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The use of technology and information for decisions that keep humanitarian vaccines cool

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Abstract

Purpose – The purpose of this paper is to analyze how far technology and information enable, facilitate or support the planning and implementation decisions in humanitarian vaccine cold chains for vaccination campaigns. The authors specifically focus on three emerging technologies that have the potential to create more flexible conditions in the field, and identify the need to further explore the link between uncertainty, information and irreversibility.

Design/methodology/approach – The authors present a basic structure for the analysis of cold chain disruptions in terms of three distinct yet connected layers of deficient infrastructure and capacity, information gaps and failures in decision making. The authors then review three humanitarian technologies and their impact on vaccine campaigns along these layers. From there, a research agenda is developed to address research gaps this review brought forward.

Findings – Three critical research gaps in the areas of technology innovation for humanitarian vaccine cold chain management are presented. The authors argue that technology to improve capacity, information and decisions need to be aligned, and that the areas of uncertainty, information and irreversibility require further investigation to achieve this alignment. In this way, the paper contributes to setting the research agenda on vaccine cold chains and connects humanitarian logistics to technology, information management and decision making.

Originality/value – This paper presents the humanitarian vaccine cold chain problem from an original angle by illuminating the implications of technology and information on the decisions made during the planning and implementation phases of a vaccine campaign. The authors develop an agenda to provide researchers and humanitarians with a perspective to improve cold chain planning and implementation at the intersection of technology, information and decisions.

Keywords Uncertainty, Information management, Cold chain, Humanitarian technology, Irreversible decisions, Vaccine campaign

Paper type Research paper

1. Introduction

Epidemics thrive in the aftermath of disasters. Health standards deteriorate as infrastructures are destroyed and access to clean water and sanitation facilities cannot be provided (Watson *et al.*, 2007). For complex disasters, the breakdown of healthcare systems

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degrades essential services such as vaccination programs (Leaning and Guha-Sapir, 2013). As such, vaccination campaigns are instrumental in humanitarian operations.

The lack of reliable cold storage and inefficient cold chain management results in high waste rates and poor immunization coverage (MSF, 2014). WHO (2014) reports that in 2011, more than 2.8 million doses of vaccines were lost due to cold chain disruptions in five countries, and various studies pointed out the risk of freezing for Indonesia (Nelson *et al.*, 2004), the USA (Setia *et al.*, 2002) and, most recently, Tunisia (Lloyd *et al.*, 2015). Polio outbreaks in South Africa have resulted from vaccine damaged by cold chain breakdowns (Schoub and Cameron, 1996). Vaccines that are exposed to too hot or too cold temperatures may not only lose their effectiveness but also prove deadly to the vulnerable populations they are intended to protect. A recent incident has once more focused the global humanitarian community's attention on the importance of vaccine cold chains: in May 2017, 15 children died of "severe sepsis" and "toxicity" from contaminated vaccines in Kapoeta in South Sudan[1]. A joint WHO/UNICEF report stated that the vaccination team did not follow the cold chain protocols as specified in the Measles Supplementary Immunization Activities guidelines, and that the vaccines were stored in a building without cooling facilities for four days[2]. In addition, as prices for vaccines continue to rise, the loss of large quantities of vials due to defect cold chains increases the precariousness of the global vaccination effort.

In response to these challenges, a series of technologies have been tested to help solve some of the most pressing challenges of vaccine cold chains (hereinafter cold chains). As in many other humanitarian logistics problems, decision makers need to coordinate a complex series of tasks along the supply chain, while dealing with uncertainties about capacities and needs, as well as unreliable reporting cycles. Cold chain decisions, however, are unique because they are irreversible: if, at any one point, the vaccines cannot be kept within the safe temperature zone, the cold chain is disrupted, and vaccines turn from potential lifesavers into a threat.

Despite the political, financial and humane implications of vaccine cold chains so far, the overarching challenges of decision making in technology-supported cold chain management have received little attention in humanitarian logistics research. As is the case in many emerging fields, a research agenda is needed as a means to synthesize the hitherto fragmented streams of research on technology and decisions in the cold chain, and to identify promising topics for future work. To begin bridging that knowledge gap, in this paper, we focus on the role of technologies to support decision makers in cold chain information management, operational decisions and planning. We focus on four current humanitarian technologies that promise to solve particular cold chain challenges: drones and solar refrigerators promise to improve capacity and create flexibility for operational decision makers, while monitoring and tracking technologies, and information systems can help to reduce uncertainty and keep an overview of the situation. From there, we proceed with analyzing in how far the combination of technologies through their impact on capacity and information helps decision makers to address the problem of irreversible decisions.

Starting in Section 2, we develop our study by providing essential background on logistics challenges in a vaccination campaign. In Section 3, we present our methodology based on a cold chain analysis framework consisting of three distinct and connected layers. In Section 4, drones and solar refrigerator technology solutions are reviewed with respect to their impact on capacity and infrastructure. Section 5 discusses the monitoring and tracking and information systems to plug information gaps and reduce uncertainty. Section 6 is dedicated to identifying critical cold chain decision problems and the impact of technologies on those decisions. We then propose a research agenda in Section 7, putting forward three key areas in need of further research in cold chain management. Finally, we conclude in Section 8 by discussing our findings and their implications for humanitarian practice and research.

2. The humanitarian vaccine cold chain

2.1 The vulnerability of vaccines

Vaccines can only save lives if they remain cool. Most vaccines are developed for a temperature range of 2-8°C (35-46°F), their so-called "safe range." Although usually heat exposure is in focus, freezing was identified as a problem in an astonishing 75-100 percent of vaccine chains (Lloyd *et al.*, 2015). Vaccines with active ingredients will spoil automatically if frozen, but have generally better heat stability (Matthias *et al.*, 2007). With temperatures higher than 8°C; however, the efficacy of a vaccine decreases (Chen and Kristensen, 2009), and may do harm if not cooled and handled appropriately.

Immunization supply chains were initially designed to manage few, inexpensive and bulky vaccines. Health workers were encouraged to use one vial (i.e. a small container, typically cylindrical and made of glass) per child, although each vial provided 10-20 doses leading to wastage rates of 60-70 percent (Humphreys, 2011). Since the cost of newer vaccines has risen from a few cents to 3.50-7.50 US$ per dose, those vaccines are now typically provided in single or two-dose packages (UNICEF, 2014). While this helps to reduce wastage, it also means that they require more cold chain space (WHO, 2014), significantly increasing the cost for transportation and storage. For instance, for the rotavirus, Wolfson *et al.* (2008) estimate a cost increase of 60 percent through the new packaging. Overall, immunization supply chains are increasingly stressed by a widening variety of new vaccines and complex immunization schedules, increasingly demanding cold chain requirements, and the rapid expansion of vulnerable populations living in hard to reach areas (WHO, 2014).

2.2 Managing a vaccine campaign – a humanitarian logistics perspective

A typical vaccine campaign has three phases, dedicated to planning, implementation and evaluation respectively. The planning phase is dedicated to the design of the vaccine campaign, including sourcing, network planning and distribution or inventory management policies. Given the long lead times for cooling equipment and vaccines (several weeks or months; UNICEF, 2015a), these planning decisions can typically not be revisited and changed during the ensuing campaign. In the implementation phase, vaccines are transported from national warehouses through a chain of district and regional warehouses until they are distributed (Humphreys, 2011; MSF, 2014; UNICEF, 2015a); cf. Figure 1.

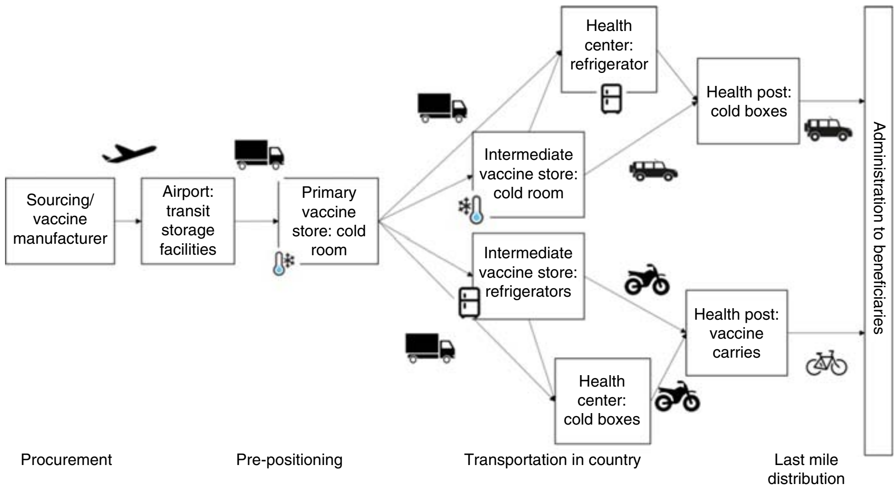

Figure 1. General structure of a cold chain in a vaccination campaign

The post-campaign phase is dedicated to an evaluation with the purpose to inform advocacy, strategic planning and training.

Figure 1 shows the flow of vaccines from sourcing and the port of entry down to the health posts and eventually administration to the beneficiaries during the implementation. Throughout all cold chain stages, from the arrival at the airport to last mile distribution, vaccines must remain within the recommended temperature range. This implies that vaccines must be stored, packed and transported under cold chain conditions. Cooling systems, however, are typically not standardized. While standards and availability of equipment generally deteriorate deeper in the field, there are different options typical for the respective level (cf. Figure 1).

Cold chain equipment can be categorized into active refrigeration systems and passive cooling devices. Although particularly the passive cooling solutions may seem basic, the cost for setting up the cold chain can amount to almost 50 percent of the total campaign cost (Lydon *et al.*, 2014).

Active systems include mains refrigerators and off-grid refrigerators. Mains refrigerators are cooled by compressors that are powered by the electric grid. Off-grid refrigerators include two main subsets: absorption refrigerators powered by the burning of liquid petroleum gas or kerosene, and solar-powered adsorption refrigerators, which use electric compressors that may be driven from batteries that have stored the power generated by solar panels (solar battery-powered), or directly from the solar panels themselves. For active cooling systems, the reliable functioning of technology and its correct use are essential for keeping the cool; they are more robust to delays and therefore do not require minute planning.

Passive cooling devices include cold boxes and vaccine carriers. Cold boxes are larger devices (6-25 litres), generally transported by motor vehicles, while vaccine carriers are smaller (0.5-3.5 litres), and generally carried by hand or on bicycles or motorbikes. They are called passive because there is no active refrigeration mechanism – the cooling is provided by coolant packs containing phase change material (traditionally plain water) frozen into solid form. To avoid freeze damage to vaccines in passive cooling devices, an extra step of "conditioning" is required, taking coolant packs out of the freezer long enough so that they begin melting before placing them in the device (Robertson *et al.*, 2017). Alternatives include gel packs (often formulated for specific temperature ranges), or other products with sufficient thermal mass to contribute to the temperature control such as frozen meat[3]. In the cold chain stretches, for which passive cooling is used, timing is of the essence, and the cold chain can be disrupted if there are delays.

3. Methodology

In the reality of the field, the management of cold chains can be hampered by a variety of disruptions. In his seminal paper, Van Wassenhove (2006) argues that a humanitarian supply chain needs to be designed to support and align material and informational flows. The movement of material requires physical capacity in terms of infrastructure, storage capacity and resources such as vehicles. The informational flows are meant to support the coordination of the physical flows and decision making along the supply chain. Following the three-fold understanding of a supply chain in terms of physical movement of goods, informational flows and decision making, we attribute cold chain failures to a failure in any of these categories: lack or failures of the physical layer (infrastructure, capacity, goods) leading to a disruption of material flows; information gaps and the lack of ability to manage flawed information; and failure of decision making, coordination or planning. These categories are related to specific cold chain challenges in Table I.

These layers and their dependencies are depicted in Figure 2: the infrastructure and capacity layer is an enabler of information and communication flows, which, in turn, enables

Category	Disruptions
Disruption of material flows	Critical infrastructure failure, e.g. power blackouts, disruptions of transportation network, closed warehouses (Schoub and Cameron, 1996); Failure of equipment and lack of redundancies, e.g. lack of fuel, spare parts and back-up energy (WHO, 2014)
Information gaps	Failure of monitoring and tracking systems; incorrect use of vaccine vial monitors; no tracking of minimum and maximum temperatures (Lloyd *et al.*, 2015) Breakdown of communication and information systems Lack of ability to manage the complex information stream, and work with delayed, lacking or uncertain information
Failure of decision making	Deficiencies in vaccine storage and handling and lack of training (Setia *et al.*, 2002; Thakker and Woods, 1992) Lack of mitigation and management options for possible disruptions and lack of planning (Trostle *et al.*, 2003) Lack of operational decision support (Lemmens *et al.*, 2016)

Table I.
Cold chain disruption taxonomy

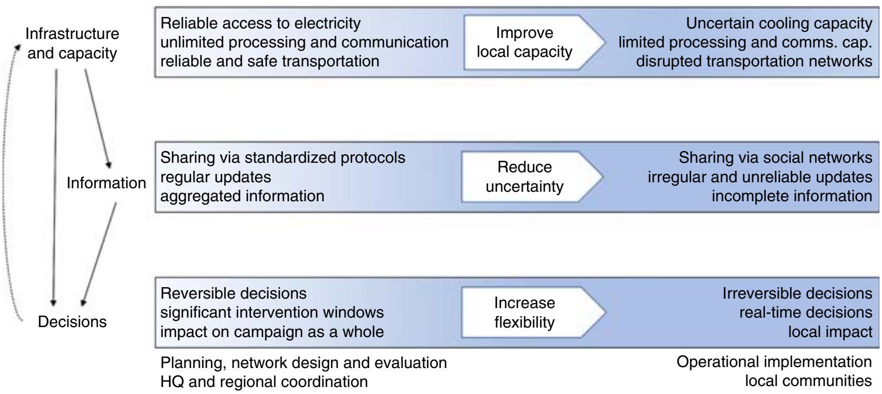

Figure 2.
Analysis grid for cold chain review

and supports decision making that impact the physical layer. Humanitarian technologies are increasingly used, or at least intended, to overcome the specific obstacles and barriers in the different layers: by improving local capacity to address infrastructure problems; by reducing uncertainties or information gaps; and by increasing flexibility to correct deficient decision making.

We focus on technologies that have shown great promise and recently received considerable attention in the humanitarian policy debate: solar panels and drones for the physical layer; monitoring and tracking solutions, and information systems on the information layer. While these technologies are by no means exhaustive and ever newer technologies are being hailed as a potential breakthrough (Blockchain, for instance), the usage of these three technologies specifically for vaccine cold chains is currently established (solar panels, information systems) or actively explored (drones and monitoring, and tracking systems).

Although our selected technologies are increasingly debated in practice, there is not yet a considerable body of academic literature that would allow us to perform a review based on techniques such as content analysis or descriptive statistics. Rather, our work is exploratory in nature and adaptive to the available content in the respective field, complementing academic literature with insights from practice.

On the practice side, we based our work on a review of humanitarian best practices and recent recommendations including reports from UN agencies, international NGOs and the logistics cluster. To account for the dynamics of technology development, we include references to technical reports and news items. For the academic literature, we based our search on Google Scholar, using the term "vaccine" and "cold chain" with different combinations of "drones"/"UAV," "solar refrigerator" and "monitoring"/"tracking"/"ICT." To complement the academic literature, we include more broadly humanitarian supply chains, specifically selecting studies that focus on technology to support transportation and distribution, storage or data collection and analysis. For the decision layer, we refer to a recent review by Lemmens *et al.* (2016) who conclude that current work on vaccine supply chain models is insufficient in terms of representing uncertainties to capture possible disruptions as well as specific requirements of cold chains. This is in line with previous reviews on food cold chains (Akkerman *et al.*, 2010).

In the following section, we begin our review with solar panel and drone technologies in the infrastructure and capacity layer of the cold chain. Section 5 presents our findings on the use of information and information systems in the cold chain information layer, while Section 6 is about the third cold chain layer, the decision layer.

4. The humanitarian vaccine cold chain: infrastructure and capacity layer

As listed in Table I, critical infrastructure disruptions may include power blackouts or damaged roads or bridges. In addition, the telecommunication network may be unavailable and warehouses or sea and airports may be damaged. Equipment may fail and lack spare parts, trucks may be stalled because of lacking fuel, and energy or water systems may be down due to power failures. As these infrastructure and capacity disruptions are all too common in disaster-affected areas, it is not surprising that technological innovations are brought into the field to overcome these obstacles. In the following subsections, we review two such technologies: drones to overcome limited accessibility, and solar refrigerators to overcome the lack of reliable power systems. We stress the tensions between the expectations and the potential the evolving technology, the quality and relevance of field testing and field performance, and considerations of how the technology may be usefully deployed to protect cold chains.

4.1 Technological innovation case: drones for accessibility

The last mile problem whereby aid supplies reach a central hub but cannot be distributed due to damaged or absent infrastructure is a key challenge for humanitarian supply chains in general. Humanitarian disasters can result in the decrease of the accessibility to particular regions for a long time, thereby causing the resurgence of nearly eradicated viruses (Lemmens *et al.*, 2016). While humanitarian last mile challenges so far have been conceived primarily in the context of rural areas, accelerating urbanization with attendant problems of congestion, safety and infrastructure problems will likely be increasingly come to the fore.

The utility and ethics of so-called "humanitarian surveillance drones" has been the subject of much discussion in the humanitarian community over the last couple of years (Sandvik and Lohne, 2014). More recently talk about the potential of cargo drones to help bridge the last mile to bring vaccines, blood supplies or HIV diagnostic kits to suffering African populations in countries like Lesotho, Malawi, Rwanda or Madagascar has been heavily promoted by the drone industry and has received significant attention from global media (Sandvik *et al.*, 2017)[4]. Despite the experimental and immature state of the technology, proponents of cargo drones present the cargo drone as a "game changer" (Sandvik, 2015) arguing that they can solve the last mile challenge, and address its challenges of effectiveness, efficiency and timeliness in the cold chain with guaranteed delivery in minutes, irrespective of ground conditions (Markoff, 2016). Technology optimists envision that at the point of need, a health worker phones the nearest district store with exact requirements: the drone delivers exactly what is needed, patients are treated, waste is reduced and there is no guesswork. The potential for drones entails savings at local clinic inventory, and increases healthcare capacity. Minimum inventory levels will reduce wastage from wrong, overstocked or expired medication, hence leading to lower costs. In sum, cargo drones promise to make systems responsive rather than predictive. This is particularly significant for cold chains, where storage requires important investments, and transportation needs to be quick to ensure that vaccines remain cool.

However, in the academic literature, very few articles consider the use of drones specifically for cold chain problems. For "humanitarian drone" or "humanitarian UAV" and "cold chain," there are only three references in Google Scholar, all of them very recent (published in 2016 and 2017). We therefore broadened the scope of the review including technical and pharmaceutical publications on vaccine deliveries. Easterbrook *et al.* (2017) focus on hepatitis diagnostics and briefly reference the possibility of using drones for healthcare deliveries, including vaccines, to remote locations with poor transport routes. Martini *et al.* (2016) discuss drones in an urban resilience context, including delivering critical relief items such as medicines. The main focus of their work, however, relates to drones as "resilience building technology," emphasizing the potential of drones to support the sharing economy. Amukele *et al.* (2017) investigated the impact of drone transport on the integrity of blood samples. Tatham *et al.* (2017) published a case study on using drones for transportation of medical maggots in Western Australia. This paper is the only humanitarian logistics publication, and highlights organizational challenges related to the use of drones. The study is situated in a development context, where the challenge is reaching populations in very sparsely populated areas with sporadic demand, opposite to vaccine campaigns with a surge demand across rural and urban areas. In addition, maggots are more robust to changing temperatures[5] than vaccines.

Overall, the literature falls into technical studies (feasibility and integrity), or drones are peripherally referenced as a solution to logistics challenges in disasters. There are no academic studies specifically on the use of drones in vaccine chains, or for densely populated urban areas. Hence, there is clearly a need for studying the use and impact of drones for vaccine chains from a managerial, logistics and operations research perspective.

Cargo drones can potentially solve simultaneously the challenges of humanitarian airdrops (which are costly and ineffective, and medicines are typically not dropped) and the last mile problem. However, so far, experiments indicate significant challenges with respect to airworthiness, durability, energy supply and the problem of absence of weather data, which make navigation difficult (Sandvik and Lohne, 2014). Tatham *et al.* (2017) emphasize the organizational challenges, but emphasize the feasibility of using UAVs. However, since the context of their work, which is situated in Australia, is different from the setting of many resource-poor countries in the Global South, their findings may not be representative.

From a supply chain perspective, the use of drones crucially depends on human resources in terms of availability of trained staff that runs and maintains the drone system. On a more strategic level, to use drones the efficiently and realize the promise of zero waste, a lean management strategy needs to be implemented, in which warehouses and distribution centers can match the supplies as they are needed locally. Given the current push-based approach for vaccines campaigns with long lead times, this requires a shift of the supply chain strategy to ensure that local demands can be met in real-time. Otherwise, this strategy will only lead to an increase of inventories and eventually wastage at central hubs.

4.2 Technological innovation case: solar refrigerators for power supply

Similarly to cargo drones, solar refrigerators have also been described as "cheap, rugged and game-changing"[6], and construed as having both humanitarian and ecological impact (Proefrock, 2010). For example, in April 2016, the ICRC installed solar panels at 32 healthcare clinics in the Gaza Strip to ensure that vaccines remain refrigerated in "the power-starved territory" (AP, 2016). As a technological fix to cold chain problems, solar refrigerators were introduced already in the early 1980s in the context of the Expanded Program on Immunization (WHO, 1981, Charters and Oo, 1987), and has surfaced intermittently as a potential solution to cold chain problems: for example, by 2006, 50 solar refrigerators donated by ECHO to be used as a power source for immunization cold chain equipment and help insure uninterrupted immunization services were described as being expected to "make an enormous difference in helping [...] protect hundreds of thousands of children from deadly and crippling diseases that can be prevented through vaccines, like measles and polio" (UNICEF, 2006).

Solar power is an off-grid technology (Franceschi *et al.*, 2014), and most of the countries urgently needing vaccines are geographically suitable for solar cooling (Santori *et al.*, 2014). In particular, the UN frames solar power as being beneficial to women and children, in ensuring their safety (cooking stoves instead of open fires) or for educational benefits (reading lights) and basic healthcare (Pritchett, 2015). It is argued that solar cooling "could have an important impact on vaccines savings, increasing the number of vaccines available for administration and consequently reducing mortality" (Santori *et al.*, 2014). UNICEF advocates solar refrigerators in a recent report, pushing for replacement of traditional absorption refrigerators that are consuming kerosene or gas, largely because of problems to guarantee access to kerosene/gas, environmental aspects and difficulty of temperature maintenance (UNICEF, 2015b). In addition, there are currently no kerosene- or gas-driven refrigerators that qualify under the minimum standards established by the WHO Performance, Quality and Safety system (McCarney *et al.*, 2013).

Reflecting the maturity of the technology, in comparison with the academic analysis on the use of cargo drones in cold chains, there is a substantial literature on solar refrigerators in humanitarian cold chains. Nevertheless, a recent review on active refrigeration for food chains in humanitarian contexts by Aste *et al.* (2017) emphasizes that while the feasibility of solar cooling has been widely and often successfully tested under lab conditions, only few devices have been successfully tested on-field in rural areas. Among the successful implementations are a solar-powered adsorption refrigerators in Nigeria (Anyanwu and Ezekwe, 2003) and Burkina Faso (Buchter *et al.*, 2003). However, these contributions focus largely on the technical feasibility and performance of refrigerators. Problems of installation, use and maintenance at the local or community level are not addressed.

Specifically for vaccine cooling, McCarney *et al.* (2013) review performance of solar refrigerators across a series of use cases. Core problems and relatively high failure rates are related to lacking incentives to support long-term maintenance and repair; system design not considering the local context and conditions; inadequate monitoring of temperature performance; and lack of protocols to manage deviations or disruptions.

Overall, however, the literature is very sparse when it comes to integrating solar refrigeration into humanitarian supply chains. To date, there is insufficient research on the use, maintenance and impact of solar refrigerators in cold chains. Solar refrigerators are still vulnerable: technical problems, problems with spare parts, theft, rain and clouds constitute fundamental problems. Similar as for drones, the success of solar refrigerators depends on local capacities to maintain the system. Moreover, solar power is "weak power" whose presence under the banner of the urgency or difficulty of the conditions of the humanitarian crisis may lead authorities to refrain from having to invest in appropriate infrastructure (Redfield and Robins, 2016).

From a supply chain perspective, the presence of solar refrigerators adds buffer and storage capacity in remote locations independently from access to the power grid. Their efficient use in the cold chain depends on enabling local staff to use and manage this decentralized storage system. To make informed scheduling or routing decisions, for instance, local decision makers need to know where there is spare cooling capacity, if the refrigerator is functioning and if its location can be reached in time to cool vaccines, given the status of the transportation network. Such information needs to be continuously updated and fed into a logistics planning system. Currently, however, logistics information systems suffer from fragmentation, focus on strategic planning and accordingly, long reporting cycles (Comes and Van de Walle, 2016; Laguna Salvadó *et al.*, 2016). We will address the challenges of information and decision making next.

5. The humanitarian vaccine cold chain: information layer

As indicated in Table I, information gaps may arise from simply missing information on the current status of the infrastructure following a disaster (for which, for instance, drones can be used to map out the actual situation and access the affected population) or from a failure to accurately monitor the cold chain deployed in the field, in particular with respect to safeguarding the temperature limitations of the vaccines. Lack of adequate information is recognized as one of the biggest challenges in immunization logistics, especially in terms of detailed information from the local level (Anderson *et al.*, 2014).

The notion that information is vital to humanitarian response is a mainstay of the humanitarian technology discourse, and increasingly also of the general humanitarian discourse. According to the World Disaster Report 2013, "self-organization in a digital world affords opportunities unfeasible in the analogue past. Disaster-affected populations now have greater access to information, and many of their information needs during a crisis can be met by mobile technologies" (IFRC, 2013). Such statements represent a move to see information as relief (Sandvik *et al.*, 2014). However, it is increasingly realized that while information is required, it is by itself not sufficient for the provision of aid, or the alleviation of suffering. In the following, we first review the use of monitoring and tracking systems, before detailing the more broader discussion on information technology and management for the cold chain.

5.1 Technology innovation case: monitoring and tracking systems

Fueled by the rapid developments in information technology, it has become possible to monitor, track and trace goods across the globe. Location-based services have become widespread in the last few years thanks to the mass availability of location chips in every internet-enabled mobile and portable device: smartphones, wearable or embedded devices, and low-cost computing platforms, e.g. Raspberry Pi and Arduino (Schumann-Bölsche and Schön, 2015). Such devices combine motion, location, environmental and physiological sensors that enable advanced location and tracking (Yang *et al.*, 2011).

Besides tracking locations or the movement of humanitarian supplies, monitoring the safety of vaccines is vital. The only reliable way to verify the integrity of the cold chain is continuous temperature monitoring. While it is still common practice in developing countries that thermometers are put into refrigerators and temperatures are checked at given intervals (Thakker and Woods, 1992; Lloyd *et al.*, 2015), only fridge tags, min/max thermometers and vaccine vial monitors can reliably provide information whether the safe range was maintained or breached (WHO, 2014; Trostle *et al.*, 2003). The amount and complexity of vaccine campaigns, however, make vaccine tracking difficult: vaccines are often packed in small containers that cannot individually be monitored due to the high cost and effort in monitoring and updating temperature logs (Carullo *et al.*, 2009). Therefore, the design of cold chain tracking and monitoring systems needs to balance the investment in the monitoring system and the potential gains in terms of reduced waste rates or improved immunization coverage.

The sparse academic literature there is on the topic largely focuses on the results of monitoring in terms cold chain disruptions (see e.g. Lloyd *et al.*, 2015; Matthias *et al.*, 2007; Nelson *et al.*, 2004), Daskalopoulos *et al.* (2014) being the exception in their presentation of an internet of things approach to develop a seamless monitoring system, which is tested for its ability to detect disruptions of the cold chain.

From a supply chain perspective, monitoring and tracking technologies support data collection that is directly related to the material flows. In this sense, they offer the opportunity to complement existing information flows by reliable information about individual vaccines. However, their impact on supporting coordination and steering the material flows can only be used successfully if they support existing information management practices and systems.

5.2 Technology innovation case: information management systems

Information management covers the various stages of information processing from production to storage and retrieval to dissemination toward the better working of an organization. Increasingly, information technology is playing a key role in enabling effective and efficient information management. Information management systems integrate the technology within the work processes of the humanitarian actors (Van de Walle *et al.*, 2009). Despite its importance, no comprehensive academic attention has been given to the interlinkages between "information management" or "information systems" and "humanitarian cold chain." In the humanitarian logistics literature, information management is usually referred to as a responsibility of clusters, or as an important skill (Abidi *et al.*, 2015; Jensen and Hertz, 2016). While Schumann-Bölsche and Schön (2015) investigate the use of sensors and Raspberry Pi in medical supply chains in Sub-Saharan Africa, they do not address overall challenges of integration and interoperability within an information system. In a review by Dasaklis *et al.* (2012) on general epidemics control and logistics considerations beyond the humanitarian context, the lack of information management consideration was considered a research gap.

The humanitarian information management literature, on the other hand, is largely focused on case studies, e.g. for the 2010 Haiti Earthquake (Altay and Labonte, 2014; Van de Walle and Dugdale, 2012), Typhoon Haiyan (van den Homberg *et al.*, 2014; Comes, Vybornova and van de Walle, 2015) or the Ebola Outbreak (Laguna Salvadó *et al.*, 2015; McDonald, 2016; Vybornova and Gala, 2016). Yet, while the contributions emphasize the need to tailor information flows to support specific decisions and problems and the role for ICT in broader logistics operations, none of them specifically addresses the problems of cold chains. The dichotomy between different coordination layers and time frames has been documented for other humanitarian operations and is often reported as a source of friction (Van de Walle and Comes, 2015).

Given the fragmented and emergent state of the literature, there is a need to systematically analyze how cold chain information systems can be designed to serve its three-fold purpose:

(1) facilitating coordination and adaptive planning at national or reginal level;

(2) enabling local real-time decision making to ensure that vaccines are kept cool; and

(3) data collection for evaluations and advocacy.

Introduction of technology can support data collection, but also, in turn, requires data to work efficiently. This implies that any new technology will make information management more complex, and requires systems that facilitate and foster information sharing in a decentralized network respecting the context of the respective users, decision makers or operators.

From a supply chain perspective, information flows are to support coordination and align flows of material (Van Wassenhove, 2006). However, it is still common practice that planning and advocacy dominate information management. Instead of supporting coordination along, the chain data are collected, verified, triangulated and aggregated only at national coordination or headquarters level before redistributing to the field, leading to long information lead times. To adapt to the local and dynamic challenges for cold chains, humanitarian information management needs to refocus and contextualize information to support the core functions of a cold chain, i.e. coordinating a distributed systems and support decision makers detecting and adapting to changing conditions in terms of access, infrastructure, needs or capacities.

6. The humanitarian vaccine cold chain: decision layer

As discussed in the two preceding sections, technology innovations have the potential to overcome cold chain disruptions caused by fragile, damaged or missing infrastructures. Information gaps can be addressed by deploying management information systems, and the storage and delivery can be monitored and tracked by dedicated systems. Despite the technical weaknesses of immature technologies, and the precariousness of deploying technology in unpredictable and insecure contexts, these technologies are changing the conditions and possibilities for decision makers.

To support decision making, particularly in complex and uncertain problems, the humanitarian operations management literature has developed a broad set of decision support systems, optimization tools and simulation models. These models and systems typically assume that the conditions for the decisions to be made are given, for instance, in terms of preferences and objectives, or in the way uncertainties are represented. Here, however, we are interested in the question on how the changing technology on the information and capacity layers is changing the characteristics of the decision-making problems that are addressed, and in particular in how far they help to address the problem of irreversibility which is pivotal for successful cold chains. In the academic literature, decision support studies for vaccine cold chains falls squarely into two categories: case studies, largely from a medical background, or operations research models that consider cold chain requirements as constraints.

Within the first category, Date *et al.* (2011) report on the difficulties of cholera vaccinations in post-earthquake Haiti, when, ultimately, cholera vaccination was not implemented because of limited vaccine availability, the complex logistical and operational challenges of a multi-dose regimen and obstacles to conducting a campaign in a setting with population displacement and civil unrest. For the vaccine campaigns that had been rolled out, WHO's evaluations suggest that managerial oversight and the complexity of the supply chain problems had been largely neglected and underestimated[7]. Anderson *et al.* (2014) emphasize the lack of information as a key barrier to tactical and operational decision making.

For the second category of operational research modeling, a number of recent review papers are relevant. Problem areas related to general healthcare or pharmaceutical supply chains are identified by Privett and Gonsalvez (2014) and Christian *et al.* (2011), but both focus on commercial settings and related problems (e.g. pricing strategies). Lemmens *et al.* (2016) review supply chain network design models for vaccine supply chains. They point out that the majority of publications focus on strategic decisions at planning level. Operational decisions, particularly real-time adaptations that are so characteristic for humanitarian disasters, are largely neglected in the literature. The authors also emphasize the difficulty of modeling all relevant decisions or constraints as derived from local communities. Similarly, for models that address uncertainty, the clear focus is on variations of demand. Neither the first nor the second category of relevant literature, however, explicitly considers disruptions of infrastructure, technology solutions as well as problems related to the use of technology.

Table II provides an overview of important decision characteristics in humanitarian vaccine cold chain management, differentiating between long-term decisions made during the planning phase, and real-time decisions made during the implementation phase. While, in the planning phase, there is time for deliberative processes and the development of models or simulations, during the implementation phase, decision makers must act quickly on the basis of incomplete information, relying on their experience and intuition – an approach prone to possible cognitive biases (Comes, 2016; Gralla *et al.*, 2016).

Table II illustrates the differences in scope (time and geography), in the decision makers and the level at which they make decisions, as well as in the location of the power to implement for the two phases. Moreover, the decision makers have different sets of options or alternatives, and need to maximize different objective functions to make decisions at a different frequency. The decision paradigms greatly differ between the two phases: in the planning phase, decision makers typically make use of operational research models, while the decision makers in the field often rely on heuristics shaped by their experience. Decisions made in the planning phase are typically irreversible, for instance, because of long lead times to source the necessary equipment or medicine. In the field, decision makers often are unaware whether a decision can be reversed or not, depending on the level of disruption that is expected or is known. Last but not least, uncertainty plays a key role in both phases. Whereas in the planning phase, uncertainty is taken into account in probabilistic forecasting or scenario models, uncertainty in the field often stems from missing or conflicting information on the environment in which the decision makers deploy the cold chain.

Characteristic	Planning phase	Implementation phase
Time scale	Weeks/months	Hours, days
Geographical scale	Global to regional	Local
Decision level	Strategic: e.g. network design and capacity planning; policies; information systems set-up	Strategic adaptations if needed and possible; Operational: e.g. scheduling; routing; resource allocation; inventory management; information management
Decision maker	Headquarters and regional level	Headquarters and regional level
Power to implement	Headquarters and regional level	Regional to local level
Frequency of decisions	Once per campaign	At least daily
Set of decision alternatives	Continuous set of options	Few, predetermined through constraints from planning
Objective function	Efficiency: minimize campaign cost, time, waste and resource	Effectiveness: ensure that immunization targets are met respecting constraints (resources, time, dynamic access and infrastructure constraints)
	Equity considerations through immunization targets	
Decision paradigms	Multi-objective decision theory or adaptive planning with scenarios; sensitivity analyses	Experience-based heuristics; discrete optimization or multi-attribute decision making
Reversibility	Irreversible for upcoming campaign (long lead times)	Uncertain mix of reversible and irreversible decisions: decision makers do not know if their decisions will be reversible or not
Uncertainty	High levels of uncertainty related to forecasting and prediction, probabilistic or scenario approaches	Uncertainty related to lacking information or infrastructure disruptions and false planning figures; models typically deterministic or exploratory and experience based

Table II. Decision characteristics in the cold chain planning and implementation phase

7. Humanitarian vaccine cold chains: a research agenda

Drawing from the above discussion on the respective cold chain layers, we now put forward an encompassing research agenda in order to address the most critical problems in cold chain management. We have argued that technology is promising to improve local capacity and reduce uncertainty. Through our review and analysis on cold chain management, we identified major gaps primarily related to the question how technology supports actions on the ground, and helps decision makers to ensure the integrity of the chain. We therefore focus on the information and decision layers in our research agenda, and derive three key areas of research that are critical for advancing successful cold chain management: planning and implementing cold chains under conditions of uncertainty; the role of information in implementing cold chains in the field; and coping with decision irreversibility at the planning and implementation phase.

7.1 Planning and implementing cold chains under conditions of uncertainty

An important driver behind data collection effort is the need to reduce uncertainty and make evidence-based decisions (Darcy *et al.*, 2013). Acknowledging that the nature of uncertainty in humanitarian disasters is such that they cannot be completely reduced, drones and refrigerators offer different ways to manage uncertainty by providing flexibility and buffer capacity.

Time is a driver of deep uncertainty as it limits the possibilities to collect and analyze data. As such, time determines the approaches that can be taken to manage and model uncertainty. The IFRC's (2016) World Disaster Report recently advocated scenario planning to consider uncertainties and involve communities. Another popular method in humanitarian logistics is stochastic programming (Özdamar and Ertem, 2015). Both can be applied in the planning phase because there is time for data collection, modeling and simulations, or deliberation and discussion. Moreover, for planning purposes, it is vital to establish an aggregate overview of the campaign including international sourcing decisions to the layout of a distribution network at national level. The time horizon considered will typically encompass the campaign itself, plus longer term strategic considerations and partnerships.

Contrarily, real-time decisions that need to be made at local level during the implementation require only information about (few) locally feasible alternatives. Uncertainties in the implementation phase stem often from gaps, flaws or insufficient updates in data collection. Because of the time pressure, those uncertainties cannot be reduced or fully modeled. Rather, decisions need to be made based on incomplete information, using rapid heuristics, experience or the proverbial gut-feeling of many responders. While most models are deterministic or stochastic assuming that the nature of uncertainties is known (Galindo and Batta, 2013), systems to support real-time decisions need to be developed to acknowledge lacking information and deep uncertainty.

For long-term planning, so-called "Dynamic Adaptive Policy Pathways" have been proposed to address far-reaching uncertainties (Haasnoot *et al.*, 2013). The method is based on two complementary approaches for designing adaptive plans: "Adaptive Policymaking" (planning and identification of early warning signals) and "Adaptation Pathways" (exploring and sequencing a set of alternatives). To fit to the setting of the implementation phase of a vaccine campaign, such methods need to be adapted to take into account real-time scenario construction (as, for instance, proposed by Comes,Wijngaards and Van de Walle, 2015) as well as the impact of shocks on forecasting and decision making (Durbach and Montibeller, 2017).

By using appropriately sourced and field-tested new technologies such as drones or solar refrigerators, the number of options available to safely store and transport vaccines increases, and thus also the flexibility of cold chains. The impact of the increased number of options, however, critically depends on the ability of decision makers at all levels to access, understand and process information before vaccine temperatures exceeds the safe range. This includes the time to note that a disruption may be occurring, the time to adapt the plans and decide, and the time for implementation.

7.2 The role of information in implementing cold chains

Along with the information explosion driven by new technologies, many generic information products are developed, hinting at a growing lack of clarity on whose decisions should be supported (Altay and Labonte, 2014). Indeed, the problem often is the sheer number and heterogeneity of decision makers in the field and the choices they need to make (Gralla *et al.*, 2013). The very set-up of a cold chain provides only a limited and clear set of options to keep vaccines cold within the relatively short time frames available. As such, cold chains constitute a promising case to analyze and model decision makers' information needs in the field.

The cold chain distribution network and the strict requirements on vaccine temperatures limit the numbers of feasible options at local level. For instance, the number of warehouses equipped with cooling facilities that a transport can reach will, in most cases, be very small. As such, vaccine campaign information systems that support and empower local planning can make use of rapid heuristics, and does not require a global overview of the supply chain. The local information about access, infrastructure, capacity needs to be updated continuously. If such information is not available, at least knowing under which conditions a planned route or schedule leads to a disruption of the cool chain provides an indication of the most crucial information needs and critical thresholds.

Information that is being collected is intended to improve the cold chain implementation and the timely delivery of vaccines to those affected by disaster. Yet, this very information can become a threat endangering these very lives, if it is inaccurate, misleading or falls in the hands of malevolent groups. In the past decade, so-called humanitarian information principles have been identified to guide the processes of collecting, checking, sharing and using information (Van de Walle *et al.*, 2009). Earlier findings from field research in a natural and complex disaster setting indicate that in both disaster types the application of these humanitarian principles can be extremely challenging (Van de Walle and Comes, 2015). In natural disaster response, the processes leading to information products are more "tried and tested" and streamlined. The resulting automation of standard products, however, may reduce the flexibility in tailoring to actual needs, or even prevent the actual verification altogether whether the products meet the needs for which they were generated in the first place. In complex disaster response, information sensitivity and a lack of adequate procedures to handle it may lead to an exaggerated concern for security, and only that information of which one is absolutely certain is considered for the planning and implementation decision processes. More research is needed to elucidate the role of information in disaster settings, natural or complex, in the implementation of cold chains.

7.3 Decision irreversibility in planning and implementing cold chains

Many optimization models assume that decisions are taken at a single point in time and that the events that affect their results can be modeled exhaustively (Altay and Green, 2006). In practice, however, each choice influences the options that can be implemented in future, in other locations, or at another hierarchical level (Comes, 2013). For instance, if vaccines do not reach their destination because the cold chain has been disrupted, decision makers need to arrange for another transport, shifting inventories and re-allocating resources. Hence, decisions should be modeled as a nested series of interdependent decisions that need to be aligned.

One fundamental aspect of restricting future choices, which is particularly relevant in cold chains, is the reversibility of a decision. Although many decisions within a vaccine chain can be irreversible in nature – because vaccines cannot be used any more, or even turn into harmful substances – there is thus far no published research that addresses irreversible cold chain decisions. Even the broader searches of "irreversible" and "humanitarian" in Google Scholar only lead to articles on irreversible evidence and irreversible change, but not of decisions. Henry (1974) defined a decision as irreversible "if it significantly reduces for a long time the variety of choices that would be possible in the future," while Arrow and Fisher (1974) defined an irreversible action as one that is infinitely costly to reverse. Henry's phrase "for a long time" is strictly relative. A long time in one decision problem may be a short time in another. This qualification implies that we should be concerned over actions that are costly to reverse within a relevant time frame.

While there has recently been some work on responsive supply chains (Balcik *et al.*, 2015) and related information systems (Laguna Salvadó *et al.*, 2016; Comes and Van de Walle, 2016), the specific conditions of the cold chain requires further research.

Because of the long lead times many strategic decisions in the planning phase are irreversible within the time frame of the upcoming vaccine campaign: it is often prohibitively costly to source and order further vaccines, or to install additional cooling equipment, once a campaign has been announced for launch. The resulting lack of flexibility has important implications for the implementation phase. Theories of flexible decisions in supply chain management emphasize that strategies whose initial decisions limit future options as little as possible have advantages in the uncertain and often chaotic environment of disasters (Charles *et al.*, 2010; Comes, 2013). Intuitively, a flexible strategy should be preferred over a rigid one, for it offers the possibility to adapt upon receiving new information. Therefore, the reduction of lead times and increased flexibility with respect to capacity and facility location planning are important in cold chains to enable operational staff to re-consider, re-evaluate and modify the vaccination campaign's strategy.

During a vaccination campaign, a series of decisions at operational and tactical level must be made. Given the typical lack of information about infrastructure status or cooling capacity, decision makers will frequently not know whether their decision will be irreversible. For crises, Pauwels *et al.* (2000) showed that by not taking into account the irreversible nature of a decision, the performance of the operations can suffer. As such, any allocation, scheduling or routing decision should be supported by information about the critical points that can prevent a decision to become irreversible. For instance, this can be the information about back-up cooling capacity that can still be reached on time, or surplus inventories that can be used to replace vaccines if cold chains are disrupted.

8. Discussion and conclusions

Humanitarian disasters often result in mass population movements and resettlement in camps that are often short of clean water and nutrition, and have poor sanitation and waste management. In addition, disasters also cause disruptions of routine health services. These risk factors place particularly vulnerable populations like children and pregnant or nursing women at risk. Many diseases that typically spring up in the aftermath of disasters, such as cholera in Haiti after 2016 Hurricane Matthew[8] or polio in refugee camps in the Middle East[9], can be prevented by vaccines. As such, vaccine campaigns are an important component in humanitarian operations to break the downwards spiral for the most vulnerable populations. Cold chains are vital for vaccine campaigns. The temperature of vaccines, which need to be kept at a range of 2-8°C, poses a significant constraint on storage, handling, transportation, distribution and management.

Our motivation for writing this review is a concern with the current push for technology as a solution to broader problems in the humanitarian field, where claims and expectations toward technologies are frequently made in the general absence of crosscutting analysis of technology, information and planning processes. New technologies are endlessly promoted as "game changers" that have the potential to dramatically improve humanitarian interventions through better access, more capacity, increased flexibility and better information. Generally, this type of change rhetoric is frequent with respect to technological innovations "looking for" humanitarian problems to solve (Sandvik, 2017). For private sector actors, particularly start-ups, the ability to refer to one's work as "humanitarian action" and to one's products as "humanitarian goods" can simultaneously be a public relations strategy, a way of engaging in corporate social responsibility and a means of obtaining access to new markets. Problematically, some actors have also perceived the humanitarian setting as an appropriate a site for experimental testing of products that have either been too immature or too controversial for testing in non-emergency jurisdictions. The vaccine cold chain is a particularly emotive aspect of humanitarian logistics that lends itself to both branding and experimentation agendas. An important objective of the paper has been to caution against this type of de-contextualized understanding of the cold chain, its problems and possible solutions. But we have also tried to contribute to a better understanding of how, with appropriate testing and procurement, these technologies can soon also be a significant contribution to keeping the cold chain intact.

Delivery of vaccines through drones, the use of solar refrigerators or implementing tracking and monitoring systems may in the near future change the constraints and parameters for the cold chain management problem. For these innovations to be fully effective, however, several key problems need to be further researched in order to achieve responsive supply chains. Indeed, the granularity, scope, frequency and time for the cold chain decision-making process vary across the different decision levels and phases of a campaign. Because of the vaccines' fragility as well as the disruptions in the local conditions caused by the humanitarian disaster, the planning and implementation of cold chains are confronted with significant challenges. A better understanding of uncertainty, information and irreversibility in the planning and implantation phase, as argued in this paper, is therefore key to advance the effectiveness and efficiency of humanitarian vaccine cold chains.

Notes

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