to adjust from strategic deviance or change in demand can thus be expected [Tohamy, 2017]. To initiate such a change, humanitarian culture should emphasise innovation and drive change [Pettit and Beresford, 2009, Altay et al., 2018]. Today, the humanitarian

sector is not that accustomed to performing continuous improvement [Davidson, 2006] preferring an approach based on lessons learned after the fact. There is little literature on these topics and large opportunities for new products, services, processes or paradigms [Altay et al., 2018].

The organizational structure of a system, like the work structure and openness to external relationships, is also recognized as a key element of success [Lambert and Cooper, 2000, Fertier, 2018, Abidi et al., 2013]. Nowadays, differentiation and competition is no longer centralized at the isolated business level but between one SC versus another [Lambert and Cooper, 2000]. However, currently, there is little coordination and collaboration between HSC members, whether horizontal or vertical (i.e. within the same activity sector or not). Difficulties lie in the lack of regulation and visibility regarding each HO's role and specialization, as well as the fact that there are no standards and protocols to coordinate activities in such a context [Pettit and Beresford, 2009, Ado et al., 2014]. In addition, there is little information transmission, only on a sparse and need-to-know basis, due to funding competition leading participants to keep information private [Pettit and Beresford, 2009, Stephenson, 2005, Ado et al., 2014].

Coordination is recognized as essential in improving relief performance as it influences operation costs, delivery lead time and ultimately the level of service provided [Balcik et al., 2010]. That is certainly why, PI emphasises the interconnection of actors. In this perspective, one proposal is to facilitate communication and exchanges by the use of standardised contracts and protocols [Ballot and Montreuil, 2014]. Speaking the same language and using the same working rules should facilitate partnerships and make them last in the long run. This concept builds on the ease of connection and the development of trust, deemed fundamental [Pettit and Beresford, 2009].

Using common standards would also apply to managing the physical flow as well. Using standardized packaging and handling equipment would ease the transfer of goods, enabling agile rerouting in case of disruption and in the end, speeding up deliveries [Ado et al., 2014]. At that moment, cardboard or plastic boxes of various sizes are used to pack the relief items. These are gathered onto pallets and if required into standard containers. Such systems generate non-optimum transport fill rates and waste. The PI-containers, on the contrary, can easily fit into the various transportation means and into one another, are design to be reusable and embed sensors for tracking purposes.

Furthermore, by taking opportunity of real-time and centralized systems connecting actors and sharing available capacity as well as requirements would automatically increase the use of resources in a win-win perspective. Indeed, by knowing the commitment intentions of each actor, the requirements and current state of the relief should allow a better workload distribution among the parties engaged in the relief and avoid the demand being over- or under-met. This central platform could also benefit in-kind donations management. Today, donations generate a significant slowdown of the delivery flow due to unsolicited and inappropriate donations but also due to unequal funding distribution among the on-going relief operations. For instance, International Federation of Red Cross and Red Crescent Societies (IFRC) reported in 2006 an example where a tsunami was funded up to 475% while a crisis in Djibouti was funded only up to 39% [Ado et al., 2014]. By centralizing donations and offering visibility regarding the covered and uncovered requirements should increase

the equity, traceability and speed of the aid provided. Furthermore, aid is increasingly distributed to beneficiaries in the form of cash rather than goods. This currently poses cash transfer issues from a technical point of view and is being debated as a potential source of anti-social and discriminatory distribution [Bailey et al., 2008]. This again underlines the need for appropriate tracking and tracing tools. Within a hyperconnected world, the use of PI-oriented information and communication tools such as Blockchain [Baharmand et al., 2021] or the ICONET project currently being explored could help in this challenge. By benefiting from high-technology systems and the IoT revolution, centralized systems could provide an end-to-end visibility of PI-objects and information exchange in a secure, adapted and real-time manner to all relevant actors from donors to beneficiaries.

Finally, it is recognized that human resource management heavily influences the ability of an organization to respond effectively [Pettit and Beresford, 2009]. Today this is a key issue as there is a lack of volunteers, experts and well-trained resources. Volunteers, representing most of the human resources in comparison to permanent staff, present a high turnover. Indeed, from an individual perspective, the psychological effects and efforts required are demanding. Moreover, employers do not always allow their employees to perform another activity. Some supporting operation departments, such as logistics, have difficulties in recruiting as they are regarded as less attractive than front-end activities in the field. Finally, there is a lack of well-trained experts, especially at the local level [Pettit and Beresford, 2009]. To meet this challenge, using a PI-based logic, we can imagine human resources that are no longer dedicated to a single organization but rather forming a global or regional pool. This would offer more diversity and flexibility in meeting requirements. Training could be grouped, offered by real experts and providing a wider benefit to the greatest number using videoconferencing tools, for instance. Thus, training practices would be standardized and emphasize resource versatility to facilitate collaboration and partnerships.

In the following table (See Table 2.2) all of the critical HSC factors previously identified are brought together (See Table 2.1). In addition, it presents current practices compared to proposals for HHSC practices inspired from PI concepts and new trends. Stepping back, the work here is partly aligned with the suggestions proposed by Ado et al. [2014], L’Hermitte et al. [2018]. However, it differentiates in the approach used to end up with this set of new practices, which leads to a widening of the scope of applicability by addressing additional sectors.

2.4 Illustrative Case Study

To roughly assess HHSC potentials we developed a basic and fictive case study inspired from practices in Indonesia and serving as a support to highlight first perspectives of the PI interests for the humanitarian sector.

2.4.1 Case study definition

Note that, the following case is inspired by the current Indonesian Red Cross organization following a 10-day field survey made in July 2019 and completed with

Table 2.2: Critical factors and key decisions influencing HSC performance (1/3)

Factor subdomain	Factor name	Factor description	Current practices	Possible PI-oriented practices
	Humanitarian Supply Chain Network [Abidi et al., 2014, Chopra, 2018, Spitzer, 2007, Lambert and Cooper, 2000]			
Network architecture [Lambert and Cooper, 2000, Chopra, 2018]		Members diversity, connections and leadership structure	Isolated/Siloed businesses, Limited connection (only horizontal), Unilateral network [Charles and Laurs, 2011, Ramalingam et al., 2009b]	Integrated businesses, Interconnected horizontally & vertically, Multi-directional network (matrix-type) [Ado et al., 2014]
	Logistics facilities [Le Moigne, 2013, Ado et al., 2014]	Logistics facility typology	Classical logistics nodes (port/airport/warehouses) Population & GDP oriented	Certified PI-logistics nodes (transit hub, PI-gateway...)
Assets management [Le Moigne, 2013, Ado et al., 2014]	Assets location & allocation strategy [Ado et al., 2014]	Coverage strategy to anticipate needs	[McGlynn Scanlon and Alawiyah, 2014, Kusumastuti et al., 2010], nearby dense areas and opportunity, mostly permanent	Demand and readiness oriented, agile deployment, different longevity levels
	Assets governance [Pettit and Beresford, 2009, Ado et al., 2014, ALLICE-ETP, 2020]	Usufruct degree, accessibility, ownership	Owner's right of use, responsibility and maintenance [Cross et al., 2012]	Shared and accessible to all network members, third party ownership and responsibility

Table 2.3: Critical factors and key decisions influencing HSC performance (2/3)

Factor subdomain	Factor name	Factor description	Current practices	Possible PI-oriented practices
Humanitarian Supply Chain Processes [Abidi et al., 2014, Spitzer, 2007, Lambert and Cooper, 2000]				
Demand management [Pettit and Beresford, 2009]	Operational planning [Pettit and Beresford, 2009]	Operational task planning, demand assessment method	Experience based [Hillson, 2001], discretely planned and monitored [Haight, 2012]	Predictive analysis and real-time monitoring
	Inventory pre-positioning [Pettit and Beresford, 2009, Ado et al., 2014, ALICE-ETP, 2020]	Demand anticipation measures related to the inventory	Practically non-existent, global and uniform [Ado et al., 2014]	Relying on prediction, dynamically deployed
Inventory management [Pettit and Beresford, 2009, Ado et al., 2014, Abidi et al., 2013]	Product specification [Cross et al., 2012, Ado et al., 2014]	Type and diversity of relief item managed and provided	Standard, selection, and family package [Cross et al., 2012]	Customized and packed on demand
	Inventory policy [Pettit and Beresford, 2009, Le Moigne, 2013, Chopra, 2018]	Stock constitution rules and dimensioning	Limited stock constitution for frequent items only and more specific ones are acquired on demand [Beamon and Balcik, 2008]	Need anticipation, partnerships to secure inventory, favour local sourcing
	Donations management [Cross et al., 2012, Ado et al., 2014]	Organize donation promises and management	Unsolicited, unadapted and earmarked donations [Tomasini and Wassenhove, 2009], Limited usage, congestion and difficult to manage and trace [Ado et al., 2014]	Digital platform to manage worldwide requirements
Transport management [Pettit and Beresford, 2009, Ado et al., 2014]	Routing protocols [Le Moigne, 2013, Ado et al., 2014, L'Hermitte et al., 2018]	Routing decision to organize the transport journey	Non optimized, on demand, shortest path, direct shipment, empty return [Blecken, 2010]	Real-time adjustment of assignments and routings supported by optimization and decision support systems
	Transportation privacy [Pettit and Beresford, 2009, Ado et al., 2014, ALICE-ETP, 2020]	Accessibility of transport opportunity	Dedicated fleet, independently mobilized at every node [Ado et al., 2014, Kovacs and Spens, 2007]	Shipment consolidation, coordinated deliveries
	Transport intermodality [Pettit and Beresford, 2009, ALICE-ETP, 2020]	Freight change	Limited, badly designed interfaces, cost inefficient and risky [Montreuil, 2011]	Multi segment and multi-modal transportation
Warehousing management [Kilci et al., 2015, Pettit and Beresford, 2009]	Handling equipment [Pettit and Beresford, 2009, Ado et al., 2014]	Handling equipment for goods and packing unit manipulation	Large diversity of convey and material handling devices	Standardized and adapted pi-material handling devices to easily manipulate PI-containers
	Supply management [Ado et al., 2014, Cross et al., 2012]	Replenishment method, supply sources possibilities	Limited supply source(s), Available products nearby are not taken as an advantage [Balcik et al., 2010, Ado et al., 2014]	Use of existing in-country sources, multi-sourcing
Distribution management [Ado et al., 2014, Le Moigne, 2013]	Last mile delivery [Forum, 2021]	Organization of the final part of the goods journey from hub to final destination	Amphibious craft, horses, bikes for remote and areas difficult to access [Pettit and Beresford, 2009]	Customized transport systems and vehicles, new technology advanced systems [Ado et al., 2014, Altay et al., 2018]
	Goods track and trace [Ado et al., 2014, Forum, 2021]	Monitoring of goods movement	Egalitarian and monitoring difficulties with ad hoc and basic tools [Ado et al., 2014]	Use of advanced technology and digital platforms to frequently collect and disseminate data

Table 2.4: Critical factors and key decisions influencing HSC performance (3/3)

Factor subdomain	Factor name	Factor description	Current practices	Possible PI-oriented practices
Strategic planning	Humanitarian Supply Chain Management Components [Abidi et al., 2014, Chopra, 2018, Spitzer, 2007, Abidi et al., 2013, Lambert and Cooper, 2000]	Decision horizon, strategy, market analysis	Not prepared enough [Pettit and Beresford, 2009], short term [Eng-Larsson and Vega, 2011], reactive [Hillson, 2001]	Prescriptive [Tohamy, 2017], long term [Ado et al., 2014], value market oriented [Spitzer, 2007]
		Interfacing degree [Pettit and Beresford, 2009]	Communication degree between SC members	Limited, ad hoc, interoperability issues [Pettit and Beresford, 2005, Ado et al., 2014]
Work and relationship structure [Lambert and Cooper, 2000, Abidi et al., 2013, Fertier, 2018]	Work standards & Protocols [Ado et al., 2014]	Operating procedures, collaboration and/or coordination degree	Disorganised, no regulation in the coordination of activities between various actors [Ado et al., 2014]	Regulation and clarity of roles and available resources to assign, frame and coordinate the relief activities [Ado et al., 2014]
		Driving change [Pettit and Beresford, 2009, Altay et al., 2018]	Ability to change and upgrade	Little regarded and integrated [Davidson, 2006], paucity of the literature on this topic [Altay et al., 2018]
Continuous improvement [Pettit and Beresford, 2009]	Performance evaluation [Pettit and Beresford, 2009, Spitzer, 2007, Lambert and Cooper, 2000, Abidi et al., 2013]	Collecting, analyzing and/or reporting degree of information regarding the performance	Partially developed, short-term oriented [Laguna-Salvadó et al., 2019]	Real-time adjustment, continuously monitored, strategically important
		Product flow facility [Pettit and Beresford, 2009, Kovacs and Spens, 2007]	Encapsulation system, packaging level and diversity	Variety of dimensions and encapsulations systems, not always reusable
Information flow facility [Pettit and Beresford, 2009, Kovacs and Spens, 2007]	Information transmission [Pettit and Beresford, 2009]	Capability and interest of communicating information to other players	Sparse and on basis of need, competition limits the share of strategic data [Stephenson, 2005, Ado et al., 2014]	Real time and adapted information sharing
		Data collection management [Pettit and Beresford, 2009, Fertier, 2018]	Data granularity collected and processed	Data silos, fragmented, non-reliable and after the fact [Tohamy, 2017, Pettit and Beresford, 2009]
Financial flow facility [Kovacs and Spens, 2007]	Information and Communication systems [Pettit and Beresford, 2009]	Technology system storing, processing and transmitting information in a digital form	Ad hoc and basic tools and methods [Hillson, 2001, Ado et al., 2014]	State-of-the-art tools and methods (pad, virtual reality, IoT...)
		Sized compared to requirements, obtention speed, complexity to manage	Unilateral and uncertain [Charles and Lauras, 2011]	Centralized systems providing end-to-end visibility and requirements
Corporate culture and attitude [Lambert and Cooper, 2000]	Trust, partnership degree with SC members	Trust, partnership degree with SC members	Competition among agencies, few commercial partnerships [Pettit and Beresford, 2009]	Win-win relationship sharing benefits and costs, mutualization
		Staff capacity, training, management	Lack of resources, experts and training [Pettit and Beresford, 2009]	Single or regional Human Resource pool, skill versatility, standard training and working procedures
Human resource management [Pettit and Beresford, 2009]				

Table 2.5: Case study HOs' relief items catalogue

	HO_1	HO_2	HO_3	HO_4	HO_5
Product 1 (P1)	✓			✓	
Product 2 (P1)			✓	✓	
Kit 1 (K1)	✓	✓			✓
Kit 2 (K2)		✓	✓		✓
Kit 3 (K3)	✓		✓		

this from [Kusumastuti et al., 2010]. It has been designed to be as generic as possible and applicable to diverse regions of the world where HOs would be positioned.

As a start, let us consider a region where populations are distributed and upon which, HOs are engaged in the perspective of delivering relief items to victims in case of a disaster. As any territory, the model is divided into several administrative layers. For simplification purposes, as displayed in Figure 2.10, the region encompasses three provinces differentiated by red lines, each of them containing about sixteen districts highlighted by black lines. Finally, each district supervises twenty five sub-districts or villages appearing as coloured squares. Since HOs are closely linked to people, population density has been integrated in the model. Concretely, through a dedicated Python code, we generated a population density mapping based on statistics and distribution rules defined at the region and district levels. The generated population distribution is depicted in Figure 2.10 by colouring the sub-districts in light, medium or dark blue according to the assigned population density. Also, from the survey about relief logistics practices in Indonesia [Kusumastuti et al., 2010], we identified different types of HOs (governmental, Non-Governmental Organization (NGO)s...) and associated roles (coordinator, ministries, local or international that may co-exist within the same territory. For the case, we have considered five different HOs represented by geometric shapes (star, circle, triangle, pentagon and octagon), and managing two or three of the five relief items defined for the case: Products 1 & 2 (P1, P2) and Kits 1,2 & 3 (K1, K2 and K3) (See Table 2.5). The logistics network of each HO, depicted in Figure 2.10, is based on criteria outlined in [Kusumastuti et al., 2010] and field observations in terms of location of the permanent relief logistics facilities. Finally, the response behavior and preparation strategy of HOs are inspired from practitioners' interviews.

2.4.2 Case study testing design

As a reminder, the experiment intends to assess the advantages of introducing the PI approach in the humanitarian domain and to show the impacts on response performance. Since this represents a large spectrum, the scope has been restricted to two core functions of the downstream part of the chain, namely the warehousing and delivery activities. Using the case study, we investigate how different transport and storage strategies, relocations, as well as the addition of the interconnection concept, tend to affect some major metrics such as the coverage level, transportation costs and the asset utilization, expressed here in percentages. The coverage is calculated by counting the number of complete or predominant green squares compared to the total. Regarding the transportation "cost", it is calculated by organization by

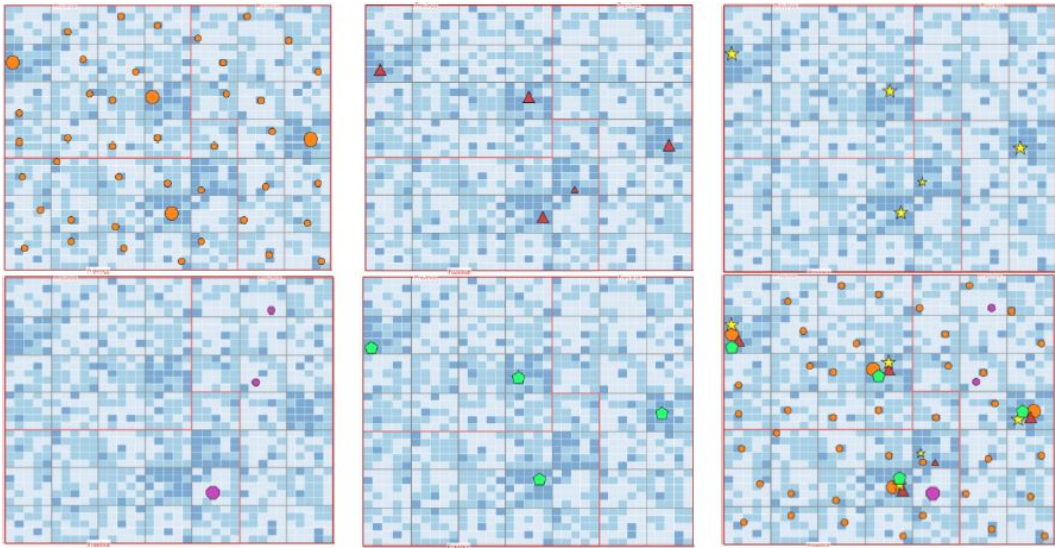


Figure 2.10: (from 1st to 5th map) Logistics distribution of the five different HOs across the region. (6th lower right map) The aggregation of the different network nodes displayed on the same territory [Grest et al., 2020]

counting the number of paths (i.e. edge of a square) followed by a truck to reach the disaster area. The analysis is made possible by comparing the different metrics values between the two approaches. Regarding the experimental testing, since the case is fictional, we decided to lead the investigations through several experimental illustrations.

2.4.3 Case study results & discussion

So far, each HO is accustomed to position facilities autonomously, and tends to base its decisions on administrative, transport access and human resources criteria. This is illustrated in Figure 2.10, which shows the distribution of the different logistics networks associated with each HO through HO-specific maps, and then their overlapping on an integrated map. It stands out that the coverage over HOs is heterogeneous. Indeed, facilities are mostly concentrated in areas with clusters in high-level population density areas, while four districts have no facilities from any HO.

In the event of a disaster, the first few hours are decisive in reducing the number of victims. That is why aid agencies must be prepared to provide first aid at any moment and this, as fast as possible. In that sense, investigation of the response time to supply relief items across the territory, i.e. the delivery coverage, shows variances between the different relief products. If we consider the green circles as the reachable zones in 24 hours, the 24-hour coverage has been assessed for P1, P2, K1, K2 and K3 respectively as 28, 88, 24, 83 and 83% (see figure 2.11).

By merging and sharing facilities, as a PI-approach would imply, any HO would have access to additional storage areas and gain the opportunity to fulfil remaining spaces with their products. Consequently, the delivery lead time for products K1 and P2 would significantly decrease while the asset use and global service level would increase (see figure 2.12). Additionally, we can expect to optimise assets and coverage.

First, by reducing the number of facilities in some areas where there is too much coverage, and then by relocating them smartly. In this way it is possible to increase the coverage with the same number of assets. It is not even necessary to relocate them all. For the same coverage level, the total amount of relief facilities can be reduced, and the money saved could serve other purposes. However, reducing this amount would probably involve resizing some facilities according to the demand. As an illustration, by evaluating the number of sub-districts uncovered, the coverage level reaches 88% with 61 assets while in the second scenario, it is possible to obtain 96% coverage with only 47 positions (see figure 2.12). Now considering delivery, both within the same organization and between agencies, some adjustments are possible.

Currently, within the same institution the supply and delivery between the different warehouses are generally organized according to a hierarchical tree. In other words, regional warehouses oversee supplying district facilities and so on from district to sub-district. This type of organization has been set up for strategic reasons, such as better control and minimal safety stock, yet it increases delivery lead time and transportation costs, notably when the target supplier node does not have the stock required. One opportunity suggested by the PI approach is adding a horizontal flow capability to the up-to-now hierarchical vertical distribution. The different facilities could supply based on need and availability (see figure 2.13). Consequently, we can expect to increase stock agility, enabling inventory to be moved based on disaster-prone seasonality. Moreover, the delivery lead time between nodes would be reduced, as well as the transportation costs.

HOs are accustomed to using dedicated delivery networks. This approach is simpler to manage, offers less interference and guarantees a higher control and availability of the assets. However, as a result, we note a duplication of transport means targeting the destinations and so, a duplication of costs and trucks less than fully filled (see figure 2.13, on the left). To overcome this issue, the PI could consolidate transport, e.g. grouping deliveries that have the same destination. Consolidating deliveries shows promise in increasing truck loading rates, reducing transport costs and transport-induced gas emissions. As an illustration, Figure 2.13 presents, on the left the current approach where each institution is sending a vehicle and where most of them are only partly filled. Alternatively, in the right part of 2.13, horizontal and transport consolidation has been employed, leading at an organization level to transportation cost reduction of 42% for the yellow organization, 59% for orange, 41% for red and 24% for purple, based on the routes taken and shared. Additionally, the improved coordination leads to optimized delivery with fewer trucks, less mileage, and less greenhouse gas emissions.

Obviously, these primarily results should be nuanced as the scope is limited to the downstream part of the HSC and building upon a fictive case with a limited number of products. However, they feed our reflections and enhances the need for a solid and quantitative experiment that has been developed in a second phase and discussed in Chapter 4.

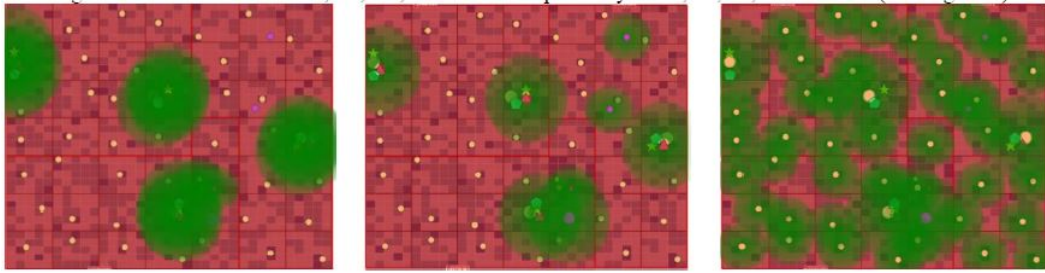


Figure 2.11: (From the left to the right) 24% as product coverage for K1, 28% for P1 and relatively identical for P2, K2 & K3 with a range from 83 to 88% [Grest et al., 2020]

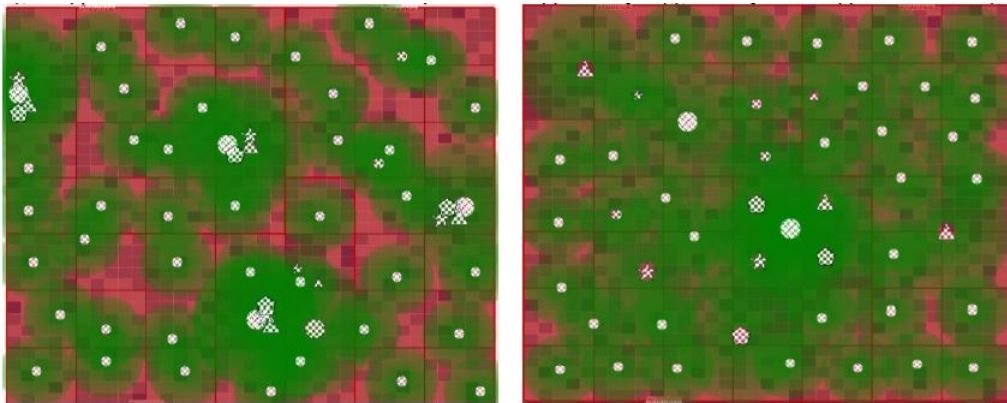


Figure 2.12: (Left) Current HOs positioning resulting in an 88% coverage with 61 assets (Right) Suggestion of relocation leading to a 96% of coverage with 47 facilities [Grest et al., 2020]

2.5 Key Takeaways

Currently, the HSC faces various challenges in many domains. Basically, it encounters problems related to data collection and information systems, while the precariousness of the local environment poses relief issues. Finally, a lack of resources, coordination issues and external pressures all have an impact on the performance of the logistics.

This Chapter aimed to investigate the effect of an in-depth reorganization of current HSCs inspired from PI principles. In this perspective, a proposal for a new humanitarian paradigm named HHSC has been designed through three impactful SC performance levers. A literature exploration highlighted that the SC network structure, the SC business processes and the SC management components identified for SC also influence the performance of relief chains. From these three dimensions, we have made a list of related factors to which have been assigned some descriptions regarding current practices. From this situational practice analysis, we suggested proposals for new PI-oriented approaches which are recalled in a summary table (See table 2.2). Avenues under consideration are the introduction of PI-equipment and facilities, standardized protocols and a better interconnection of actors for coordinating the relief in an effective, efficient and sustainable manner.

The expected benefits have been demonstrated in an approximate way through a basic and fictive case study. Some network organization and delivery related factors

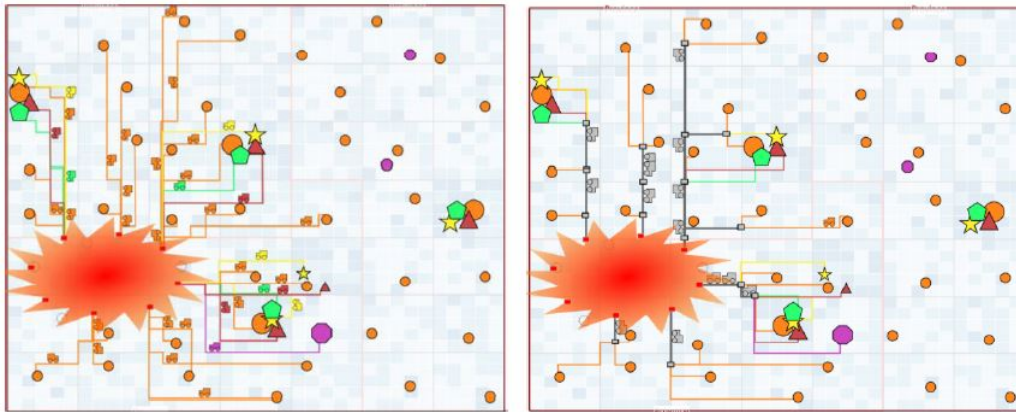


Figure 2.13: (Left) Current delivery approach with HOs using their own network and vehicles (Right) Optimized delivery with the introduction of the transport consolidation and interconnection of the HOs [Grest et al., 2020]

have been tested and the results show a tendency towards a reduction in the delivery lead time and gas emissions, an optimization of the means of transport and storage areas, as well as an increase in responsiveness thanks to better coverage. A second experiment, using a more detailed and realistic case study, to better ascertain and quantify such promises is developed in Chapter 3 and tested in Chapter 4.

DESIGN AN EXPERIMENT ABOUT THE HYPERCONNECTED HUMANITARIAN SUPPLY CHAIN

To paint is not to copy the object slavishly, it is to grasp a harmony among many relationships.

– Paul Cezanne, *Artist, Painter*, (1839-1906)

The chapter’s main materials have been originally published as part of the papers entitled “Assessing Physical Internet potential for Humanitarian Supply Chains” in the proceedings of the 54th Hawaii International Conference on System Sciences (HICSS), 2020 and “Conception d’un modele de simulation pour l’évaluation de la pertinence de l’Internet Physique pour les chaines d’approvisionnement humanitaires” of the Conférence Internationale Génie Industriel Qualita (CIGI-Qualita21), 2021.

3.1 Context, Objectives and Methodology

By planning the research to be carried out, the researcher focuses on the “research design” or “research methodology” identified as a key step before any implementation. This ensures the validity of the research into the problem and ensure tangible and reliable results [Bairagi and Munot, 2019]. Besides, it facilitates the orientation of the research in the right direction as it reduces the risks errors and wasted efforts. Generally the research design requires details about:

- The research problem along with the context and considered objective(s),
- The planned approaches and techniques to employ for collecting data,
- The planned analysis methods to process the data, generate and communicate results,
- The experimental approaches/configurations to execute,
- The evaluation and justification of methodological choices.

As a reminder, in the humanitarian context, the number of humanitarian operations is expected to increase in line with the growth in the number of disasters. Funding allocated to support humanitarian operations is limited and so far does not cover all the needs (see chapter 1 for more details). As a result, Humanitarian Organization (HO)s are criticized for their lack of effectiveness in delivering aid to victims of disasters [Haavisto and Goentzel, 2015]. Meanwhile, their logistics, which account for 80% of the effort [Van Wassenhove, 2006] is recognized as showing symptoms of being ineffective, inefficient and unsustainable [Ado et al., 2014].

3. DESIGN an experiment about the Hyperconnected Humanitarian Supply Chain

The research motivation lies in the desire to improve the living conditions of people affected by disasters. To this end, the focus is on increasing the ability of HOs to mobilize logistics resources in the right proportions, at the right time and in the right place. In a shortened form, the aim is to work on improving the effectiveness, efficiency and sustainability of Humanitarian Supply Chain (HSC)s and thus to improve humanitarian operations.

In this perspective, as discussed in Chapter 2, taking inspiration from the classical Supply Chain (SC) would not be relevant as the two SC types are not that similar. Besides, classical logistics also presents inefficient and unsustainable symptoms, with empty return deliveries and under-utilized trucks as an illustration [Montreuil, 2012]. Therefore, the Physical Internet (PI), an innovative logistics concept breaking with current practices as it seeks to interconnect network actors by the means of resource sharing and enhanced coordination through interoperable means and information systems, appeared as an inspirational approach for the humanitarian sector. Its mechanisms, such as the encapsulation system or certificates and protocols could benefit humanitarian operations performance in speeding up delivery while better managing resources. Better coordination among the humanitarian players and better monitoring of resources are also expected. The strength of such an ideated network would not only lie in its effectiveness, efficiency and sustainability, but even more so in its resilience, flexibility and agility in dealing with the unexpected.

We therefore assume in this study, as a kind of bet, that a translation of PI concepts adapted to the humanitarian sector and their integration at the organizational level of the HSC would result in an improvement in the operational performance results. This brings us back to the second research question identified in Chapter 1:

RQ2 How to assess the application of PI concepts to HSC levers and its impact on performance?

The term “*assess*”, synonym of “*evaluate*” involves manipulating and analyzing quantitative data, related here to the performance. Secondly the term “*impact*” implies studying the causal relationship between practices at HSC levers and performance results. Since we want to test the above hypothesis and study the relevance of the PI approach for the humanitarian sector, we have decided to undertake a quantitative experimental research study designed to be appropriate to establish cause-and-effect relationships and test assumptions [Bairagi and Munot, 2019]. Consequently we shall consider an experiment able to compare, through performance indicators, the difference between a baseline system (i.e. representing current practices) and alternative systems that while fundamentally similar, embed different degrees of PI concepts.

In this type of research, time must also be spent defining the experimental design which is required to identify the variables to manipulate and the variables to evaluate, to define the environment of the experiment and the equipment needed, as well as the protocol to follow, the changes to operate at the variables level and, finally, to measure the results [Bairagi and Munot, 2019].

We do not lose sight of the need for relevant research, as highlighted by Kunz et al. [2017] and discussed in Chapter 1. Therefore, we paid attention to the credibility of the research work through verification and validation steps as well as frequent interactions with practitioners.

Finally, as the novelty of associating the PI with HSCs is quite unexplored, an ad hoc experiment for the intended investigation is envisioned. Since the exploratory landscape is broad, we restricted the scope of the study by focusing only on natural disasters and the relief item distribution relating to them. The reasons for this choice lie in the confirmed and growing trend of an increasing number of natural disasters expected in the future and by the fact that relief supplies are recognized as crucial in disaster management [Shao et al., 2020].

To frame and ensure the proper development of such a specific experiment, a literature investigation have been performed, as a first step, to become familiar with the concepts related to a systems engineering approach and simulation modeling methodologies. From there, and thanks to the knowledge gained regarding HSCs (see chapter 2 for more detail) the experimental design was formulated and is presented in a central section in this Chapter 3. The planning of the experiment includes the definition of (i) a functional framework (i.e. a sequencing of tasks to perform to prepare the experiment) and (ii) a technological framework (i.e. an experimental support) from which we will be able to perform the experiment and generate results. I draw the reader’s attention to the fact that this Chapter 3 is conceptual and imagines and describes an experiment that will only be executed and discussed in the following Chapter 4. This experiment was initially simulation-oriented due to the complexity of the HSCs we were considering. However, we believe it is generic enough to be (re)used in another experimental context.

3.2 Literature Investigations

In view of the constraints and research objectives previously mentioned, this section will first provide features about simulation modeling, as identified as a suitable approach to support our study. Furthermore, it will help in designing the functional framework. Then, a section will be dedicated to the System Engineering (SE) approach as it is a powerful modeling method that helped a lot in bringing credibility to the experiment envisioned, especially to conceptualize the technological framework.

3.2.1 Simulation & Modeling

A simulation is “*the imitation of the operation of a real-world process or system over time*” [Banks, 1998]. It enables the study of a complex system and its behavior over time. Informational, organizational or environmental change can be applied and the effect of these alternative system behaviors can be observed and measured. At the end, the knowledge gained should suggest avenues of improvement for the system. It is a popular problem-solving methodology for various problems to answer what-if questions [Banks, 1998].

3.2.1.1 Simulation principles & models

Simulation evolves around two key concepts that need to be defined before going further. These are the system and the model. A system is defined as “*a collection of*

3. DESIGN an experiment about the Hyperconnected Humanitarian Supply Chain

entities, e.g., people or machines, that act and interact together toward the accomplishment of some logical end" [Law, 2014]. It can exist in reality (e.g. a queue line at the bank) or it may be more conceptual (e.g., the spread of a disease).

When we want to study a system and gain insight regarding the relationships between the entities under specific conditions and observe its performance, several type of experiment can be considered. If possible and cost-effective, leading an experiment with the actual system is preferred as it guarantees the validity of the study. In practice, it is rarely feasible as it is too costly and complex to implement or too disruptive for the actual system. Thus, experimenting with a model of the system is preferred.

A model is the representation of an actual system according to a selected point of view (several may exist), in a defined formalism and level of detail [Borshchev, 2013, Benaben, 2012]. The point of view, formalism and level of detail have to be properly selected according to the experimental objective pursued. In this sense, it can not be a perfect representation of the system and relies on a set of assumptions regarding the way the system operates and interacts with its environment. Consequently, questions related to the verification and validity of the model should not be neglected, to ensure the reliability of the conclusions drawn.

Different types of model exist. Physical models are generally miniature systems such as cockpits disconnected from the airplane, or tanks in swimming pools for diving initiation to train people in secure and almost real-life conditions [Law, 2014]. Mental models are built every day in our daily life without us knowing it. They are our understanding about someone's personality or how we think things work. Moreover, it is not rare to find out that we were wrong and that person or situation did not behave as expected [Borshchev, 2013]. These types of model do not represent the majority of models developed, especially in operations research and systems analysis. Mathematical models, on the other hand, are, and represent a system with its core relationships that are manipulated to test and observe how the model reacts. If the model is simple enough and be solved analytically in a short time with a pencil and paper then this approach is preferred. However, today, many systems are too complex and have too many interactions to be studied that way and in this situation simulation is considered [Law, 2014].

3.2.1.2 Simulation advantages & drawbacks

Simulation models are always executable models. In other words, they can be run, and the trajectory of the system state can be visualized and observed over time (see figure 3.1). These models are composed of a set of rules (equations, state-charts, flowcharts, schedules) that influence the next state of the system. By introducing inputs to the simulation model, outputs of the model can be produced and observed as long as the model is running [Borshchev, 2013].

The application of simulation is very wide and can help investigate types of abstraction at the micro-level (pedestrian movement, control systems, etc.), medium level (business processes, call centers, warehouses, etc.) to macro-level (economics, social systems, ecosystems, etc.) [Borshchev, 2013]. Today, three modern simulation modeling approaches exist and are used depending on the abstraction the level considered: discrete-event, agent-based and system dynamics. According to Borshchev [2013], system dynamics generally serve for systems with minimum details or with a high abstraction level. This method is chosen when it comes to investigating the

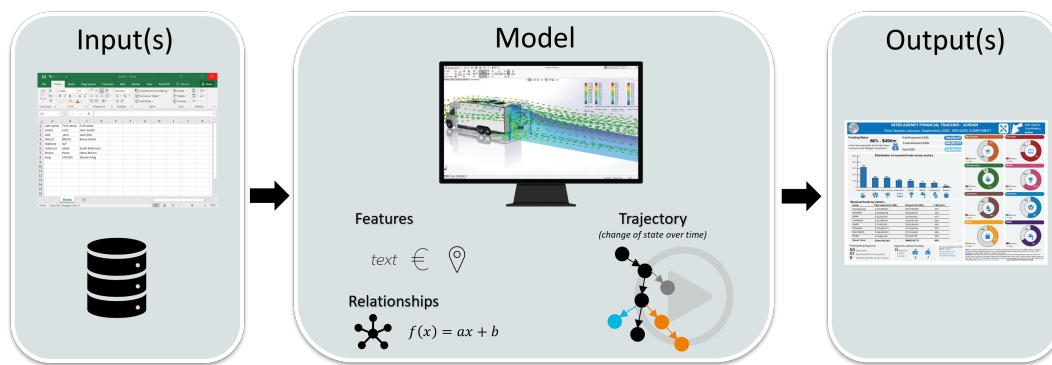


Figure 3.1: Simulation model components adapted from [Borshchev, 2013]

relationship between accumulating components of a system and or its environment (called 'stocks') and the circulating flows in between relying on the physics laws. Such a modeling approach helps in understanding and anticipating the change of a system and can be used when data is missing. However, it can rapidly become complex and difficult to interpret with many variables. Discrete event modeling has a process-oriented approach and considers a system with a state evolving over time after events occurrence. It mostly supports medium-level details and tactical considerations which is why it has been largely used for warehouse dimensioning, machine breakdowns impact on the production or call center flow issues [Petitdemange, 2020]. With such a technique, a balance must be found between too much accuracy and too many events slowing down the simulation and a too simplistic model that would generate unreliable results. Finally, agent-based modeling and simulation appeared more recently at the start of the millennium and relies on agents that are autonomous entities that can interact with others or their environment. They are defined via distinctive features and rules setting their behavior. Those characteristics may change over time or depend on the dynamic of the environment in which they evolve. Such agent-based models can be used for very detailed systems or operational explorations as well as high-abstraction level systems where agents can be companies, vehicles, pedestrians or governments. This method is not preferred when data are homogenous with similar distribution losing the interest of agent individuality.

Simulation is an appropriate tool to make experiments without significant cost and disruption. It allows estimates to be made of the performance of an existing system under (projected) operating conditions. It can allow the comparison of alternative operating policies to evaluate which best meet some requirements before making any change. It also allows a system behavior to be visualized and investigated over a long period of time through simulation animations. In other words, it is a powerful tool to diagnose problems, explore possibilities, develop knowledge and visualize and build consensus to prepare for change [Banks, 1998]. Besides, there are opportunities to embed optimization components within the simulation to test alternative decision-making policies and go beyond the usual what-if analysis [Osorio and Bierlaire, 2013]. However, simulation models and analysis can quickly become expensive and time-consuming to develop. Modeling requires special training and knowledge to be performed properly and a large diversity of formalisms exist. Besides, simulation results may be difficult to interpret by determining if the effect on outputs are due to interrelationships or randomness. It can be used inappropriately or lead

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to erroneous conclusions as it produces estimates [Banks, 1998]. However, these alert points can be offset if the model is properly performed along with the simulation coding. To ensure this is the case, simulation methodologies have been developed to frame the simulation development while ensuring a valid model, as well as the proper coding to support the experiment objective pursued [Law, 2014].

Modeling and Simulation Methodology

Several modeling and simulation methodologies have been developed so far. Examples have been made in a flowchart form by Banks [1998], Law [2014], Sargent [2010]. Some minor features distinguish them from each other but they all roughly follow the same logic. Key steps deal with:

- Designing the simulation experiment,
- Gaining understanding about the real-world system,
- Building the conceptual model from the real-world system,
- Building the computerized model from the conceptual model,
- Executing the design and
- Analyzing and presenting the results.

To further ensure the credibility and reliability of the experiment, intermediate steps are interspersed to verify and/or validate the steps performed beforehand. The sequencing of the steps differs slightly from one methodology to another, but all contain go-back loops, as building a simulation is not linear and require changes throughout its development.

The key steps will be discussed next, while the verification and validation steps will be addressed in a following section 3.2.1.3.

Design of the simulation experiment

The simulation experiment design is one of the first mandatory steps to perform, as it directly influences both the conceptual and the computerized models. This step ensures that the problem to study has been correctly understood and to do so, requires to specify the problem and the issues to address, as well as the objective pursued and the approach considered [Law, 2014, Banks, 1998, Chung, 2004]. As with any experiment, careful attention must be paid to the design and analysis aspects, as these will condition the success or failure of the experiment to be undertaken [Law, 2014, Chung, 2004]. The design part has to ensure the experiment contains as much relevant information as needed to draw solid conclusions, but limited to essentials so as to avoid unnecessarily increasing the complexity of the development and analysis. As for the analysis part, it has to ensure that useful data are extracted to perform adequate analysis from the experiment. In practice, this step requires (i) formulating the problem statement through the definition of the issues to address, the hypothesis to test and the questions to be answered and (ii) selecting and defining the experimental approach planned in terms of the manipulation to perform related to the system itself or at the operating environment level, the definition of the criteria to use for evaluation and the establishment of the planning and resources to mobilize [Law, 2014, Banks, 1998, Chung, 2004]. This key step should be considered as dynamic so that, as progress or constraints emerge, the approach may be questioned and updated [Chung, 2004, Banks, 1998].

In an experiment and particularly in a simulation context, the experimenter deliberately changes one or more variables (called *independent factors* and more specifically *endogenous factors*) to observe the effect on the system's response (called *dependent factors*) [Nielsen et al., 2015] (see figure 3.2). Both factor types can be continuous (temperature, length, etc.) or discrete (brand, boolean, etc.). The *modality* of a factor is the number of possible values it may take within or during the experiment, while the *level* of a factor is a particular value [Pillet, 1997]. Whatever the experimental method, there are independent factors that are controllable by the experimenter, such as inputs for the systems, and that are configurable in terms of the set of rules and assumptions made for representing the real-world system. Examples of input factors may be the territory considered, or the population, while configurable factors might be the supplier selection policy. There are also non-controllable factors, known as *exogenous*, mostly related to the experimental environment and these may influence the results, such as the temperature or the hydric rate [Equixor, 2014]. In the context of a simulation, such factors can, in fact, be controllable as we are building a kind of digital world. Response factors are generally quantitative, such as a cost, a duration or a boolean. Both sub-types (endogenous and exogenous) of independent factors are required as they shape the behavior of the system under study.

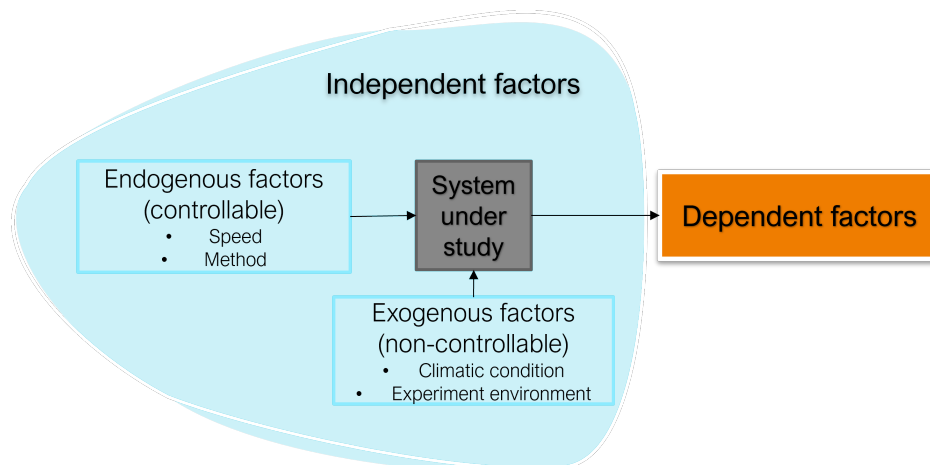


Figure 3.2: Factor typology in an experiment context. Adapted from [Equixor, 2014]

Gain understanding of the real-world system

To build a credible conceptual model, the real-world system must be correctly studied. According to the objective pursued, key information, essential sub-systems and relationships must be identified to capture the essential components of the behavior under study. There is a trade off to find between a detail level that is sufficient to represent reality and excessive detail, which becomes costly to develop and analyze [Law, 2014]. Attention must be directed towards the the group of components that receive inputs and deliver outputs and how they make that conversion. Also, the influence of the environment must not be neglected [Chung, 2004]. Operational context or specific events and the sequencing of tasks or processes must also be investigated. Information and data should be collected from the system of interest and analyzed to identify if a theoretical distribution exists for the randomness in the model [Law, 2014]. Input data may be obtained from historical records, literature,

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experts, or observations from the real-world system. This step is one of the most difficult, because data provided are not always appropriate, reliable or consistent, or worse may even not exist. This implies making many estimates regarding the driving values or assumptions regarding the operating rules which inevitably affects the reliability of the model [Chung, 2004].

Build the conceptual model

The activity of deriving the conceptual model from the real-world system is referred to as the simulation modeling step [Banks, 1998]. In parallel to a growing familiarization with the real world system, the key components also become clearer, as does the level of detail. The scope of the model emerges and various interrelations are highlighted [Chung, 2004]. Many modeling formalisms exist and can be used for describing the system of interest with specifications from different points of view. Examples of standardized modeling methods are Unified Modeling Language (UML) for representations of entity association relationships, causal loop diagrams for cause-and-effect relations description or Business Process Modeling Notation (BPMN) for modeling processes.

Build the computerized model

The activity for turning the conceptual model into the computer-based representation is named simulation programming [Banks, 1998]. It consists of two main steps, first the selection of the programming language and then the translation of conceptual components into code, give shape to the collected data and generating experimental data outputs [Law, 2014]. Obviously each project is unique, but common activities at this stage include version management, programming commenting, program development planning and mnemonic naming conventions [Chung, 2004].

Execute the design

Normally, if everything beforehand was well prepared, the design execution should run smoothly. It simply requires following the defined plan and ensuring the collection of raw data and records from what happened. In the end, if necessary, reset equipment to its original state if additional investigations or runs are required [Croarkin and Tobias, 2012].

Analyze and present the results

Once the experiment has been executed following the defined design, and the outputs data has been collected, it is time for the data analysis part. Basically, this phase is done by performing the organization and cleaning of the data for analysis (i.e. Data Preparation), then performing the description of the data (i.e. Descriptive Statistics) and finally testing the hypothesis and model (i.e. Inferential Statistics) [Trochim, 2016].

Data Preparation Data preparation mostly involves checking that the obtained measurements are reliable and consistent, that nothing is missing and that orders of magnitude are respected. Then, it is about transforming the data if needed in the units that would make sense for analysts and decision makers. Finally, it is about building a structure database that would integrate all the cleaned data for the analysis phase.

Descriptive Statistics Descriptive statistics focuses on providing a summary of the measurements. It aims to describe the global features and trends of the data set with visual graphics or rapid calculations, such as average or standard deviations. Generally, investigations are related to the data distribution using frequency distribution charts, for instance, and central or dispersion tendencies with box plots.

Inferential Statistics Inferential statistics goes further than descriptive statistics. By testing models or hypotheses, this steps aims to extrapolate trends from the sample to make generalities. It also investigates if the conclusions are the effect of chance or of interrelationships between the factors considered. Examples of the methods used here can be drawn from a general family of statistical models known as the General Linear Model. This includes the t-test, Analysis of Variance (ANOVA), Analysis of Covariance (ANCOVA), regression analysis, and many of the multivariate methods like factor analysis, multidimensional scaling, cluster analysis or discriminant function analysis.

Any time one of these steps are taken, the simulation analyst may consider additional runs, investigations or amendments to perform and may go back to upstream step(s) [Banks, 1998]. Once satisfied, documenting and presenting the results is important for numerous reasons. First, to do such an amount of work only for the results not to be implemented is most probably a sign of a failure of design [Law, 2014]. Then, if the simulation or experiment has to be re-used or improved, it needs to be documented to make it easier for a successor to take over [Banks, 1998]. Often too little effort is spent on this phase while it a question of accountability for the experiment initiator.

3.2.1.3 Building Valid, Credible Simulation Models

One major difficulty in doing experiments is to ensure the reliability of the conclusions made. This is quite challenging, especially in a simulation context, and particularly during the two derivation steps performed during the simulation modeling and simulation programming phases. Indeed, investigations related to the validity and coherence of, and between, the conceptual and computerized models compared to the actual system are crucial to establish the experiment's credibility as it can be the source of many mistakes. Although verification and validation are simple concepts, they may become an arduous task if only carried out at the end of the simulation development process [Law, 2014]. Indeed, the many interrelationships between the different models and actual system imply the checking process to be iterative and regularly repeated along the methodology progression [Banks, 1998]. Total validity of the representations made is near impossible, or too costly, but efforts have to be driven towards gaining sufficient confidence in the models and ensuring proper suitability with the intended application [Sargent, 2010]. Examples of techniques for verifying the simulation program can be found during the development or building phases, using a top-down design or breaking the simulation model into sub-models (i.e. performing program modularity). Also, the models and data generated should be checked by several people and simulation animation can represent a useful verification approach. As for the validation methods, expert acknowledgement is essential and can be carried out by sensitivity analysis, extreme-condition and consistency tests and/or comparison between reference data and the simulation outputs [Banks, 1998].

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Credibility is also ensured by making sure the experiment is aligned with the goal pursued or the client specifications, for usability reasons, that it is documented and properly performed, for reasons of interoperability with other models/simulations, if needed [Foures, 2015].

3.2.1.4 Modeling and Simulating Supply Chains

Modeling and simulation of SCs is generally performed to generate knowledge regarding issues and variable interactions, for developing and validating improvements, testing alternative policies or quantifying benefits. Investigations can focus on the network design (node connections, localization, etc.), or in support of the decision-making process at the strategic, tactical or operational levels. Conclusions can lead to policy changes or resource reorganization, for instance. This experimental method applies perfectly to SCs as they are too complex to be modeled with mathematical functions and real testing is too disruptive and expensive. Simulating SCs can be performed using spreadsheets, business games or system dynamics, discrete event simulation, agent-based simulation or a mix of all of these [Campuzano and Mula, 2011]. As for the HSC field, since humanitarian operations are complex situations characterized by a wide number of actors, flows and resources, a system dynamics approach is demonstrated as well adapted to deal with such complexity and highlighting the interrelationship [Besiou and Van Wassenhove, 2021]. That is why, it is commonly adopted for exploring and discussing HSCs issues.

3.2.2 System Engineering approach

Nowadays, the number of complex systems is increasing. They have to interact with a rich variety of other systems, serve a variety of purposes and meet increasing performance requirements, such as reliability or stability. Consequently, such systems are more complicated to develop and produce; They require the coordination of a large number of contributors from diverse disciplines Ramos et al. [2012]. Besides, reports have shown, although a similar idea can be applied to most types of project, that only 29% of software development projects were successful (i.e. the system met the requirements) Group [2015]. Based on these observations, it appears that attention must be paid to the definition of the need and to the system design, as this can be the source of some cost and time savings Boehm [1976].

To help in that sense, methods have emerged to standardize modeling steps and ensure consistency and reliability. The Overview, Design concepts and Details (ODD) protocol for describing agent-based models is a widely accepted example. However, it shows limits towards its full adoption due to a lack of guidance and clarity in the steps and for the evaluation the limits when dealing with highly complex systems [Grimm et al., 2020]. Another method, within the field of SE emerged around 1970 and is increasingly attracting the attention of both researchers Ramos et al. [2012] and engineers Cloutier [2020]. Intended to deal with complex and interdisciplinary systems and enabling their successful realization Ramos et al. [2012], SE is based on a holistic approach (i.e. it considers the system as a whole and takes account of the interactions with its environment). It also captures the whole identity of the system via a description from a different point of view Ramos et al. [2012]. It also presents the advantage of enhancing communication between stakeholders by providing a shared understanding of the system thanks to a collection

of standardized modeling languages and also by structuring the system design with a process-based approach Cloutier [2020]. Indeed, each step of the system life cycle (i.e. from the business requirements to the system deployment) is described as a process by the ISO/IEC/IEEE15288:2015 ISO et al. [2015]. Finally, SE presents the aspect of integrating validation and verification actions through all steps of the life cycle. Respectively defined as, “*the set of activities ensuring and gaining confidence that a system is able to accomplish its intended use, goals and objectives (i.e., meet stakeholder requirements) in the intended operational environment. The right system was built*” and “*the set of activities that compares a system or system element against the requirements, architecture and design characteristics, and other properties to be verified*” ISO et al. [2015], these regular interventions guarantee the compliance of the system with its purpose.

3.3 Design of a simulation based ad hoc experiment

When you have a project in mind and want to turn it into reality, such as a house you wish to build, for instance, you generally do not start straight away. Beforehand, time should be spent on defining the requirements and specifications of the project to smoothen the implementation and ensure nothing is missing at the end. This phase may end up with representation diagrams and action plans showing different levels of detail. In this sense, we have designed a simulation-based experiment to quantify the impact of PI-concept integration at HSC level. It consists of: 1) a simulation-oriented methodology, named the *functional framework*, which acts as the protocol to conduct the experiment and generate outputs and 2) a *technological framework* in the form of a prototypical agent-oriented discrete-events simulator, defining the experimental architecture. More explicitly, these are the required components to conduct the experiment (like the ingredients of a recipe)(see figure 3.3). Both frameworks will be further discussed in the following sections.

The authors recognize that there is no added value to designing a simulation-oriented experiment to support the research ambition as it is a common research method. However, the originality lies in the combination of a functional and technological framework to design such an ad hoc experiment, in a field that has been under-studied so far, with the intent to carry out a first end-to-end application to generate some preliminary quantified results (see chapter 4 for this second point). Besides, while the functional framework is adapted from common simulation and modeling approaches, the technological framework is, on the contrary, a contribution as it provides a new HSC modeling perspective considering both its inner key component (network, processes and management components) and its environment influencing the operational condition and thus the relief performance.

3.3.1 Functional framework

In the experimental design, the functional framework has to be seen as a sequencing of tasks to perform to prepare the experiment and build the technological framework. The latter has to be viewed as an experimental support from which we will be able to execute the experiment and generate results.

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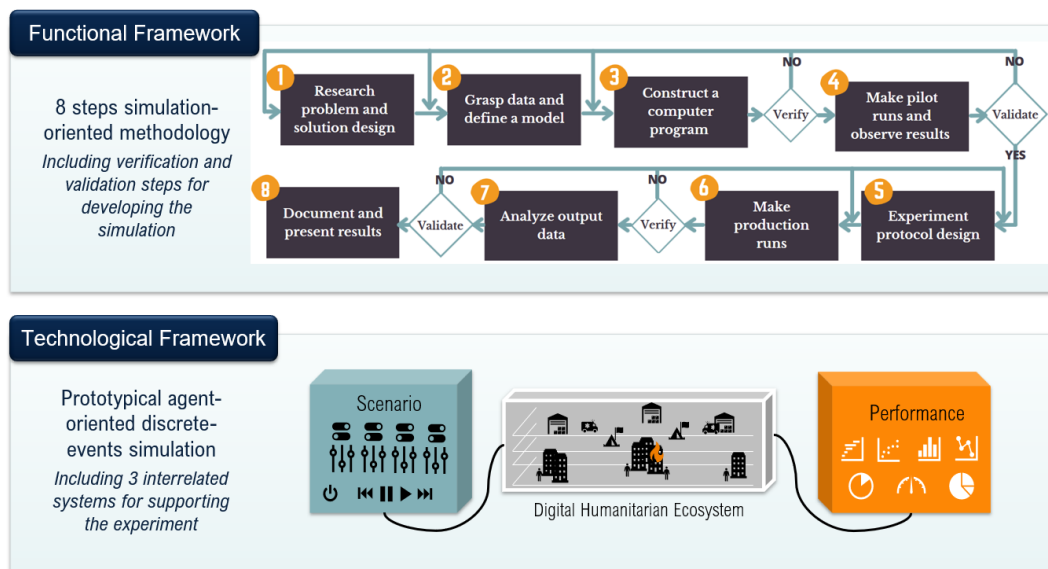


Figure 3.3: Experiment design proposal & components

The following functional framework (see figure 3.4) ensures the proper development and credibility of the experiment. In this perspective, it is largely inspired and adapted from the simulation modeling methodologies developed by Law [2014], Banks [1998], Chung [2004] and discussed in the literature review section. It consists of eight steps detailed as follow.

- 1) **Research problem and solution design** The first step to perform is to describe the research problem and plan the study. To do so, first, a high-level understanding should be acquired of the problem in the context of the relevant research domain. Then comes the research problem statement, which should be put into context to formulate a case to study. From there, adequate objective(s) for the experiment should be provided to address the research problem [Law, 2014]. The last activity consists in planning the project.
- 2) **Grasp data and define a conceptual model** The second step focuses on the system definition and model description. Basically, it represents the activity of translating the real-world system into a conceptual model [Banks, 1998]. This phase includes activities to state the system scope, identify model components, and define input data to collect and output data to generate [Chung, 2004].
- 3) **Construct a computer program and verify** Essentially, this step represents the activity of coding the conceptual model in a computer-recognizable form [Banks, 1998]. Before starting to code, decisions regarding the language and software to utilize must be made. While coding, the verification procedures should appear all along the process to ensure the model is built correctly and performs properly [Chung, 2004].
- 4) **Make pilot runs, observe results, and validate** This step involves conducting the experiment with pilot tests to certify the proper experiment completion and the reliability of observed results [Law, 2014]. In this perspective, time should be spent on calibrating the system under development, based on a

reference system [Chung, 2004]. While coding, the verification procedures should appear all along the process to ensure the model is built correctly and performs properly [Chung, 2004].

- 5) **Experiment protocol design** After implementing and validating a working program architecture, we determine the systems variants to study. Any change, at the set-up of the initial conditions or in the level of the factors (i.e., the variables affecting the system behavior), will become a scenario. Depending on the objective(s) and formulation of the experiment, the tester may want to study different approaches through a set of scenarios to run via the simulation. [Chung, 2004].
- 6) **Make production runs and verify** During this phase, the simulation practitioner launches a simulation-based experiment that involves running a set of scenarios to generate performance data to be analyzed in the following step. They ensure that the experiment operates as expected and gather the scenario outputs for evaluation [Law, 2014].
- 7) **Analyze output data and validate** After the completion of the runs defined during the design of the experiment phase, simulation outputs should be analyzed. First, the simulation model is validated by analyzing the confidence interval of the data generated and if necessary, adjusting the experiment [Banks, 1998]. After verifying the relevance of the experiment, the second step is to apply statistical techniques to drive conclusions and make recommendations.
- 8) **Document and present results** Finally, to give credit to the effort made and increase the probability of the recommendation being implemented by practitioners, results should be shared with field-experts. To do so, various supports are possible from written reports to presentation media. In addition, documenting the experiment enhances the reliability of the work and ensures its re-usability [Chung, 2004].

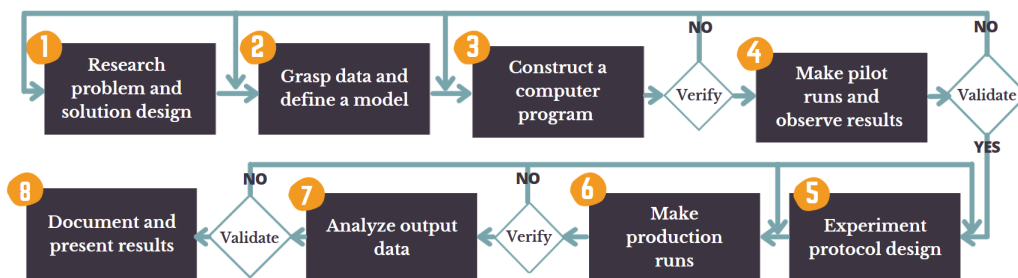


Figure 3.4: Functional Framework - 8 steps simulation-oriented methodology including verification and validation steps [Grest et al., 2021a]

This methodology is not necessarily a sequential process and may require going back over some steps as new elements of the technological framework are added and the vision becomes clearer.

3.3.2 Technological framework

The experimental design requires a good comprehension of the system to be studied. To ensure this, system variables must be identified and selected for their predicted influence on the behavior to be monitored. In our case, the literature investigation in Chapter 2 has mainly highlighted that HSC performance is closely linked to the management of the network structure, business process and management components. Those categories concentrate the possible variables for the experiment, such as the replenishment strategy or the information dissemination level (Discussed in Chapter 2, see table 2.1 in particular). These are independent factors and appear in any SC, but represent operation rules or procedures that may vary from one organization to another.

Additionally, when research investigates cause-and-effect relationships, confounding variables should not be ignored. Indeed, these have a double influence on the independent and dependent variables (i.e the outcomes measured). In a chemistry experiment, the temperature of the room may have a possible influence on the results, even if it is not one of the variables the research intends to evaluate. In the humanitarian context, it is recognized that the operational context or, put another way, the nature of the emergency, challenges humanitarian operations and thus the performance of the operation [Beamon and Balcik, 2008, Kovacs and Spens, 2009, Ramalingam et al., 2009b]. The disaster type, or the affected areas are examples of confounding variables to consider.

Based on these elements, the architecture of the simulation is made of three key systems: the *scenario system*, concentrating independent and confounding variables, the system under study (depending on the parameterization, it may represent the test or reference chain) named the “*digital humanitarian ecosystem*”, and the *performance system*, with indicators such as dependent variables to monitor (see figure 3.5).

The interest of such an experiment is the possibility to observe and measure the cause-and-effect relationship of key HSC characteristics, and possibly external factors, on the performance results. It has been deliberately developed to be as generic as possible and allows additional explorations other than the research objective pursued here.



Figure 3.5: The technological framework embedding three sub-systems: the scenario, the digital humanitarian ecosystem and the performance systems [Grest et al., 2021b]

3.3.2.1 Performance system

As surprising as it may seem, we will start with the third system announced: the performance system. The main reason for this choice is that the outputs to be

monitored should be defined first, so as to avoid the risk of bias in choosing convenient indicators that match the set up.

The performance system represents a dashboard that brings together all the indicators to be consulted and is a key element in deciding on the hypothesis defined above and in meeting the objective set. Indeed, seeking to improve performance implies knowing beforehand what performance is, and more importantly what it means in a humanitarian context. Performance is defined through the measurement of results and objectives. If the results fall short of the objective, it is called “counter-performance”, whereas performance is achieved if the results exceed expectations. Now, in a humanitarian context, what does this mean more specifically? Taking the definition from [Ramalingam et al., 2009b], performance in a humanitarian setting is about saving lives, alleviating suffering and maintaining human dignity, without differentiation. This objective applies to all types of HOs, regardless of the phase. It is also emphasized that aid must be effective and well managed in its use of resources [Ramalingam et al., 2009b]. In addition, it is generally accepted that organizations that monitor their performance outperform those that do not, as this is one way of improving [Abidi et al., 2014]. Other aspects are also highlighted, such as the fact that the response must be “agile” [Tomasini and Wassenhove, 2009], “flexible” [Kabara and Ramesh, 2016], or “sustainable” [Salvadó and Lauras, 2017]. Such constraints need to be measured to ensure that the behaviour is as expected. Examples of performance metrics used to monitor the effectiveness can be the fulfilment rate of needs [Laguna-Salvadó et al., 2019], the percentage of appeal coverage or even the donation-to-delivery time [Davidson, 2006]. For measuring the efficiency, the operations cost [Laguna-Salvadó et al., 2019], the actual spend versus budgeted spend [Davidson, 2006] or the warehouse fill rate [Haavisto and Goentzel, 2015]. The flexibility of an organization can be measured by calculating the mix of different types of supplies that the relief chain can provide in a specified period or the number of critical supplies that an organization can provide within a defined period [Beamon and Balcik, 2008]. As for sustainability, it can be the carbon footprint from an environmental perspective or, from a social viewpoint, the local sourcing rate [Laguna-Salvadó et al., 2019]. Other performance measures can be related to quality, such as the percentage of procurement requests with mistakes, or to reliability, with the availability of the fleet, the percentage of orders met on time; They can even be related to accountability, through internal audit results, for instance [Haavisto and Goentzel, 2015]. Beneficiary "satisfaction" tends also to be measured, even if it is difficult to assess as it is more qualitative and perception oriented [Laguna-Salvadó et al., 2019]. Questions asked may include whether the type or quality of relief supply were as expected or if distribution points were easily accessible [Kusumastuti et al., 2010].

3.3.2.2 Scenario system

The scenario system - like a music mixing desk - allows the setting and adjustment of key variables of a manipulated system (e.g. volume or reverb in the case of sound) which provides nuanced outputs. Here, the scenario configures the digital humanitarian ecosystem (i.e. the manipulated system) with indications at two possible levels (i.e. values) for the experiment. The first configuration area is the context of humanitarian relief and related confounding variables. It defines the geographical perimeter (a region, a country, etc.) and the population distribution, as

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well as the period considered (week, month, year). These indications are used to initialize the virtual HSC environment.

Parameterization also occurs at the level of the system itself concerning: 1) a certain number of fixed hypotheses (e.g. the speed of trucks) that will not vary from one experiment to another and also 2) the value of the independent variables to be tested. For example, one can try to observe the consequences of conventional transport versus consolidated transport. This will require in both cases to consider the same environment and assumptions, but to select one variable option (e.g. “conventional”), run the simulation, retrieve the results and then with this same context, select the other option (e.g. “consolidated”) in order to retrieve the associated data to perform the comparison.



For clarification purposes, we will call a “*scenario*”, a specific setting and combination of all independent variables in a particular context. For instance, if we consider three independent variables and each has two possible values, either “low” or “high”, then there are eight possible scenarios, and one of them is factor 1 = “low”, factor 2 = “high”, factor 3 = “low”.

3.3.2.3 Digital humanitarian ecosystem

The digital humanitarian ecosystem is, in this experiment, the equivalent of a Petri dish for the biology researcher. Indeed, these small containers made of clear glass or plastic boxes allows the evolution of micro-organisms to be observed in a closed and appropriate environment. The researcher may use several Petri dishes to test a hypothesis. For instance, testing the effectiveness of different soaps used for cleaning hands. Generally, one of the Petri dishes is saved in its current state and represents the control group that serves as a reference for the comparison. In the others the researcher will apply different changes to the environment or individuals level depending on the experiment (s)he wants to conduct. The comparison between the containers allows conclusion to be drawn about the change made and the effect on results.

In this study, the same philosophy as a Petri dish experiment applies for the design of the experiment. The digital humanitarian ecosystem, as its names suggests, is a recreated set of humanitarian stakeholders organized in a SC, evolving and interacting with their environment, and set up using simulation technology. The designed experiment aims to recreate and play the role of different organizations within the HSC and then compare the relief performance results of each when faced with the same emergency. In this context, the control group should be a model representing current practices.

When defining this experimental objective, we realized that most HSC models found in the literature did not reach the desired level of abstraction and detail to permit their use as the imagined digital humanitarian ecosystem. One needs to see the digital humanitarian ecosystem as a sort of meta-model of the HSC. In other words, a model bringing together common key elements of any HSC, such as the transport network or key decisions like the replenishment strategy. One HSC may not have the same values or methods as another, but both of them make decisions and take positions with regard to these topics. Moreover, this meta model is intended to be as generic as possible and can be instantiated for modeling any particular HSC.

In our situation, it is particularly interesting to free the model from HSC specificities and to be able to draw global conclusions.

Therefore we decided to design such a digital humanitarian ecosystem for the planned experiments; However, we faced some constraints. First, the literature gave a possible reason for such a lack of HSC generic representations. This was that the complexity of such systems requires the formulation of a set of assumptions [Law, 2014]. Indeed, if we rely on Sheard and Mostashari [2011] criteria to assess the complexity of a system, HSCs can be regarded as complex first of all because of their structure. As a matter of fact, a multitude of various actors are part of the HSC and this induces the existence of many type of assets (e.g. warehouses, fleets) and communications to supply people in need. Secondly, complexity comes from the dynamics of the system. Many logistics activities are performed and adjusted under the influence of the environment (e.g. a destroyed road leads to rerouting), and adapted to the various phases of the operation. Finally, the presence of media, donors and government influencing the relief brings additional socio-political complexity to the system [Tomasini and Wassenhove, 2009].

The second constraint comes from our desire to conduct a credible experiment drawing objective conclusions. In this perspective, we had to ensure the validity and reliability of the representation and this is often one of the biggest challenges [Montreuil et al., 2015]. According to Law, credibility comes from the approval by the client of the correctness of the system behavior in comparison with reality. However, being credible does not guarantee that the model is valid, even if validating helps to establish credibility Law [2014].

Consequently, based on (i) the HSC complexity generated from external factors (i.e. environment, socio-politics) and internal ones (e.g. humanitarian actors, assets) as well as all the flows that result from them, and (ii) the need to validate the research, the SE approach appears to be a good solution for properly modeling the digital humanitarian ecosystem. SE properties allow complex, multi-disciplinary systems to be managed while ensuring the verification & validation of the system throughout its life-cycle phases. We thus developed a framework based on the SE System Definition process, defined by the Systems Engineering Body of Knowledge (SEBoK) (see figure 3.6). Such a framework also preserves the property of SE that consists of having validity actions at every step. It encompasses three stages, namely, the *system mission*, the *system architecture* and the *system design*. The first step in this process aims to define the problem addressed by the system and its context. It is intended here to end up with the need(s) description and validation. The system architecture paints a picture and validates (i) the purpose of the system and its context, (ii) the logical architecture (i.e. its behavior scenario) and (iii) the physical architecture where the system elements are explained. The last step, system design, helps in identifying the necessary information and data for the implementation of the system elements [Grest, Montreuil, and Lauras, 2020].

Step 1 - System Mission

Starting by defining the problem addressed by the system (i.e. the HSC) and its context, the global study focuses on the assessment of a PI approach on HSC performance. Before being able to experiment any PI-induced changes by adjusting variables or parameters and assessing the impacts, it appears logical to gain some understanding first about the real system and thus build up a realistic conceptual model. Given its complexity, to represent its behavior the formulation of a set of

3. DESIGN an experiment about the Hyperconnected Humanitarian Supply Chain

Step	Label	Description
1	System Mission	Define the problem addressed by the system and its context
2	System Architecture	Define the elements and interactions of the system of interest <ul style="list-style-type: none"> ▪ Context definition ▪ Logical architecture ▪ Physical architecture
3	System Design	Identify necessary information and data for the implementation of the system elements

Figure 3.6: The digital humanitarian ecosystem modeling process inspired from system engineering processes [Grest et al., 2020]

assumptions is required [Law, 2014]. Besides, to draw objective conclusions at the end of the study, we have to ensure the reliability of the representation and this is often one of the biggest challenges [Montreuil et al., 2015].

Step 2 - System Architecture

The second phase of the System Definition process defined by the SEBoK is the system architecture sub-process. It consists in providing a conceptual solution that answers the previously-defined requirements which can be implemented through technology. To this end, the focus is on the description of the high-level structure of the System of Interest (SoI) and its interactions. The main tasks to perform are to define the context and to develop the logical and the physical architecture models.

- **Step 2.1 Definition of the context of the Digital Humanitarian Ecosystem**

The system context phase describes the selected system-of-interest in relation to its environment and this is generally expressed as a diagram [Flood and Carson, 1993].

Before starting the description, the global definition of a system is required. According to the International Organization for Standardization (ISO), a system is “a combination of interacting elements organized to achieve one or more stated purposes” [ISO et al., 2015]. The term “element” used in the definition is defined as a component of a system that may be also part of a sub-system. The term “interaction” refers to the manner in which elements influence each other. Finally, the word “purpose” underlines the requirement for a system to meet a need related to the performance (e.g. reliability, capacity, usability), the costs (e.g. price, ROI) or the lead time (e.g. durability, milestones) [ISO et al., 2015].

Now that the concept of a system is established, to start defining the system of interest, we can rely on one of the most cited definitions related to HSCs. Indeed, since logistics is a determinant activity for successful relief operations [Van Wassenhove, 2006], it seems logical to approach the model with this focus. Then, according to Kovacs and Spens [2012], it “encompasses the planning and management of all activities related to material, information and financial flows in disaster relief. Importantly, it also includes coordination and collaboration with supply chain members, third-party service providers, and across humanitarian organizations” [Kovacs and Spens, 2012]. Based on this definition, it stands out with the digital humanitarian ecosystem that: (i) the elements are the logistics activities and the various actors (ii)

the interactions are represented through the three types of flows and the notion of coordination and collaboration and (iii) the purpose lies in “disaster relief”, which encompasses the main mission of humanitarian aid, saving lives and alleviating suffering [Haavisto and Goentzel, 2015]. At this point, the “internal” description of the system of interest, that will be named the “humanitarian response system”, is established.

Then, as suggested by the holistic approach, the description of the environment and its influence on the system needs also to be covered. To that end, if we rely on Kovacs and Spens [2009]’s article related to the identification of humanitarian logistics challenges, which offers a conceptual model for program development, it appears that: “the actual challenges faced in a disaster depend on the type of the disaster as well as the region the disaster occurs in” [Kovacs and Spens, 2009]. They also identify the different phases of the disaster relief as having an impact on the logistics activities [Kovacs and Spens, 2009]. In other words, there is a dynamic before and after the disaster to consider. Lastly, the two other challenges detected (i.e. the variety of HOs and the coordination of actors) strengthen the need for the presence of those two components in the model.

Based on these elements, we developed an illustration providing an overview of the HSC system context (see figure 3.7). The HSC system context contains the “humanitarian response” system which is the SoI [Cloutier, 2020], interacting with the demand system as part of the wider system and including the SoI as well. Then, arranged around the latter, the “territory” and “disaster” systems (i.e. the external systems that are part of the environment influencing the wider System [Cloutier, 2020]).

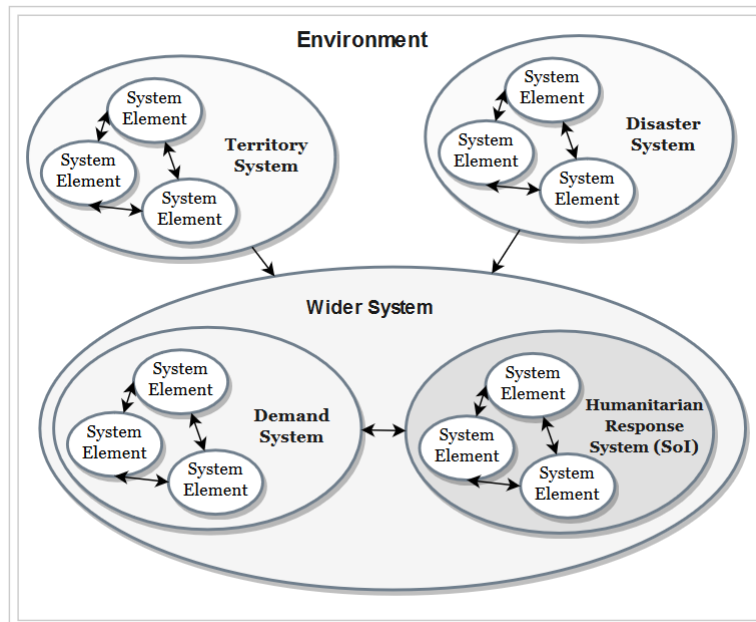


Figure 3.7: Digital humanitarian ecosystem context diagram [Grest et al., 2020] - Adapted from the general description of System Context (SEBoK original) [Cloutier, 2020]

- **Step 2.2 Logical Architecture of the Digital Humanitarian Ecosystem**

3. DESIGN an experiment about the Hyperconnected Humanitarian Supply Chain

The logical architecture is a sub-process of the system architecture process defined by the SEBoK. The objective of the logical architecture is to describe the behavior of the system as it should operate in reality (see figure 3.8). It offers a high-level view by presenting how elements sequence and transform inputs into outputs. The resulting illustration depends on the domain [Cloutier, 2020].

Due to the complexity of the HSC and the variety of activities performed, and in light of our research positioning, we focused on relief item delivery only. Basically, according to Thomas and Kopczak [2005], once a disaster occurs at a location, it causes damage and creates victims. The people affected need relief and generate a demand for items to supply. For this reason, a system to deal with the demand, called the “demand system”, is required. From that moment, the response phase starts, with aid agencies becoming active through their logistics activities and thus, mobilizing stock and organizing transportation and deliveries [Thomas and Kopczak, 2005]. The influence of supply on the demand system needed to appear as HSCs performance is a decisive factor to save lives [Tomasini and Wassenhove, 2009]. Such a typical scenario only applies from the response to the recovery phases. As for the preparedness stage, it relates to the anticipation of needs by pre-positioning means at strategic locations, but it is not always performed by HOs due to difficulties in assessing and anticipating future impacts [Tomasini and Wassenhove, 2009].

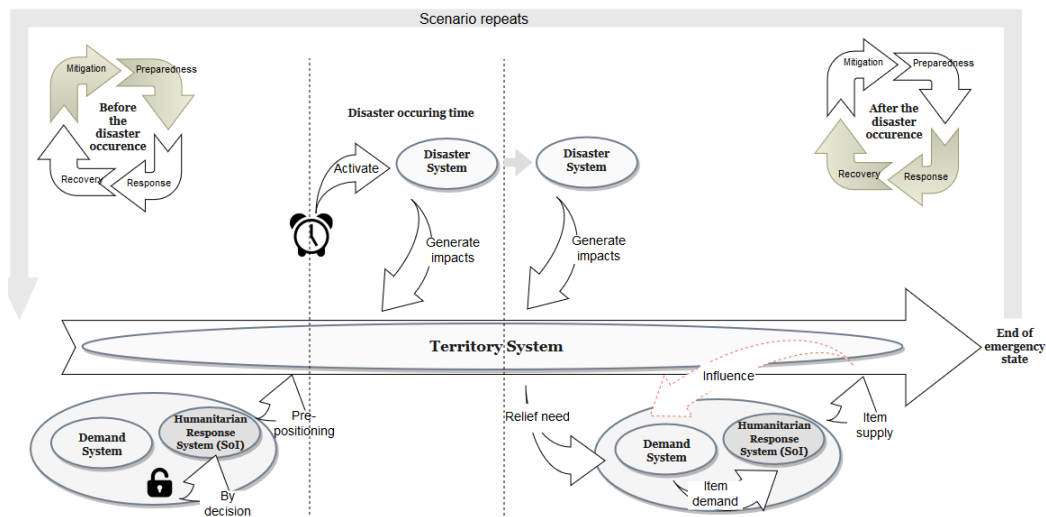


Figure 3.8: Logical architecture of Digital humanitarian ecosystem [Grest et al., 2020]

- **Step 2.3 Physical Architecture of the Digital Humanitarian Ecosystem**

In this part, related to the system’s physical architecture, the objective, as suggested by Cloutier [2020], is to depict each sub-system in terms of objectives and elements. The illustration of the digital humanitarian ecosystem from a physical architecture point of view has been made and draws on the systems related to the system context (see figure 3.9).

- *Territory System*

The territory system is part of the environment of the SoI. It evolves continuously over time and represents a territory susceptible to be affected by a disaster. It can be a country or smaller piece in the administrative breakdown like a province or an island. That is why it may be necessary to specify the administrative breakdown structure. The territory can be represented as an overlay of layers namely, the topography, the population, the infrastructures and the transport network. The topography may be of some influence in the delivery speed or road state and lead to unconventional delivery systems, which is why it has been integrated [Charles et al., 2010]. The population is obviously required as it determines the demand of items as well as the buildings, such as houses or public structures, that may require the need for specific supplies like tents or medicines. At last, the transport network integrates two sub-elements: (i) the “transport roads” encompassing the different type of roads (car, sea, air, etc.) and (ii) the “transport nodes” connecting the roads with seaports or airports. All of them are followed by transportation and delivery activities.

■ *Disaster System*

The disaster system constitutes the second side of the environment of the SoI. It is a discontinuous system representing events hitting the territory and provoking damage. To reproduce the notion of impact, key characteristics of a disaster (e.g. type, intensity) and its dynamics during the entire period of its existence are required.

■ *Demand System*

The demand system is a related system of the SoI. It activates when a zone requires humanitarian assistance and generates a demand for items or services from aid agencies for the whole duration of the emergency state. It consists of two interacting sub-systems: the “human and material impact system” and the “requirement system”. The first one aims to provide figures regarding the number of victims and the amount of damage over time. The second indicates the specific needs associated with an event. Both of them require inputs from the environment to operate and together they assess the relief demand. This system encompasses the work performed by assessment teams. It is a choice to separate it from the humanitarian response system, since it is not always considered as a relief logistics activity, but more as an input. It has also been set apart to introduce the notion that it is influenced by the humanitarian response. It is logical to assume that the speed of the response or a delay in supplies will influence the number of lives saved [Tomasini and Wassenhove, 2009].

■ *Humanitarian Response System*

The humanitarian response system aims to represent the establishment of a HSC after the disaster event. As seen previously in the System Context definition, the key elements of such a system are the actors (e.g. aid agency, government, donors, suppliers), the containers to encapsulate the products from cardboard boxes to the means of transportation (e.g. trucks, boats) and the storage assets. The interactions between these components are due to the physical, information or financial flows driven by the different logistics activities.

Step 3 - System Design

3. DESIGN an experiment about the Hyperconnected Humanitarian Supply Chain

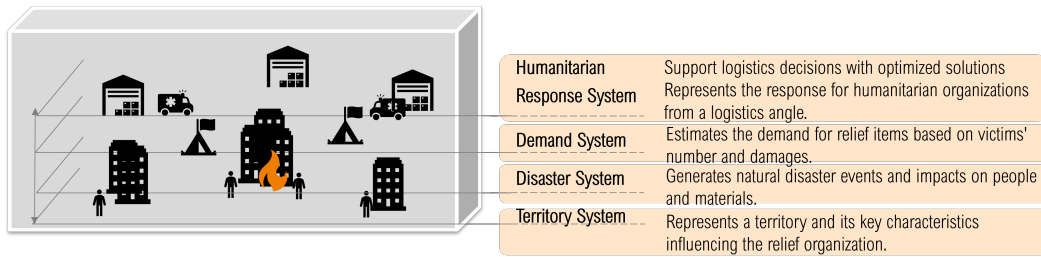


Figure 3.9: Physical architecture of the Digital humanitarian ecosystem [Grest et al., 2021b] illustration

Normally, the objective of the System Design process is to complete the architecture with information and data for the future implementation of the system elements Cloutier [2020]. In that sense, we will here highlight the data needed to collect to instantiate each system element and build the simulation depending on the case study whose performance is to be measured.

The territory system intends to represent a geographical zone where the population are living and distributed. The key information identified as defining any given environment is related to the natural, social and governance aspects [JBB, 2018]. The natural dimension of a territory gathers elements that coexist with humans beings but which exist autonomously, such as the relief, climate, hydrology, soil, fauna and flora. The administrative breakdown of the area, which gives its geographical boundaries, also needs to be considered. The social dimension describes the human distribution (demography, population, density), living standards, human working activities (agriculture, industry, etc.) and relationships such as the constitution of the household. It may be associated with the cultural information, defining local habits and customs. The political dimension gives a structure, rules to respect and penalties in the event of non-compliance, through legislative, executive and legal frameworks for humans living in societies [Demaret and Mersch, 2012]. Also of interest may be information related to buildings, such as houses or private/public facilities, as well as the transport network in terms of paths and nodes (seaports, airports, etc.). Indeed, all of this information is useful to HOs to different degrees, in order to prepare the relief efforts or to respond. Government or statistical websites are generally of help and provide data, analysis and reports about territories and populations.

The disaster system reproduces disaster behavior and generate impacts on the territory. The disasters may have actually existed or they may be created by the experimenter to test crisis scenarios beforehand for preparedness purposes. To reproduce the behavior, information such as the disaster type, occurrence time and location or its severity and duration are required. Such characteristics coupled with territory hazard vulnerability and risk exposition generate different degrees of impact. With regard to impacts, most disaster databases, such as the International Disaster Database (EM-DAT) provide information related to different classifications of affected people (e.g. dead, injured, missing), locations and economic losses. Websites that conduct hazard monitoring (for instance, the Earth Observatory by NASA), or disaster-type-specific websites such as USGS for earthquakes or hazard risk awareness websites like ThinkHazard, all provide much useful information related to disasters, their behavior and their (potential) impacts.

The objective of the demand system is to turn a potential or firm relief need resulting from a potential or occurring disaster into a product/service demand over time. This demand is thus a trigger of the humanitarian response system and initiates a process of mobilizing and organizing the delivery or pre-positioning of the item. In current practices, the demand system is embedded in humanitarian activities during the assessment phase. Assessment teams composed of sector experts (e.g. in health, food or sanitation) are in charge of evaluating the needs for products or services, based on their own observations and experience. Such evaluations are relatively specific to a single or cluster of HOs and accumulated needs are rarely documented or made available in reports. The same can be said for combined data on the evolution over time of people in need and, indeed, on their location. Besides, advanced information systems with large storage and dissemination capabilities, as suggested in a PI context, may also be used for predicting the demand and better managing proposals and deliveries. For simulation purposes, we simplified and formulated the demand as a combination of a victim classification and product/service need. It can easily be assumed that an injured person will need immediate medical assistance rather than tools for rebuilding his house. In the same way, a person living in a hot region may not need a woollen blanket. These two examples illustrate that a binary link (yes/no) can be made between items and victim typology. Besides, this link appears indirectly in the stock rotation and some analysis about stock movement history and events could be undertaken.

Finally, the humanitarian response system gathers different types of elements to operate as a HSC. First of all, warehouses located across and eventually beyond the considered territory. They hold inventory of a variety and quantity of relief items with different sizes, volumes, price, perishable duration and use. When temporary warehouses set up close to affected areas require inventory to be distributed to the affected population, the warehouse network starts to organize. “Orders”, like in commercial SCs, are sent to external suppliers or network members describing the product, quantity and delivery location expected. The requested amount is prepared inside warehouses and transported via one or several means of transportation which may vary in size and capacity until reaching the point of delivery. Information related to the HOs’ network within a territory, such as the warehouse capacities and locations, are difficult to find without having contacts. In addition, stock inventory movement is hard to follow due to the lack of an efficient information track and trace system. The only source found providing baseline logistics capacity insights for the use of the humanitarian community is the Logistics Capacity Assessments (LCAs) website hosted by World Food program (WFP).

From a global perspective, regarding the data, it has to be noted that most of the information mentioned is to be used for the system initialization in the form of inputs. However, there would also be data generated when the system is running following the logic inside the different systems and the connections between them.

3.4 Key Takeaways

This Chapter’s objective was to answer the research question previously defined in Chapter 1 regarding the manner by which to assess such an original association of

3. DESIGN an experiment about the Hyperconnected Humanitarian Supply Chain

a PI approach applied to HSC key performance levers. Some intentions were set out at the end of Chapter 1 and described the creation of a quantitative experiment using simulation to compare a baseline scenario (representing current practices) and alternative scenarios integrating different degrees of hyperconnectivity. In addition, we limited the scope of the experiment to natural disasters as the number of occurrences is unfortunately expected to increase and to the delivery of relief items only, as this is recognized as a crucial activity in relief operations. Besides, as we are aware of the novelty of such a study, the first of its kind, paving the way for a large range of investigations, and we were thus concerned about the credibility of the research work undertaken. This is why the contributions offered in this Chapter were developed based on rigorous approaches. The first contribution is a methodological one, named the functional framework as it provides a logical work process to prepare and develop a simulation-based and specific experiment to support the previously mentioned research objective. Inspired from classical and widely-used simulation modeling methodologies [Chung, 2004, JBB, 2018, Law, 2014] it consists of eight steps integrating verification and validation phases to guarantee the alignment with the targeted research objective and generating credible results for drawing conclusions. The second is a conceptual contribution at the centre of the technological framework. This is a simulation architecture envisioned for conducting the experiment. From the investigations made to understand the mechanics influencing performance in a humanitarian context, the technological framework consists of three systems: a *performance system*, a *scenario system* and a *digital humanitarian ecosystem*. The first two systems are there for the requirements of the experiment: the performance system to monitor and collect simulation outputs and performance indicators, and the second system to parameter the scenarios, which is defined as a combination of practices to observe in managing a disaster. By running the different scenarios in a certain amount of replications based on a factorial experiment design, datasets obtained and analyzed will serve to answer the third research question regarding the recommendations to be made to practitioners that would orient their SC towards more hyperconnectivity. The last system - by no means the least important - is the digital humanitarian ecosystem. Using the term ecosystem shows the holistic philosophy this model has been built upon and is in line with. As we discovered that the performance relationship was not only reliant on decisions and operational management approaches but also may come from the operational environment itself (the affected territory, the disaster features, etc.), it appears relevant to us to consider the whole in the simulation. Such a model is a new model for humanitarian supply chains, as it takes a holistic perspective and is organized in layers specifically made for the experiment. However, the genericity of the components considered make, *in fine*, both this technological framework and the HSC model generic enough to be used or adapted for another experimental context. Now it is time to give substance to these architectures with a field-based case study to finally apply the conceptual and methodological contributions proposed so far and to carry out the long-awaited end-to-end quantitative experiment visible in the next Chapter 4.

TEST THE HYPERCONNECTED HUMANITARIAN SUPPLY CHAIN PARADIGM IN SITUATION

The journey of a thousand miles begins with a single step.

– Lao Tzu, *Dao De Jing*, (4th century BC)

The chapter’s main materials have been originally published as part of the papers entitled “Design of a Simulation-Based Experiment for Assessing the Relevance of the Physical Internet Concept for Humanitarian Supply Chains” in the proceedings of the 8th International Physical Internet Conference (IPIC), 2021.

4.1 Context, objectives and methodology

Natural disasters affect millions of people and cause damage to communities all around the world. Humanitarian response efforts take place immediately after a disaster and gather many different actors that plan for pre- and post-disaster efforts. As the intensity and frequency of natural disasters are both expected to increase with the impact of global warming and climate change, the importance of Humanitarian Supply Chain (HSC) operations, which concentrate most of the efforts [Van Wassenhove, 2006], is ever increasing. Besides, since human lives can be at stake after a disaster, it is crucial for HSCs to be effective while trying to help as many people as possible within the shortest possible time. However, the current practices and operations of HSCs are being highly criticized for their lack of performance [Haavisto and Goentzel, 2015], and the need has emerged to reorganize HSCs and improve their operations.

In the last decades, several approaches have been introduced to improve the efficiency and effectiveness of HSCs. For example, as reported by [Jahre et al., 2016], there have been significant innovations in preparedness to improve their efficiency and effectiveness during response efforts: pre-positioning inventory, advanced coordination between stakeholders (public and private), as well as enhanced education and training. Relative to the environment, there has been a drive toward sustainable HSC operations and reverse logistics [Peretti et al., 2015]. Green efforts include the collection of relief item waste that can be reused, repaired or recycled appropriately [Farahani and Rezapour, 2011]. The innovations above are insufficient for the HSCs to meet growing and tight performance expectations, as they do not alter the flawed core of their current schemes.

By considering moving towards a more in-depth HSC reorganization, inspired from Physical Internet (PI) concepts, in order to overcome HSC’s challenges and

4. TEST the Hyperconnected Humanitarian Supply Chain paradigm in situation

improve performance, we can expect improvements in effectiveness, resilience, and sustainability, as these capabilities have been shown to be possible with commercial Supply Chain (SC)s. However, PI requires changes of long-lasting habits and paradigms, an adaptation to new cutting-edge approaches, and some investment. So, its potential value and suitability for HSC operations still need to be investigated, especially given the inherent differences between commercial and HSCs. [Ado et al. \[2014\]](#), [L’Hermitte et al. \[2018\]](#) were the first to investigate the conceptual applicability of PI concepts on HSCs, and to highlight the potential benefits. However, this intuition has never been demonstrated, giving rise to the third research question:

RQ3 How to support decision-makers relevantly and explore the consequences of such a major structural change?

This question strengthens the need to conduct an experiment to measure the potential impacts of PI-oriented changes on HSC performance. In this perspective, the experiment undertaken has required rigorous design, modelling of Hyperconnected Humanitarian Supply Chain (HHSC) scenarios and technology implementation efforts. Due to the complexity of humanitarian systems, the use of simulation has emerged as the most suitable method to answer this question [[Sheard and Mostashari, 2011](#)]. However, to ensure the reliability of the results and to avoid a series of pitfalls when the time comes to modeling and coding the simulation [[Law, 2014](#)], a functional framework - already discussed in Chapter 3 (see figure 3.3) - has been followed and adapted to suit our experimental context. Adapted from the simulation study process of [Law \[2014\]](#), the methodology consists of eight steps;

- Step 1** – Design the research problem and method,
- Step 2** – Collect data and define a model,
- Step 3** – Construct a computer program and verify,
- Step 4** – Make pilot runs, observe results and validate,
- Step 5** – Design the experiment protocol,
- Step 6** – Run the program and verify,
- Step 7** – Analyze output data and validate,
- Step 8** – Document and present results.

This methodology is not necessarily a sequential process and may require going back over some steps as new elements are added and the vision becomes clearer.

Throughout the process, a prototypical agent-oriented discrete-events simulator was developed by relying on the technological framework to support adequate simulation creation and development [[Grest et al., 2021b](#)] (see figure 3.3 developed in Chapter 3). Accordingly, the simulation architecture includes three key systems for the proper running of the experimentation: the scenario system, the digital humanitarian ecosystem, and the performance system. The scenario system, as a configuration interface for the tester, provides context elements and SC parameters inputs to integrate into the ecosystem to form a particular scenario, forming a unique digital humanitarian ecosystem to observe. Different settings at the scenario-system level and runs of the simulation will offer, based on a full factorial design, a set of scenarios to compare thanks to the performance system that keeps track of the evolution of performance indicators over time. Such functionalities will allow

comparing a baseline scenario (representing current practices of humanitarian logisticians in responding to disasters) to be compared to alternatives integrating different hyperconnected degrees. To facilitate the analysis, all scenarios will have to respond to the same emergency context.

Furthermore, to give substance and realism to the study, the trials and scenarios are based on an Indonesian case study. This choice was made because of the difficulties faced by this country, which concentrates the fourth largest population and most of the natural-disaster occurrences in the world. Certainly, it is one of the most challenging environments, but it represents an opportunity for our investigations and extrapolation perspectives. Besides, as mentioned in the problem statement dedicated section 1.4.1, the case considers only major incidents and disasters related to sudden onsets events. The main reason for such a choice relies on the partnership we had with International Federation of Red Cross and Red Crescent Societies (IFRC) during this research work. So, we aligned with their relief operation speciality that is natural disasters and mostly sudden onset. Besides, we believe that if our work shows potential added values for this type of crisis, then it should be possible to extend it relatively easily to longer-term crises. Finally, incidents do not require any particular effort. On the contrary, catastrophes are chaotic environments, each time unique, for which one cannot try to propose repeatable organisational schemes. So we decided to focus on major incidents and disasters mainly. Also, we decided to emphasis on the relief item distribution as it is recognized as a key activity in disaster management [Shao et al., 2020] is also at the centre of IFRC activities.

Following the functional framework structure, the experiment was carried out step-by-step . The first steps, up to the fifth, are to prepare the experiment with the case study construction and factorial design. The remaining steps concern the running of the experiment, and the results and analysis made. More details are provided in each of the dedicated sections.

4.2 Design & Prepare the experiment to be conducted

This section gathers the first five steps of the functional framework as they describe and prepare the experiment, before the results and analysis phases.

4.2.1 Step 1 – Define the research problem and method

This step aims to summarize the issues determining the experiment, as well as the objective pursued and the scope of the investigation.

The hypothesis under study is the following: a reorganization of HSCs towards a hyperconnected (i.e. PI-oriented) version will positively impact the performance results of humanitarian players in assisting the people affected. From there, an experiment needs to be undertaken to assess the impacts of such an original association, which has been under-studied to date. To do so, a comparison through performance results will be conducted between a HSC baseline scenario, representing current practices, and some alternative hyperconnected scenarios. Since HSCs are complex systems and a non-tangible concept, simulation is the required experimental form. By recreating an environment prone to disasters and by programming the

4. TEST the Hyperconnected Humanitarian Supply Chain paradigm in situation

HSC behaviors to be tested, an evaluation will be possible through the measurement of performance indicators. To do so, it is required to build a model representing the actual system considered. Generally, the question arises of the reliability of such a representation. This is ensured by validation steps. In our situation, Indonesia, one of the most disaster-prone countries, and the Indonesian Red Cross, the main humanitarian actor in this country, will serve as an inspiration for constructing the model.

Finally, as the novelty in associating PI with HSC is quite unexplored and the humanitarian operating field is broad, we will limit the perimeter of the study to the improvement of HSC performance in delivering relief items to victims of natural disasters. The reasons for this choice lie in the confirmed growth in the number of natural disasters expected in the future and by the fact that relief supplies are recognized as crucial in disaster management [Shao et al., 2020].

These ambitions pave the way for different working areas presented and detailed in the following sections.

4.2.2 Step 2.1 – Collect information & data

This step aims to describe the case study used and the information collected to build the model.

4.2.2.1 Indonesia: a disaster prone country

The republic of Indonesia, in South East Asia, is the world's largest archipelagic state with around 17,000 islands. Given its proximity to the equator, the tropical climate ensures, on average, a temperature of 28° celsius and an 80 percent humidity rate. In terms of geography, the country benefits from lowlands, large rain forests and mountainous areas concentrated around its five major islands: Sumatra, Java, Kalimantan, Sulawesi and Papua. The administrative breakdown consists of two levels operating under the national government. The first administrative level consists of 34 provinces, headed by governors who supervise 416 regencies and 98 cities that are also regarded as part of the second administrative level. This country hosts the 4th largest population in the world with 271 million people and is expected to be the scene of the highest population growth in the future. In terms of distribution, the population is mostly concentrated in Java island (60%), which accounts for only 7 percent of the total area of the country [UNDRR, 2020]. Finally, the road infrastructure supports most of the movement of people and goods, respectively estimated at 85% and 90%. National and provincial roads only account for 18% of the road infrastructure while the remainder are city or village roads. Main roads are generally overloaded, facing regular traffic jams and in need of repair, limiting vehicle speed to below 40km/hour [Leung, 2016].

Indonesia is also significantly prone to hazards, with almost one disaster occurring per day and one major event per month. In the last 30 years, the citizens endured over a dozen major and deadly natural disasters, such as the Indian Ocean tsunami of 2004 or the Yogyakarta earthquake in 2006. Due to its location on the Pacific Ring of Fire, the country is in an area with a high degree of tectonic activity, and is exposed to a large diversity of disasters. It has even been called the *Laboratory of Disasters*. Among the natural disasters the country faces are earthquakes, tsunami, volcanic eruption (500 volcanoes with 128 active), flooding, drought, typhoons and

landslides, while technology failures, forest fires and epidemics, such as the recent COVID-19 pandemic, are anthropogenic hazards [Wibowo et al., 2013]. According to the statistics provided by the Indonesia Disaster Database (DIBI), over the last ten years, the number of disaster events has increased significantly, reaching 4,888 events in 2020, which is 2,4 times more than in 2010. Relying on the EMDAT database, the top three natural disaster in frequency are floods, earthquakes and landslides, while the most disastrous are floods, earthquakes and tsunamis. The trend of disasters events in Indonesia, as is the case worldwide, is expected to increase in future due to climate change and global warming [Wibowo et al., 2013].

4.2.2.2 Relief actors in Indonesia

The main disaster actor in Indonesia is the government. Its main missions are to protect citizens from the threat of disasters and to coordinate activities and relief participants through the disaster life cycle. To do so, the Indonesian National Board for Disaster Management, Badan Nasional Penanggulangan Bencana (BNPB) agency was established in 2007 after several major disaster occurrences. Its roles are to coordinate relief operations in case of a disaster, establish disaster management policies in Indonesia and manage international in-kind donations. In addition, government ministries with different specializations are also active in the disaster management process. The Ministry of Social Welfare and Health provides support in maintaining central warehouses used for supplies, food and tents deliveries and in providing medical services through allocated crisis centers. The Ministry of Public Works takes care of the transport and communication infrastructures by clearing and repairing them [Kusumastuti et al., 2010]. Provincial, municipal and district governments can also run operations, since they are the first to take action unless the event exceeds their capabilities. So, they have their own disaster management organization and budget. Such a decentralized organization with embedded government agencies at the different administrative breakdown levels is a strategic choice due to the archipelagic structure and large size of the country. In practice, such co-governance is challenging and leads to cooperation inefficiencies. Indeed, the capacity disparities among the actors and the variance in policies and objectives limits the smooth running of disaster operations management [UNDRR, 2020].

Other government actors contributing to relief aid but under BNPB supervision are the Indonesian National Armed Forces and Indonesian National Police [UNDRR, 2020].

The private sector also play an important role in disaster management but mainly focuses on providing short-term aid in the different sectors of humanitarian action e.g. water, health, construction or logistics. Humanitarian actors are currently striving to increase business participation in the preparedness phase. However, despite their coordination efforts, BNPB face difficulties with some, especially sub-national, private actors that operate autonomously and in an uncoordinated way [UNDRR, 2020].

Many international stakeholders such as Non-Governmental Organization (NGO)s, the United Nations (UN) or the Red Cross and Red Crescent (RCRC) are also regularly involved in developing community resilience projects or responding to disasters in Indonesia. Among the existing range of actors, United Nations Children's Fund (UNICEF), World Food program (WFP), World Bank, IFRC, all contribute to answering the needs according to their sector orientation [UNDRR, 2020]. National and local NGOs, estimated to be around 3,000 in Indonesia, also participate in

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everyday life or during disaster events as part of civil society. The most active national NGO in Indonesia is Palang Merah Indonesia (PMI), meaning the Indonesian Red Cross, which acts as an auxiliary of the government. Moreover [McGlynn Scanlon and Alawiyah \[2014\]](#) showed that NGOs are very different in terms of mission, size, capabilities and their connection with other NGOs.

Other players includes technical institutes and academic institutions, who are developing technical knowledge and innovations through customized and evidence-based tools and methods. Communities spread around the different islands also count numerous volunteers forming an effective network that can be quickly mobilized to take rapid action [[UNDRR, 2020](#)].

4.2.2.3 HSC and logistics organization in Indonesia

Resilience indicators about a country's logistics give an idea of the capability of SCs to provide life-saving commodities and manage the effects of a disruptive event. [WFP \[2017\]](#) identified 26 indicators were measured by the World Bank and other famous institutions across five areas to assess the vulnerability areas of a country's logistics. The SC resilience score for Indonesia is 63/100, which is close to the average of countries in Asia (India is 57 and Thailand 60). The best country in Asia is Japan with a score of 81, while North Korea with 22 is the most vulnerable to disruptions.

In a more detailed perspective (see figure 4.1), regarding the transport infrastructure, the country manages air transportation well but humanitarian aid faces difficulties in reaching remote and difficult-to-access areas [[Hadi, 2018](#)]. However, the transport network has limited capacity at the entry points, and the maritime connectivity for container shipping, measured via the number of ships, container-carrying capacity and number of available services, presents a low score. This leads to weak shipping connectivity within the country and also to limitations at the international level [[Hadi, 2018](#)]. As regards logistics performance, the quality of the logistics services, the ability to track and trace consignments and the timeliness of shipments all score reasonably well compared to the average in this region, reaching a 59 over 100 score for this global indicator. The local market characteristics (in terms of food security, local supplier quality, export diversification, etc.) and the economic and social factors (represented by the access to electricity, internet users, access to essential medicines, and so on) present good scores in alignment with the average in this region. However, the governance and customs group of indicators is the less well scored even if it is close to the average regional results due to complicated bureaucratic procedures, especially related to customs and some political instability and violence [[WFP, 2017](#)].

Disaster management and the organization of relief agencies are influenced by government policy and administrative logic. Consequently, most organizations with a significant structure have representatives at the provincial and district level. For example, BNPB counts twenty offices at the provincial and forty-four at the district level, while PMI is present in most of the provinces and districts, as are the various ministries. Large scale NGOs may have some representation at the provincial level while international NGOs are generally providing help by associating with local partners. As for relief logistics organizations, PMI, BNPB and ministries have their permanent facilities and separate network. Permanent facilities can be positioned at the national, regional, provincial or district levels while temporary facilities are set up close to the affected areas. Different criteria are used to strategically locate

facilities and depend on the Humanitarian Organization (HO)s’ mission orientation. However, these tend to be close to urban areas where human and material resources are more available and benefit from a good transport network [Kusumastuti et al., 2010]. UNDRR [2020] highlighted that there is a positive correlation between the number of NGOs and a given region’s Gross Domestic Product (GDP). In other words, the greater the economic activity of the region, the more it is susceptible to attracting NGOs.

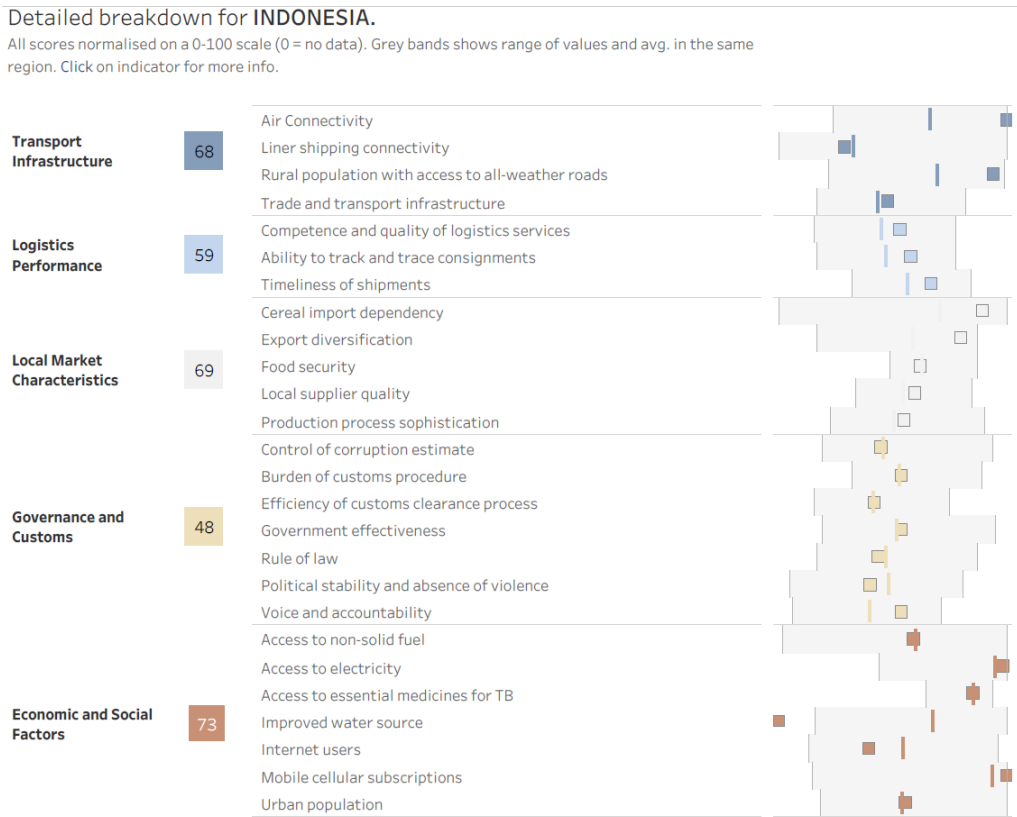


Figure 4.1: Indonesia: assessment of logistics resilience indicators extracted from [WFP, 2017]’s web-based tool

4.2.2.4 HSC and logistics organization within the Indonesia Red Cross (PMI)

The Indonesia Red Cross (Palang Merah Indonesia (PMI)) is acknowledged by the government of Indonesia as the only red cross organization and recognized as an auxiliary to the government. It is guided by the 7 principles of humanity, impartiality, neutrality, independence, voluntary service, unity and universality. PMI’s mandate in the disaster management context is to assist the government and cooperate with strategic partners to provide high-quality humanitarian assistance [PMI, 2014]. In this context, PMI is regularly in touch with BNPB for coordinating the distribution of aid.

Basically, PMI activities can be split up into three categories, namely: programs/services, development actions and supporting activities. Programs or services are part of PMI’s front line activities and include disaster management, blood transfusion and health services. Disaster management focuses on preparedness, emergency

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response and disaster recovery. Preparedness programs that are currently initiated and implemented by PMI are more involved in strengthening community capacity, such as volunteer training and preparing communities to be resilient. Emergency response activities deal with evacuations, sanitation constructions and providing relief items. PMI, as a core business activity, also manage blood donation collection within the country (unique organizer) to support hospitals and medical services during disasters. Regarding health, PMI raise awareness about good health behaviors and HIV, provide first aid and ambulances for daily incidents and also give psychological support. Supporting activities of the programs/services are regarded as the “back office” and include logistics, information technology, finance and HR & administration and law. Finally, the development activities concentrate on strategic activities related to the planning & monitoring, fundraising and volunteer training and management [IFRC, 2016]. Most of the human resources are volunteers while 2% are permanent members. The difficulty in mobilizing volunteers for emergencies is that they have regular jobs that do not allow them to be always available. Besides, volunteers tend to prefer activities performed in the forefront than in the background.

The logistics service in PMI supports other programs such as disaster management, health and first aid by meeting the demand expressed by those units. To do so, it relies on; the logistics assessment to plan what is needed, where it is possible to source it and how to move it to its destination, the procurement to mobilize what is needed, transportation to transfer it where it is needed, warehousing and stock management for securing it and reporting to inform key stakeholders about its follow up. This department is motivated by the 5 “rights”: getting the demand at the right place, right time, right quantity, right quality and right price while using the means in the best possible manner [Cross et al., 2012]. An interview with the PMI’s head of the logistics department has highlighted some difficulties faced, such as the heavy costs carried (80% of the budget for emergency response is allocated to logistics) while the financing of the logistics is not prioritized compared to the other organizational functions, as it is not attractive and regarded as a back-end service.

In terms of networks and assets, PMI has a decentralized and demography-oriented strategy to support a “6-hour arrival” objective to be on the ground and provide help. In this sense, 6 regional warehouses have been positioned over the country to cover a certain ratio of population and all are supervised by the headquarters located in Jakarta (Indonesia’s capital). However, the population growth rate means that today the number of regional warehouses is insufficient compared to the original ratio defined, and a development project is being planned to install more in the future. Provincial warehouses, covered by the regional warehouses, are sized for covering the potential needs of a population at the scale of a province as well as the demand of the district or branch warehouses they are themselves supposed to cover. Mobile Storage Units (MSU) are temporary and easy-to-deploy warehouses for emergency storage purposes. In fact, the network organizational design of PMI can be regarded as hierarchical, since nodes are arranged in a tree-like structure and most of the interactions take place only between close agents. Entities higher in the tree have a more global view, as is the case with the headquarters, which monitors disasters at the national level and oversees operations management. The network can also be regarded as a multi-divisional hierarchy since each node exploits its localization and has complete control of its resources and decision-making process [Horling and

Lesser, 2004]. It is only when the disaster overwhelms the capacity of the node that the upper node in the hierarchy takes the operational lead.

The field survey also enabled us to gain a process-oriented vision and to understand the strategies regarding how PMI prepares and responds to natural disasters. As part of their logistics preparedness, PMI stores key relief items to give basic comfort and help affected people rebuild their lives after a disaster occurrence. These regularly provided non-food items are; tarpaulins that consolidate shelters, blankets, kitchen sets, jerry cans - regarded as household items - and also hygiene kits for personal hygiene. Some of these are provided to each individual while kits are generally for several people and are composed of many items. IFRC uses a standard kit size for 5 people living together. PMI turned from cardboard boxes for kit packaging to plastic boxes that can be re-used by beneficiaries and which are not subject to moisture effects. Kitchen sets, school kits, tarpaulins and blankets are generally provided once for each household while other kits have an expected consumption time of one month. This list of items may vary depending on the country, the disaster context and specific needs but pre-positioning key relief items allows the delivery lead time of the first aid to be reduced and not dependent on local market availability [Cross et al., 2012]. As for food items, they are bought locally and mainly consist of rice.

During a relief operation, for coordination purposes, PMI commits to providing assistance to a ratio of the total affected people or specific areas in one or several humanitarian action sectors. This decision relies on the disaster size, the number of HOs involved and available capacity. When it comes to relief item distribution, PMI is responsible for supplying the Point of Delivery (POD), located close to the affected population with a minimum delay. To do so, the logistics department supports the relief team in organizing the procurement, transport, warehousing, delivery and reporting of the items. In practice, once a disaster occurs, small teams are sent to the affected zone to make a rough first assessment of the disaster size, the number of victims and accessibility. Those observations allow an estimation of the needs in basic relief items and lead to the drawing up of a plan of action. Then, logistics teams evaluate their options and make the logistics assessment. In parallel, PODs for relief item distribution are deployed near densely-populated areas to wait for the arrival of supplies. Next, the warehouse in charge, normally the one responsible for the affected area, responds to the demand with inventory on hand, finds an appropriate fleet, organizes the delivery to the PODs, and manages shortages by procuring what is missing. Procurement sourcing options are local or global suppliers, the closest IFRC hub in Malaysia, partners or donors. Once supplies arrive at PODs, relief teams reception, store and then distribute goods to beneficiaries. First assessment is generally performed in 1 or 2 days, while within a week experts provide a more detailed assessment with more accurate figures and specific needs. As long as the relief operations progress, continuous assessments are performed and the plan of action is updated.

4.2.3 Step 2.2 & 3 – Define a model to be used for constructing a computer program and verify

The second part of step 2, i.e. the model definition, and step 3 will be described together in this section, as they are closely related. Indeed, the model in step 2

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is a theoretical model representing relief logistics in Indonesia while step 3 is the programmed model derived from the previous one implemented in the simulation.

Based on the knowledge gained in step 2, we can now instantiate the technical framework. The simulation integrates four essential components in a relief context:

- the territory system represents a territory and its key social and geographical characteristics that have an influence on the relief organization,
- the disaster system generates natural disaster events and impacts on people and materials,
- the demand system estimates the demand in relief items based on victims numbers and damage,
- the humanitarian response simulation represents the HSC and logistics operations.

Each of those components will be detailed, with the elements from the case study considered, in the respective sections below.

4.2.3.1 Territory System

The territory system intends to represent a territory and its key social and geographical characteristics that have an influence on the relief organization. Here, the region considered and recreated in the simulation is Aceh (one of the 34 provinces in Indonesia) and its 21 districts over the 23 that compose the mainland. The two remaining are islands, which will be ignored as we are not considering maritime or air transportation yet. This region was chosen because Aceh has faced major natural disasters in the past and presents disparities in terms of population distribution, which makes it an interesting case study. For simplification purposes, we are only considering people in general and no distinction is made regarding gender or age. We are also not considering the impacts on buildings and public facilities. With regard to the transport network, AnyLogic provides GIS maps to recreate the existing main-road network as well as the territory boundaries and related geography (see figure 4.2).

4.2.3.2 Disaster System

The disaster system generates natural disasters events and their impacts on people and materials. Currently, only earthquakes, as a sudden-onset disaster type, are considered due to their frequent occurrence in this region. To represent an emergency context as accurately as possible, we based the system on reports about a major earthquake striking Aceh province on the second of July 2013. This 6.1 magnitude earthquake severely struck Bener Meriah and Aceh Tengah districts. It will be represented with circles of different sizes and colors according to the Modified Mercalli Intensity (MMI) scale. In general, intensity waves from an earthquake are not real circles but since Indonesia is a rather flat country and data related to intensity perimeters were not easily accessible, we chose to use circles as a reasonable approximation (see figure 4.3).

The disaster caused deaths, injuries and damage to houses and community facilities. As we are focusing on relief item delivery only, we limited the scope of beneficiaries to Internally displaced person (IDP)s. These are defined as people forced to leave their home but remaining within the country's borders, unlike refugees. They



Figure 4.2: Aceh Province (Indonesia) modeling in AnyLogic software

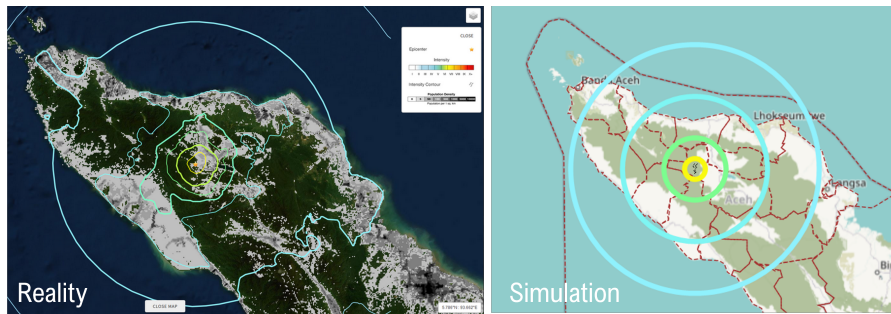


Figure 4.3: Modeling in AnyLogic software of the 2 of July 2013 earthquake event hitting Aceh province (Indonesia)

will be considered in the simulation as the affected people that the relief logistics will supply in relief items.

The disaster system can recreate any fictive or historical earthquakes as long as the date, duration, coordinate and impacted zones are provided.

4.2.3.3 Demand System

The demand system estimates the demand in relief items based on the number of victims and the damage. Given that the disaster may continue to generate damage and/or that the aid is still being provided, the needs in relief items evolves over time. Such information is provided by the assessment teams on a regular basis to the disaster management and logistics department. However, this information is difficult to obtain and predict, as figures are often inaccurate or provided irregularly by reports. Besides, the damages made by a disaster depends on many factors related to the disaster characteristics (severity, duration,...) but also the vulnerability of the affected region (geography, population vulnerability,...). In this situation and for simplification purposes we decided to make some assumptions regarding the demand generation and sequencing.

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Affected People Calculation First, based on the report we had about the historical earthquake, we assigned the districts with a vulnerability percentage [OCHA, 2013]. Then based on the population of each district provided in input, the affected population turns out to be the vulnerable part. This way, the estimates are close to the final and real affected numbers available in the reports.

Relief Item Needs Calculation Once we had the affected people number we had to calculate the number of relief item needs. Again, this step is not obvious as each disaster is unique and humanitarian actors tend to use expertise and experience to provide those numbers. However, some supplies were identified as priorities in the first hours of any type of emergency (e.g. jerry cans, tarps, tents, blankets, hygiene kits) [Beamon and Balcik, 2008]. Consequently, we decided to focus on some key items furnished by PMI that are provided in most emergency cases. These selected products are: blankets, jerry cans, kitchen kits, tarpaulins and hygiene kits. Product characteristics for the dimensions, volume, weight and price were provided to us. With the exception of hygiene kits, which are designed for 5 people and have an expected consumption duration of one month, the other items are provided individually and generally only once. Normally, working with family kits does not imply distributing one kit per affected family, as it may depend on the size of the family and the specific needs identified by the assessment team [Cross et al., 2012]. Here, for simplification reasons, we assume that the need for each relief item is equal to the number of affected people divided by the product coverage in number of recipients.

Establish Consumption Profile In a real context, the number of affected people is expected to grow as long as the assessment becomes more accurate with time. Besides, some items have a consumption duration that may require considering some replenishment if the emergency lasts. Such elements made the consumption profile complex and difficult to establish, as we are missing information related to evolutions in the number of people affected. Therefore, in the simulation, we decided to consider that the total number of recipients has been known since the first assessment and this figure will not change over time. The demand is available to the humanitarian response simulation 48 hours after the disaster occurrence, as is usually the case. Consequently, the demand profile looks like a step function. Besides, we are only focusing on the rapid response phase of the delivery of the aid. For this event, the government declared a state of emergency from 3 to 17 July 2013 [OCHA, 2013]. which bring us to consider the first month as a window to monitor the delivery and the performance.

Generate Demand Finally, after a disaster, homeless people usually stay in shelter areas. These are temporary settlements where supplies are distributed. There are many criteria to consider to establish shelter sites such as reachability, terrain structure, or proximity to health and electricity infrastructures. As it has been the place for many research and optimization problems, so far, and slightly out of the scope in this experiment, we have decided to randomly locate them within the affected districts. Obviously, shelter sites and PODs are two distinct elements, but in our case, we will only consider PODs as demand generators and final destinations for the items. Therefore, the direct distribution

from PODs to recipients is not considered in the simulation. Additionally, the number of PODs to deploy is also a decision made by humanitarian actors that relies on various factors. We assume, in agreement with red cross practitioners, that PODs are deployed 48 hours after the event, one for every 5,000 affected people. For simplification reasons again, the number of people assigned to, and benefiting from each POD is shared equally among the locations. As soon as the temporary warehouses are set up, they send what we call Order Line (OL)s, which are replenishment orders for each of the five products we consider. Last but not least, PMI is not the only actor involved during this event for distributing non-food items particularly. Of the 52,133 IDPs, PMI committed to assisting 5,000 individual (1,000 families) by providing relief and medical support with a 60/40 split between Aceh Tengah and Bener Meriah [IFRC, 2013]. Accordingly, the demand considered in the simulation is 10% of the number of total affected people for each district. As we are aware that human impacts are uncertain and that they fluctuate a lot depending on the disaster context, we consider a nominal value of 50,000 affected people in total with a range of, at a minimum, half of it (25,000) and, at a maximum, five times the number (250,000), following a triangular distribution. The limits of this distribution are set to maintain the affected number within the scope of a medium/large size disaster not requiring international assistance.

4.2.3.4 Humanitarian Response System

The humanitarian response system aims to represent the HSC and logistics operating during the response phase, based on predetermined preparedness and network design choices.

PMI predetermined supply network

In the simulation, we focus only on PMI and its network to cover Aceh Province. As permanent warehouses, this network consists of one Regional Warehouse (RW) located in Western Sumatra (Sumatera Barat) and outside of Aceh in another province, one Province Warehouse (PW) located in Banda Aceh (capital of Aceh province) and twenty District Warehouse (DW)s. This information is taken from the PMI website (see figure 4.4). Temporary warehouses - the sink nodes of the network considered in this simulation - are the PODs mentioned in the Demand system section (See 4.2.3.3). As POD deployment is subject to discussion and positioning depending on various criteria, we decided to locate them randomly within the affected district. Regarding the inventory, we know that PMI have a population-oriented policy and that the RW ensures a coverage of 2,000 families. Based on this, and on field visits, we assume PWs to target a level of 300 families and DW a coverage of 20. Based on this nominal value, and to be more realistic, as DWs are known to be heterogeneous in terms of capacity, we assigned each DW with a population-coverage percentage leading those with a larger population to cover with more stock than those less populated. Regarding the items, the same products: blankets, jerry cans, family kits, hygiene kits and kitchen kits are stored in all the different warehouse types. However, this new nominal value is then used to also generate variability among the different products stored within the same warehouse. A triangular distribution is again used to set the inventory level for each item between 0 to twice the nominal value of the warehouse.

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Since we are focusing on the mainland districts of Aceh province, the preferred mode of transport is by road. So, to connect the warehouses and ensure deliveries, a 5-ton truck is considered as one of the commonly-used types of vehicle by PMI logistics teams. Also due to the transport network conditions and the fact that Aceh is a mountainous region, we assume the truck speed to follow a triangular distribution and to be on average 39 km h^{-1} , with a minimum of 25 km h^{-1} and 53 km h^{-1} maximum. We assume such trucks may carry 5.000 kg and 35 m^3 as a maximum. As confirmed by discussions with PMI teams, trucks are always available within a day and are rented if needed. We also consider a loading and unloading time, following a triangular distribution varying according to the utilization rate and ranging from 30 min to 2 h with 1 h as mode.

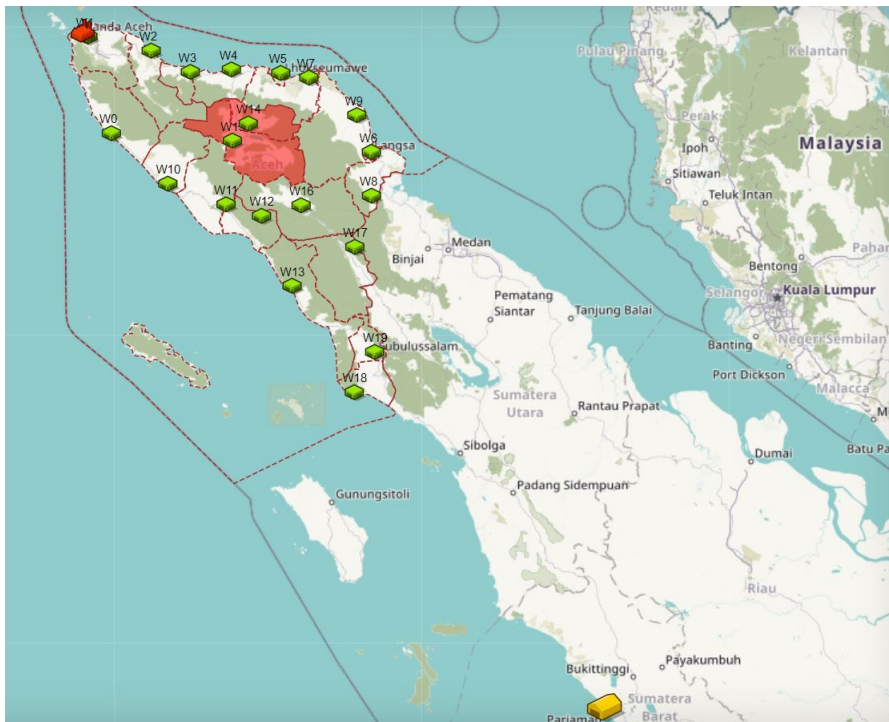


Figure 4.4: Map of PMI logistics network, DWs in green in most of the districts, PW in red in the capital and the RW in yellow

PMI and relief logistics processes

From a high-level perspective, we identified, sequenced and incorporated into the simulation four main processes (see figure 4.5). At the decision level, the logistics preparedness process, which consists in defining the product catalog and initial inventory as well as the settled humanitarian logistics network for the system to start with. This has been detailed previously. Secondly, at the operational level, the distribution process, which consists in distributing relief items from PODs to beneficiaries, but this process is not covered in the simulation except if we consider the waiting time for the truck to be unloaded at the POD. Finally, there is the mobilization process, which consists of three sub-processes: order management, replenishment management and transport management.

Order management is the process where a warehouse, whatever its type, receives a request for a product, known as an OL. An OL, as in commercial SC, is a request for

an amount of a certain product with an issue date and an expected date for delivery. In the case of an emergency, this date is the current day (i.e. as soon as possible). The destination of the item to be sent is generally the order requester. Orders are collected throughout the day, and once a day they are processed to investigate if they can be fulfilled. Most of the time, cumulative demand is higher than the inventory level. In such circumstances, several policies can be applied. Two of them are tested with the experiment and will be described in a following section 4.2.5. Once the OLs are sorted, those that can be fulfilled with inventory on hand go to the transportation management process while the others go to the replenishment management process.

The transport management process consists in organizing the transport of items for delivery to the order requester or “client”. As suggested by practitioners, there is a 24h delay between the order management and the shipping, for truck mobilization and bureaucratic reasons. As much as possible, OLs that have the same destination and contribute to filling up a truck are grouped together. Trucks are rented, made available at the departure node, then loaded, reach their destination, then are unloaded and go back empty to their initial position. The transport management process is also an area where different policies can be applied, therefore two approaches are studied through the experiment: the current practices and a PI orientation. These will be discussed later on 4.2.5.

As regards the replenishment process, based on OLs that could not be fulfilled, inventory and expected replenishment, a decision is taken to decide whether a new replenishment order needs to be placed for each of the stored items. The quantity to request is calculated using a re-order point policy and during the emergency the safety stock (i.e. nominal value at a warehouse) is not considered and only the needs required to meet the demand are taken into account. Potential suppliers for replenishment are only PMI network nodes; external suppliers are not considered in this simulation. In other words, relief items can only be sourced from DWs, the PW or the RW. The decision to define which supplier(s) a warehouse should send its replenishment order to is also subject to different approaches and these will be discussed in the following section 4.2.5. Now, whatever the selection, as sources are part of the PMI network, we assume that sending supplies between nodes is not charged. Finally, as the RW is the only entry point for supplying the global network with more inventory, we assume that its inventory is initialized to 2,000 units of each item and can be replenished within a certain time frame. This time frame is also detailed and questioned in section 4.2.5.

Finally, one additional support process dealing with inventory management is considered. It concerns product reception, where a replenishment order arrives and can be taken into account to return the inventory to its safety stock level in order to anticipate a new disaster. However, this only occurs in normal times, not during emergencies, so given our time window this last point is not covered.

4.2.4 Step 4 – Make pilots runs, observe results and validate

As conclusions will be drawn from this experiment, we have to ensure that the model and its associated results are correct. To do so, we have to verify and validate that the system considered is well represented through the theoretical model and well implemented in the simulation. Many approaches and techniques exist but [Sargent](#)

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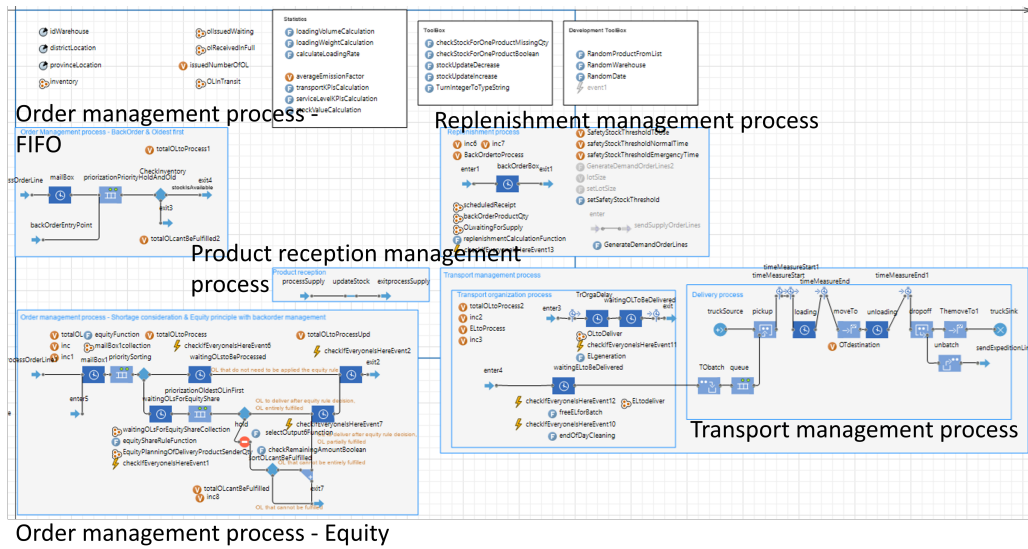


Figure 4.5: PMI relief item-related logistics processes (flowchart modeling) implemented into AnyLogic software

[2010] suggests that the data used, the assumptions made and the implementation aspect should all be checked.

Regarding the data used, our interviews and data analysis could not provide us with all the required parameters and inputs precisely. As a result, in defining the baseline scenario, we estimated some parameters. To do so, we relied on official and reliable databases and information sources such as EM-DAT for disasters, PMI and BNPB official websites, as well as reliefWeb for disaster management reports. As for the conceptual model, theories and assumptions, as well as baseline practices such as trucks being dedicated to one organization at a time and returning [to warehouses] empty after delivering items, have been validated by practitioners during regular workshop sessions. Additionally, to make sure that the representation of the system considered was appropriate for the intended objective of the experiment, we relied on the System Engineering (SE) approach, which is designed precisely for this purpose. Finally, concerning the implementation, validation and verification, we ran pilot tests to ensure that the simulated behavior is close to the historical behavior. Initial results from our pilot studies suggest that our assumptions and estimations are consistent with humanitarian situation reports found. We also verified that the model behavior through graphical animation was appropriate (see figure 4.6). First results were presented during the European Working Group on Humanitarian Operations (EURO HOpe) conference and Logistics Cluster Global Meeting in 2021 in front of both academics and practitioners.

4.2.5 Step 5 – Design the experiment protocol

Factorial experiments consist in conducting a series of trials by varying one or several input parameters (named factors) according to a range of values that they may take (we talk about levels of a factor) to change a system behavior in the perspective of monitoring outputs and drawing conclusions [Banks, 1998]. The Design Of Experiment (DOE) process related thus, consists in determining the

4.2. Design & Prepare the experiment to be conducted

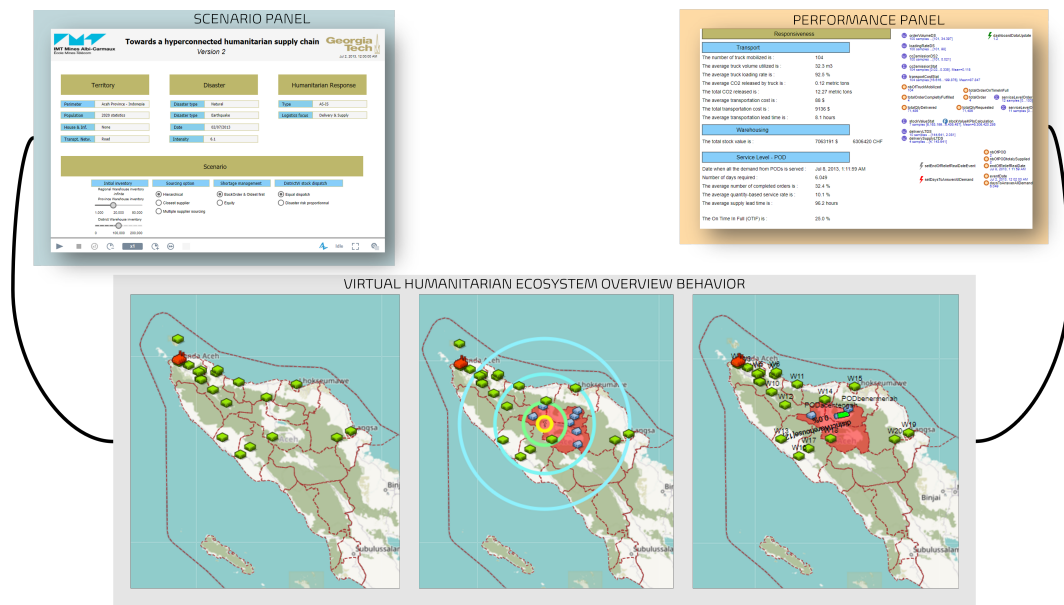


Figure 4.6: Simulation run showing the three interrelated systems: the scenario, the performance and the digital humanitarian ecosystem

objective of the experiment, then defining the independent and dependent variables (See factor typology description for more details 3.2.1.2) for the study and finally selecting an experiment design [Croarkin and Tobias, 2012].

4.2.5.1 Experimental objective

As a reminder, the experimental objective is to measure how some PI integration into key HSC levers would affect the relief performance compared to a baseline scenario. Meanwhile, it would be interesting to identify which PI-oriented policy changes would have the most significant impact on the results. As mentioned in Chapter 2, there are a lot of avenues for the PI at the HSC level for some change of practices. Once the baseline scenario has been validated, the design of the experiment phase then consists in designing scenarios variants for making comparisons [Chung, 2004]. The cost associated with the factors required to perform a series of trials is increasing exponentially. The concept of two-level factorial experiment has meanwhile become popular as it is less costly but still gives good result. This is therefore the direction we have chosen.

In this experiment, we will define a *scenario* as a particular setting of the digital humanitarian ecosystem that is created at the scenario-system level before running the simulation. It consists in selecting the associated level (i.e. the value) to test for each factor or variable, and thus defining one of the possible combinations.

4.2.5.2 Factor list and parameters description

As the implementation into the simulation of all the levers identified in Chapter 2 was not feasible, we limited the number of factors to test to the most accessible and potentially promising ones at the network design and logistics process levels of HSCs. As such, we identified 4 factors with 2 levels each: level 0, representing current practices, and level 1, representing PI-oriented practices (See Table 4.2). Each of them

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represents a key operating rule for the associated operational processes it supports (i.e. order management, replenishment management and transport management). As we are considering the digital humanitarian ecosystem from a high-level and flow-oriented perspective, we have worked with factors that serve to interconnect actors, which is one of the key pillars of PI. In this perspective, we investigate a level 1 for factors that could take advantage of the connections of new actors and benefit from an increased and shared visibility of information, while only using existing PMI network resources.

The first factor considered is named the *RW replenishment lead time*. Here we are investigating the replenishment lead time, as we know it is a challenging aspect in the humanitarian context. Long bureaucratic procedures and limited suppliers tend to extend the delivery lead time, although it is a crucial factor. The interest and expected impact of such an improvement on the performance is clearly evident. As in the simulation context, we do not consider business suppliers, because the only entry point when global stock is insufficient is the RW, so we investigate the replenishment lead time for this warehouse only. Today, the replenishment lead time of the RW supplying the local network is relatively long and we can assume the duration to be 15 days (10 business days) once the demand is known, as confirmed by practitioners. This figure also seems reasonable because Indonesia is a manufacturing country with many and various suppliers and, as a partner, IFRC's warehouse in Malaysia is nearby. In contrast, with the PI philosophy, whereby standardized protocols and an increase in source offers and visibility would speed up the information and physical flow, we assume a shorter replenishment lead time of 3 days.

When there is no time to lose and when demand exceeds the available resources, a decision has to be made to supply the POD in the best possible manner. In a humanitarian context, this situation is frequent and different approaches are possible, which is why we consider, as a second factor, the *Shortage policy*. Currently, the singularity of each disaster lead this decision to be adapted based on criteria and experience, making it difficult to define. However, for practical reasons, PMI would tend to use the First In First Out (FIFO) approach. This means, in the simulation, that OLs are sorted based on their issue date and the first received are the first served with inventory on hand. Obviously, as much as possible, OLs are fulfilled as long as there is enough inventory. Equity is also another possible approach and this is an issue during the decision-making process, although not obvious to put in practice. It is one core objective of humanitarian actors and is monitored as a performance result by donors also. This decision is important and should be integrated into the simulation. It is also quite aligned with the PI philosophy of promoting a change in practice towards more sustainability, and the social aspect is key regarding this goal, especially in a humanitarian context. In practice we coded equity as follow: based on the percentage of the demand of each product for each client, we allocated to each client a part of the available inventory, and thus defined an inventory dispatch plan for the set of daily clients. Based on this, OLs are sorted depending on whether they are completely, partially or not at all fulfilled, and are positioned accordingly in either the transport management or replenishment management process.

[Blecken \[2010\]](#) said that “*Transport has the objective of to overcome the spatial separation of point of source and point of demand in an optimal manner.*” Managing transport is a critic process in disaster relief including a large range of activities such as consolidation, contracting and cost minimization [[Pettit and Beresford, 2009](#)].

However, decisions are often decentralized, which may lead to inefficient use of resources and capacity competition among aid agencies [Huang et al., 2012, Pettit and Beresford, 2009]. As of today, when there is an emergency, vehicles are chartered at every supplying node and sent to the disaster locations [Kovacs and Spens, 2007]. Consequently, in the simulation, 24 hours after the order management process has happened, OLs that can be fulfilled at a node are grouped if they have the same destination and can thus increase a truck’s utilization rate. They are then assigned to an Expedition Line (EL), which is allocated to a chartered truck. When the loading time is due, the truck departs, moves to the client location following the shortest path, unloads items at the destination and goes back empty to its original destination to be “desactivated”. For the previously-mentioned reasons, we believe PI has a lot to offer at the *Transport consolidation* level and this is why it is the third factor we consider. Indeed, by better coordinating the deliveries, we can expect a better use of means and a transportation costs reduction. In this perspective, we developed an optimization model that propose a simple manner of consolidating the deliveries (See Appendix B). As it is closely linked with the following factor, more details about this optimization model are provided in the next paragraph.

The final, but not the least important factor considered is named the *Sourcing policy*. When products are needed, one or several suppliers are generally called to fill the gap. Choosing the right supplier is a complex task depending on various factors such as availability or quality within the replenishment process. Currently, PMI is organized in a hierarchical structure. This means that DWs have the PW as a unique contact and supplier, which is itself supplied by the RW. Consequently, information and physical flows are disseminated in a cascade. With the PI approach, we investigate a change in the hierarchy system toward a horizontal and vertical connection of all the network nodes, and we authorize multi-sourcing. While it is determined in the current context, such changes increases the sourcing offers and raise the question of supplier(s) selection. By taking opportunity of the increased information visibility and technology usage to support smart decision making, as the PI considers it, we developed two optimization models and integrated an orchestrator into the simulation. The orchestrator does not represent any real entity but acts as a decision-making agent for supplier selection in a matrix network (i.e. all nodes are interconnected). Instead of directly sending replenishment orders to an assigned supplier as dictated by the hierarchy structure, OLs are centralized by the orchestrator, who has total visibility regarding each nodes’ inventory. Once a day, the orchestrator manages these orders and indicates a set of suppliers for each “client” in a way that would minimize the total transportation cost in moving items from their stocks. The objective is the same for the both optimization models but the difference is that one is applied when the multi-sourcing approach is combined with the decentralized transport consolidation (See Appendix A) while the second selects suppliers while consolidating the deliveries (See Appendix B). For both models, the main assumptions are: (i) that deliveries can be completed within a day, (ii) for the same day, a client for a product cannot be selected as a supplier of the same product and (iii) there is no truck limit and only one type is used and (iv) deliveries from warehouses to PODs, PODs to PODs, PODs to warehouses, and warehouses to warehouses are allowed. One particularity to mention is that both models also consider the defined shortage policy. Indeed, when he/she starts managing the OLs, the orchestrator first as to assign the quantity received by each client (likely different

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from to its initial demand) because the global network inventory is under-resourced. This adjusted demand, which results in different values according to the shortage policy applied, is used as an input parameter for the optimization model.

All the factors and parameters of the simulation model are summarized in a table form (See table 4.1).

Table 4.1: Simulation model factors and parameters

Uncertainty category	Label	Factor exogenous	Factor endogenous	Parameters (Fixed for all scenario)	Rule
Data	Demand profile			X	The demand is totally known 48h after the event occurrence
	Victim number (= global demand)	X			Triangular distribution (min = 1/2 * nom = 25 000, nom = 50 000, max = 1.5 * nom = 75 000)
	Disaster complexity			X	Single event
	Localization			X	Bener Meriah & Aceh Tengah
Environment	Disaster severity			X	6
	Disaster type			X	Earthquake
	Disaster scale (impact)			X	Medium size
Resources	Human : Loading/Unloading lead time			X	Triangular distribution (tx utiliz*30min, tx*1h, tx*2h)
Transportation	Truck speed			X	Triangular distribution (min = 25km/h, mode = 39 km/h, max = 53 km/h)
Product flow	Replenishment lead time of the RW		X		15 days or 3 days
	Product catalogue			X	5 products PMI
	Stock Initialization	X			Triangular distribution (0, assigned warehouse NV, 2*NV)
	POD Allocation (victim repartition)			X	Equal same for each POD
	POD Location			X	Randomly positioned
Storage	POD quantity			X	1 for 5,000 victims
	Assets			X	Existing network
Coordination	Stakeholder complexity (number)			X	1 HO
	Coverage target/(split)			X	10% total demand
Operation management	Shortage policy		X		FIFO or Equity
	Sourcing policy		X		Hierarchical or Multiple sourcing
	Transport consolidation policy		X		Private or Consolidated deliveries

4.2.5.3 Performance indicators

While measuring the performance of HSCs, our focus will be on three main dimensions: effectiveness, efficiency, and sustainability.

Effectiveness is the extent to which the beneficiaries' needs and requirements are met [Beamon and Balcik, 2008]. The two main performance indicators related to effectiveness will be the response speed and the service level. The response speed is calculated as the delivery lead time to serve all the demand as soon as it is provided once the assessment is completed (48 hours after the event). It is expressed in days. As for the service level, in percentage, it is the value of the quantity supplied by the quantity requested at 15 days for the state of relief deadline.

Table 4.2: Factors identified and associated levels used for designing the experiment

Factor code	Factor label	Level 0	
		Current practices	Level 1 oriented practices
SR	Sourcing policy	Hierarchical	Multiple sourcing
RL	RW Replenishment lead time	Long	Short
SH	Shortage policy	FIFO	Equity
TC	Transport consolidation	Decentralized, Private deliveries	Consolidated deliveries

Efficiency measures the correctness of the needs evaluation, the speed of adaptation to changes, and resource utilization [Neely et al., 1995]. As mentioned before, HSCs work with limited resources and budgets and must use these limited resources with high utilization rates for accurately assessed needs. The cost of transportation and the utilization rate of trucks will be used as indicators of efficiency. The cost of transportation is calculated as the distance travelled (km) \times an average fuel consumption factor (liter/km) \times a fuel cost (\$/liter) where the average fuel consumption factor equals, in Indonesia, 0.285 liter/km [Hine et al., 2000] and the fuel cost was 0.835 (\$/liter) when consulted [McKinnon and Piecyk, 2011]. Regarding the utilization or loading rate, it is calculated in percentage as the maximum between (i) the volume occupied compared to the truck capacity in volume (35 m³) and (ii) the transported weight by the truck weight capacity 5.000 kg.

Finally, the UN defines sustainability as “*meeting the needs of the present without compromising the ability of future generations to meet their own needs*” [UN Secretary-General and World Commission on Environment and Development, 1987]. Since HSCs conduct very large-scale operations, following green SC practices can have a large impact on global warming and climate change issues. In our model, CO₂ emissions resulting from transportation efforts will be the indicator for sustainability. To calculate the greenhouse gas emissions, Mathers et al. defines a simple formula as: the distance travelled (km) \times the shipment weight (tonne) \times the mode’s specific emissions factor (gCO₂/tonne-km). For the road transport, the average emission factor used is 62 gCO₂/tonne-km [McKinnon and Piecyk, 2011]. As the formula considers the weight of the shipment, the indicator monitored in the simulation does not take into account empty trucks returning after a delivery.

This set of performance indicators can be expanded with more detailed and specific indicators as well; at this level of the research, we are considering very generic indicators.

4.2.5.4 Experimental design type selected

The experimental design should be aligned with the objective and the number of factors considered [Croarkin and Tobias, 2012]. According to the Croarkin and Tobias [2012] design selection guideline table, as we are considering 4 factors with an objective of investigating effects and variance from factors on performance indicators (i.e. defined as a screening objective) we may use a full or fractional factorial. The difference remains in the number of combinations considered. Here, as the number is relatively below 5 factors and the duration of a simulation run is quite short (a few minutes), we will choose a full factorial. Since 4 factors are considered, each at 2 levels, then there are 16 possible combinations. However, as the transport consolidation relies on an hyperconnected logic, where the inventory level from the whole set of nodes is visible by the orchestrator and shipments authorized between the different nodes, it can not operate in a hierarchical system. Consequently, the combination of the two factor options is unauthorized, reducing the number of scenarios to 12 (see figure 4.7). The lowest path of the full factorial experiment tree combines the current practices of PMI for each investigated factor as determined from the interviews made. At the top, is represented the most hyperconnected scenario possible while all the remaining scenarios in between are gradual scenarios towards hyperconnectivity, similar to those in the experiment described in Kim et al. [2021] experiment.

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Table 4.3: Scenario coding system presentation

Scenario code	Sourcing		Transport		Replenishment LT		Shortage	
	Hierarchical	Matrix	Private	Consolidated	Long	Short	FIFO	Equity
(0,0,0,0)	✓		✓		✓		✓	
(0,0,0,1)	✓		✓		✓			✓
(0,0,1,0)	✓		✓			✓	✓	
(0,0,1,1)	✓		✓			✓		✓
(1,0,0,0)		✓	✓		✓		✓	
(1,0,0,1)		✓	✓		✓			✓
(1,0,1,0)		✓	✓			✓	✓	
(1,0,1,1)		✓	✓			✓		✓
(1,1,0,0)		✓		✓	✓		✓	
(1,1,0,1)		✓		✓	✓			✓
(1,1,1,0)		✓		✓		✓	✓	
(1,1,1,1)		✓		✓		✓		✓

A scenario coding system has been generated for handling and analysis simplification reasons. Accordingly to the factor level considered, the scenario may be assigned a 0 value if it uses a current practice and 1 if it tests a PI-oriented one. So, a scenario is described by a combination of four figures separated by commas. The set of possible scenarios and assigned code is visible in the following 4.3.

4.3 Experiment execution, Results & Analysis

This section describes the three last steps of the functional framework, as they are less conceptual and more related to simulation outputs and their analysis.

4.3.1 Step 6 – Make production runs and verify

Production runs aim to generate output data from each doublet scenario and replication with the simulation. This phase provides an associated set of key performance indicator results necessary for making analyses and recommendations driven by the experimental objectives defined [Chung, 2004].

To ensure the validity of the conclusions drawn, a verification phase is required beforehand to make sure the model has been programmed correctly [Sargent, 2010]. In this study, verification consisted in checking possible errors in the code, such as spelling mistakes, variables or types based on the programming language properties. Then, dynamic tests regarding the data generated at the end and during the execution were performed. The techniques used were input-output relations, data validity and consistency checks and material flow tracing. Finally, as the model integrates probabilistic distributions that induce variability in the data outputs, it is necessary to perform scenario replications to avoid incorrect recommendations due to randomness. If this is obvious, it is less so regarding the appropriate number to perform as a basis for the analysis, and this is the objective of replication analysis [Chung, 2004].

A pre-requisite of this analysis consists in performing a rapid run of all the scenarios with a small number of replications. So, we started arbitrarily with ten replications, which at the same time allowed us to check the proper functioning of the

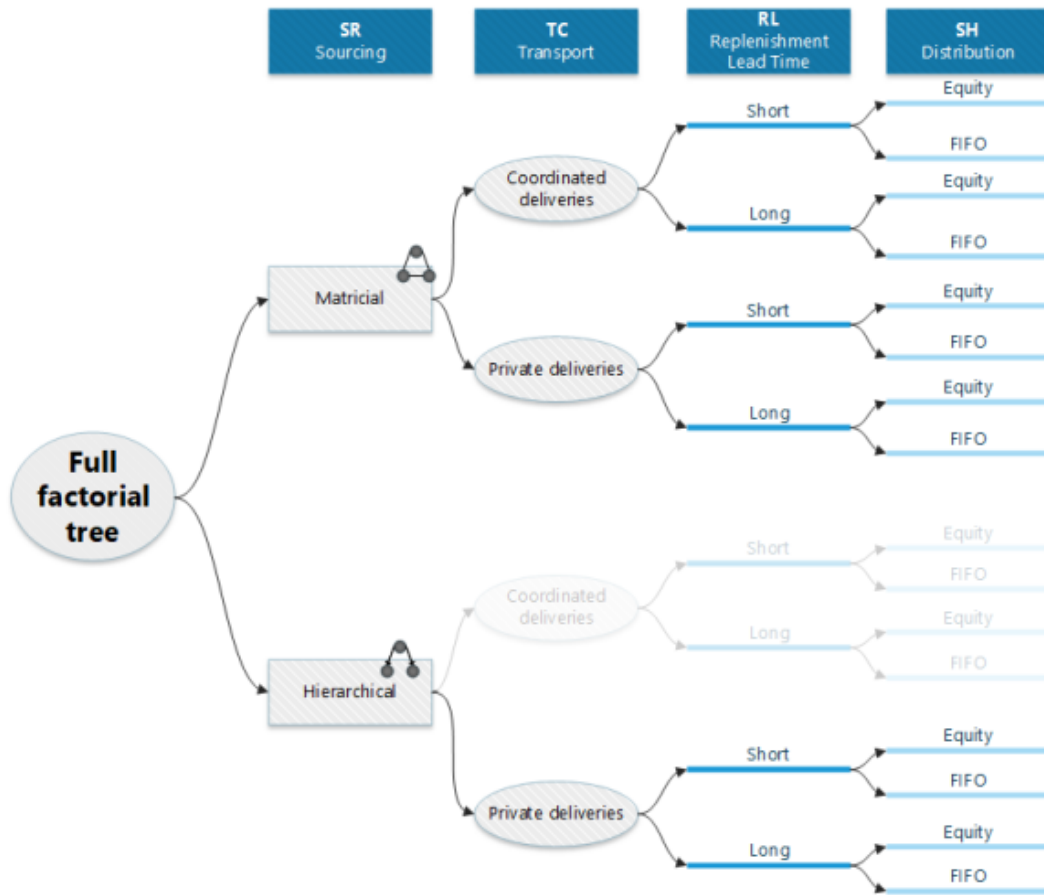


Figure 4.7: 2^k two-level, full factorial experiment tree reduced by four impossible scenarios

experiment from end to end. From there, according to Chung [2004], the replication analysis process started with the calculation of the standard error. This represents the accuracy with which a sample represents a population. Calculated here for the mean, it provides an estimate of the mean of the population within an interval for a certain confidence level. It is calculated using the standard deviation and number of observations of the sample. It also requires the t from the t probability distribution with a level of confidence set to 95% and the degree of freedom (here $10 - 1 = 9$). This standard error was calculated for each scenarios and for each Key Performance Indicator (KPI) considered after calculating the standard deviation and associated mean. From there, the number of replications can be calculated based on a level of precision to decide upon. In other words, it is the degree of trust in the means calculated to correctly represent the behavior of the model. We arbitrarily decided to use 10% as absolute precision. It means that we want the standard error to be below 10% for each of the scenarios and KPI means. The associated number of replications is calculated by taking the square root of the standard error previously calculated by the absolute precision. Most of the KPI considered for each scenarios indicated a number of replications required between 1 and 20, except four the total initial demand, the initial network inventory level and the transportation costs indicators

(total and 15 days), which showed a need from 40 to 184 replications, but on average 99 replications.

The replication analysis does not end here. The next step is to verify that the number of replications decided to meet the desired absolute precision. So, we chose 100 replications, as suggested by the average. On this basis, a successful experiment run was conducted based on the experiment design and case study previously depicted. Overall, a set of 12 scenarios were simulated for a period of 40 days, with 100 replications each leading to 1,200 runs. We again calculated the standard error but only for the four critical KPIs previously mentioned. It appeared that this number was sufficient and all standard errors were below 10%, while only two out of forty-eight were equal. We now had confidence in the outputs and could rely on them for making robust statistical analyses and drawing conclusions.

4.3.2 Step 7 & 8 – Analyze output data, validate and present results

Data analysis aims to extract useful information from data and base decisions upon it. It generally involves preparing the data, describing the data using descriptive statistics and testing hypotheses and models using inferential statistics. The difference between those two types of statistics is that the first describes what the data shows while the second extrapolates about the population from the sample. [Trochim, 2016].

As a reminder, the main experimental objectives are to:

- Assess the relationship between the experiment design factors and the KPIs
- Compare the different scenarios with each other
- Make recommendations to practitioners based on the analyses

As the experiment uses agent & discrete event simulation and a factorial experiment, the descriptive analysis methods identified and selected are box plots, scatter plots and time series, generated using Tableau software and XLSTAT.

To conduct the analyses we will first focus on three main dimensions identified by Ado et al. [2014] as crucial to a relief intervention: cost, time and quality. In our situation, the cost referred to is the transportation costs, the time is the total lead time to serve the demand and the quality is the service level at 15 days. Then, in a second step for finer and more specific analyses, other operational performance indicators, such as the CO2 emissions released from deliveries and the truck loading rate have been used. Also, the initial demand and initial inventory were recorded to give some insight regarding the influence of the operational context on the performance.

4.3.2.1 Data Preparation

Before starting the descriptive analyses, data preparation has consisted in checking the output data file regarding missing values and ignoring rows related to the impossible scenarios. Then, we searched for outliers. To do so, we identified for each scenarios and KPIs values above the upper limit and below the lower limit defined by the J. Tukey method i.e. out of the 1.5 interquartile range [dub, 2013]. During the outliers detection, five runs drew your attention with abnormal values for the lead time to serve total demand KPI at 0 and are thus, regarded as data errors more than real

outliers. According to Kwak and Kim [2017] in this situation, the abnormal value can be modified. Since, we do not want to reduce the size of the sample by excluding runs, we assigned a new value for the lead time based on this of closer scenarios in initial demand and inventory. For the rest of the outliers identified, since the method does not take into account the initial demand and inventory that may bring variability to the results and nothing suggest they are impossible scenarios, they have been preserved.

4.3.2.2 Scenarios supplying profile study using time series analyses

Since the beginning of humanitarian aid, the main criterion is the effectiveness of the aid. In this sense, we decided to start the descriptive analysis of the simulation outputs by performing a time series analysis through the perspective of the service level indicator. The objective is mainly to compare scenarios and eventually sense the effect of certain approaches on this indicator.

Context elements

Time series analysis allows us to analyse the evolution of indicator values collected over a period. In our context, for each scenario and replication we collected the quantity supplied and the demand over the forty simulated days. The collection started at 48h since this is the moment the demand is provided to the supply network in order to represent the assessment time it takes for experts to evaluate real needs. For this historical event, the government stated that the relief operations would last for 15 days from the disaster occurrence, which is why we position a vertical dotted line to help in our analysis. As there is variability on the demand for each replication and to authorize comparisons between the scenarios, we calculated the service level as a percentage for each as the median of the quantity delivered by the initial demand. To help in the analyses, we placed a horizontal dotted line at the 50% service level, meaning that half of the quantity requested at the start has been fulfilled and delivered to PODs.

The following time series graph has been drawn (see figure 4.8), displaying for each scenario its delivery profile.

Baseline Scenario (0,0,0,0) - Black

The baseline scenario, representing current practices, can not supply more than 5% of the demand for 23.5 days due to the limited inventory on hand within the network. The two first inflection points around 150 hours and 250 hours are the moments respectively taken for the relaying of information from the DW to the PW and from the PW to the RW, as well as the transport organization. The third more significant than the others, comes once the RW is supplied in large quantity, as an entry point, by the international network and the goods have transited through the hierarchical system to reach the PODs.

Scenario (0,0,0,1) - Grey

Scenario (0,0,0,1) tests the equity approach for dealing with the shortage compared to the baseline. While the warehouses are considering orders of one product and as the amount is too significant for the DW and the PW only the hygiene kit, which is the only product distributed to five people, can be mostly sourced within the internal network. With the equity approach, the demand can be partially met with inventory on hand. Indeed, unlike the FIFO approach, where the demand is served if

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there is enough inventory, the equity tend to satisfy both PODs in accordance with the amount expressed and the inventory on hand. This way there are more goods provided in the short term and a larger diversity. For the rest, the same supplying rythme applies to this scenario as the baseline and both meet the total demand in 25 days with 10 days delay regarding the end of the relief state.

Scenario (0,0,1,0) - Orange

Scenario (0,0,1,0) tests the impact of a replenishment lead time reduction at the RW compared to the baseline. The supplying profile happens until the moment the RW obtains a large inventory. From there on, it is just the time for the relief items to go down the hierarchy system.

Scenario (0,0,1,1) - Yellow

Scenario (0,0,1,1) combines the equity with a short replenishment lead time at the RW compared to the baseline. It presents a similar supplying profile as the scenario testing the equity only, but once the RW is replenished then it is the time for the total demand to be served and to transit through the different warehouse types. As a result, both this scenario and the previous one meet the initial demand in 12.5 days, which is below the relief state deadline.

Scenario (1,0,0,0) - Green

Scenario (1,0,0,0) experiments the multiple sourcing approach in comparison to the baseline. It means the hierarchical structure does not exist anymore and any node can communicate and exchange items with any other node. These additional connections offer an access to additional resources in a close perimeter. In the short term it increases the quantity delivered and reduces the supply lead time by getting rid of the information relay and goods transit delay that needed to go through the hierarchical system. However, there is still a need to wait for the long replenishment lead time of the RW to meet all the demand.

Scenario (1,0,0,1) - Light green

Scenario (1,0,0,1) experiments the multiple sourcing approach combined with the equity approach. The supply profile is similar to the previous scenario but the equity allows the scenario to increase the quantity delivered and be the first going beyond the 50% service level after only five days. The gain is that it takes the same amount of time for this scenario a and the previous one to cover 100% of the demand and this, in 21 days.

Scenario (1,0,1,0) - Red

Scenario (1,0,1,0) tests the multiple sourcing approach combined with a short replenishment lead time for the RW. Here, the scenario benefits from a large local supplier panel to deliver beneficiaries in the first moments. Then, the rapid arrival of international aid allows the total demand to be met in only 9 days by organizing most of the transport movement from this point to the POD directly.

Scenario (1,0,1,1) - Pink

Scenario (1,0,1,1) is similar to the previous scenario but integrates in addition the equity approach instead of the FIFO. Again, the supply profile is similar and the equity allows more relief items to be provided over the same time period. It

is, with the (1,0,0,1) scenario, the first to go beyond the 50% as service level, with completion in only 6 days. Besides, it is also one of the first scenarios - along with the previous one - to fulfill the total demand in the shortest time (9 days) since the disaster happened.

Scenario (1,1,0,0) - Purple

Scenario (1,1,0,0) experiments multiple sourcing with the transport consolidation approach. Here the supply profile is less linear than the others and presents numerous inflection points. Multiple sourcing allows the supply of resources from very a close partner to PODs in a rapid time frame. Then, deliveries are consolidated from remote nodes, which slow down the material flows. However, it enables more frequent arrivals almost every day mainly due to the variability in the transport speed, especially in the case of the RW delivering to PODs, where it could vary between 19 and 41 hours.

Scenario (1,1,0,1) - Light Purple

Scenario (1,1,0,1) has a very similar behavior to scenario (1,1,0,0) but uses the equity approach. Again, this method allows more items to be distributed in the same amount of time as with the FIFO approach. However, it is at the relief state deadline that 50% of the demand is met with this scenario. Finally, similarly to the previous scenario as well as (1,0,0,0) and (1,0,0,1) that differ in the use of the consolidated deliveries, they need 21 days to meet 100% of the demand.

Scenario (1,1,1,0) - Blue

Scenario (1,1,1,0) integrates three PI-oriented practices: multiple sourcing combined with transport consolidation and a short replenishment lead time of the RW. This scenario shows a hybrid supply profile of rapid and significant service level increases brought by the multiple sourcing in the short time and the short replenishment lead time combined with a “shaking” and slow profile between those jumps, due to the transport consolidation approach. At the end, once the missing inventory available at the regional warehouse arrives, it takes around 5 days to meet 100% of the initial demand.

Scenario (1,1,1,1) - Light Blue

Scenario (1,1,1,1) is the most PI-oriented scenario and the most distant from current practices. This has a similar behavior to the previous one but, unlike the others pair-like scenarios, the equity does not allow delivery of more items and in fact tends to be the opposite on average. This and the previous scenario present the same similarity that is to serve more demand than requested. This is explained by the fact that a first optimization calculation to deploy the goods is launched once the need assessment is provided. On this basis, the deliveries start from the nodes that are the most distant and those very close to the PODs. The arrival of the international goods to fuel the network one day later, stops the previously defined planning and there are lots of truck in transit at this moment. Then, the second optimization is launched, based on a calculated theoretical inventory, using the truck in transit. The second deployment plan is followed, cancelling the previous one. As we did not authorize the orchestrator to pick up excessive inventory from a POD, as it was originally supposed to be used as a consolidation point for delivering the second POD, there remains inventory in surplus at one of the two PODs while the second is still waiting and deliveries still need to be organized for it.

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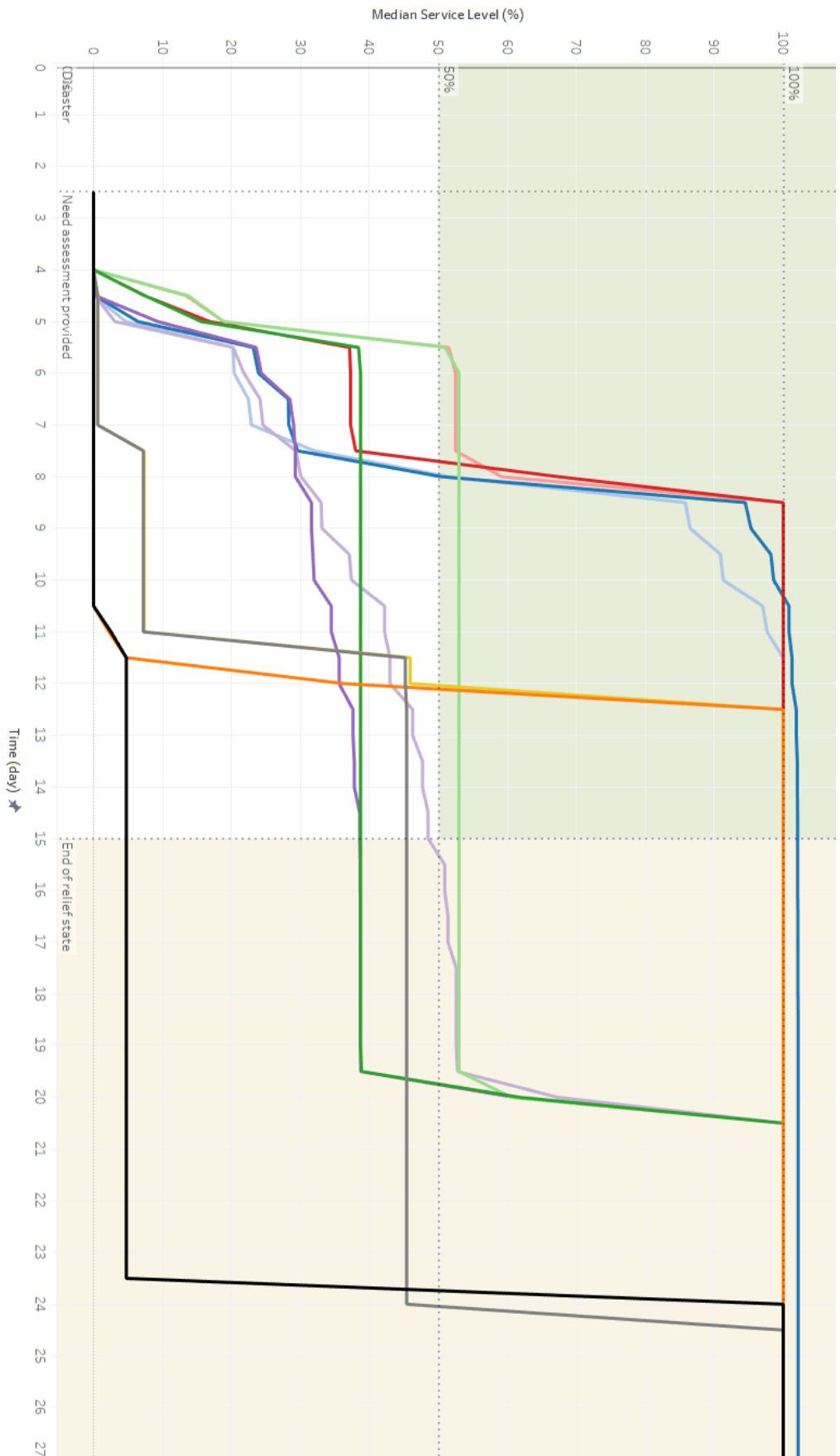


Figure 4.8: Scenario supply profile over time - (0,0,0,0) black, (0,0,0,1) grey, (0,0,1,0) orange, (0,0,1,1) yellow, (1,0,0,0) green, (1,0,0,1) light green, (1,0,1,0) red, (1,0,1,1) pink, (1,1,0,0) purple, (1,1,0,1) light purple, (1,1,1,0) blue and (1,1,1,1) light blue

Scenario comparison & factor influence

From a global perspective, the time series graph (see figure 4.8) presents the delivery profile of each scenario using the median service level indicator, that is the quantity delivered over time compared to the initial demand known two days after the event. It appears that the baseline scenario (0,0,0,0) representing current practices is the least efficient of all regarding this KPI. Indeed, only 5% of the demand can be served for 24 days due to the limited inventory of the local network, a single-sourcing approach acting as a bottleneck and the loss of time due to the relaying of information up the hierarchical structure. In contrast, the best scenario is the (1,0,1,1), which integrates most of the PI-oriented practices (multiple sourcing, short replenishment lead time at the RW and the equity) except the transport consolidation approach. Indeed, it covers more than 50% of the total demand within 4 days, once the demand is known, and needs 3 days more to reach 100%. To do so, it exploits the multiple-sourcing approach that benefits from more local resource offers, the short replenishment lead time that rapidly fuels the network with the missing relief items and the equity authorizing partial demand answers.

From the previously-described supply profile for each scenario, it seems that the shortage management policy does not have a real impact on the behavior. Indeed, scenarios only differing by the FIFO and the equity presented the same profile (e.g. (0,0,0,0) with (0,0,0,1)). The difference was the offset in quantity delivered at the same time. Equity allowed more demand to be met within the same time frame and larger product diversity than the FIFO except for the scenarios integrating the coordination of deliveries, where the reverse was the case. From the scenarios using transport consolidation, we can observe a trend to slow down the physical flow and the generation of more frequent arrival of small quantities. Private transportation seems unlikely to offer more direct deliveries or to limit the detours generating delays. As for the sourcing policy, it appears that multiple sourcing allows better exploitation of the local network in the first days and serves more demand than the hierarchical approach. It shows capacity limits, but combined with the short replenishment lead time in a second phase allows the remaining demand to be fulfilled efficiently. Not surprisingly, the 15 days replenishment lead time generates a significant delay for the affected population.

4.3.2.3 Factor influence on performance study using box plot analyses

While the aid not only fall under the obligation of being effective, it is also expected to be more efficient and sustainable. With the objective of investigating the relationship of factors levels on the performance, we decided to perform a box plot and 3D scatter plot analysis to respectively appreciate the individual and combined influence of the different practices on the performance. Such analysis is performed in light of the three main performance indicators considered: the service level at 15 days expressed as a percentage, the total transportation cost of the relief operation in US dollars and the total lead time to serve all the demand in days.

Box plot analysis is often used in descriptive analysis as it provides a summary of the data. In this perspective, it indicates five key descriptive elements of a data set: the minimum and maximum score excluding outliers, the lower quartile, the median and the third quartile. With these, it visually shows the distribution and skew of the numerical data. It is also useful for identifying differences between different samples or groups.

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Graphically, see figure 4.9, each KPI is represented by 12 box plots, one for each of the scenarios considered. The displayed distribution relies on the output value for each scenario and replication doublet. The graduation is the same for each box plot within the same row and the PI-oriented practice is positioned at the right of the current practice.

Endogenous factors influence study on performance

Service Level

If we consider the service level first and the sourcing policy only, the different box plot positioning among the two approaches show a large variability (from 0% to 100% as the median) indicating the factor itself is non-significant regarding this indicator. The same conclusion can be drawn for the transport consolidation and the shortage factors. This suggests that the study of the practice itself is not sufficient to apprehend the effect on the performance and so, the combination of approaches needs to be considered. As for the replenishment lead time, on the contrary, the influence stands out. Indeed, whatever the other practices selected, scenarios with a long replenishment lead time achieve as an average median 38.2% of the initial demand, ranging from 0 to 53% as median, while with a short replenishment lead time all scenarios reach as an average median a 100% service level. In addition, we can observe that the FIFO approach tends to serve less demand than the equity when local inventory is limited, if we compare the associated distribution. Indeed, the service level difference between the medians ranges from 10 to 40%. This is explained by the restrictive approach of FIFO, which fulfils orders only when there is enough inventory on hand. A difference can be noted when consolidation is combined to 3 days replenishment, where FIFO responds beyond the demand expressed, with a high variability which is probably due to another factor not considered here. Finally, it clearly stands out that the baseline scenario is the least efficient regarding this indicator and so, the combination of current practices for each factor pulls down delivery effectiveness.

Lead Time to serve all the demand

As for the lead time to serve all the demand indicator, we observe a similar distribution attitude of the pair-box plots. Moreover, the dispersion is smaller and narrower compared to the other indicator. Again, no significant difference is revealed between the box plot pairs between each practice except for the replenishment lead time. Indeed, the shorter replenishment lead time allows the gap in supplies the local network could not fulfil to be met and so, helps in reducing the total time to serve the demand. Scenarios with a 15 days replenishment lead time are among the slowest to serve the demand, between 18 and 22 days, while the rest save a minimum of 7 days and meet the demand in 6, 8, 10 or 11 days. The similarities between this indicator and the service level tend to show that scenarios performing well within 15 days keep the pace and are among the first to deliver all the demand. Finally, we note that FIFO or equity do not bring a difference in the matrix environment while they can generate a slight difference of 1 day in the hierarchical structure.

Total transportation cost of the supply operation

Regarding the total transport cost at the end of the supply operation, box plot analyses reveals other interesting elements. For this indicator, the sourcing policy

makes a clear difference in the results. While the hierarchical system presents variability among the practice combinations, the matrix structure is rather homogeneous. On average, the median is 8.6 k\$ with a narrow dispersion from 4.7 to 12.9 k\$ as extreme scores while hierarchical scenarios range from 7.8 to 50.5 k\$ as the minimum and maximum values. For this indicator, the replenishment lead time does not bring much difference alone. It is rather the equity in the hierarchical context compared to FIFO that makes a difference. Indeed, it tends to significantly increase the cost, as it mobilises many small quantities within the local network and generates more physical flows. The difference is even more significant if coupled with a short replenishment lead time generating a large difference of 26\$ as a median, compared to FIFO. Besides, the dispersion for this scenario is wide and may be due to another factor not studied here.

Influence study on performance of exogenous environmental factors

When a system is under study, it is also important to consider the so-called “*exogenous variables*” part of the independent factors. These are elements generally part of the experiment environment which may influence the outputs [Equixor, 2014]. While they are said to be “non-controllable” in reality, in a simulation, these factors are of our own making and are integrated as probabilistic distributions. In this model, the two major variability sources are the initial inventory that the local inventory is initialized with and the initial victim number generating the initial relief item demand. We wish to spare some time to analyze the influence of such factors on the lead time, cost and quality indicators considered, using scatter diagram analyses.

Scatter analysis is used to compare two data sets to identify a possible relationship. Scatter plots help in visualizing relationships (positive, negative, strong, weak, linear or nonlinear) or clusters.

The initial demand effect

Scatter plots investigating the initial inventory in relation to the three studied performance indicators are available here 4.10. Globally, we can observe three types of patterns, linear, curvilinear and no significant relationship with random dispersion.

There appears to be clear independence between the demand and the scenarios using private deliveries regarding the lead time. There is also independence at the demand service level for scenarios using private deliveries with 3 days as replenishment. Also, the demand has no effect on the baseline scenario (0,0,0,0). Then we can observe two negative, curvilinear and weak relationships when the equity is employed with a 15 days replenishment lead time. Regarding the transportation costs, the influence stands out with weak, moderate and strong relationships. Scenario (0,0,1,1) presents a very high positive 0.948 correlation value at 5% and a p-value below 0.0001 according to the Pearson test. This explains why the boxplot width (i.e. the variability of the results) was wide for this particular scenario. The others range from high to low positive correlation with a very small p-value confirming the linear relationship. The remaining graph with randomness dispersion does not help in drawing a conclusion regarding the impact of the demand for such scenarios.

The initial inventory effect

As for the initial inventory influence, two types of patterns appear either independence or no clear association. Graph 4.10, presents horizontal value distribution for scenarios combining private deliveries with 3 days replenishment for both the

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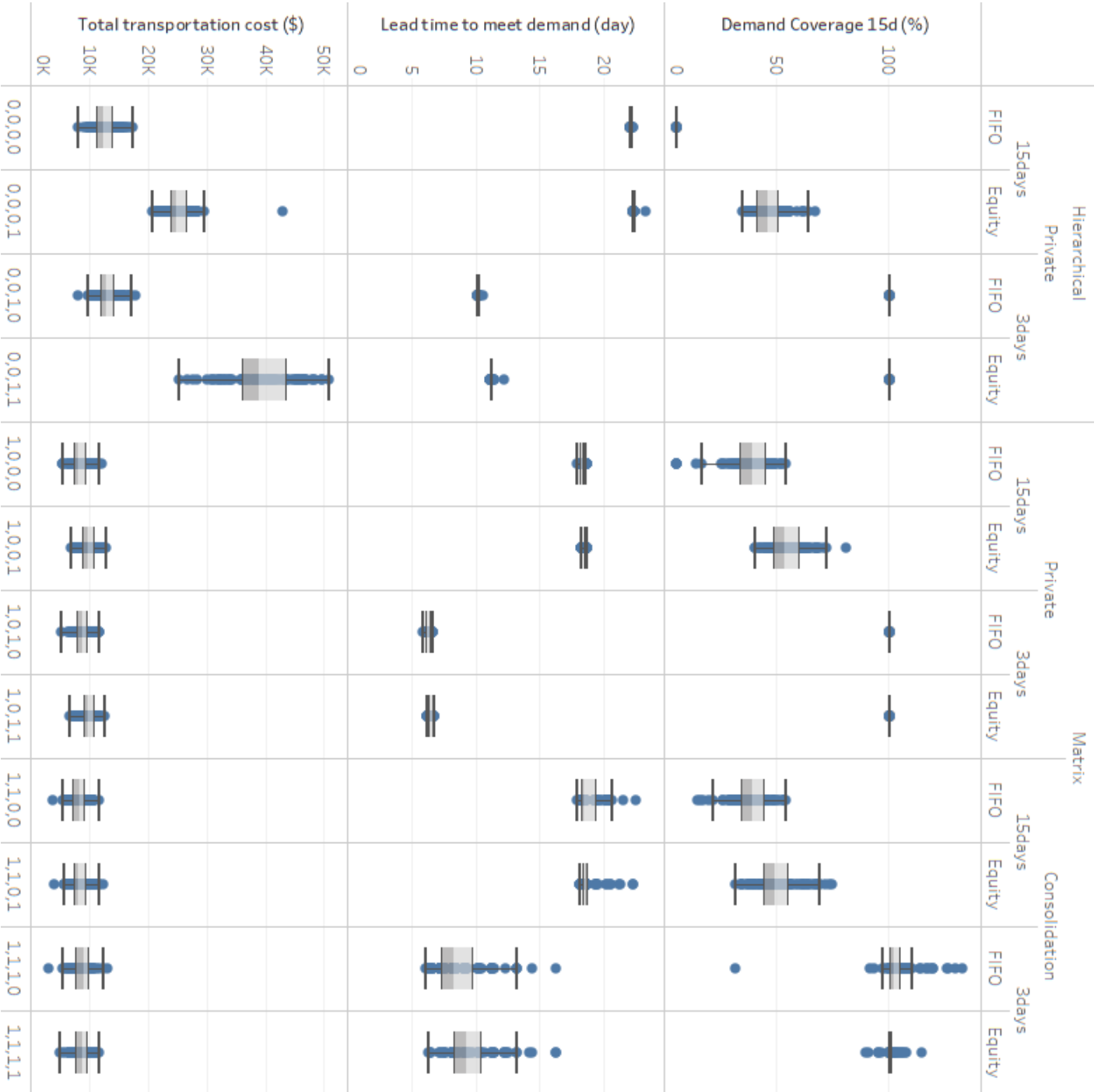


Figure 4.9: Scenarios distribution in light of the Service Level, Lead Time and Transportation Costs

service level and the lead time indicators. The baseline is also in this situation as well as scenarios employing FIFO with 15 days and private deliveries regarding the lead time indicator. For all the remaining graphs, and especially for the total cost indicator, there is no significant association to state. This can be explained by the limited dispersion between the mode and the maximum and minimum values of the triangular distribution implemented.

4.3.2.4 Scenario comparison using 3D scatter plot analyses

So far we have obtained a good understanding of the factor influence on the performance indicators considered. However, the time series analysis regarding only one indicator, and the box plots, while giving some insights, did not provide solid elements to be able to identify efficient scenarios in light of the service level, lead time and cost simultaneously. To this end, we implemented 3 dimensional and 2 dimensional scatter plot analysis, as detailed in the following.

Global scenario distribution using 3D scatter plot analysis

A scenario distribution of all the 100 replications in a 3 dimensional scatter plot was performed using Python and panda and matplotlib libraries (see figure 4.12). A K-means algorithm used for finding patterns in the dataset allowed similar scenarios to be gathered into four distinct clusters. The similarity, as defined by the K-Means algorithm, lies in the distance separating data points. The algorithm tends to minimize the sum of the distances between each individual and a centroid. The clustering distribution is visible in Figure 4.13a and gathered in blue, scenarios using a multiple sourcing approach combined with a long replenishment lead time (1,1,0,0)(purple), (1,1,0,1)(light purple), (1,0,0,0)(green) and (1,0,0,1)(light green) plus the baseline (0,0,0,0). These are scenarios showing a long lead time to serve the demand with low transportation costs and a variable service level at 15 days. Regarding this last indicator for this group, the lowest service level are achieved by the baseline (0,0,0,0) (black) and the (1,0,0,0) (green) scenarios, only testing the multiple sourcing approach (see figure 4.13c). Then, better serving the demand at 15 days comes (1,1,0,0)(purple), then (1,1,0,0)(light purple) and (1,0,0,1)(light green). This group presents scenarios that remains below the 80% service level line at 15 days. A second group colored in yellow by the K-means algorithm only gathers scenarios (0,0,0,1)(in grey on the other graphs). This last group, only testing the equity approach, is characterized by medium transportation costs, a long lead time to serve the demand and a medium service level at 15 days. The orange cluster also concentrates on one scenario, that is (0,0,1,1)(yellow) experimenting the equity combined with a short replenishment lead time. This scenario presents medium to large transportation costs, with a medium lead time to serve the demand and a high demand coverage at 15 days. This can be considered as a relatively efficient scenario regarding effectiveness. However, its positive correlation with the demand quickly makes it expensive if the demand is high. Last but not least, the cluster in violet bring together scenarios (1,1,1,1)(light blue), (1,1,1,0)(blue), (0,0,1,0)(orange), (1,0,1,1)(pink) and (1,0,1,0)(red). These all test the short replenishment with a multiple sourcing approach, except the (0,0,1,0)(orange) scenario. In terms of performance, they demonstrate low transportation costs, with a low or medium supply lead time and a high demand coverage at 15 days. This performance level is the most interesting and relevant from a humanitarian perspective. The following summary table 4.4 summarizes all the main features of each group.

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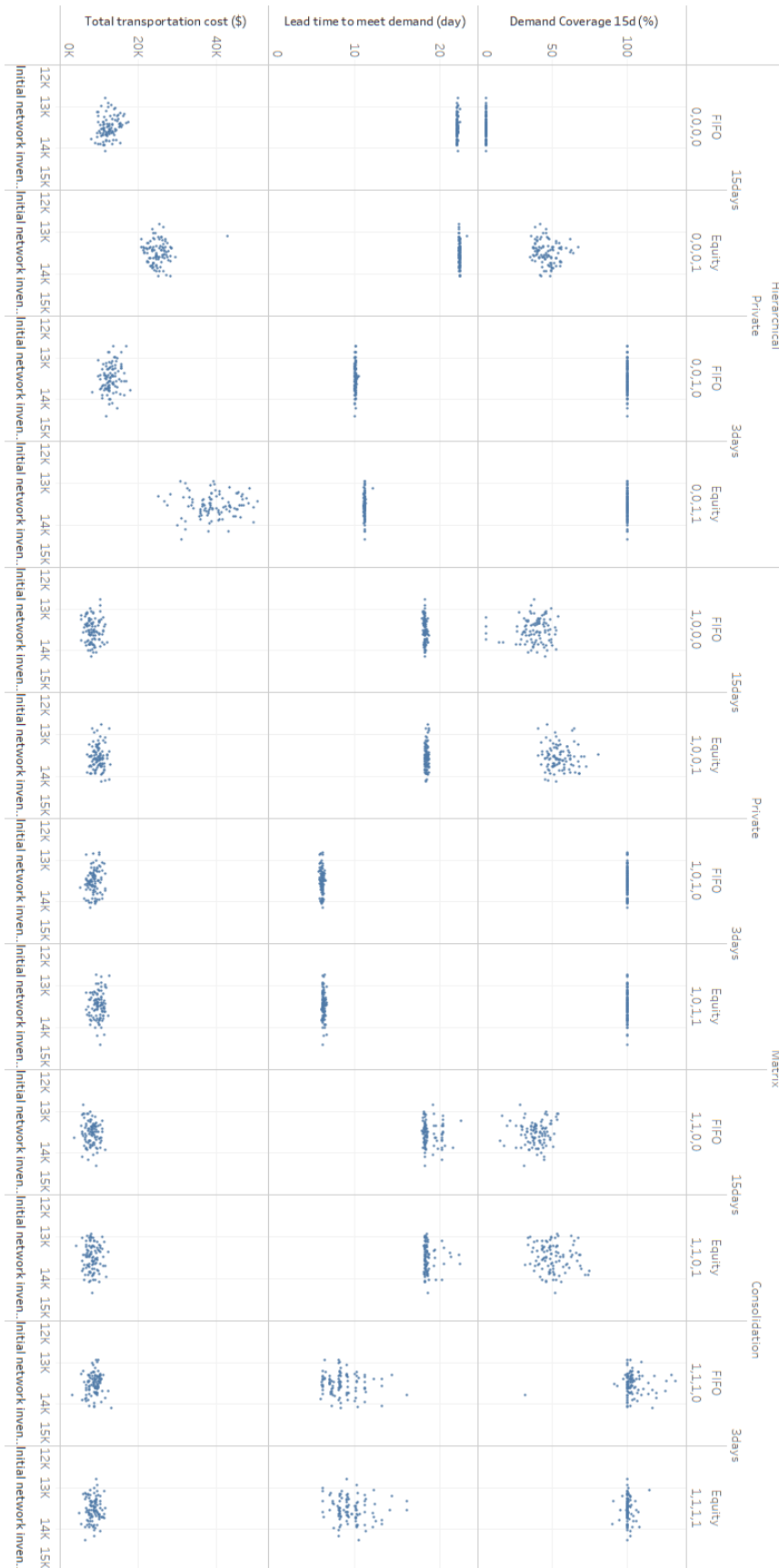


Figure 4.10: Initial inventory effect on the performance indicators per scenario

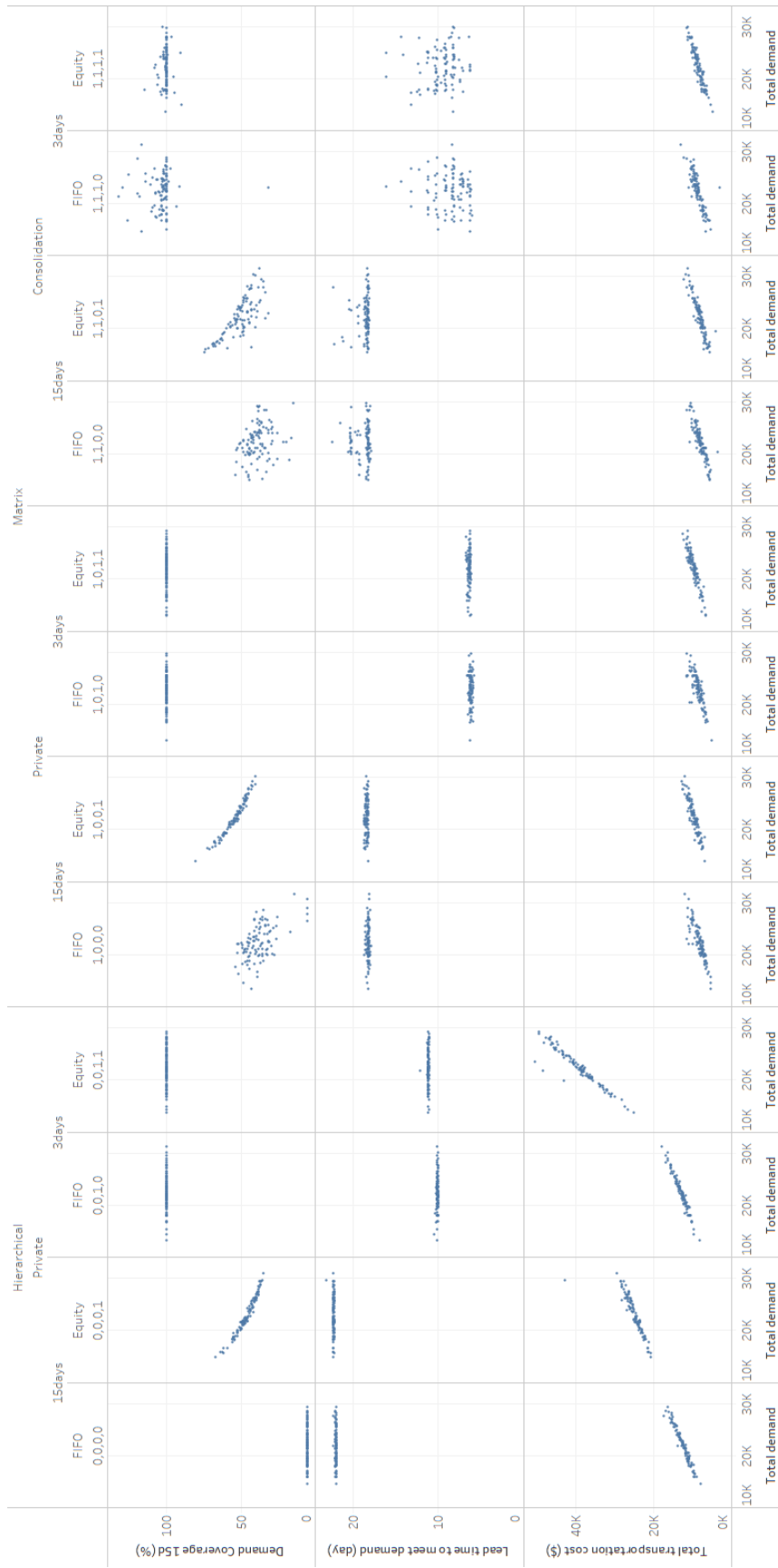


Figure 4.1.1: Initial demand effect on the performance indicators per scenario

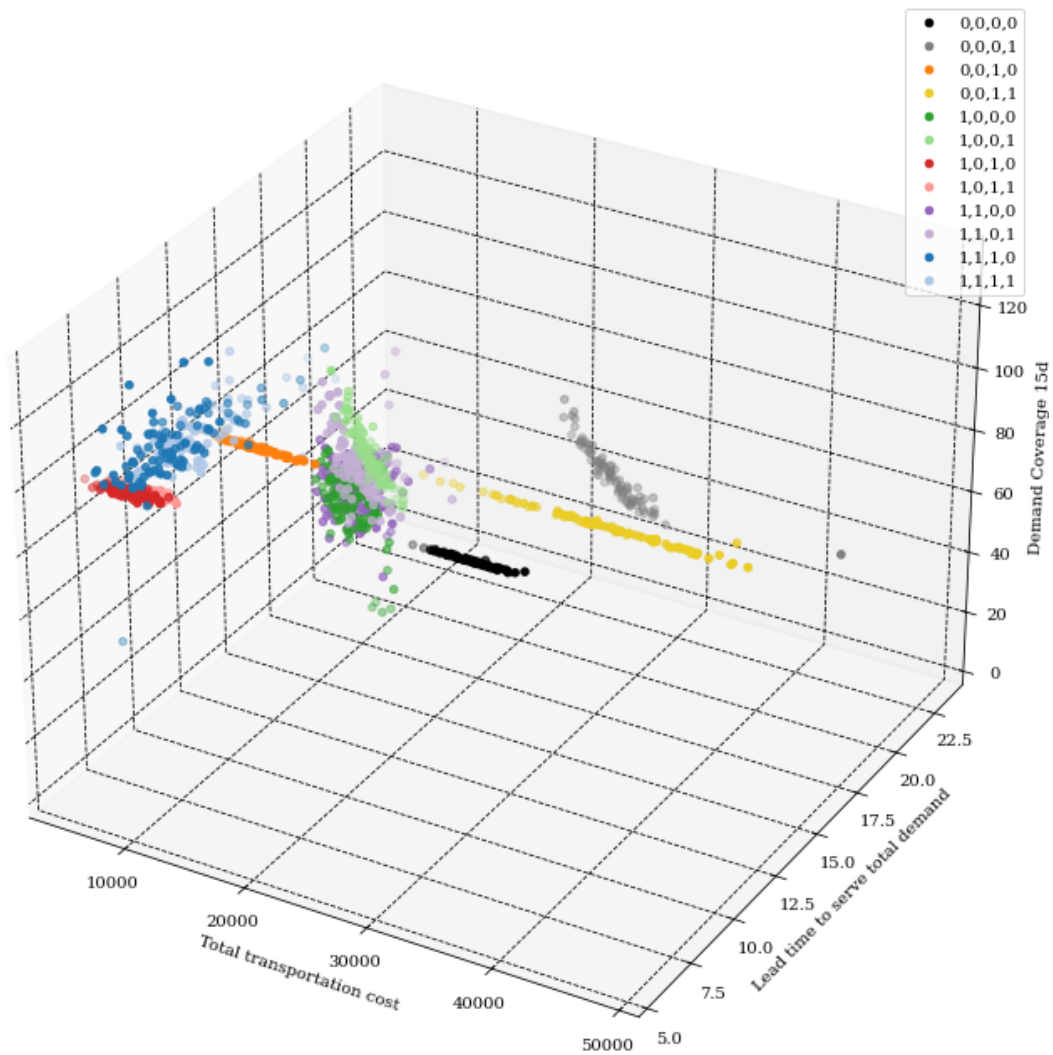
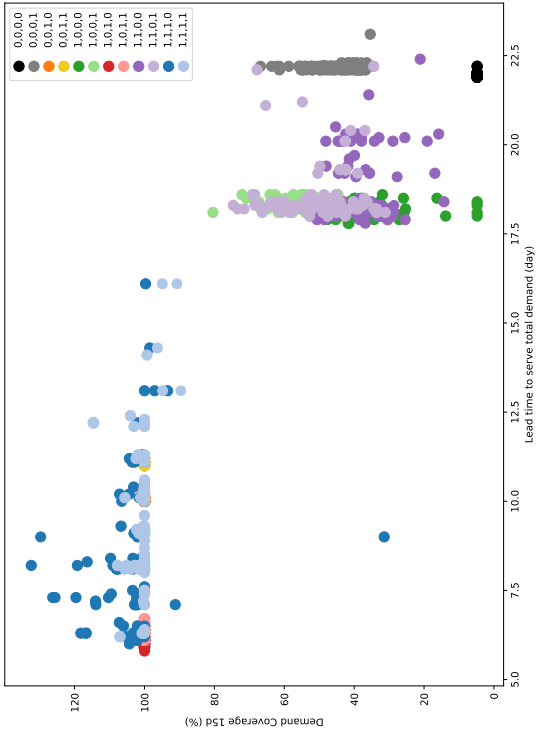


Figure 4.12: 3D Scenario distribution overview

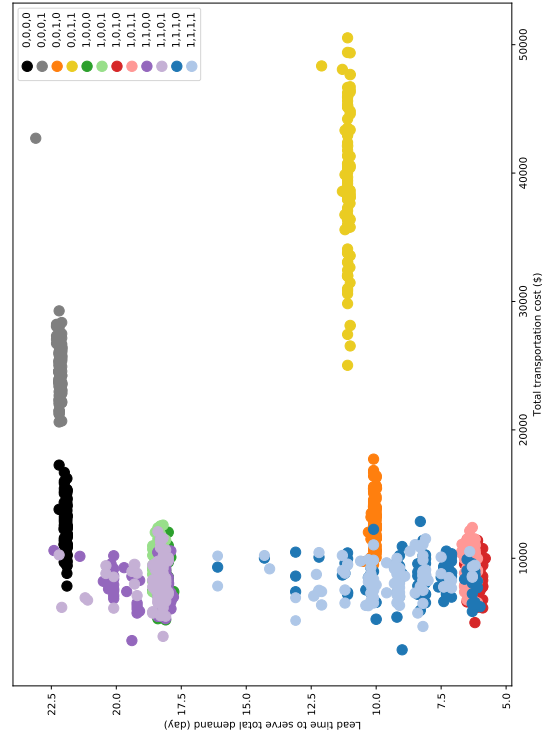
Best performing scenarios investigation

To pursue the analysis and comparison of the violet cluster scenarios, we rely on a summary table (See Table 4.5) providing for each scenario the median value for the service level, transportation costs and lead time, as well as two sustainable related logistics indicators: the CO2 released in metric tons and the truck loading rate as a percentage. These come as complementary information to help in refining the analysis and are important aspects to be taken into account if a selection is to be made. The table is sorted by decreasing service level and the row coloring is according to the k -means algorithm clustering and coloring.

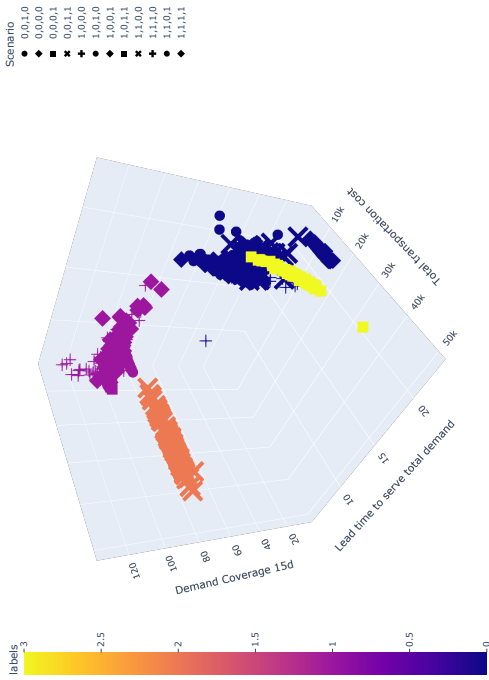
From the set of best scenarios (in purple), two scenarios draw our attention with the highest service level and lowest lead time at 6 days: (1,0,1,1) and (1,0,1,0). These use multiple sourcing with a short replenishment lead time. One uses FIFO while the other the equity approach for shortage management. Scenario (1,0,1,0) using FIFO is less expensive by 1,129\$ as a median, better fills trucks by 29% and has a relatively similar total CO2 released. The second (1,0,1,1) is critical in the filling of the trucks (43% as the median) which is twice less efficient than the baseline



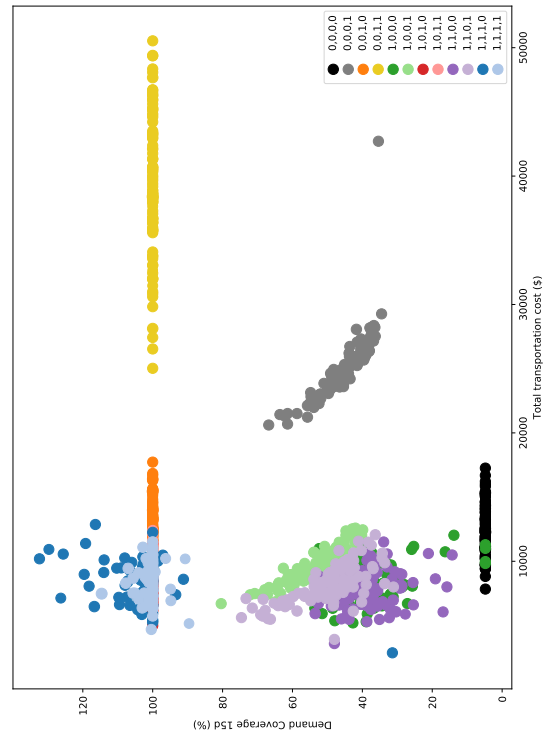
(b) Scenarios scatter plot along Lead Time and Service Level axes



(c) Scenarios scatter plot along Transportation Costs and Service Level axes



(a) *k*-means algorithm clustering of similar scenarios



(d) Scenarios scatter plot along Lead Time and Transportation Costs axes

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Table 4.4: Scenarios performance summary based on k -means algorithm clustering

Cluster	Scenario	Service Level	Lead Time	Trans. Cost
Blue	(0,0,0,0) (1,0,0,0) (1,1,0,0) (1,1,0,1) (1,0,0,1)	Low-medium	High	Low
Yellow	(0,0,0,1)	Medium	High	Medium-large
Violet	(1,0,1,0) (1,0,1,1) (0,0,1,0) (1,1,1,0) (1,1,1,1)	High	Medium	Low-medium
Orange	(0,0,1,1)	High	Medium	Medium-Large

Table 4.5: Summary descriptive table of scenario performance, sorted by decreased Service Level, with row coloring based on k -means algorithm clustering

Scenario	Median Service Level (%)	Median Lead Time (day)	Median Trans. Cost (\$)	Median truck loading rate (%)	Median C02 released (metric tons)
1,1,1,0	102	8	8,800	61	5
1,1,1,1	100	9	8,514	56	4
1,0,1,1	100	6	9,615	43	4
1,0,1,0	100	6	8,486	72	5
0,0,1,1	100	11	38,644	86	22
0,0,1,0	100	10	12,576	89	7
1,0,0,1	53	18	9,599	43	4
1,1,0,1	49	18	7,993	60	4
0,0,0,1	45	22	24,587	78	13
1,1,0,0	39	18	8,006	68	4
1,0,0,0	39	18	7,985	74	4
0,0,0,0	5	22	12,246	88	7

(88%) regarding this criterion. Moreover, these two scenarios present a low sensitivity to the initial inventory and demand level. A good compromise between the two regarding sustainability aspects is the (1,1,1,0) scenario, experimenting the transport consolidation with FIFO. The total transportation cost is lower than the scenario using equity as well as better in filling the trucks with 61%, even if it can be still judged insufficient. Besides, it requires two days more to meet the demand, which is not negligible.

4.4 Key Takeaways

This chapter is divided into two main parts. The first dedicated to the experiment description and the second to its end-to-end conduct and to a results analysis.

The experiment description is based on the technological and functional framework defined in Chapter 3, and details several phases. Among them, major steps consisted of the case study description and knowledge gained from a field visit in the Indonesian Red Cross offices and a disaster history investigation. From there, a model was produced, inspired by the activities performed and network organization of the Indonesian Red Cross in response to disasters. As the complexity of the HSCs is high and challenging, data was not always available and due to some simulation feasibility constraints led to making a certain amount of assumptions and decisions. The study credibility, however, has not been overly impacted thanks to numerous verification and validation phases along the simulation development process. Choices have also been made in the KPIs considered (service level, lead time and transportation costs as principal indicators and CO₂ released and loading rate as secondary) to perform the analysis. Finally, additional decisions and adjustments occurred during the factorial design phase to select among the PI-oriented proposals in Chapter 2 those to be tested in a simulated environment. Time and feasibility constraints limited our original intention to four two-level factors, experimenting with different key practices and their combination during the shortage, sourcing and transport management processes. After several months of programming, the simulation was ready and all parameters and factor combinations were implemented. Several hours were required to generate the dataset of 100 replications of the 12 possible scenarios of the factorial plan and associated KPI outputs.

From there, an analysis phase took place using descriptive and multivariate analyses through visual tools such as a time series diagram, box plots and scatter plots. The two main analysis objectives were 1) to assess the effect of practices on the considered KPIs and 2) to compare scenarios to identify the most relevant from a humanitarian perspective. Regarding the impact of factors, the main conclusions are that the replenishment lead time of the local network has a significant impact on the supply lead time to serve the demand and service level. Indeed, when the local network is under capacity, the rapid mobilization of the relief items from external sources is key in the effectiveness of the relief. Besides, the study shows that the full connection between the actors and increased visibility regarding the available capacities, through the multiple sourcing approach, minimize the transport cost. Indeed, sourcing as much as possible in the local area limits the distance to cover, and the direct connections limit the waste of time due to the relaying of information

4. TEST the Hyperconnected Humanitarian Supply Chain paradigm in situation

within hierarchical structures. Regarding the transport consolidation, the benefits are interesting from a transportation costs and service level perspective. Besides, it also presents correct results regarding the lead time to serve the demand, if used in a situation where a large flow has to be handled. Finally, the fact that FIFO was not authorizing partial deliveries compared to the equity lead scenarios, which used this approach to deliver less quantity than those using the equity. However, it restrains the transportation costs variation, which is explosive when equity is applied in a hierarchical context without consolidation. Indeed, this last scenario was found to be very sensitive and strongly correlated to the initial demand value. Moreover, this parameter was not that impactful when inventory could be mobilized rapidly but had an obvious effect on the transportation costs. As for the initial inventory, as the variability was limited it did not show up as affecting the performance indicators.

With regard to the second analysis objective related to scenario comparison, what clearly stands out at first is the fact that the lowest performance comes from the baseline scenario (0,0,0,0) at the service level (median: 5) and lead time (median: 22) compared to other scenarios. This shows that even a small PI-oriented change can lead to some improvement and a lot of avenues are thus possible. Furthermore, a k -mean clustering allowed us to generate four groups of similar scenarios. One group draws our attention to relevant characteristics from the humanitarian perspective i.e. low/medium transportation costs with a high service level at 15 days and a low lead time to serve the demand. All of these scenarios are at least using multiple sourcing with a short replenishment lead time. Among them, the most successful in terms of the service level and the lead time are scenarios (1,0,1,1) and (1,0,1,0). These operate with private deliveries that appear slightly more cost-effective if compared with similar scenarios using the transport consolidation approach. However, with the equity that handles more flows than the FIFO approach, the consolidation approach is more interesting, as is the case with truck filling.

CONCLUSION & PERSPECTIVES

Hello there, happy to see you back! From what I can see, you took some notes and you probably have questions. Before this, maybe we can spend a short moment to take stock of what you have just gone through or maybe missed on your way. At the same time, you may also find something to take away from my reflections.

Humanitarian Supply Chain Context & Problem statement

As a reminder, you must have clearly understood that humanitarian operations today are heavily questioned by public opinion, the media and even donors. Indeed, the quality of the aid provided is sometimes judged ineffective and shows symptoms of unsustainability. However, this aid is essential for the future of the population affected by natural disasters. When people are left with nothing overnight or even get isolated due to severe damage on main transport axes, they can rely on Humanitarian Organization (HO)s to provide assistance. Help provided can take the form of medical support, cash transfers, helping hands for rebuilding or cleaning or relief item distribution for providing basic comforts such as blankets, jerrycans or kitchen kits. However, the challenges encountered by HOs, in providing these services, are numerous, especially from a logistical point of view. Indeed, mobilizing goods from different sources, transporting and then distributing them to recipients is already quite challenging for commercial supply chains. However humanitarians, in addition, have to face a destabilized environment, short timeframes as lives are at stake, and many uncertainties regarding the needs, location and quantities, which makes it even more challenging. Besides, the uniqueness of the events, as well as the variety and number of humanitarian actors wishing to take part in the relief generate physical flow congestion, competition over transport means and funding, and uncoordinated actions. Despite their best efforts, HOs struggle to coordinate due to interoperability issues, different objectives and incompatible operating approaches.

There are fortunately researchers and practitioners working on solving these specific challenges. A literature exploration has shown that most of the investigations focus on improving key Humanitarian Supply Chain (HSC) and logistics areas showing weaknesses, focusing on each specific issue. However, I'm afraid this way of overcoming issues will only offer solutions on a small and piecemeal scale. You know, I have always preferred solving issues by searching for root causes. I find that it provides better results in the long term but it requires longer and deeper research into various areas of expertise.

This is why I found the Physical Internet (PI) interesting in this perspective of overcoming logistics challenges and symptoms of unsustainability. It provides a way to redefine how objects should be created, moved, stored and used. In fact, the

PI just focuses on a part of the change envisioned for society, but it is a key one. Indeed, our consumption needs are constantly growing and the logistics required are not in line with the environmental pressures and the measures required to ease them. The PI, similarly to how the digital internet operates today, envisions a new logistics paradigm for transiting objects or even human beings. The main idea behind this new concept is to dispose of an open logistics network where services and logistics resources (warehouses, equipment, etc.) would be shared and readily accessible. No more dedicated means, not fully utilized or empty returning trucks but rather open and shared means in addition to consolidated deliveries. To make it work, standardized protocols, equipment, containers and information systems to interconnect actors and give real-time information and visibility is required. The end goal is to provide a global and unique logistics network so that it meets the needs in an efficient, effective, agile and sustainable manner.

Due to the novelty of the concept, with only the very first pilot projects being conducted within the commercial sector, hardly any existing studies have investigated the value of this concept for the humanitarian sector so far. As the specificities of the humanitarian system make it different from the commercial sector, this research work constitutes a first exploratory stage in assessing the impacts and interests of such a concept on relief chain performance. The little research performed, with just two articles found that focus on this original association, has just started conceptualizing what PI-oriented HSCs would mean. Our intention with this research work was to go one step further by providing not only a proof of interest but also a proof of concept, by demonstrating through numbers the feasibility and the effect on the quality of the aid delivered. In this perspective, we went through four main phases, represented by the four Chapters which constitute this manuscript, leading in turn to three major contributions.

Contribution, limits and perspectives

Chapter 1 – Discover the humanitarian universe

Chapter 1 focused on exploring the humanitarian context and main challenges from a global and a logistics perspective to end up with a study and investigations that would make sense and be relevant for practitioners. In this sense, we limited the scope of the study to natural disasters (sudden onset in particular) and relief item distribution during the response phase, which we thought were the best places to start. During this phase, we also defined three research questions in order to assess PI interests and application perspectives to HSCs:

- RQ1** What are the avenues for change in practices, at the HSC level, by taking advantage of PI concepts to improve the performance of humanitarian relief?
- RQ2** How can the application of PI concepts to HSC levers be assessed in terms of its impact on performance?
- RQ3** How can decision-makers be supported in a relevant way and what are the consequences of such a major structural change?

Each question represented a guideline for the discussions and investigations undertaken in each of the following chapters.

As the exploratory fieldwork is wide, choices were made to focus on natural disasters rather than man-made, or on sudden onsets rather than slow onsets, on relief items rather than cash, medical supplies or human resources mobilization. These selections can be explained mainly by the partnership we had with the International Federation of Red Cross and Red Crescent Societies (IFRC) part of the Red Cross movement during the time allocated for this research work. As they opened their doors to make interviews, visit their logistics infrastructures and collect data, it was both fair and motivating to align with their areas of expertise. Besides, while disaster data and relief operations reports are of easy access on the Web, information and fine data are very limited from a logistics perspective. However, I see here potential avenues for further research on the topics not addressed here (slow onsets, cash transfer, man-made disasters for instance) as there are emerging fields where the PI could also have a place. In addition, I would also suggest presenting such an innovative association to as many practitioners as possible. Indeed, like any innovation, this concept of a Hyperconnected Humanitarian Supply Chain (HHSC) needs to be discussed, challenged and improved to capture in the best manner the requirements of its potential users. Then, we need to grasp the opportunities to make additional partnerships to broaden the study with other case studies and eventually conduct pilot studies to gain in conclusion robustness. This is required to gain the support of as many people as possible and see the PI concept developed and deployed.

Chapter 2 – Ideate about the future of Humanitarian Supply Chains

The chapter's 2 intention was to address the following question:

RQ1 What are the avenues for change in practices, at the HSC level, by taking advantage of PI concepts to improve the performance of humanitarian relief?

To do so, the objectives were to (i) study the relationships of HSC practices and organization systems on the supply performance and (ii) ideate the future of HSCs, inspired from PI principles, towards the HHSC. Chapter 2, in fact, captures the creative phase that consisted in ideating the HHSC paradigm. To frame and ensure the completeness of an in-depth reorganization of current HSCs, we relied on three impactful Supply Chain (SC) performance levers. A literature exploration highlighted that the SC network structure, SC business processes and the SC management components identified for SCs are all key influencers of the performance of relief chains. From these three dimensions, we made a list of 28 related factors to which we assigned a description regarding current practices. In a second stage, we investigated the PI literature to gain knowledge of the components and main mechanisms. From there, and the list of key HSC levers of performance previously identified, we were able to identify opportunities of translations and suggestions of new PI-oriented practices and organizational structure. This constitutes the first contribution of this research work, through the relative thoroughness of the proposals made and the method used.

Suggestions consider the introduction of PI equipment and facilities to speed up the physical flow transit, advanced information and technology systems to facilitate communications and the decision-making process, or even standardized protocols to facilitate HO coordination. Also, we suggest the interconnection of humanitarian actors based on an information- and resource-sharing approach for coordinating the relief in an effective, efficient and sustainable manner. The promise of benefits

was demonstrated in an approximate way, for the first time, through an illustrative experiment. It mainly highlighted lead time delivery reduction, while asset use and global service level showed increasing perspectives for improvement.

From this first contribution and the list of identified factors, many research avenues of investigation are possible. Even if each factor is part of a third granularity level, they still remain high level. Refinements about how concretely such proposals would operate and be compatible with each other need to be ideated and discussed by both academics and practitioners. Besides, I think there are additional factors to identify within the network organization to make coordination between the HOs possible at a large scale. This is essential for the future of aid as the gap between humanitarian needs and funding is growing significantly. Besides, the present humanitarian system is struggling and the expectations regarding the aid provided are becoming more stringent (more effectiveness, efficiency and sustainability, agility, etc.). The PI seems to indicate a solution to these challenges by organizing differently, by building on the existing and sharing both the means and the essential information. The positive aspect is that a certain autonomy and independence in the goal(s) pursued by any actor would not be compromised in such a new paradigm. Indeed, only the logistics system and services would be opened and shared.

Also, in the list of factors, I identified research avenues that I did not fully exploit as they were a little distant from the initial research scope. I'm thinking in particular about the financial and human resource management aspects. These are essential elements of the HSC as donations fuel the humanitarian system and cash transfers are growing. Besides, human resource management in terms of volunteer and expert mobilization and also in terms of training are essential to provide rapid and efficient assistance. I see perspectives for a mutualization of human resources, with central or regional management, for instance. Possibilities exist for disseminating knowledge and mutualized learning at a large scale from recognized experts. Also, knowledge can be built and standards raised through the sharing of experience from various HO actors. This could lead to global and regional standards as each region has its specificities. Indeed, in my opinion, when it comes to standards and protocols, attention should be paid to standardizing the specificities of an area or domain, but without occulting them too much.

Chapter 3 – Design an experiment on the HHSC

As for Chapter 3, it discusses the design of an adapted experiment to meet the main research goal of quantifying the interest and relevance of PI for the humanitarian sector. The research question associated to this Chapter was:

RQ2 How can the application of PI concepts to HSC levers be assessed in terms of its impact on performance?

As we are aware of the novelty of such a study, the first of its kind, and which is paving the way for a large range of investigations, we were obviously concerned about the credibility of the research work undertaken. This is why the contribution offered in this Chapter is based on rigorous approaches.

Consequently, the second contribution consists in:

Technological Framework a simulation architecture envisioned for conducting a factorial experiment. From the investigations made to understand the mechanics influencing performance in a humanitarian context, the technological framework

consists of three systems: a performance system, a scenario system and a digital humanitarian ecosystem. The first two systems are there to fulfil the requirements of the experiment: the performance system to monitor and collect simulation outputs and performance indicators, and the scenario system to parameter the operational rules and emergency environment on which the digital humanitarian ecosystem is to be based. Each value is assigned and the combination is associated to form a scenario relying on a factorial plan. Scenarios are therefore defined as a combination of practices to observe when facing a disaster. Last but not least is the digital humanitarian ecosystem. Such a system is original, as it considers HSCs from a holistic perspective. It does not only consider humanitarian practices but also exogenous factors (initial inventory, the total number of victims, etc.). This part of the environment may also influence the performance results. Such a holistic perspective, considering the environment, has been induced by the System Engineering (SE) approach used to design and model HSCs.

Functional Framework An auxiliary methodology, adapted from recognized modeling and simulation methodologies, to frame the development of a simulation to test different hyperconnected humanitarian approaches compared to a baseline scenario. This consists of eight steps integrating verification and validation phases to guarantee the alignment with the targeted research objective and generating credible results from which to draw conclusions.

The high-level considerations adopted throughout, make *in fine*, this technological and functional framework generic enough to be used or adapted for other experimental contexts. Even if simulation oriented, the functional framework can serve or be easily adjusted for other experimental methods. Besides, the integration of verification and validation steps to ensure the proper alignment with the initial research objectives are of real use. In addition, I recommend the use of the SE approach to help in research for modeling any complex systems, whether in a simulation perspective or not. It helped in guiding the reflections, proposing different study angles to come up with a fairly accurate view of the system under study. All of this, plus ensuring the alignment with the initial objectives and the proper development with numerous verification and validation steps.

Chapter 4 – test the HHSC paradigm in situation

Last but not least, Chapter 4 intended to finally demonstrate the interest of the PI for the humanitarian sector, as was our stated research intention at the end of Chapter 1. The objective as a reminder is to test the behavior of HHSC in situation using a simulation experiment to answer the third and final research question:

RQ3 How can decision-makers be supported in a relevant way and what are the consequences of such a major structural change?

To do so, we relied on the three previous Chapters to come up with a third applicative contribution. This appears as an end-to-end factorial experiment using simulation, providing results to analyze. The experimental objective is to compare a baseline scenario representing current practices with alternative scenarios integrating different degrees of hyperconnection. In this perspective, the Chapter is divided into two main phases: a preparation phase with the building of a case study, simulation development

and factorial experiment design, to end up with the experiment execution and an analysis phase.

During the preparation phase, a case study was built to (i) define a baseline scenario, inspired from the practices and organizational network of the Indonesian Red Cross, as a combination of current practices and (ii) to define an emergency context inspired from a historical earthquake hitting Indonesia in 2013, which will be the same for all scenarios. Then, the full factorial plan considered and implemented in the simulation consisted of four two-level factors leading to not 16 but 12 scenarios since there were impossible combinations. Respectively, each factor was the place for testing different practices at the sourcing, transport, replenishment and shortage-management level. More specifically, the sourcing factor allowed a hierarchical network with limited node connections to be tested compared to an interconnected network with multi-sourcing opportunities. Transport-related factors made it possible to test private and direct deliveries compared to consolidated deliveries. The replenishment factor was used to observe the effect of a short replenishment of the entry node of the local network for imitating international supply compared to a long lead time. Finally, the shortage-related factor questioned the current First In First Out (FIFO) approach versus a vertical equity approach authorizing partial deliveries.

Each scenarios' behavior was monitored and the associated performance, using lead time, service level and transportation costs indicators, were captured in the situation of an earthquake. Through descriptive and multivariate analyses, major findings indicated that even a small introduction of PI-oriented practices could lead to performance improvement in comparison to the baseline performance results. Multiple sourcing and a short replenishment lead time of the local network had the greatest impact on the effectiveness of the delivery process. Transport consolidation offered the perspective of more economical and better use of resources, but it slowed down the supply lead time to serve the expected demand. The use of a similar equity approach as the one tested in combination with a hierarchical structure certainly inflates transportation costs.

The main limits of the experiment so far concern the parameters of the experiment. Indeed, the focus on: a portion of territory and not the whole country, on one means of transportation while several are used in reality, on one occurring disaster and only a single type (earthquake only) and the fact that only one HO is considered over a short period all represent limits that will need to be relaxed in future research. Besides, more sensitivity analyses would have been a plus to test the experiment robustness in situations with more demand fluctuations or a more chaotic propagation of the disaster, for instance.

However, as simple as this case study may seem, the results show interesting perspectives and lead to initial conclusions. Among them, the multiple-sourcing approach highlights, in my opinion, several aspects. First of all, the benefits to be gained from an increased visibility of locally available resources or capabilities and the sharing of this information. Although we were considering only one organization in this case, it was truly representative of a reality where even within a single HO the network can be fractured into siloed nodes. The nodes operate on their own and several may target and mobilize trucks for the same relief operation without communicating among themselves. Even without the PI operating as it should, opportunities are there to take inspiration from it and operate differently. In this perspective, I suggest undertaking prospective work to identify possible local resource

points. Similarly as the hierarchical barriers to multiple sourcing are broken down, there are additional resources outside the humanitarian network that could be of use. Business suppliers, supermarkets, communities or local governments may have unused resources or be willing to share capabilities such as available space or items. However, to operate successfully, information should be available on a large scale and updated regularly to provide an accurate and centralized information system. There is a lot to gain from investigating local resource opportunities and rapid local mobilization, as the consequences of lead time elongation of an under-resourced network are seen in increased local waiting time for international supplies to arrive. Moreover, this is in line with current trends to support local economies in the event of a disaster and to distribute more suitable items that match what beneficiaries are accustomed to. As for transportation consolidation, it shows interesting promise, leading to better resource usage and cost-efficiency. However, its place is probably not during the first days of the response phase but probably in a second phase for less critical items or at congested nodes such as airports or seaports when a large amount needs to be transported and capacities are limited. Finally, from a practical perspective, I think some work should be undertaken to try to standardize practices or at least ways to connect and exchange information or items. A lot of time would be saved during exchanges and partnerships would be facilitated by levelling up practices and interconnections as much as possible to facilitate coordination, especially for nodes within the same network.

Now that the simulation backbone exists, some of these ideas make up part of our future intentions for simulation upgrades to take the research one step further by investigating the benefits of the PI. Although the results are satisfactory at first sight, some additional research is required in other contexts and more specific aspects need to be discussed to take the full measure of the value of the Physical Internet for the humanitarian sector.

Indeed, from an academic perspective, a large avenue of research opportunities has now opened. Some research suggestions could be related to shortage management policy. Specifically, *in fine* the analysis highlighted two performance scenarios that differed in terms of shortage management practice: FIFO or equity. The FIFO approach, as it was implemented, was too strict and led to less supply and a lower diversity of supply than the equity approach over the same period. On the other hand, the equity approach, which is important from a human and egalitarian perspective, can be very costly as it mobilizes many small flows and is highly sensitive to the demand in terms of costs. In the end, none of the two selected scenarios was found to be completely convincing due to this trade-off. There is something to explore at this level, either a hybrid format or a two-phase approach, or even something different. In addition, the rapid study that was carried out of the initial demand and inventory capacity led to the conclusion that there are some opportunities to explore the preparation of operations by studying the operating environment factors and their influence on the network performance or the risks they may pose. Obviously, there are a huge number of additional research perspectives that can be selected and developed directly from the list of hyperconnection proposals made in this study. In addition, the experimental structure or case study used in this work could be used to run additional tests with other disaster types, phases or territories. Other possibilities could be to complexify the factorial experiment. Indeed, the integration of additional factors testing major PI principles must be considered in the future.

Among the possibilities, I would suggest investigating multiple HOs responding to the same disaster. This would raise questions about how to coordinate the physical flow, especially when the product catalogue managed presents similar items, and how to organize the dispatch. Besides, we can expect transport consolidation challenges if HOs present some speed difference in mobilizing items. Another key PI principle to test in the experiment is warehouse sharing. First, it would mean setting capacity constraints and occupation rules for each HO. In a second phase, reflections could be related to the warehouse location and allocation to optimize the network. Today, most humanitarian warehouses are located near populated areas, and optimization investigations would be required to set the adequate amount, capacities and positioning of the warehouses. After that, there would be opportunities for testing new sort of assets, the PI hubs and relatives. Eventually, dynamic warehouses could be explored as an anticipation of the demand or for facilitating the physical flow deployment in the event of a disaster. We can also investigate the impact of a transport or even logistics network that would be partially out of service. By doing so, there would be opportunities for exploring rapid re-routing or even multi-modal shifts. In addition, the test of the new encapsulation system offered by the PI with PI-containers should be considered. More than testing the standardized size, which would be interesting, it would also raise questions about the possibility of a recognisable symbol or colour dedicated to HOs to give priority to those containers. Another topic that comes to my mind is the interest of PI for the preparation phase. I mentioned optimizing the network with warehouses, but further research could explore demand uncertainty using machine learning or advanced intelligence to help in estimating the need and better preparing the response.

If I had to sum up the whole methodology of research undertaken in a few words, I would say that: Chapter 1 gave justification about WHY and for WHO are we conducting this research and experiment, Chapter 2 gave elements regarding WHAT we want to experiment and Chapter 3 about HOW are we going to do it. All of these in the perspective to DO it with Chapter 4.

**“Now this is not the end. It is not even the beginning of the end.
But it is, perhaps, the end of the beginning.”**

Winston Churchill (1874-1965)

GLOSSARY

ALICE Alliance for Logistics Innovation through Collaboration in Europe.

ASEAN Association of Southeast Asian Nations.

BNPB Indonesian National Board for Disaster Management, Badan Nasional Penanggulangan Bencana.

BPMN Business Process Modeling Notation.

CARE Cooperative for Assistance and Relief Everywhere.

CSCMP Council of Supply Chain Management Professionals.

CSF Critical Success Factor.

DI Digital Internet.

DOE Design Of Experiment.

DW District Warehouse.

EAS East Asia Summit.

EL Expedition Line.

EM-DAT Emergency Events Database.

FAO Food and Agriculture Organisation.

FIFO First In First Out.

GDP Gross Domestic Product.

HHSC Hyperconnected Humanitarian Supply Chain.

HO Humanitarian Organization.

HSC Humanitarian Supply Chain.

HSCM Humanitarian Supply Chain Management.

ICRC International Committee of the Red Cross.

IDP Internally displaced person.

IFRC International Federation of Red Cross and Red Crescent Societies.

IGO International Governmental Organisation.

INGO International Non-Governmental Organization.

IoT Internet of Things.

ISO International Organization for Standardization.

JHLSCM Journal of Humanitarian Logistics and Supply Chain Management.

KPI Key Performance Indicator.

MSF Médecins Sans Frontières.

NGO Non-Governmental Organization.

OCHA United Nations Office for the Coordination of Humanitarian Affairs.

ODD Overview, Design concepts and Details.

OL Order Line.

PI Physical Internet.

PIF Pacific Islands Forum.

PMI Palang Merah Indonesia.

POD Point of Delivery.

PW Province Warehouse.

RCRC Red Cross and Red Crescent.

RW Regional Warehouse.

SAARC South Asia Association for Regional Cooperation.

SC Supply Chain.

SCM Supply Chain Management.

SCOR Supply Chain Operations Reference.

SE System Engineering.

SEBoK Systems Engineering Body of Knowledge.

SoI System of Interest.

UML Unified Modeling Language.

UN United Nations.

UNHCR United Nations High Commissioner for Refugees.

UNICEF United Nations Children's Fund.

WFP World Food program.

WHO World Health Organisation.

WoS Web of Science.

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Appendices

SUPPLIER SELECTION OPTIMIZATION MODEL

A.1 Context

All day long, at the orchestrator level, there is a mail box gathering replenishment orders for a variety of products from a set of clients (PODs or warehouses) that are looking for a supplier to send their request to. Once a day, the orchestrator has to manage these orders and indicate a set of suppliers that would minimize the total transportation cost in moving items from their stocks. In this context, we only consider one type of truck.

Before even considering which of the suppliers would be the best options, as occurs most of the time the case in a humanitarian context, we know that the global inventory level from all the suppliers does not have the capacity to meet the whole demand from the clients. In this situation, based on the strategy defined to manage shortages (FIFO or equity approaches according to the factorial plan), the original demand from clients is adjusted, prior to the optimization solving phase, and this is the demand we considered as an input parameter of this optimization problem.

Initial assumptions of this model are :

1. A client node of a product p cannot be a supplier of the same product. this means Point of Delivery (POD) can be used as a transit node but not as a supplier.
2. We consider only one type of truck for all the transportation movements.
3. Truck number is unlimited and available on demand at any node.

A.2 Sets and Indexes

<i>Sets</i>	
F	a set of suppliers
O	a set of clients
P	a set of products
<i>Indexes</i>	
$i \in F$	a supplier index
$o \in O$	a client index
$k \in P$	a product index

A.3 Parameters

$u_{i,k}$ the available inventory of product k of the supplier i [unit: quantity]
 $a_{o,k}$ adjusted demand to be satisfied at client node- i . $\forall k \in P, \forall o \in O_k$ [unit: quantity]

$$\alpha_k = \frac{s_{o,k}}{d_{o,k}} \quad \forall o \in O \quad (\text{A.1})$$

$c_{i,o}$ the cost for a truck (not depending on the product type). [unit: \$]
 It is previously calculated as follow:

$$fixedCost + distance \times FuelConsumption \times FuelCost \quad (\text{A.2})$$

where

- FuelConsumption = 0.285 liter/km [Hine et al., 2000]
- FuelCost = 0.5712 \$ /liter [McKinnon and Piecyk, 2011]

b^w the truck maximum capacity in weight [unit: kg]
 b^v is the truck maximum capacity in volume [unit: m3]
 e_k^w the product's weight [unit: kg]
 e_k^v the product's volume [unit: m3]

A.4 Decision Variable

$x_{i,o,k}$ the quantity of product k to request from supplier i for client o [unit: quantity]
 $y_{i,o}$ the number of trucks required to move $x_{i,o,k}$ of each product k from supplier i to the client o [unit: quantity]

A.5 Objective

The objective is to minimize the transportation cost associated in transporting items from suppliers. Here the transportation cost is calculated considering the number of trucks required and the cost of moving items from suppliers to the client's location.

$$\min \sum_{i \in F, o \in O} y_{i,o} \times c_{i,o} \quad (\text{A.3})$$

A.6 Constraints

Each supplier i for each type of product k can not supply a sum of demands from different client o , that would exceed the supplier inventory on hand.

$$\sum_{o \in O} x_{i,o,k} \leq u_{i,k} \quad \forall i \in F, \forall k \in P \quad (\text{A.4})$$

The total quantity to request of product k from suppliers should be equal to the demand of client o .

$$\sum_{i \in F} x_{i,o,k} = a_{o,k} \quad \forall o \in O, \forall k \in P \quad (\text{A.5})$$

The number of trucks required for sending $x_{i,o,k}$ items from supplier i to client o should be rounded up to the next integer that is a multiple of the quantity to send compared to the truck capacity.

$$y_{i,o} \geq \frac{\sum_{k \in P} x_{i,o,k} \times e_k^w}{b^w} \quad \forall i \in F, \forall o \in O \quad (\text{A.6})$$

$$y_{i,o} \geq \frac{\sum_{k \in P} x_{i,o,k} \times e_k^v}{b^v} \quad \forall i \in F, \forall o \in O \quad (\text{A.7})$$

It is necessary that $y_{i,o}$ the number of trucks is an integer.

$$y_{i,o} \in \mathbb{N} \quad \forall i \in F, \forall o \in O \quad (\text{A.8})$$

It is necessary that $x_{i,o,k}$ the quantity to move is an integer.

$$x_{i,o,k} \in \mathbb{N} \quad \forall (i, o, k) \in F \times O \times P \quad (\text{A.9})$$

A.7 Mixed Integer Linear Programming (MILP) Problem Formulation Summary

$$\begin{aligned} \min \quad & \sum_{i \in F, o \in O} y_{i,o} \times c_{i,o} \\ \text{s.t.} \quad & \sum_{o \in O} x_{i,o,k} \leq u_{i,k} && \forall i \in F, \forall k \in P \\ & \sum_{i \in F} x_{i,o,k} = a_{o,k} && \forall o \in O, \forall k \in P \\ & y_{i,o} \geq \frac{\sum_{k \in P} x_{i,o,k} \times e_k^v}{b^v} && \forall i \in F, \forall o \in O \\ & y_{i,o} \geq \frac{\sum_{k \in P} x_{i,o,k} \times e_k^w}{b^w} && \forall i \in F, \forall o \in O \\ & y_{i,o} \in \mathbb{N} && \forall i \in F, \forall o \in O \\ & x_{i,o,k} \in \mathbb{N} && \forall (i, o, k) \in F \times O \times P \end{aligned}$$

TRANSPORT CONSOLIDATION OPTIMIZATION MODEL

B.1 Context

The model described below is inspired from a minimum-cost flow problem which is an algorithmic problem drawn from graph theory and developed to find the most cost-efficient way to transport a resource in an oriented and capacity-constrained network from a set of sources to sink nodes.

In our situation, all day long, at the orchestrator level, there is a mail box gathering replenishment orders for a variety of products from a set of “clients” that can be PODs or warehouses. Within the network considered, there are also “suppliers” that own inventory and represent possible sources to meet the clients’ demand. Once a day, the orchestrator has to manage these orders and indicate a set of suppliers that would minimize the total transportation cost in moving items from their stocks.

Before even considering which of the suppliers would be the best options, as is usually the case in a humanitarian context, we know that the global inventory level from all the suppliers does not have the capacity to meet the whole demand from the clients. In this situation, based on the strategy defined to manage the shortage (FIFO or equity approaches according to the factorial plan), the original demand from clients is adjusted, prior to the optimization solving phase, and constitutes the demand we considered as an input parameter of this optimization problem.

Initial assumptions of this model are :

1. the network is not constrained i.e. there is no capacity constraint for the arcs and this is due to the fact that we are not limiting the number of trucks on the arcs. Indeed, we consider trucks to be available on demand at any node at any time.
2. Deliveries between warehouses to PODs, PODs to PODs, PODs to warehouses, and warehouses to warehouses are allowed.
3. A client node of a product p cannot be a supplier of the same product. this means POD can be used as transit node but not as a supplier.
4. Truck number is unlimited and available on demand at any node.
5. We consider only one type of truck for all the transportation movements.

B.2 Sets and Indexes

Sets	
N	the set of all the nodes in the network, including warehouses and shelters. Based on assumption number four, it is possible to have $N = F_p \cup O_p$
P	the set of products (relief items)
F_p	the set of suppliers for product p . Represents the source nodes with positive inventory for product p . $F_p \subset N, \quad \forall p \in P$
O_p	the set of clients for product p . Represents the sink nodes with positive demand for product p . $O_p \subset N, \quad \forall p \in P$
Indexes	
$i \in N$	an origin node index
$j \in N$	a destination node index
$p \in P$	a product index

B.3 Parameters

$u_{i,p}$	available inventory of product p at node $i, \quad \forall i \in N, \quad \forall p \in P$
$a_{i,p}$	adjusted demand to be satisfied at client node- $i, \quad \forall p \in P, \quad \forall i \in O_p (a_{i,p} \leq 0)$
$c_{i,j}$	cost for sending a truck from node i to node $j, \quad \forall i, j \in N$.

It was previously calculated as follow:

$$fixedCost + distance \times FuelConsumption \times FuelCost \quad (B.1)$$

where

- FuelConsumption = 0.285 liter/km [Hine et al., 2000]
- FuelCost = 0.5712 \$ /liter [McKinnon and Piecyk, 2011]

b^w	truck maximum capacity in weight [unit: kg]
b^v	truck maximum capacity in volume [unit: m3]
e_p^w	product's weight [unit: kg]
e_p^v	product's volume [unit: m3]

B.4 Decision Variable

$x_{i,j,p}$	quantity of product p to transport from node i to node $j, \quad \forall i, j \in N \quad \forall p \in P$
$y_{i,j}$	quantity of trucks from node i to node j , used to carry the product flow from node i to node $j, \quad \forall i, j \in N$
$z_{i,p}$	amount of product p to be sent from source node- i to satisfy demand at one or several client nodes. $\forall p \in P, \quad \forall i \in F_p (z_{i,p} \geq 0)$

B.5 Objective

The objective is to minimize the transportation cost for meeting the adjusted demand of the nodes from pre-allocated inventories at the source nodes. Here the transportation cost is calculated considering the number of trucks required for each arc and the cost of a truck for moving items between two nodes.

$$\min \sum_{i,j \in N} y_{i,j} \times c_{i,j} \quad (\text{B.2})$$

B.6 Constraints

In a network flow problem, a balanced flow is required. It means that flow leaving and entering the node i must equal the supply (z)/demand (a) at the node.

$$\sum_{j \in N} x_{i,j,p} = \sum_{j \in N} x_{j,i,p} + a_{i,p} \quad \forall p \in P, \forall i \in O_p \quad (\text{B.3})$$

$$\sum_{j \in N} x_{i,j,p} = \sum_{j \in N} x_{j,i,p} + z_{i,p} \quad \forall p \in P, \forall i \in F_p \quad (\text{B.4})$$

Inventory limits the amount we can source from each supplier node i

$$z_{i,p} \leq u_{i,p} \quad \forall p \in P, \forall i \in F_p \quad (\text{B.5})$$

To have a the required flow, the total offer (amount to be sourced from suppliers) should be equal to the total demand. In other words, there should be enough allocated inventory for each product to satisfy the predetermined demand.

$$\sum_{i \in F_p} z_{i,p} = - \sum_{i \in O_p} a_{i,p} \quad \forall p \in P \quad (\text{B.6})$$

There must be enough trucks on arcs to carry the whole product flow from origin to destination:

$$y_{i,j} \geq \frac{\sum_{p \in P} x_{i,j,p} \times e_p^w}{b^w} \quad \forall i, j \in N \quad (\text{B.7})$$

$$y_{i,j} \geq \frac{\sum_{p \in P} x_{i,j,p} \times e_p^v}{b^v} \quad \forall i, j \in N \quad (\text{B.8})$$

It is necessary that $y_{i,j}$ the number of trucks is an integer.

$$y_{i,j} \in \mathbb{N} \quad \forall i, j \in N \quad (\text{B.9})$$

It is necessary that $x_{i,j,p}$ the quantity to move is an integer.

$$x_{i,j,p} \in \mathbb{N} \quad \forall i, j \in N, \quad \forall p \in P \quad (\text{B.10})$$

It is necessary that $z_{i,p}$ the quantity to send is an integer.

$$z_{i,p} \in \mathbb{N} \quad \forall i \in N, \quad \forall p \in P \quad (\text{B.11})$$

B.7 Mixed Integer Linear Programming (MILP) Problem Formulation Summary

$$\begin{aligned}
 \min \quad & \sum_{i,j \in N} y_{i,j} \times c_{i,j} \\
 \text{s.t.} \quad & \sum_{j \in N} x_{i,j,p} = \sum_{j \in N} x_{j,i,p} + a_{i,p} && \forall i \in O_p, \quad \forall p \in P \\
 & \sum_{j \in N} x_{i,j,p} = \sum_{j \in N} x_{j,i,p} + z_{i,p} && \forall i \in F_p, \quad \forall p \in P \\
 & \sum_{i \in F_p} z_{i,p} = - \sum_{i \in O_p} a_{i,p} && \forall p \in P \\
 & y_{i,j} \geq \frac{\sum_{p \in P} x_{i,j,p} \times e_p^w}{b^w} && \forall i, j \in N \\
 & y_{i,j} \geq \frac{\sum_{p \in P} x_{i,j,p} \times e_p^v}{b^v} && \forall i, j \in N \\
 & y_{i,j} \in \mathbb{N} && \forall i, j \in N \\
 & z_{i,p} \in \mathbb{N} && \forall i \in N, \quad \forall p \in P \\
 & x_{i,j,p} \in \mathbb{N} && \forall i, j \in N, \quad \forall p \in P
 \end{aligned}$$

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RÉSUMÉ LONG EN FRANÇAIS

Le travail de recherche, ici présent, sous forme d'un manuscrit de thèse, a été réalisé entre Janvier 2019 et Janvier 2022. L'objectif de fond, qui sous-tend ce travail, a consisté à améliorer le sort et les conditions de vie des populations impactées par des catastrophes. La motivation, en plus des nombreuses vies humaines que font chaque année les catastrophes, se traduit autour d'un système d'aide aux perspectives préoccupantes. Aujourd'hui, le système d'assistance aux victimes montre des limites de capacité et d'efficacité face à des besoins humanitaires toujours croissants. Face à ce constat, le travail de thèse a débuté par une phase exploratoire du domaine humanitaire soulevant différentes pistes de travail. Cette phase s'est achevée par un positionnement vis-à-vis d'un problème à adresser, à savoir l'amélioration de la performance de livraison des produits de première nécessité (couvertures, jerrycans, kits d'hygiène...) aux victimes de catastrophes naturelles de type « soudaine », reconnues comme activité clé, en s'inspirant d'un nouveau paradigme logistique : l'Internet Physique (IP). Ensuite, une seconde phase plus conceptuelle s'est donc attachée à imaginer les Chaînes d'Approvisionnement Humanitaires (CAH) de demain selon la philosophie de l'IP. Dans un troisième temps, afin de répondre à l'objectif défini en amont d'amélioration de la performance, nous avons imaginé une expérience quantitative basée sur la simulation afin de mesurer les effets de nouvelles politiques d'organisations inspirées de l'IP en comparaison des pratiques actuelles. Une fois l'expérience planifiée au travers d'un protocole à suivre et de ressources identifiées et à mobiliser, une quatrième phase s'en est suivie. Cette dernière plus applicative et concrète que la précédente a consisté à tout d'abord préparer un cas d'étude avec des données et informations terrains et développer une simulation avec possibilité de simuler différents scénarios de réponse à une catastrophe naturelle. Tout ceci dans le but, ensuite, d'exécuter l'expérience afin de générer des résultats dans le but d'étudier et d'analyser les propositions faites en vue d'améliorer la performance des CHAs. Le manuscrit s'articule donc autour de ces quatre grandes phases qui ont toutes un chapitre dédié. Par ailleurs, les trois dernières phases comportent chacune une contribution au domaine scientifique auquel ce travail de recherche se rapporte. Chacun des chapitres est résumé au travers de sections dédiées qui suivent.

Chapitre 1 – DÉCOUVREZ l'univers de la Chaîne d'Approvisionnement Humanitaire (CAH)

Le premier chapitre permet de poser le contexte de recherche en fournissant aux lecteurs une base de connaissance en lien avec l'aide humanitaire. Sur cette base, il a également pour objectif, comme prémices à tout travail de recherche, d'aboutir à un énoncé de problème et une approche de résolution à tester. Ce chapitre s'articule donc autour de quatre étapes, une première étape exploratoire afin de se familiariser avec le contexte humanitaire, une seconde qui décrit une méthodologie afin de définir les questions et objectifs de recherches, une troisième exploratoire à nouveau qui au travers de l'application de la méthodologie permet d'affiner le domaine d'étude, ses problématiques associées et d'identifier d'éventuelles solutions et enfin une dernière étape qui pose finalement les objectifs et les questions de recherche.

Contexte de la recherche : qu'est-ce que l'aide humanitaire ?

Il existe plusieurs types de contextes menant à des urgences humanitaires qui peuvent se développer progressivement (famine, sécheresse, crise politique...) ou se produire soudainement (tremblement de terre, inondations, attaque terroriste...). Les impacts de ces événements sont mesurés en termes d'impact économique (infrastructures publiques, réseaux de transport ou habitations détruites) et humain (décès, blessés, séparations des proches, d'ordre psychologique...). Pour prévenir ou limiter les dégâts causés par les catastrophes quand elles surviennent, plusieurs types d'actions sont possibles. Très en amont de l'évènement, des mesures de mitigation lors de la construction des bâtiments ou bien des plans d'évacuation ou sessions de sensibilisation permettent, entre autres, d'éliminer un certain nombre de risques. Peu de temps avant l'arrivée de la catastrophe, des systèmes d'alerte ou des mesures anticipées permettent de prévenir les populations et d'organiser les secours pour intervenir au plus vite. Dès que l'évènement se produit, les secours s'organisent, dans un premier temps en secourant les victimes, déblayant ou restaurant les voies de communication et évaluant les besoins. Dans un second et rapide temps, un plan d'action est défini et des produits de première nécessité (couverture, fournitures médicales, kits d'hygiène...) sont distribués aux personnes dépourvues de leurs biens. Les activités se concentrent autour des besoins fondamentaux (manger, disposer d'un abri, hygiène, accès à l'eau...) qui sont identifiés et visés à être comblés dans les premières semaines qui suivent la catastrophe. Une fois ces besoins assurés, l'aide humanitaire apporte un soutien d'ordre plus sociétal pour un retour à l'état d'avant catastrophe autour d'activités de reconstruction ou relance de l'activité économique, de l'éducation, etc. Ces phases (mitigation, préparation, réponse et réhabilitation) constituent les quatre phases du cycle d'une catastrophe et intègrent des activités humanitaires diverses et variées.

La plupart des activités mentionnées précédemment, quelle que soit la phase, ne sont rendues possibles que grâce à des chaînes d'approvisionnement ou logistiques qui permettent de mobiliser des ressources humaines ou matérielles de points-sources à des points de demande où se concentrent les populations touchées en attente de services et produits. Ces chaînes rassemblent une large diversité d'acteurs (gouvernements, militaires, organisations non gouvernementales (ONG), entreprises...) s'organisant sur la base de moyens logistiques dédiés (camions, entrepôts...). Contrairement aux

entreprises, les OHs ne sont pas rémunérées en compensation de l'aide fournie et fonctionnement uniquement grâce à des dons et des financements extérieurs.

Des rapports récents [Rouyer, 2021, Griffiths, 2021] ont mis en évidence la croissance significative des besoins humanitaires sur la dernière décennie et projetée. Cette croissance s'explique par le fait que les personnes les plus vulnérables sont les plus impactées par les catastrophes et que le taux de pauvreté augmente partout dans le monde. De plus, les besoins ont encore plus été accentués par la récente crise sanitaire du COVID-19 augmentant les besoins existants, mais générant également de nouvelles crises. Enfin, l'exposition des personnes les plus vulnérables augmente en lien avec le nombre croissant de catastrophes naturelles partout dans le monde à cause du réchauffement climatique (incendies en Australie 2019, froids polaires aux États-Unis en 2021, tsunami au niveau des îles Tonga en 2022...). Le nombre de réfugiés également en augmentation comptant 82,1 millions de personnes en 2020 est aussi préoccupant.

Au regard de ces éléments, la motivation derrière ces travaux de recherche ne peut malheureusement pas se concentrer sur la réduction du nombre de catastrophes (bien que ce soit un vrai sujet), mais s'intéresse plutôt à améliorer les conditions de vies des personnes impactées par ces catastrophes. Dans cette perspective, le périmètre d'étude s'est donc restreint au niveau des procédures et mécanismes d'acheminement de l'aide humanitaire jusqu'aux victimes.

Chaîne d'approvisionnement humanitaire enjeux et challenges

Au niveau académique, le domaine de la gestion des chaînes d'approvisionnement d'ordre général a fait l'objet de recherches intensives, tandis que le sous-domaine humanitaire n'a été examiné, lui, que par une poignée de chercheurs. Cependant, depuis une dizaine d'années, le domaine de la logistique humanitaire et gestion des CAHs a fait l'objet d'une attention croissante par les universitaires et les praticiens qui reconnaissent désormais son importance [Behl and Dutta, 2018]. La recherche depuis peu s'inscrit dans un courant qui se veut plus en adéquation avec les besoins des praticiens et pertinente en vue d'applications terrains [Kunz et al., 2017]. Les principaux sujets adressés par les chercheurs se concentrent autour du transfert des connaissances [Banomyong et al., 2017, Altay et al., 2018], l'information et les technologies [Banomyong et al., 2017, Behl and Dutta, 2018, Altay et al., 2018], la logistique et les opérations [Banomyong et al., 2017, Chiappetta Jabbour et al., 2017, Altay et al., 2018] et la gestion de la performance [Chiappetta Jabbour et al., 2017, Behl and Dutta, 2018, Altay et al., 2018].

Parmi ces sujets et en vue d'améliorer la réponse des CAHs nous avons passé un second temps à nous familiariser avec le concept de performance dans un contexte humanitaire et les challenges actuellement rencontrés au niveau des CAHs. En nous penchant vers les challenges opérationnels rencontrés par les praticiens, nous avons pu identifier une série de difficultés dans des domaines variés.

Tout d'abord, le contexte urgence et la difficulté à prévoir les catastrophes ainsi que les dégâts associés génèrent des incertitudes et limitent la prise de mesures anticipées [Kovacs and Spens, 2007]. L'environnement déstabilisé économiquement, socialement, politiquement et au niveau des infrastructures génère du désordre et des difficultés à prendre part et à organiser les secours de manière fluide. Les ressources sont souvent limitées, en termes d'infrastructures (les zones vulnérables sont souvent assez peu

et bien équipées) [Wood et al., 1995], de personnes (manque de personnes qualifiées ou disponibles) [İlhan, 2011] et les moyens financiers tardent souvent à arriver et dépendent du niveau de médiatisation de l'évènement [Seaman, 1999]. La livraison des ressources et généralement ralenti à cause de capacités logistiques limitées, de besoins importants qui dépassent les moyens en local, de longues procédures administratives [Balcik et al., 2010] et de dons non sollicités ou inadaptés à gérer en plus [Ado et al., 2014]. Enfin, le nombre d'OHs à prendre part aux opérations de secours est souvent important tandis que le manque de clarté du rôle et objectifs de chacune ainsi que des moyens et manière de fonctionner entraînent des difficultés à se coordonner menant à une inégale répartition et traitement des activités ainsi que des gaspillages [Ado et al., 2014, Stephenson, 2005]. De plus, il ne s'agit plus seulement de porter assistance aux victimes et sauver des vies, les OHs doivent désormais aussi répondre de manière efficiente (en limitant les ressources utilisées) [Beamon and Balcik, 2008] et durable (en utilisant à bon escient les ressources) sous peine de voir leurs sources de financement s'amenuiser [Salvadó and Lauras, 2017].

Objectifs et questions de recherche

La menace et l'impact du changement climatique ainsi que les guerres en cours, l'augmentation de la pauvreté et des personnes vulnérables dans le monde ainsi que la pandémie de COVID-19, ont tous entraîné une augmentation du nombre de catastrophes de différents types et, conséquence, du nombre de personnes touchées. Aujourd'hui, les besoins humanitaires ont atteint des niveaux record et les estimations des années suivantes devraient être plus élevées que le précédent, affectant environ 274 millions de personnes dans pas moins de 63 pays en 2022 [Griffiths, 2021]. Néanmoins, l'aide humanitaire est restée stagnante en termes de financement ces dernières années et l'écart des besoins non satisfaits s'est creusé [Rouyer, 2021]. Face à ces tendances, il devient urgent de repenser l'aide humanitaire telle qu'elle est fournie aujourd'hui et étudier comment répondre aux exigences tout en réduisant les dépenses. Étant donné que la limitation des tendances aux catastrophes n'entre malheureusement pas dans le cadre de ce travail, l'ambition de la recherche est plutôt de contribuer à l'amélioration des conditions de vie des personnes touchées par des catastrophes naturelles en accélérant la fourniture des produits de première nécessité aux victimes. En parallèle de le faire efficacement et durablement. Cela peut faire une énorme différence dans les taux de survie parmi la population touchée ou plus tard concernant les aspects économiques ou sociaux durant la période de réhabilitation.

Selon [Van Wassenhove, 2006], les CAHs sont en retard par rapport au secteur privé et ont mis beaucoup de temps à réaliser le potentiel d'une CA efficace. Logiquement, perspective d'amélioration suggérerait que le secteur humanitaire cherche à combler son retard vis à vis du secteur marchand, pourtant jugé peu performant et sujet à de nombreuses voies d'améliorations. Ce faisant, les CAHs perdraient du temps, tandis qu'en envisager de contourner cette lacune et de cibler directement un système plus adapté aux enjeux actuels, les organisations gagneraient en efficacité et en pérennité et aussi faire des économies. Par conséquent, deux voies s'offrent aux OHs désireuses d'envisager d'améliorer leur CAs et donc leur performance :

1. Optimiser le système existant et tendre vers la maturité des CAs commerciales. C'est là que se concentrent aujourd'hui la plupart des recherches.

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2. Accepter de remettre en cause certains principes fondamentaux et envisager une refonte logistique. Ce qui a été assez peu envisagé jusqu'à présent.

Notre intention de recherche et terrain d'exploration se situe au travers de ce deuxième point. Un tel choix est renforcé par des rapports récents discutant les tendances actuelles et futures de l'action humanitaire et identifie d'éventuelles opportunités [Griffiths, 2021, Rouyer, 2021]. Concernant la situation actuelle, Rouyer [2021] souligne que le COVID-19 a « *intensifié la pression sur un système humanitaire qui lutte pour faire face aux défis existants* » et que « *les progrès dans la réforme de l'acheminement de l'aide humanitaire doivent être consolidés et accélérés* ». Griffiths [2021] ajoute que « *l'action humanitaire doit s'adapter à la crise climatique* » et « *C'est le moment de redoubler d'efforts [...] et de prendre des actions décisives dans l'intérêt de tous* ». Les rapports suggèrent des mises à l'effort autour d'une meilleure coordination inter-agences [Griffiths, 2021] et des livraisons plus efficaces [Griffiths, 2021, Rouyer, 2021].

En résumé, alors que beaucoup s'accordent en faveur d'une amélioration des capacités des CAHs à mobiliser des ressources logistiques de manière efficiente et durable en vue d'offrir une assistance aux victimes efficace, car c'est une question de viabilité pour les OHs aujourd'hui, la question de la manière d'atteindre cet objectif semble moins discutée et évidente. Pour répondre à ces exigences, notre recherche de solutions a conduit à la découverte de l'Internet Physique (IP), un nouveau concept logistique en rupture avec les pratiques actuelles, et qui peuvent présenter un intérêt pour le secteur humanitaire [Montreuil, 2011].

Dans cette perspective, la recherche sera basée sur l'hypothèse principale que l'IP a beaucoup à offrir au secteur humanitaire en transformant les pratiques des CAHs. Par conséquent, les efforts de recherche seront concentrés à répondre à trois principales questions :

- QR1** Quelles sont les pistes de changement de pratiques logistiques, au niveau des CAHs, en tirant profit des concepts de l'IP pour améliorer la performance de l'aide humanitaire ?
- QR2** Comment évaluer l'application des concepts inspirés de l'IP au niveau de leviers clés ayant un impact sur les performances des CAHs ?
- QR3** Comment accompagner les praticiens de manière pertinente et quelles sont les conséquences d'un changement structurel aussi important ?

Ces questions trouveront chacune une réponse respectivement au travers des trois chapitres du manuscrit et demeurent au cœur de l'étude.

Chapitre 2 – IMAGINER le futur des Chaînes d’Approvisionnement Humanitaire (CAH)

Tout comme un client n’est pas toujours au clair avec la solution qui répondrait le mieux à ses besoins, l’enjeu autour de ce chapitre consiste à imaginer un fonctionnement différent des chaînes d’approvisionnement humanitaires qui répondrait au nombreux challenges aujourd’hui rencontrés tout en offrant une assistance aux victimes à la fois efficace, mais aussi efficiente et respectueuse de l’environnement. Dans cette perspective, le présent chapitre cherche à répondre à la première question de recherche identifiée à savoir : Quelles sont les changements de pratiques envisageables, au niveau des CAHs, profitant des concepts de l’IP à considérer afin d’améliorer la performance de l’aide humanitaire ?

Pour répondre à cette question, nous nous sommes basés sur le principe de cause à effet et avons donc cherché à identifier et évaluer le lien entre des stratégie ou choix logistiques et leur impact sur la performance d’une chaîne d’approvisionnement humanitaire. Dans cette perspective, la démarche a d’abord démarré avec une phase d’acculturation autour du concept de chaîne d’approvisionnement au sens large et ses composants clés et puis ceux des CAH plus particulièrement. Puis, nous avons abordé le principe de l’IP et ses fondements pour nous familiariser avec le concept et ses enjeux. Enfin, nous avons recherché des articles associant les concepts CAH et IP. Ces différentes investigations ont permis d’identifier des changements de pratique possibles (dits leviers de performance) et de définir de nouvelles règles opérationnelles orientées IP à considérer en vue d’améliorer les résultats de performance des CAHs.

Revue de la littérature

La chaîne d’approvisionnement

Une chaîne d’approvisionnement (CA) est définie en premier lieu comme un réseau d’organisations de différentes natures et secteurs d’activités. En s’associant, elles créent de la valeur à destination de clients sous la forme d’une offre de service ou de produits. Chacune d’entre elles représente un maillon clé et est en charge d’une ou plusieurs activités comme la production, la livraison ou la vente. Pour fonctionner correctement et assurer que le produit ou service sera prêt pour répondre à la demande, les noeuds de la chaîne interagissent sous forme d’échanges de biens, d’informations ou monétaires. Aujourd’hui, les chaînes d’approvements comportent un grand nombre d’acteurs et de connexions puisque la demande en biens et service ne cesse d’augmenter et de se diversifier. Ceci rend les chaînes complexes et difficiles à gérer et demande à ne pas perdre de vue leur structure. Par ailleurs, les variables managériales, comme la philosophie de l’entreprise ou le contrôle des opérations, permettant l’intégration et le bon fonctionnement des processus ainsi que des liens de bout en bout de la CA. Dans une perspective de CA gérée avec succès Selon ces caractéristiques, [Lambert and Cooper \[2000\]](#) définissent les CAs selon trois composantes interconnectées : la structure du réseau, les processus opérationnels et les composantes du management (voir 2.2).

La chaîne d'approvisionnement humanitaire

Le management des CAHs est défini comme le planning et le management de toutes les activités de secours et d'assistance nécessitant des flux physiques, d'informations et financiers. Il est important de noter qu'elle comprend également la coordination et la collaboration de tous les membres de la chaîne d'approvisionnement que ce soit les prestataires de services logistiques et fournisseurs ou bien les OHs entre elles [Kovacs and Spens, 2012].

En termes de flux physique, les CAHs peuvent être amenés à gérer des produits (nourriture, articles de secours, équipements, etc.) et des ressources humaines (médecins, experts, volontaires, etc.). Au vu des besoins, de nombreuses sources (fournisseurs, réserve de bénévoles...) sont sollicitées puis mobilisées de différents lieux pour être acheminées jusqu'aux points de demande. La bonne gestion des flux physiques requiert des échanges d'informations et une bonne communication entre les membres et les processus de la chaîne, au travers par exemple de rapports de stock, de la progression de la livraison ou encore la connaissance et mis à jour des besoins. Pour autant, ces activités opérationnelles sont rendues possible que sur la base d'engagements financier [Charles and Lauras, 2011]. Pendant longtemps, le flux financier était unidirectionnel et provenait des donateurs en direction des OHs pour assurer leur fonctionnement. Aujourd'hui, de nouvelles formes d'aide apparaissent, comme une assistance financière via un transfert de fonds directement aux bénéficiaires plutôt que de fournir des produits laissant toute liberté au receveur de répondre à ses besoins [Altay et al., 2018].

L'Internet Physique : objectifs et enjeux

L'IP est un concept émergent et innovant de réseaux logistiques interconnectés capitalisant sur l'opportunité de mutualiser les actifs et les compétences [Montreuil et al., 2012b]. Il a été défini comme : « *[un] système logistique mondial hyperconnecté permettant un partage transparent des actifs ouverts et une consolidation des flux grâce à la normalisation encapsulation, modularisation, protocoles et interfaces* » [Montreuil, 2017]. Comme souligné par définition, le PI remodèle complètement les fondements de la logistique. Le terme « hyperconnecté » fait référence à la connexion étroite et intensive entre les acteurs et les composantes physiques du réseau. Ce rapprochement opère à travers plusieurs couches, c'est-à-dire aux niveaux numérique, physique, opérationnel, commercial, juridique et personnels grâce à une optimisation des différents contenants et des normalisations des échanges [Montreuil et al., 2012b].

Présentement, le système logistique présente trop de symptômes peu respectueux de l'environnement et qui participent à compromettre les objectifs de l'accord de Paris [Ballot and Montreuil, 2014]. Avant qu'il ne soit trop tard, l'IP a été conçu pour offrir un plus un service logistique résilient, efficace, durable et adaptable à ses utilisateurs en changeant la façon dont les objets physiques sont manipulés le long du réseau [Montreuil et al., 2012b]. Jusqu'à présent, utiliser les concepts PI pour repenser les pratiques humanitaires actuelles a reçu peu d'attention de la part des chercheurs. L'état de l'art autour du concept d'une Chaînes d'Approvisionnement Humanitaire Hyperconnectée (CAHH), utilisant la combinaison de mots clés tels que « Internet Physique » ou « Hyperconnecté » et « Humanitaire », a abouti à très peu de résultats. Une explication possible réside dans le fait que le PI est un concept récent et bien qu'il commence à se déployer dans le secteur commercial, il semble plausible que peu d'applications dans d'autres domaines aient été étudiées à ce jour.

Vers une chaîne d'approvisionnement humanitaire hyperconnectée (CAHH)

Au regard de l'état de la littérature concernant les chaînes d'approvisionnements humanitaires hyperconnectées (CAHH)s, il est apparu que le domaine n'a bénéficié que d'une attention limitée de la part des chercheurs en comparaison des études croissantes de l'IP sous le prisme des CA commerciales. En effet, seuls deux papiers ont pu être relevés : [Ado et al., 2014, L'Hermitte et al., 2018]. Tous deux s'évertuent à définir les concepts décrivant ce que signifierait être hyperconnectée dans le secteur humanitaire et mettent en évidence, de manière qualitative, quelques premiers éléments positifs à cela (voir figure 2.6).

Sur la base des éléments structurant une chaîne d'approvisionnement et identifiés comme leviers de performance (identifiés par [Lambert and Cooper, 2000] : la structure du réseau, les processus opérationnels et les composantes du management) au regard des éléments plus spécifiques des CAHs et des concepts de l'IP, nous avons pu et c'est là notre première contribution, décrire et structurer les caractéristiques essentielles du concept de CAHH en catégories. S'en suivent, uniquement les propositions tirées de ce cadre ayant servi d'inspiration aux besoins de l'expérimentation, elle même décrite dans le chapitre 4. D'autres propositions sont disponibles et sont listées dans le tableau récapitulatif suivant 2.2.

La structure du réseau des CAHH

En effet, selon les principes de l'IP, des propositions en termes de configuration du réseau ont été imaginées et décrites au regard des pratiques actuelles.

Aujourd'hui, au sein même d'une organisation, comme la Croix-Rouge ou la Fédération Internationale de la Croix-Rouge et du Croissant-Rouge, les sites ont tendance à être isolés et cloisonnés entre eux. Cela conduit à des échanges essentiellement unilatéraux et à une limitation des connexions et des offres de services possibles [Ramalingam et al., 2009b]. La philosophie du Physical Internet (PI) va dans le sens du type matrice ou réseau multidirectionnel. La connexion sera être autorisée verticalement et horizontalement, améliorant ainsi le niveau d'intégration des nœuds au sein du réseau existant. En outre, en augmentant le niveau d'information partagée et la visibilité sur la capacité de tous les nœuds, la CAHH offre la possibilité de mieux exploiter le réseau de ressources en local et, plus largement encore.

De plus, dans le système actuel, les OHs possèdent également leurs propres entrepôts ou centres de distribution dédiés au stockage des produits. Ceux-ci sont généralement situés de manière permanente, sans consultation et saisie à l'occasion, à proximité des zones urbaines en corrélation avec le Gross Domestic Product (GDP) [McGlynn Scanlon and Alawiyah, 2014], ce qui entraîne une répartition hétérogène sur le territoire (voir Figure 2.7). Avec le PI, celles-ci ne seront plus privées, mais accessibles à tout utilisateur du réseau. En tant que hubs ouverts et partagés, n'importe quel Humanitarian Organization (HO)s pourrait prépositionner les stocks de ces actifs permanents et profiter de toute opportunité d'espace disponible. Ainsi, le flux de n'importe quelle organisation pourrait transiter par le réseau et être déployé de manière dynamique et agile en fonction de la demande et de l'état du réseau de transport [Ado et al., 2014] L'allocation et la localisation des actifs et l'emplacement seraient adaptés de manière dynamique à la demande prévue ou à un changement de la demande, en utilisant des entrepôts humanitaires fixes, transitoires ou mobiles certifiés PI. Une telle perspective permettrait de réduire le nombre d'actifs, mais

de les positionner de manière plus optimale et donc d'augmenter la portée de la couverture tout en limitant le risque de dommages au réseau. En outre, l'évaluation des performances de secours permettrait d'évaluer l'organisation globale du réseau en tant que telle, et non plus celle d'une seule agence, comme c'est le cas aujourd'hui.

Les processus des CAHH

D'autres propositions d'évolutions des pratiques vers un système plus hyperconnecté ont pu également être définies concernant, maintenant, les processus.

Dans le cadre des opérations de secours, le processus d'approvisionnement est identifié comme l'un des plus critiques puisqu'il s'assure que les produits sont disponibles là où ils sont attendus [Le Moigne, 2013]. Décisions concernant le choix des fournisseurs ou la stratégie de mobilisation des produits en provenance de plusieurs sources sont fondamentales dans ce processus. Une des difficultés concerne le choix de s'approvisionner en local ou bien à l'international puisque les deux présentant des avantages et des inconvénients. S'approvisionner localement signifie participer à l'économie locale, réduire les délais de livraison et s'approvisionner en articles adaptés aux habitudes de la population locale. Cependant, cette approche génère une augmentation des tarifs et donc une inflation pour les locaux. De plus, les stocks peuvent être limités ou ne pas répondre aux spécifications requises [Kusumastuti et al., 2010, Wibowo et al., 2013, Beamon and Balcik, 2008]. Quant à l'approvisionnement au niveau international, il peut offrir plus de possibilités d'approvisionnement et de disponibilité des stocks et ainsi permettre des achats groupés et donc de réduire les coûts. Cependant, elle implique des processus de transport qui prennent du temps (longues procédures de dédouanement, appel d'offres) et d'importantes capacités de transport pour l'envoi des marchandises [Balcik, Beamon, Krejci, Muramatsu, and Ramirez, 2010, Kusumastuti, Insanita, and Wibowo, 2010].

L'approche IP, en tant que réseau ouvert et interconnecté, élargirait les possibilités de sources d'approvisionnement et augmenterait la visibilité sur les capacités disponibles afin de tirer parti des sources d'approvisionnement de proximité. En outre, le recours à plusieurs sources d'approvisionnement serait facilité afin d'éviter de prélever trop de ressources de certaines régions et de fournir une meilleure répartition. Par ailleurs, on peut s'attendre à ce qu'une meilleure coordination entre les HO limite l'approvisionnement à ce qui est réellement nécessaire, permettrait de mutualiser les envois et éviterait ainsi de nombreux gaspillages (voir figure 2.8). Enfin, l'utilisation d'équipements standardisés (containers, matériel de manutention...) permettrait de mieux gérer le flux de matières, et ce de manière efficace lors des entrées/sorties des entrepôts.

Les composants de management des CAHs

Enfin, des évolutions des pratiques concernant les composants de management identifiés par Lambert and Cooper [2000] ont également été sujet à réflexion.

Si on se penche sur l'organisation de la structure des CAH actuelles, il apparaît peu de coordination ni collaboration entre les membres et ceux horizontalement comme verticalement. Les difficultés proviennent d'un manque de régulation et de visibilité quant au rôle et spécialisation de chaque OH. Par ailleurs, peu de standards et protocoles communs existent pour faciliter les efforts de collaboration [Pettit and Beresford, 2009, Ado, Ben Othmane, Matei, and Montreuil, 2014]. La transmission de l'information est limitée au strict minimum en partie de la compétition entre les

organisations pour obtenir des financements [Pettit and Beresford, 2009, Stephenson, 2005, Ado, Ben Othmane, Matei, and Montreuil, 2014].

Pourtant, la coordination est reconnue comme essentielle dans la perspective d'améliorer les performances de l'aide apportée aux bénéficiaires puisqu'elle conditionne les coûts des opérations, le temps de livraison et, en fin de compte, le niveau de service [Balcik, Beamon, Krejci, Muramatsu, and Ramirez, 2010]. C'est certainement la raison pour laquelle, l'IP met l'accent sur l'interconnexion des acteurs. Dans cette perspective, une proposition consiste à faciliter la communication et les échanges par l'utilisation de contrats et de protocoles standardisés [Ballot and Montreuil, 2014]. Parler le même langage et utiliser les mêmes règles de travail devraient faciliter les partenariats et les rendre plus durables. Ce concept basé sur la facilitation de la connexion et le développement de la confiance paraît essentiel [Pettit and Beresford, 2009]. L'utilisation de normes communes s'applique également à la gestion du flux physique. L'utilisation d'emballages et d'équipements de manutention normalisés faciliterait le transfert des marchandises, ce qui permettrait un réacheminement plus agile en cas de perturbation et, au final, accélérerait les livraisons [Ado, Ben Othmane, Matei, and Montreuil, 2014]. Aujourd'hui, le fonctionnement est tel que des boîtes en carton ou en plastique de différentes tailles sont utilisées pour emballer les produits de secours. Ceux-ci sont rassemblés sur des palettes et, si nécessaire, dans des conteneurs de taille standard. De tels systèmes génèrent des taux de remplissage non optimaux et des déchets. Les pi-conteneurs, au contraire, peuvent facilement s'insérer dans les différents moyens de transport et s'emboîter les uns dans les autres (voir figure 2.9). Ils sont également conçus pour être réutilisables et disposent de capteurs le suivi de la marchandise.

Cas d'étude illustratif

Pour évaluer grossièrement le potentiel des CAAHs, nous avons développé une étude de cas basique et fictive inspirée des pratiques de la Croix Rouge Indonésienne (CRI) relevé lors d'une visite des locaux en 2019 afin de pour mettre en évidence les potentiels bénéfiques de l'IP pour le secteur humanitaire. Une zone du monde divisée en sous-éléments et sur laquelle une population a été répartie a été formalisée. Suivant les habitudes de positionnement des entrepôts des organisations humanitaires, les bâtiments ont été positionnés sur ce territoire fictif (voir figure 2.10). Chaque organisation dispose de certains produits stockés dans les entrepôts dont elle dispose parmi les 5 produits possibles pour le cas (voir tableau 2.5).

La stratégie de positionnement des entrepôts et l'utilisation de moyens de transport et de stockage privés ont ainsi pu être challengées au travers de ce cas d'étude. Le positionnement des entrepôts pour chaque OH au plus près des zones de forte densité génère de la disparité avec des zones moins accessibles que d'autres et donc des délais de livraison plus longs avec un niveau de couverture en moins d'une journée à 61% du territoire (voir figure 2.11). Ce qui va, en plus, à l'encontre du souci d'équité souhaité par les OHs dans la distribution des ressources aux victimes. En partageant les entrepôts et en les répartissant différemment sur le territoire, selon la philosophie de l'IP, il est possible de passer de 88% de couverture pour l'ensemble des produits avec 61 bâtiments à un niveau de 96% en couverture avec 23% de bâtiments en moins (voir figure 2.12). La stratégie d'avoir des transports privés pour l'acheminement des produits au lieu de catastrophe nécessite un nombre important de ressources, pas toujours remplies de manière optimale et générant une grande quantité de CO2.

L'approche de mutualisation des transports en partageant les véhicules empruntant le même chemin, comme suggéré par l'IP, montrent une réduction des coûts de transport d'en moyenne 42% pour les OHs, sur la base des itinéraires empruntés et partagés. De plus, l'amélioration de la coordination permet d'optimiser les livraisons avec moins de camions, moins de kilomètres parcourus et moins d'émissions de gaz à effet de serre. (voir figure 2.13).

Évidemment, ces premiers résultats doivent être nuancés, car le champ d'application est limité à l'aval de la CAH et s'appuie sur un cas fictif avec un nombre limité de produits. Cependant, ils alimentent nos réflexions et renforcent le besoin d'une expérience plus étendue et surtout quantitative. C'est pourquoi une deuxième expérience, utilisant une étude de cas plus détaillée et plus réaliste, pour mieux quantifier les intérêts de l'IP est développée au chapitre 3 et testée au chapitre 4.

Chapitre 3 – DÉVELOPPER une expérience pour simuler une Chaîne d’Approvisionnement Humanitaire Hyperconnectée

Ce chapitre marque la seconde étape en direction d’une CAHH ayant pour but d’améliorer l’organisation du secours pour les victimes des catastrophes. Il jalonne une démarche souhaitant non pas seulement imaginer le futur des CAHs mais tester par l’expérience les concepts et mécanismes intrinsèques d’une CAHH imaginés dans le chapitre 2 afin d’en assurer l’intérêt et la pertinence. La question de recherche au coeur de ce chapitre discute donc de la manière d’évaluer l’application des concepts inspirés de l’IP au niveau de leviers clés ayant un impact sur les performances des CAHs. En effet, au vu de la relative nouveauté du concept de l’IP et du peu de recherche à ce jour menée considérant une CAHH, la question d’une expérience est à ce jour novatrice. Il est donc à noter que tout doit être planifié et construit en amont de l’exécution d’une telle expérience. C’est pourquoi ce chapitre se concentre à la préparation et la conceptualisation d’une expérience spécifique et adaptée à notre projet. Le chapitre suivant qui sera l’application de celui-ci s’attachera à développer un cas d’étude avec des données d’entrée, exécuter l’expérience de bout en bout sur la base d’un plan factoriel d’expérience et réaliser les analyses qui permettront de tirer des conclusions quant aux apports de l’IP.

Dans cette intention, plusieurs sujets ont retenu notre attention et nécessité une investigation préalable avant de se lancer sur le design de l’expérience. Il a donc fallu se familiariser avec les concepts de simulation & modélisation puisque jugés comme des méthodes nécessaire afin construire notre expérience. Également l’étude du concept d’Ingénierie des Systèmes (IS) s’est avérée pertinente dès que lors que l’on souhaite développer un système complexe (tels que les CAHs) tout en assurant sa fiabilité de bout en bout.

Revue de la littérature pour encadrer la construction d’une expérience spécifique

Une simulation est définie comme « *l’imitation du fonctionnement d’un processus ou d’un système du monde réel sur temps* » [Banks, 1998]. Il permet l’étude d’un système complexe et de son comportement dans le temps. Des changements d’ordre informationnels, organisationnels ou environnementaux peuvent être appliqués au niveau du système et les effets engendrés au niveau du comportement peuvent alors être observés et mesurés. Différents tests et situations expérimentales devraient laisser entrevoir des pistes d’amélioration du système. C’est une méthode de recherche populaire pour résoudre diverses problématiques et tester des hypothèses [Banks, 1998]. L’avantage de la simulation est d’être exécutable et de pouvoir observer le système évoluer dans le temps au travers d’états s’enchaînant. Ceci en recréant une copie (i.e un modèle) du système à étudier afin de pouvoir réaliser des tests en s’affranchissant de certaines contraintes techniques et coûts, d’éviter d’éventuels dommages ainsi que de mobiliser le système pour mener les tests. Toutefois, cette méthode présentent les inconvénients de demander à disposer des compétences solides et variées à la fois pour la conception d’un modèle, la programmation d’une simulation représentant un système complexe ainsi que l’analyse des résultats issus et de s’assurer

de la fiabilité des conclusions à tirer. Pour garantir le bon déroulement de ces étapes, des méthodologies ont été mise au point parmi lesquelles, celles de Law [2014], Banks [1998], Sargent [2010].

En parallèle des étapes décrites par ces auteurs, et afin d'assurer la crédibilité et la fiabilité de l'expérience et du développement de la simulation, des étapes intermédiaires de vérification et/ou de validations sont régulièrement réalisées. L'enchaînement des étapes diffère légèrement d'une méthodologie à l'autre, mais toutes contiennent des boucles de retour, car la construction d'une simulation n'est pas linéaire et nécessite des réajustements d'étapes amont tout au long de son développement.

Pour aider dans la phase de construction du modèle conceptuel, nous nous sommes appuyés sur l'approche IS plutôt utilisée en ingénierie bien que de plus en plus adoptée dès lors que l'on a affaire à des systèmes complexes. Cette approche est définie comme : « *l'ensemble des activités assurant la capacité d'un système à accomplir ce pour quoi il a été conçu, dans l'environnement opérationnel dans lequel il est censé évoluer. Ainsi on s'assure que le système a été correctement construit.* » et comme « *l'ensemble des activités comparant le comportement du système ou de ses sous-systèmes aux attentes, à l'architecture et autres caractéristiques imaginées* » [ISO et al., 2015], ces activités de validation et de vérification interviennent régulièrement tout au long de son cycle de vie afin de garantir la conformité du système à sa finalité.

Définition d'une expérience spécifique visant à tester des approches inspirées de l'IP dans un contexte humanitaire

Lors d'un projet de construction de maison, on ne commence généralement pas tout de suite à monter les murs. Préalablement, du temps doit être consacré à la définition des exigences et des spécifications du projet pour faciliter la mise en œuvre et limiter les déconvenues. Cette phase peut aboutir avec des schémas de représentation et des plans d'action montrant différents niveaux de détails.

Dans cette idée, nous avons conçu une expérience basée sur la simulation pour quantifier l'impact de l'intégration d'approches inspirées de l'IP au niveau des CAHs. Elle se décompose en deux éléments requis pour mener à bien l'expérience envisagée (comme les ingrédients d'une recette) (voir Figure 3.3) :

Un cadre fonctionnel Il s'agit d'une méthodologie, contenant une série d'actions à réaliser, encadrant la construction de l'expérience et de la simulation tout en garantissant leur cohérence avec l'objectif défini précédemment.

Un cadre technologique Il s'agit d'un outil, à l'image d'un prototype de simulation, définissant l'architecture et les fonctionnalités dont la simulation doit disposer pour exécuter l'expérience imaginée.

Chacun de ces éléments sera détaillé plus amplement dans les sections suivantes. Ils constituent à eux deux, une des contributions de cette thèse de par l'originalité d'une telle expérience à orientation quantitative dans un domaine sous-étudié jusqu'à présent. Elle se destine à réaliser les tests d'une refonte des CAHs basée sur l'approche IP dans un contexte humanitaire et générer des mesures afin d'en évaluer les effets sur la performance.

Description du cadre fonctionnel

Dans la conception expérimentale, le cadre fonctionnel doit être vu comme un séquençement des tâches à effectuer pour préparer l'expérience et construire le cadre technologique. Cette dernière doit être considérée comme un support à l'expérience à partir de laquelle nous pourrions pour exécuter l'expérience et générer des résultats.

Le cadre fonctionnel suivant (voir Figure 3.4) assure le bon développement et la crédibilité de l'expérience. Dans cette perspective, il s'inspire largement et est adapté des méthodologies de modélisation et de simulation développées par [Law, 2014, Banks, 1998, Chung, 2004] découverts lors de la revue de la littérature. Il consiste de huit étapes détaillées comme suit :

1) Problème de recherche et conception de la solution La première étape vise à définir le problème de recherche à adresser et à planifier l'étude à mener. Concrètement, il s'agit tout d'abord de réaliser une étude afin d'acquérir une bonne compréhension du problème dans le domaine de recherche considéré. Vient ensuite l'énoncé du problème de recherche, qui consiste à formuler le problème à adresser et les objectifs associés [Law, 2014]. La dernière activité consiste à planifier le projet sous forme de tâches et à les organiser dans le temps accordé.

2) Collecter des données et définir le modèle conceptuel La deuxième étape vise à définir le système et décrire le modèle. Concrètement, il s'agit de l'activité de traduction du système réel en un modèle théorique dit conceptuel [Banks, 1998]. Cette phase requiert d'indiquer le périmètre et point de vue du système à modéliser, identifier les principaux composants du modèle et définir les données d'entrée à collecter et les données de sortie à générer [Chung, 2004].

3) Construire un programme informatique et vérifier Cette étape représente l'activité de transformer le modèle conceptuel dans une forme lisible par l'ordinateur [Banks, 1998]. Avant de commencer à coder, un choix concernant le langage et le logiciel à utiliser doit être fait. Lors du codage, des procédures de vérification sous forme de tests doivent être régulièrement organisées tout au long du processus pour s'assurer que le modèle est construit et fonctionne correctement [Chung, 2004].

4) Réaliser des essais pilotes, observer les résultats et valider Cette étape consiste à effectuer l'expérience avec des essais pilotes pour certifier le bon déroulement de l'expérience et la fiabilité des résultats observés [Law, 2014]. Dans cette perspective, du temps doit être consacré à l'étalonnage du système en cours de développement, sur la base d'un système de référence [Chung, 2004]. Lors du codage, les procédures de vérification doivent apparaître tout au long du processus pour s'assurer que le modèle est construit correctement et fonctionne correctement [Chung, 2004].

5) Générer le protocole d'expérimentation Après la mise en place et validation de du bon fonctionnement du programme, il s'agit alors de déterminer les variantes de systèmes à étudier et tester. Tout changement, au niveau des conditions initiales ou des facteurs (c'est-à-dire variables affectant le comportement du système), devient un scénario. En fonction de(s) objectif(s) et de l'expérience, le testeur peut vouloir étudier différentes approches à travers un ensemble de scénarios à exécuter en utilisant la simulation [Chung, 2004].

6) Effectuer des cycles de simulation et vérifier Au cours de cette phase, le programmeur de la simulation lance un plan factoriel d'expérience, défini à l'étape précédente, qui consiste à exécuter un ensemble de scénarios pour générer des données

de performance en vue d'être analysé à l'étape suivante. Par ailleurs, il s'assure que l'enchaînement des scénarios se déroule sans erreur et que la collecte des données issues des indicateurs de performance se fait correctement [Law, 2014].

7) Analyser les données de sortie et valider Une fois les scénarios exécutés et les résultats collectés, ces derniers doivent être analysés. Tout d'abord, le modèle de simulation est validé en analysant la confiance intervalle des données générées et si nécessaire, des ajustements au niveau de la simulation peuvent avoir lieu [Banks, 1998]. Après avoir vérifié la pertinence de l'expérience, la deuxième étape consiste à appliquer des méthodes statistiques descriptives et/ou inférentielles pour tirer des conclusions et faire des recommandations.

8) Documenter et présenter les résultats Enfin, pour rendre hommage aux efforts fournis et augmenter la visibilité de l'étude en vue par les chercheurs et praticiens, les résultats doivent être partagés. Pour ce faire, divers supports sont possibles, en passant par des rapports écrits jusqu'aux supports de présentation ou média. De plus, documenter l'expérimentation renforce la fiabilité des travaux réalisés et permet sa réutilisabilité [Chung, 2004].

Cette méthodologie n'est pas nécessairement un processus séquentiel et peut nécessiter de revenir sur certaines étapes au fur et à mesure que de nouveaux éléments du cadre technologique sont ajoutés et que la vision du projet s'affine.

Description du cadre technologique

La conception d'une expérience visant à étudier le comportement d'un système demande une bonne compréhension du fonctionnement de celui-ci. Pour cela, les principaux composants du système doivent être identifiés et sélectionnés parmi ceux influençant le plus le comportement à étudier. Dans notre cas, la revue de la littérature menée dans le chapitre 2 a mis en évidence que la performance des CAHs est étroitement liée à la gestion de la structure du réseau, des processus opérationnels et des composants de management. Chacune de ces catégories concentre un nombre de variables d'influence telles que la stratégie de réapprovisionnement ou le degré de partage de l'information identifiée et récapitulée dans le tableau 2.2. Ces variables intrinsèques sont appelées *facteurs endogènes* et conditionnent n'importe quelle CA. Cependant, leurs règles de fonctionnement ou procédures associées varient d'une CA à une autre d'où les disparités entre elles.

Maintenant quand une étude s'intéresse aux relations de cause à effet, il convient de ne pas omettre les *facteurs exogènes*. Ces derniers font partie de l'environnement du système et peuvent avoir une influence à la fois sur les facteurs endogènes comme les *facteurs dépendants* qui eux, sont les variables de sortie du système (voir figure 3.2). Dans une expérience de chimie, par exemple, la température de la pièce peut avoir une influence sur les résultats, même si elle ne fait pas partie des variables que la recherche entend évaluer. Dans le contexte humanitaire, il est reconnu que le contexte opérationnel ou la nature de l'urgence peuvent avoir une influence sur la performance de l'opération [Beamon and Balcik, 2008, Kovacs and Spens, 2009, Ramalingam, Mitchell, Borton, and Smart, 2009a].

À partir de ces éléments, l'architecture de la simulation est composée de trois systèmes clés : le *système de scénarios*, concentrant les variables indépendantes et confondantes, le système à l'étude (selon le paramétrage, il peut représenter la chaîne de test ou la chaîne de référence) appelée "*écosystème humanitaire numérique*" (EHN), et le *le système de performance*, avec des indicateurs tels que les variables

dépendantes. système, avec des indicateurs tels que les variables dépendantes à surveiller (voir figure 3.5).

Une telle expérience offre la possibilité d'étudier les relations de cause à effet des principales caractéristiques d'une CAH, et éventuellement de facteurs externes, sur les résultats de performance. Elle a été délibérément développée pour être aussi générique que possible et permet des explorations supplémentaires autres que l'objectif de recherche poursuivi ici.

Le système de performance est l'équivalent d'un tableau de bord ou d'une tour de contrôle qui regroupe l'ensemble des indicateurs de performance à suivre. Il est essentiel pour évaluer des apports de l'IP et tirer des conclusions. Dès lors, la question se pose de quels sont les indicateurs à suivre. Selon la définition de [Ramalingam, Mitchell, Borton, and Smart \[2009b\]](#), la performance dans un cadre humanitaire humanitaire, est associé au fait de sauver des vies, d'atténuer la souffrance et de préserver la dignité humaine, sans distinction. Cet objectif s'applique à toutes les OHs, quelle que soit la phase de gestion de la catastrophe. Il est également souligné que l'aide doit être efficace et bien gérée dans son utilisation des ressources. Des exemples d'indicateurs de performance suivis sont le taux de couverture des besoins [[Laguna-Salvadó, Luras, Okongwu, and Comes, 2019](#)], le délai de livraison [[Davidson, 2006](#)], le coût des opérations ou encore l'empreinte carbone [[Laguna-Salvadó, Luras, Okongwu, and Comes, 2019](#)] pour des considérations plus environnementales que l'efficacité, l'efficacité ou l'agilité [[Tomasini and Wassenhove, 2009](#)].

Le système de scénario est l'homologue d'une table de mixage et permet de régler et d'ajuster des variables clés d'un système manipulé. Ici, le scénario configure l'écosystème humanitaire numérique (c'est-à-dire le système manipulé) avec des variables à deux niveaux possibles (c'est-à-dire des valeurs) pour l'expérience. Le premier domaine de configuration s'oriente sur la définition du contexte de l'aide humanitaire et les variables exogènes associées. À ce stage, on définit le territoire et sa géographie (une région, un pays, etc.) et la répartition de la population, ainsi que la période considérée (semaine, mois, année). Ces indications sont utilisées pour initialiser l'environnement virtuel de l'EHN. Le second domaine de paramétrage se situe au niveau du système lui-même concernant : 1) un certain nombre d'hypothèses fixes (par exemple la vitesse des camions) qui ne varieront pas d'une d'une expérience à l'autre et 2) la valeur des variables endogènes à tester. Par exemple, on peut essayer d'observer la différence entre un transport conventionnel par rapport un transport mutualisé. Cela nécessitera dans les deux cas de considérer le même environnement et les mêmes hypothèses, mais de choisir une seule option de variable (par exemple, "transport mutualisé"), puis d'exécuter la simulation, récupérer les résultats pour recommencer, dans le même contexte, mais sélectionner l'autre option (par exemple, "transport conventionnel") afin de récupérer les données associées pour effectuer la comparaison.

L'écosystème humanitaire numérique, à l'image d'une boîte de Petri pour l'observation de micro-organismes, est un ensemble recréé d'acteurs humanitaires organisés en CA, évoluant et interagissant avec leur environnement, et cela en utilisant une technologie de simulation. L'expérience imaginée consiste à recréer une CAH et son comportement en réaction à une urgence humanitaire. Il est attendu que ce comportement varie suivant les pratiques opérationnelles intrinsèquement utilisées. L'objectif est donc, d'évaluer l'influence de ces dernières, en comparant les résultats de performance qui résulteront des choix de pratiques face à l'urgence à gérer. Dans

ce cadre le groupe de contrôle, celui qui servira de référence pour les comparaisons, sera un modèle représentatif des pratiques actuelles par les humanitaires. Dans cette perspective, un modèle de CAH suffisamment représentatif, générique et configurable pour faire varier les pratiques opérationnelles employées était requis. La revue de la littérature ne nous a pas permis d'identifier un tel modèle parmi ceux existants. Par ailleurs, il fallait que l'environnement opérationnel qui joue un rôle dans la gestion de la catastrophe soit pris en compte. Nous avons alors fait le choix de concevoir un modèle adapté à l'expérience envisagée. Partant de là, et dans un souci de créer un modèle représentatif et fiable pour nos expérimentations, nous nous sommes appuyés sur l'approche d'Ingénierie des Systèmes (IS). Cette méthode de plus en plus appréciée des chercheurs est adaptée lorsqu'il s'agit de modéliser un système complexe de manière efficace et fiable. Elle est découpée en plusieurs phases logiquement enchaînées et comportant des étapes de validation et de vérification. Ces dernières ne sont pas à négliger, et garantissent la fiabilité et la crédibilité de la représentation ce qui est un enjeu important dans tout processus de modélisation [Montreuil, Cloutier, Labarthe, and Loubier, 2015].

Nous avons donc développé une méthodologie basée sur celle définie par le *Systems Engineering Body of Knowledge (SEBoK)* (voir figure 3.6). Cette méthodologie, sous forme de processus, intègre une des caractéristiques phares de l'IS qui consiste à effectuer des actions de vérification et de validation à chaque étape. Ces dernières sont au nombre de trois et visent à décrire, d'où leur dénomination : *la mission du système*, *l'architecture du système* et *la conception du système*. La première étape du processus consiste à définir le problème abordé par le système et son contexte. Concrètement, il s'agit d'aboutir à la description et à la validation du ou des besoins. La seconde étape, l'architecture du système, dresse un portrait et valide (i) l'objectif du système et son contexte, (ii) l'architecture logique (c'est-à-dire son scénario de comportement) et (iii) l'architecture physique où les composants du système sont décrits. La dernière étape, la conception du système, permet d'identifier les informations et les données nécessaires à la mise en œuvre, de manière concrète, des composants du système.

Une fois définie, la méthodologie a été appliquée pour réaliser le modèle du système considéré (ici, la CAH) en vue de l'expérience à réaliser. Pour rappel, l'expérience vise à évaluer de manière quantitative les apports de l'IP sur la performance des CAHs (plus de détails et de justification sont donnés dans le chapitre 1). L'étape suivante nous a permis de reprendre les fondamentaux et éléments gravitant autour d'une CAH en réponse à une catastrophe. Nous avons alors identifié quatre éléments (appelés 'systèmes') à un tel contexte (voir 3.7) : le *système de réponse humanitaire*, qui est le système d'intérêt, le *système de demande* en proximité qui active le système de réponse humanitaire. Ensuite, ont été identifiés le *système de catastrophe* et le *système de territoire*, faisant tout deux partie de l'environnement du système d'intérêt et importants à considérer, car influençant les deux premiers. En quelques mots pour décrire les systèmes identifiés : Le système de territoire représente un territoire susceptible d'être touché par une catastrophe. Cela peut être un pays ou une région découpé en sous-zones dans lesquelles sont distribuées des populations. On y trouve également des infrastructures comme des bâtiments publics ou des maisons et des réseaux de transport pouvant être impactés. La topographie du terrain est également considérée, car pouvant complexifier la distribution des produits surtout sur les régions montagneuses ou limitées en termes d'accessibilité. Le système de catastrophes permet de représenter des événements de diverse nature pouvant frapper

le territoire considéré de manière localisée ou étendu, faire des dégâts humains comme matériels sur un certain horizon de temps. Le système de demande active le système de réponse humanitaire. En effet, une fois l'évaluation des dégâts évaluée et le besoin calculé et connu des logisticiens, la CAH peut s'organiser pour fournir les produits attendus. Le système de réponse humanitaire représente la mise en place d'une CAH après la survenue de la catastrophe. Les éléments clés associés sont les différents acteurs, les moyens de transport (camions, bateaux...) et les entrepôts de stockage. Les interactions et échanges entre ces éléments sont sous forme de flux physiques, d'informations ou financiers et sont régis par des décisions et règles opérationnelles nommées pratiques opérationnelles en amont. Ces différents systèmes sont étroitement liés et interagissent continuellement d'où une représentation de l'architecture physique sous forme de couches (voir figure 3.9).

En prenant un peu de recul, nous réalisons que le modèle établi, sous forme de systèmes et tenant compte de l'environnement, est d'un nouveau genre pour le panel de modèles existants sur les chaînes d'approvisionnement humanitaires. C'est là le coeur de notre contribution dans ce chapitre. En effet, il adopte une perspective holistique et est organisé en couches spécialement conçues pour l'expérience. Cependant, la généricité des composants pris en compte rend, en fin de compte, ce cadre technologique et le modèle de CAH établie suffisamment générique pour être utilisée ou adaptée à un autre contexte expérimental. Il est maintenant temps de donner corps à ces architectures et d'appliquer concrètement les contributions conceptuelles et méthodologiques proposées jusqu'à présent en menant l'expérience de bout en bout sur la base d'un cas d'étude terrain (voir le prochain chapitre 4).

Chapitre 4 – TESTER le paradigme de Chaîne d’Approvisionnement Humanitaire Hyperconnectée (CAHH) en situation

Avant d’entreprendre des changements et s’éviter des coûts et efforts inutiles si cela s’avérait être une mauvaise idée, de plus en plus d’entreprises font des essais en environnements simulés pour tester la solution considérée. L’avantage de la simulation est de pouvoir reproduire un système et le placer dans un environnement simulé semblable à celui dans lequel il évoluera dans la réalité. Cela permet d’y observer son comportement et de tirer les conclusions adéquates pour la suite du projet. C’est dans cette idée que nous avons envisagé d’utiliser la simulation pour tester le paradigme de CAHH envisagé en situation. Pour réaliser une telle expérience, nous nous sommes appuyés sur les contributions des chapitres précédents et sur un cas d’étude terrain développé à cette intention.

Conception et préparation de l’expérience à réaliser

Cette section rassemble les cinq premières étapes du cadre fonctionnel décrit au chapitre 3, qui décrivent et préparent l’expérience, avant les phases de résultats et d’analyse.

L’étape n°1 du cadre fonctionnel s’attache à décrire le problème de recherche adressé, l’objectif fixé, le périmètre de l’étude et la méthode utilisée. Pour rappel, l’hypothèse étudiée est la suivante : une réorganisation des CAHs vers une version hyperconnectée (c’est-à-dire incluant des pratiques inspirées de l’IP) aura un impact positif sur la performance des OHs dans l’assistance aux personnes affectées. Pour confronter cette hypothèse, une comparaison des résultats de performance sera effectuée entre un scénario de référence, représentant les pratiques actuelles, avec des scénarios alternatifs hyperconnectés. Puisque les CAHs représentent des systèmes complexes, la simulation est l’approche expérimentale adaptée et donc considérée. En recréant un environnement susceptible de subir des catastrophes et en définissant les pratiques des CAHs à tester, une évaluation et comparaison des scénarios sera possible par le biais des valeurs des indicateurs de performance suivis. Dans notre situation, l’Indonésie, l’un des pays les plus exposés aux catastrophes naturelles, et la Croix-Rouge indonésienne, le principal acteur humanitaire dans ce pays, serviront de source d’inspiration pour la construction du modèle de CAH. Enfin, comme l’idée d’associer l’IP aux CAH est assez peu explorée à ce jour et que le champ d’action humanitaire est vaste, nous limiterons le périmètre de l’étude à l’amélioration des performances des CAHs dans le contexte de la livraison de produits de première nécessité aux victimes de catastrophes naturelles. Les raisons de ce choix résident dans la croissance attendue du nombre de catastrophes naturelles dans les prochaines années et par le fait que la distribution de ces articles est reconnue comme activité cruciale dans la gestion des catastrophes [Shao, Liang, Wang, Wang, and Liang, 2020].

L’étape n°2 s’attache à collecter des informations et des données afin de (étape 3) construire le cas d’étude et le modèle associé. Un partenariat avec la Croix Rouge Indonésienne (CRI) nous a permis d’effectuer une visite d’une dizaine de jours durant l’été 2019 afin de rencontrer les acteurs et nous imprégner de leur environnement de travail. L’Indonésie est un des pays les plus touchés par les catastrophes naturelles (presque une par jour), possède une des plus importantes populations du monde et se compose d’îles. L’étude du pays et de ses caractéristiques ainsi que des statistiques sur les catastrophes ayant frappé le territoire par le passé ont permis de développer les

systèmes de territoire 4.2 et de catastrophes 4.3 de la simulation. Ensuite, l'étude du fonctionnement logistique de la CRI, via des interviews, nous a permis de développer le système de demande et de réponse humanitaire (figures 4.5 et 4.4).

L'étape n°4 vient s'assurer que la simulation recréant le scénario de référence fonctionne en réaction à un tremblement de terre, et ce, au travers d'étapes de vérification et de débogages. Ensuite, ce fonctionnement a été passé en revue avec des acteurs humanitaires afin de valider le modèle, son fonctionnement et les ordres de grandeur obtenus.

L'étape n°5 quant à elle, vient définir les scénarios alternatifs à tester en comparaison du scénario de référence. Dans un souci d'accessibilités et de faisabilité, nous avons défini un plan factoriel à 4 facteurs comportant chacun 2 niveaux soit 16 scénarios possibles. Le 1er facteur, *approvisionnement*, permet d'évaluer la différence entre une logique de réseau *hiérarchique* (où les entrepôts doivent suivre une hiérarchie imposée pour passer commande) et un réseau *matriciel* (où il est possible de passer commande à n'importe quel entrepôt du réseau). Le 2nd facteur, *transport*, permet de tester la différence entre des livraisons *privées* (d'un entrepôt à un autre) et des livraisons *mutualisées* (où un regroupement est effectué). Le 3ème facteur, *délai de réapprovisionnement* - sous entendu du réseau local indonésien par le réseau international, permet d'observer la différence entre un délai *court* (défini à 3 jours et envisageable d'un contexte d'IP) et un *délai long* (défini à 15 jours comme c'est le cas aujourd'hui en Indonésie). Le dernier facteur, *pénurie* de stocks et donc décision à effectuer si la demande est supérieure aux stocks disponibles comme c'est régulièrement le cas, permet d'étudier une approche *FIFO* (premier arrivé, premier servi) et une approche *équitable* (souvent difficile à mettre en oeuvre par les humanitaires, mais pourtant recherchée). La combinatoire entre l'approvisionnement hiérarchique et transport mutualisé n'étant pas possible dans ce contexte, le nombre de scénarios possibles est donc réduit à 12 (voir arbre des scénarios 4.7 et le système de codification 4.3).

Exécution de l'expérience, résultats et analyse

Une centaine de répliques pour chacun des 12 scénarios a été effectuée. Les valeurs des indicateurs associés (le délai de livraison pour couvrir la demande, le coût de transport, le niveau de service à 15 jours et la quantité de CO2 émise) ont été rassemblées dans un fichier Excel pour la partie analyse.

La phase d'analyse s'est basée sur des analyses descriptives et multivariées à l'aide d'outils visuels tels qu'un diagramme de série temporel, des diagrammes en boîtes et des diagrammes de dispersion. Les deux objectifs principaux fixés pour cette phase étaient 1) d'évaluer l'effet des pratiques (c.-à-d. facteurs et niveaux) sur les indicateurs clés de performance considérés et 2) comparer les scénarios pour identifier les plus performants d'un point de vue humanitaire.

Au sujet de l'impact des facteurs, par analyse des distributions des scénarios, les principales conclusions sont les suivantes ; le délai de réapprovisionnement du réseau local par le réseau international a un impact significatif sur le délai de livraison de la demande et donc le niveau de service. En effet, lorsque le réseau local est en sous-capacité, la mobilisation rapide des articles de secours provenant de sources externes est clé pour l'efficacité de l'aide. En outre, l'étude montre que la connexion globale entre les acteurs et la visibilité accrue concernant les ressources disponibles, par le biais d'une approche d'approvisionnement multiple ('matriciel'), minimise les

coûts de transport. En effet, le fait de s'approvisionner autant que possible en local limite la distance à parcourir, et les connexions directes limitent les pertes de temps dues à la transmission d'informations au sein de structures hiérarchiques. En ce qui concerne la consolidation du transport, les avantages sont intéressants du point de vue des coûts de transport et du niveau de service. De plus, cette approche présente également des résultats corrects concernant le délai de traitement de la demande, s'il est utilisé dans une situation où un flux important doit être géré. Enfin, le fait que l'utilisation de l'approche FIFO n'autorise pas les livraisons partielles a résulté à des quantités livrées moins importantes que ceux utilisant l'équité. Cependant, cela limite la variation des coûts de transport, qui est explosive lorsque l'équité est appliquée dans un contexte hiérarchique sans consolidation. En effet, ce dernier scénario s'est avéré très sensible et est fortement corrélé à la valeur de la demande initiale. De plus, cette pratique n'a pas eu un grand impact lorsque les stocks ont pu être mobilisés rapidement, mais avait un effet évident sur les coûts de transport. Quant à l'inventaire initial, la variabilité étant limitée, elle n'a que peu d'effet sur les indicateurs de performance.

En ce qui concerne le deuxième objectif d'analyse lié à la comparaison des scénarios, ce qui ressort principalement, c'est le fait que globalement le niveau de performance le plus bas est réalisé par le scénario de référence (0,0,0,0), avec un niveau du service (médiane : 5%) et un délai de couverture de la demande (médiane : 22 jours), par rapport aux autres scénarios (voir figure 4.8). Cela montre que même un petit changement orienté vers une approche hyperconnectée peut conduire à un certain degré d'amélioration et par conséquent, de nombreuses opportunités sont donc possibles. Ensuite, un regroupement des scénarios similaires via un *clustering K-mean* (voir figure 4.13a) nous a permis de former quatre groupes. Parmi eux, un groupe attire notre attention avec des aptitudes intéressantes d'un point de vue humanitaire. En effet, ce groupe est caractérisé par des coûts de transport plutôt faibles/moyens avec un niveau de service élevé à 15 jours et un court délai pour répondre à la demande (voir le tableau 4.4). Tous ces scénarios utilisent au moins l'approvisionnement diversifié avec un délai de réapprovisionnement court. Parmi les scénarios de ce groupe, les plus performants en termes de niveau de service et de délais sont les scénarios (1,0,1,1) et (1,0,1,0) (voir le tableau 4.5). Ceux-ci fonctionnent selon un système de livraisons privées qui semblent légèrement plus rentables si on les compare à des scénarios similaires utilisant l'approche de mutualisation du transport. Cependant, avec le système d'équité qui gère plus de petits flux que l'approche FIFO, l'approche de mutualisation est plus intéressante, comme c'est le cas également au regard du taux remplissage des camions.

Conclusion

Le chapitre 1 s'attache à explorer le monde humanitaire et les principaux challenges rencontrés. Cette étude a permis de montrer les difficultés courantes et à venir démontrant d'un système de fonctionnement à bout de souffle. L'approche IP considérée pourrait aider à inverser la tendance et permettre la pérennité à plus long terme des OHs. Cependant, cette approche originale demande à repenser et revoir les fondements de tout un écosystème et pratiques ancrées. Peu étudié et associé au contexte humanitaire, le travail de recherche ici mené cherche à pallier à ce manque et offre une première brique d'étude de ce que pourraient offrir les CAHs dans une version hyperconnectée. Dans cette perspective, le chapitre 2 s'est donc concentré à décrire les caractéristiques et potentiels apports, de manière conceptuelle, de la vision que nous avons des CAHs. Cependant pour soutenir l'objectif précédemment énoncé, cette description qualitative n'est pas suffisante pour enclencher un changement aussi important dans la réalité. Il est nécessaire de convaincre les praticiens et pour cela, nous avons souhaité évaluer quantitativement, au travers d'une expérience, l'influence de pratiques hyperconnectées sur la performance des CAHs et confronter nos pressentiments. C'est pourquoi le chapitre 3 est dédié à la structuration d'une expérience et d'un modèle de représentation des CAHs adapté et réaliste. Le chapitre 4 exécute les étapes définies dans le chapitre précédent et s'attache au développement d'une simulation à partir d'un cas d'étude terrain construit en collaboration avec des personnes ayant une forte expérience dans l'humanitaire. L'expérience a consisté à comparer différents scénarios incluant différents degrés d'hyperconnectivité en comparaison à un cas référence représentatif des pratiques actuelles. Ainsi chaque configuration de CAH (suivant les pratiques à tester) a pu être simulée et leur performance enregistrée au travers d'indicateurs de performance. L'analyse des résultats a permis de montrer que même un petit changement des pratiques vers un système plus hyperconnecté permet de gagner en efficacité et efficience. L'axe d'amélioration le plus important à considérer se situe au niveau des stratégies d'approvisionnement et joue significativement sur les résultats de performance. Une meilleure connexion des acteurs ainsi qu'une meilleure visibilité sur les ressources et moyens disponibles à différentes échelles permettent de réduire les délais et les coûts associés. Cette expérience est la première à fournir des éléments factuels en faveur de l'intégration de pratiques issues de l'IP.

Ceci dit, il est évident que la simulation compte plusieurs axes d'amélioration. Il serait pertinent, de considérer d'autres contextes opérationnels (territoires et types de catastrophes) ainsi que d'autres types de pratiques et de CAHs pour aborder de la robustesse aux conclusions tirées. Nous sommes conscients que cette étude très exploratoire ouvre le champ à une multitude de pistes de recherches possibles avec des affinages quant aux pratiques et aux fonctionnements opérationnels d'un tel paradigme par exemple. En effet, les caractéristiques décrites au chapitre 2 peuvent encore être affinées ou complétées, notamment sur la partie management où notre attention était moins concentrée. Maintenant, l'expérience décrite au chapitre 3 et le modèle de CAH sont suffisamment génériques pour faciliter le développement d'autres expériences pour venir compléter la thématique de recherche. D'ailleurs, c'est ce à quoi nous souhaitons assister, si l'on souhaite voir l'IP se développer dans le secteur humanitaire comme c'est le cas dans le secteur commercial.

VERS UNE CHAÎNE LOGISTIQUE HUMANITAIRE HYPERCONNECTÉE

Après plusieurs catastrophes majeures, le niveau de qualité de l'aide apportée aux populations impactées a attiré l'attention et généré des critiques. L'enjeu est de taille puisque des vies humaines sont en jeu et dépendent de la capacité des Organisations Humanitaires (OH)s à mobiliser des ressources. Plus particulièrement, en ce qui concerne la logistique des articles de première nécessité à acheminer. Cependant le fonctionnement associé a été jugé inefficace et non durable remettant en question la manière dont les chaînes d'approvisionnement humanitaires sont aujourd'hui gérées.

Partant de ce constat, et alors qu'une branche active de la recherche s'évertue à réaliser des améliorations localisées, nous en prenons le contre-pied et explorons une refonte plus holistique et profonde. Par conséquent, l'ambition de ce travail de recherche est de redéfinir les fondements du système humanitaire en imaginant une nouvelle version des chaînes d'approvisionnement humanitaires.

Dans cette perspective, nous nous sommes d'abord intéressés à un nouveau paradigme logistique connu sous le nom d'Internet Physique, récemment apparu comme un moyen de traiter les symptômes de non-durabilité que présentent les chaînes d'approvisionnement plutôt commerciales. L'Internet Physique est un concept global qui envisage une nouvelle façon de déplacer les marchandises dans le but de rendre la logistique et les chaînes d'approvisionnement plus efficaces, durables, intelligentes et agiles.

L'objectif de ce projet de recherche est d'explorer les potentialités d'application de ce nouveau paradigme sur les chaînes d'approvisionnement humanitaires. Cette association originale a été peu étudiée jusqu'à présent et seulement par un nombre réduit de chercheurs. À cette fin, plusieurs phases de recherche ont été menées et ont abouti à trois contributions principales. Premièrement, la proposition d'un paradigme de chaîne d'approvisionnement humanitaire hyperconnectée à la lumière des pratiques actuelles et inspiré des concepts de l'Internet Physique. Cette contribution conceptuelle est complémentaire aux premières discussions sur le sujet et se différencie par la méthode utilisée pour encadrer la phase de création. En effet, nous ne sommes non pas partis des défis rencontrés, mais des facteurs clés de performance des chaînes d'approvisionnement en général et plus spécifiquement humanitaires. La deuxième contribution est la conception d'une approche expérimentale orientée autour de la simulation afin d'évaluer la pertinence de ce nouveau paradigme envisagé pour les chaînes d'approvisionnement humanitaires. Jusqu'à présent, la nouveauté du sujet a orienté les discussions sur des aspects plus conceptuels et aucune expérience n'a encore été menée. Cette contribution méthodologique se veut générique pour être utilisée dans d'autres contextes. Elle a aussi nécessité le développement d'un modèle à la perspective nouvelle et complète des chaînes d'approvisionnement humanitaires. Troisièmement, une contribution applicative est proposée au travers de la conception et la réalisation d'une expérience utilisant un cas d'étude métier. Ce cas s'inspire de l'architecture du réseau logistique actuel et des principales activités de secours menées par la Croix-Rouge indonésienne. Les résultats obtenus à partir de la simulation indiquent des impacts positifs et majeurs quant aux propositions de pratiques inspirées de l'Internet Physique ceci en comparaison des stratégies actuelles. Des réductions significatives des délais d'approvisionnement et des coûts ont ainsi pu être démontrées ainsi qu'une nette optimisation dans l'utilisation des ressources.

Mots-clés : Humanitaire, Chaîne logistique, Internet Physique, Simulation, Hyperconnexion

TOWARDS A HYPERCONNECTED HUMANITARIAN SUPPLY CHAIN

In the aftermath of major disasters, such as the 2004 tsunami in the Pacific Ocean or the 2010 earthquake in Haiti, the quality of the aid delivered to assist the affected population was the subject of great attention and criticism. Saving human lives and relieving suffering depend on the capacity of humanitarian organizations to mobilize resources, and specifically to organize the logistics of relief items from sourcing points to distribution points. However, inefficient and unsustainable activities call into question the way humanitarian supply chains are organized.

Given this reality, and while an active branch of research is striving to achieve localised improvements, we are taking the opposite view and explore a more holistic and profound reform. The ambition of this research work is to redesign the foundations of the humanitarian system by ideating a new version of humanitarian supply chains.

In this perspective, we focused on a new logistics paradigm known as Physical Internet, which has recently emerged as a way to address the symptoms of unsustainability associated with commercial logistics. The Physical Internet is a global concept that envisages a new way for goods to be moved, supplied, designed, and used in the perspective of making logistics and supply chains more efficient, sustainable, smart, agile, adaptable and scalable. To do so, it suggests a new logistics structure based on open hubs and cooperative platforms for both data and material flows. Also, it aims to strengthen the interconnection between supply chain actors by means of shared and standardized resources, equipment and facilities.

The main idea of this innovative research project is to explore the applicative potentialities of this new logistics paradigm to humanitarian supply chains. This original association has been under-studied so far and only by very few researchers. To this end, several research phases were carried out leading to three main contributions. First, the proposition of an hyperconnected humanitarian supply chain paradigm in light of current practices and inspired from the key concepts of the Physical Internet. This conceptual contribution is complementary to very first discussions on the topic and differentiates the method used for framing the ideation phase. New Physical Internet-oriented practices were designed from the recognized performance success factors of supply chains and humanitarian supply chains. The second contribution is the design of a simulation-based experimental approach to evaluate the relevance on performance of this new paradigm envisioned for humanitarian supply chains. Thus far, the novelty of the topic has remained at the conceptual level and no experiments have been conducted so far. This methodological contribution is one of the first of its kind, generic enough to be used in other contexts and requiring the development of a rigorous, relatively complete and novel approach to the humanitarian supply chain model. Thirdly, an applicative contribution is proposed through the design and conducting of an experiment using a field-based case study. This case study is based on the network architecture and main relief activities of the Indonesian Red Cross in the context of a historical earthquake that hit Indonesia in the past. Results obtained from the simulation indicate major positive effects of the tested Physical Internet-oriented practices compared to the current strategies. Significant reductions in both supply lead times and cost were demonstrated, as well as better use of resources.

Keywords: Humanitarian, Supply Chain, Physical Internet, Simulation, Hyperconnectivity