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Modeling the values of private sector agents in multi-echelon humanitarian supply chains

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Abstract:

Humanitarian organizations (HOs) increasingly look to engage private sector supply chains in achieving outcomes. The right engagement approach may require knowledge of agents' preferences across multi-echelon supply chains to align private sector value creation with humanitarian outcomes. We propose a multi-attribute value analysis (MAVA) framework to elucidate such preferences. We formalize this approach and apply it in collaboration with a HO pilot aiming to facilitate better private sector availability of malaria rapid diagnostic tests in Uganda. We demonstrate how HOs could use criteria weights and value functions from MAVA for project evaluation; in the process, we reveal business model insights for importers, distributors, and retailers in the pilot. We also show how MAVA facilitates the impact assessment of hypothetical options (i.e., combinations of products, services, and subsidies) to guide HO resource deployment. It is important to note that specific insights and assessments, developed to illustrate applications of the approach, are drawn from a single case study and require further validation. This paper offers the first attempt, to our knowledge, to develop quantitative measures for economic and non-economic objectives involving all agents in a multi-echelon supply chain, either humanitarian or commercial. We hope that this initial step stimulates further research to validate results and develop the framework proposed.

Key-Words: OR in societal problems; humanitarian supply chains; humanitarian logistics; global health; multi-criteria decision analysis.

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1 Introduction

A supply chain engages a network of entities in the flow of materials, money, and information from production to consumption (Harland, 1996). Humanitarian supply chains differ from commercial supply chains in a few key areas, including objectives, constraints, and sustainability (Oloruntoba & Gray, 2006; Kovács & Spens, 2007). The ability to articulate and address these differences is increasingly important as humanitarian organizations seek to leverage commercial supply chains in achieving outcomes.

In exploring private sector engagement, we define humanitarian organizations (HOs) broadly – from those meeting acute needs following natural disasters or complex emergencies (i.e., disaster relief, humanitarian work) to those addressing chronic market failures in providing vital products and services (i.e., continuous aid or development work). Following disasters, HOs are well known for establishing new supply chains to deliver aid; increasingly they leverage private sector supply chains by distributing cash or vouchers to beneficiaries (Barrett, Bell, Lentz, & Maxwell, 2009; Albu, 2010; Sivakumaran, 2011; Ryckembusch, et al., 2013). In development work, HOs support public and private sector supply chains to increase the affordability and availability of products that address Sustainable Development Goals (SDGs) in areas such as health, food, water, and energy (Cameron, Ewen, Ross-Degnan, Ball, & Laing, 2009; Cameron, Ewen, Mantel-Teeuwisse, Leufkens, & Laing, 2011; Ewen, Zweekhorst, Regeer, & Laing, 2017). Some HOs support a full range of activities from disaster to development, recognizing that chronic failures in supply chains weakens the foundation for response to acute emergencies.

Private sector engagement can take various forms including public-private partnerships, corporate social responsibility, short-term projects, and long-term market facilitation (Van Wassenhove, 2006; Tomasini & Van Wassenhove, 2009; Balcik, Beamon, Krejci, Muramatsu, & Ramirez, 2010). To determine the right engagement approach, it is critical to understand the objectives and priorities of the multiplicity of agents involved (Zyck & Kent, 2014). Evidence regarding agents' preferences could inform engagement that incorporates the preferences of distinct agents yet aligns value creation across agents in the end-to-end supply chain. This should improve the likelihood of success for the overall humanitarian effort.

In this paper, we propose that multi-attribute value analysis (Keeney & Raiffa, 1993) can be used as a framework to elucidate such preferences, as it provides a normatively valid framework to represent the values of the agents involved in supply chains supported by humanitarian organizations. We formalize this approach and apply it in collaboration with a HO designing a health development pilot in Uganda to facilitate better private sector availability of malaria rapid diagnostic tests. This is an important problem for many developing countries, particularly for sub-Saharan Africa, given the widespread

malaria disease burden. Understanding of agents' preferences in this multi-echelon health supply chain may also enable better private sector engagement in addressing different humanitarian health outcomes.

The paper makes the following contributions. First, on a conceptual level, we demonstrate how multi-attribute value analysis (MAVA) can be used as a framework for quantifying the objectives and priorities of agents spanning various echelons in a supply chain. The combination of value functions, representing the marginal value of gains in performance for each attribute, and criteria weights, representing attribute trade-offs, provides a useful measure for the attractiveness of a supply chain opportunity that various agents have the option to engage in. This is the first article to our knowledge to develop such quantitative measures for economic and non-economic objectives involving all agents in an integrated multi-echelon supply chain, either humanitarian or commercial. Second, we demonstrate how HOs could use criteria weights and value functions from MAVA for project evaluation; in the case study, such evaluation revealed business model insights for various agents in the pilot, which can be used to improve future engagement efforts. Third, we show how MAVA facilitates impact assessment that could avert resource deployment in poorly designed private sector engagement; in the case study we assess how various combinations of support services and subsidies affect the value proposition for various agents in stocking malaria diagnostics. It is important to note that specific insights and assessments, developed to illustrate applications of the approach, are drawn from a single case study and require further validation. To encourage further case studies, we develop some practical considerations from implementation of the framework that may help HOs operationalize efforts to build an evidence base.

The paper has the following structure. First, a review of the relevant literature identifies the need for methods to represent the diverse interests among humanitarian stakeholders, including private sector partners. Next, we propose a framework to address this need and provide a brief theoretical conceptualization. Finally, we present a case study where the proposed approach was implemented with a health development HO to evaluate their supply chain intervention in Uganda. The subsequent discussion draws conclusions from the case study, and the paper concludes with limitations and directions for future research.

2 Relevant Literature

In this section, we review the literature relevant to engaging private sector agents in humanitarian supply chains. We consider the role of economic and non-economic objectives for agents in multi-echelon supply chains and the application of multi-criteria decision analysis.

2.1 Private Sector Engagement in Humanitarian Supply Chains

There is limited literature on private sector engagement in meeting acute needs following natural disasters or complex emergencies. Sodhi & Tang (2014) propose that for-profit or not-for-profit social enterprises coordinate preparation for and response to a flood by engaging micro-retailers in the "last mile" distribution for essential goods, calling for future research around the incentives to work together for the buttressed supply chain. Zyck & Kent (2014) conduct original research in Kenya, Jordan, Indonesia, and Haiti, observing that affected populations increasingly expect aid agencies to provide assistance through local markets; the paper also highlights the importance of understanding private sector preferences since "businesses will engage in humanitarian action in ways that support their overall business strategy and long-term relevance and profitability."

There is more literature on private sector interventions to meet chronic needs. Studies consistently show low availability of essential medicines in the public and private sectors of developing countries, and that private sector customers pay 9–25 times the international reference prices for products (Cameron, Ewen, Ross-Degnan, Ball, & Laing, 2009; Cameron, et al., 2011; Ewen, Zweekhorst, Regeer, & Laing, 2017). To address poor availability and affordability of essential products, the most common intervention considered in the literature is subsidies. Taylor & Xiao (2014) show that donors should subsidize purchases and should not subsidize sales, except for short shelf-life products in certain situations. Berenguer, Feng, Shanthikumar, & Xu (2016) confirm this result and show that subsidy programs provide stronger incentives for a not-for-profit firm than a for-profit firm. Levi, Perakis, & Romero (2016) find that uniformly providing the same per-unit subsidy to every manufacturing firm is surprisingly robust; the exception is when firms face a fixed cost of entry to the market. However, none of these studies considers the behaviors of the wholesalers and distributors that are integral in most developing country supply chains. Moreover, the studies do not consider how non-economic factors play a role in agents' decision regarding the willingness to stock essential products. Our research addresses this gap by developing a framework that incorporates all actors in a multi-echelon supply chain and considers non-economic incentives.

Given the role that non-economic factors may play, the engagement of socially responsible companies could be critical for engaging private sector capacity. Besiou & Van Wassenhove (2015) suggest the use of mixed methods to capture interactions between stakeholders and consider trade-offs that optimize system behavior in the humanitarian context. Specifically, they consider corporate social alliances and identify the key issue to be understanding the complexity of the context and the objectives of multiple stakeholders. Importantly, they assert that "the objective function and the set of constraints may have to be defined case by case, instead of the traditional 'we assume without loss of generality that…'". The next section considers how to define the "case by case" objectives of various agents in a supply chain.

2.2 Objectives of Agents across Multi-Echelon Supply Chains

Supply chain literature has long focused on making decisions and coordinating across multiple echelons (Clark & Scarf, 1960; Thomas & Griffin, 1996). In decentralized supply chains, there has been an effort to model supply chains by better characterizing the different actors (Lee & Billington, 1993; Swaminathan, Smith, & Sadeh, 1998). Lee & Whang (1999) explore management schemes to align incentives in a decentralized multi-echelon supply chain. Dong, Zhang, & Nagurney (2004) offer a supply chain equilibrium model that considers optimizing the individual behavior of manufactures and retailers. However, the focus of these articles is on economic factors alone, assuming that supply chain agents are profit-maximizers.

Consideration of non-economic objectives can be found in papers focusing on corporate social responsibility (CSR) and environmental sustainability. Wu & Pagell (2011) offer case studies in understanding the trade-offs among economic, environmental, and societal bottom-lines. Wang, Lai, & Shi (2011) study supply chain trade-offs using a multi-objective framework and the goals of minimizing cost and environmental impact. Eskandarpour, Dejax, Miemczyk, & Péton (2015) perform a literature review on supply chain network design research that considers social and environmental criteria. Other literature explores and emphasizes the link between social responsibility and economic output (Zhu & Sarkis, 2004; Srivastava, 2007; Xia, Zu, & Shi, 2015).

Multi-Criteria Decision Analysis (MCDA) is a natural approach for combining economic and non-economic objectives, and there are several application areas for MCDA in supply chain management. Environmental considerations, e.g., in biomass and recycling supply chains, are among the most common examples of this (Ma, Scott, DeGloria & Lembo, 2005; De Meyer, Cattrysse, Rasinmäki & Van Orshoven, 2014). MCDA can also be an approach for supplier selection, and Ho, Xi, & Dey (2010) offer a literature review of such applications. However, we did not find MCDA applications that engage each of the distinct agents across a multi-echelon supply chain. To our knowledge, our research is the first to use MCDA to measure economic and non-economic objectives involving all agents in a multi-echelon supply chain; in our case it is a humanitarian supply chain.

2.3 Multi-Criteria Objectives in Humanitarian Logistics

There is a small but growing body of literature that considers MCDA in humanitarian logistics. An early review by Altay & Green (2006), which synthesizes 109 articles on operations research (OR) and disaster operations management from 1980 to 2004, notes a lack of widely accepted measures of productivity and efficiency and calls for research on multi-attribute, multi-objective approaches. In their subsequent review of 155 papers from 2005-2010, Galindo & Batta (2013) conclude that, rather unfortunately, most of the gaps observed by Altay & Green (2006) still remain.

A recent literature review by Gutjahr & Nolz (2016) offers the most comprehensive analysis of multi-criteria optimization in humanitarian aid, analyzing over 40 papers published from 2003 to 2015. The authors assert "there are few other applications areas of operations research for which a multi-criteria viewpoint is more relevant." Only one article within the scope of their survey (Gralla, Goentzel, & Fine, 2014) used multi-attribute utility theory (MAUT), which is the basis for our framework.

3 Modeling Values of Agents with MCDA

Multi-Criteria Decision Analysis comprises a set of methodologies designed to support decisions involving multiple conflicting objectives. Problems in which the solution space is continuous require either linear or non-linear multi-criteria optimization methods (Branke, 2008; Miettinen, 2013) as well as goal programming (Jones & Tamiz, 2010). On the other hand, there are several MCDA methodologies for discrete alternatives, such as combinations of goods and services in humanitarian supply chains (e.g. malaria diagnostic bundles). These latter methodologies encompass those based on Multi-Attribute Utility Theory (Keeney & Raiffa, 1993), Analytic Hierarchy Model (AHP) (Saaty, 1980), and Outranking relations (Roy, 1996), among others. Recent and comprehensive reviews of these methods can be found in Greco, Ehrgott, & Figueira (2016).

We suggest employing MCDA to model objectives and priorities of agents in multi-echelon supply chains, which can then be used to assess the value of and design better, high-value options. The clear majority of MCDA methodologies, such as the AHP and Outranking-based methods, are focused on alternative-based evaluations (in which a set of alternatives is defined a priori, their performance is assessed on each criterion, and preferences are elicited to guide the prioritization of this pre-defined and constant set of alternatives). We are interested here, instead, on value-based evaluations (Ferretti & Montibeller, 2016), in which an attribute is associated with each criterion, value functions are elicited to represent the marginal value of gains in performance, and criteria weights are elicited considering the range of attributes to represent value trade-offs. Such value models enable the evaluation of existing alternatives but also support the design and evaluation of new alternatives. While some MCDA methods, such as the AHP, might be adapted for value-based evaluations, with the pre-definition of attribute ranges, this is unusual in practice (Belton & Stewart, 2002). On the other hand, Multi-Attribute Utility Theory (MAUT)-based methods can be easily employed for this type of evaluation.

There are additional benefits to employing MAUT-based methods. First, MAUT is well rooted axiomatically, on decision theory and measurement theory (see Keeney & Raiffa, 1993; von Winterfeldt & Edwards, 1986). It avoids results that contradict the desiderata of rational choice such as rank reversals that may affect both AHP methods (Dyer, 1990) and some of the Electre methods (Wang & Triantaphyllou, 2008). This is of particular concern when new options might be included in the option

set subsequently during the analysis, as is the case when the model is employed to support the design of new alternatives. Second, there are well-designed and psychometrically valid elicitation protocols for the elicitation of preferences (see von Winterfeldt & Edwards, 1986). This is often not the case with non-MAUT based methods, particularly those that employ notions of criteria weights as direct measurement of importance or assume scales that are incompatible with the nature of the variable being assessed (Belton & Stewart, 2002). Third, there is extensive research on cognitive biases that can negatively affect judgments required in the elicitation of preferences and some best practices on how to minimize these biases in preference elicitation for MAUT-based methods (Montibeller & von Winterfeldt, 2015), but a dearth of similar research for other methods.

In the elicitation of value functions, there is a distinction between decisions under uncertainty and riskless choices (Keeney & Raiffa, 1993). We will focus on the latter given the type of problem being addressed and the less demanding cognitive effort required to provide value judgments, compared with utility functions that require preferences over lotteries (Keeney & von Winterfeldt, 2007). We therefore use multi-attribute value analysis, rooted in Multi-Attribute Value Theory (von Winterfeldt & Edwards, 1986), for modeling the values of agents in multi-echelon humanitarian supply chains.

We now formalize this model. Let O_{ij} be the i-th objective of the j-th agent in the supply chain, with N objectives and M agents. These objectives have to be considered fundamental by the agents and the set of objectives must fulfill a list of logical properties; they should be essential to the decision makers, controllable (to address only the consequences of the alternatives), complete (to consider all the fundamental aspects in the decision), measurable (to be able to evaluate the alternatives), operational (to enable the data gathering of consequences), decomposable, non-redundant, concise, and understandable (for details see Keeney, 1996 and Keeney, 2013). To each objective O_{ij} we will define a respective C_{ij} criterion.

Each criterion has an associated attribute x_i, which measures the achievement of different alternatives on the respective objective and is bounded by a lower and upper bound, i.e.: $x_{i*} \leq x_i \leq x_i^*$ (for i = 1, 2, …N). Each attribute also should be adequately designed and fulfill a set of properties; they should be unambiguous, comprehensive (to cover the full range of possible consequences), direct (to describe directly the consequences), operational (to enable data gathering of the consequences), and understandable (for details see Keeney & Gregory, 2005).

In addition, a measurable value function $v_{ij}(x_i)$ should be associated with each i-th attribute and j-th agent. These functions follow the difference measurement theory proposed by Krantz et al. (1971) and are measured on interval scales of measurement. They are bounded between two any reference levels with $v_{ij}(x_i^*) > v_{ij}(x_{i*})$ that cover the consequences of all alternatives under considerations. In this case study we bounded the functions at $v_{ij}(x_{i*}) = 0$ and $v_{ij}(x_i^*) = 5$ for j = 1, 2,…, M. This measurable value

function can then be employed to assess decision alternatives a, b, c and d, which belong to the set of options S = {a. b, c, d} with a positive difference structure, so if the strength of preference between a and b is greater than or equal to the strength of preference between c and d then: $v(a) - v(b) \geq v(c) - v(d)$ (Dyer & Sarin, 1979).

Finally, a w_{ij} criterion weight needs to be elicited for the respective C_{ij} criterion, considering the range of each attribute $[x_{i*}, x_i^*]$ and the relative value of such range against the other ranges in the model. Notice that these weights in a multi-attribute value function are scaling constants that represent value trade-off and not direct measurements of importance of a criterion (see Keeney, 2002) and thus need to be elicited with appropriate protocols in which ranges are explicitly considered (see Montibeller & von Winterfeldt, 2015 and von Winterfeldt & Edwards, 1986). One of the simplest elicitation protocols for the elicitation of criteria weights is the 'swing weights' method, in which decision makers are asked to consider the range of each attribute the relative value of moving from their lowest (x_{i*}) to the highest (x_i^*) level of performance. Methods involving further reductions of cognitive complexity require only the elicitation of ordinal preferences, such as those based on ordinal ranking of attributes (see Roberts & Goodwin, 2002; Jaspersen & Montibeller, 2015), but they do require additional assumptions about the structure of preferences to derive quantitative weights.

If preferential and weak-difference independence conditions between each pair of criteria exist, an additive value function can be employed to aggregate the partial values $v_{ij}(x_i)$ of a given option, a, into its overall value for the j-th agent:

$$V_j(a) = \sum_{i=1}^{N} w_{ij} v_{ij}[x_i(a)] \qquad \text{for } j = 1, 2, \ldots, M \qquad \text{[Eq. 1]}$$

$$\text{With } \sum_{i=1}^{N} w_{ij} = 1 \qquad \text{for } j = 1, 2, \ldots, M \qquad \text{[Eq. 2]}$$

The following checks must be performed to confirm these independent conditions (see Dyer & Sarin, 1979; Keeney, 1996 for details). A pair of attributes $\{x_1, x_2\}$ is preferentially independent from the other x_k attributes (with $k \neq 1, 2$) if the preference order for consequences involving only changes in the levels of x_1 and x_2 does not depend on the levels of x_k (with $k = 3, 4, \ldots, N$). Attribute x_1 is weak-difference independent of attributes x_t (with $t \neq 1$) if the order of preference differences between two levels of x_1 does not depend on the levels of x_t (with $t = 2, 3, \ldots, N$).

If these properties do not hold, more complex aggregation rules, such as multiplicative formulas, should be employed. However, additive aggregations are widely used in practice and usually suitable for aggregating performances on fundamental objectives (Keeney & von Winterfeldt, 2007). It is therefore important to have an adequate decision framing of the problem (Barcus & Montibeller, 2008; Keeney, 1996, 2013) in which the value model only contains the fundamental objectives of the agents in the supply chain. These simple multi-criteria models also provide transparency (Edwards, Winterfeldt, &

Moody, 2008), as it is easy for decision makers to understand their logic and thus avoid considering the analysis as a black box. This is particularly relevant in facilitated decision modeling (Franco & Montibeller, 2010a) where the model is developed and analyzed on the spot with the group of decision makers in a group process facilitated by the decision analyst, the intervention mode employed in the case study. We now describe how this framework was employed in a pilot.

4 Case-Study: Health Supply Chain Pilot in Uganda

In this section, we present the case study in which the framework suggested above was employed, beginning with the motivation and research design. We then describe the elicitation of decision criteria, weights, and value functions and present results.

4.1 Motivation

The opportunity for investigation arose from HO efforts to increase availability of malaria rapid diagnostic tests (mRDTs) in Uganda. Malaria rapid diagnostic tests offer a fast and accurate means of diagnosing malaria in settings where microscopy is unavailable or unreliable. The diagnostic tests require no fixed asset investment or electricity, are easy to interpret, and entail relatively little training.

In much of the developing world, many febrile patients are diagnosed with malaria without confirmation by either mRDT or microscopy. Diagnosing malaria by clinical symptoms alone is very challenging because many malaria symptoms are nonspecific and overlap with other indications. One study found that 74% of patients with fevers in Uganda were given antimalarial medication but only 35% of the patients actually had a positive mRDT result (Mbonye, et al., 2013). Over-diagnosis of malaria is common not only in Uganda but across sub-Saharan Africa (Amexo, Tolhurst, Barnish, & Bates, 2004; Guerin, et al., 2002; Ndyomugyenyi, Magnussen, & Clarke, 2007). Accurate diagnosis is important, since non-discriminant treatment could lead to widespread resistance to artemisinin, which is the base compound for the first-line treatment. This could incite a global public health crisis, as no other antimalarial medications are as efficacious or well tolerated and few promising alternatives are in the research pipeline (World Health Organization, 2011).

The private sector uptake for mRDTs is especially critical to understand in countries like Uganda where the majority of patients first seek care from private clinics, pharmacies, and drug shops (Awor, Wamani, Bwire, Jagoe, & Peterson, 2012; Rutebemberwa, Pariyo, Peterson, Tomson, & Kallander, 2009). In a recent survey, private sector availability of the mRDTs exceeded 20% in only 3 of 10 countries. One of these countries was Uganda, with availability of around 20% in health facilities and 30% in pharmacies, but only 5% in less-formal drug shops (Poyer et al., 2015). Higher stock levels in the private sector supply chain are critical for increasing use of the devices in many countries.

Most mRDT studies have focused on factors that influence patient decisions, e.g. willingness to pay, with some study of retailer decisions, e.g. willingness to stock (Mbonye, Turinde, Magnussen, Clarke, & Chandler 2010). There is a paucity of studies that examine the upstream suppliers' decisions as a potential barrier to rapid diagnostic uptake (Pai, et al., 2015). This study fills a gap in trying to better understand the mRDT decision making criteria across the multi-echelon supply chain.

4.2 Research Design and Context

We employed an in-depth case study (Yin, 2008) in which we investigated how the conceptual framework suggested above could be applied to understand the values of agents in a humanitarian supply chain. This type of research design, in which a problem is analyzed while data about the usefulness of the intervention is also gathered, has been extensively employed to study multi-criteria interventions (Montibeller, 2007). The case study's internal validity is thus derived from this explicit action-research design (Eisenhardt & Graebner, 2007; Gibbert, Ruigrok, & Wicki, 2008). Detailed notes were taken during extensive interviews, providing the background for presenting the case study and increasing its construct validity. The external validity of our findings is clearly limited, because they are based on a single in-depth case (Gibbert, Ruigrok, & Wicki, 2008; Siggelkow, 2007). However, given limited opportunity to engage directly in a HO operation involving the private sector, there was compelling incentive in presenting results, with appropriate caveats, to stimulate further work in this line. Peer-reviewed research will hopefully encourage more willingness among HOs to engage with the methods and, thus, provide further case study opportunities to better assess the general validity of the insights.

This study evaluated a pilot program that involved agents across the health supply chain in the heavily populated Wakiso district in Uganda. The pilot program was initiated by a HO to increase availability of mRDTs by complementing subsidies with a bundle of services, including training to retailers, biohazard disposal, marketing, and barcoding of devices. Following an open invitation, the HO selected two manufacturers of devices approved by the World Health Organization (WHO). The manufacturers agreed to make provisions for the bundled services through in-country distribution partners. The HO provided technical assistance, training and supervision, and performance-based incentives along the supply chain but did not interfere with business activities. The pilot reached around 180 private sector clinics, drug shops, and pharmacies in the Wakiso district.

The supply chain is illustrated in Figure 1. The research team conducted individual interviews and focus group discussions with agents in several echelons: both first-line buyers (FLBs), all three distributors (though one distributor opted out of answering questions and thus was not used for analysis), and 28 retailers. Note that while the number of upstream actors in the sample was low, data collection included the full population of actors exposed to this bundled service option. Since the penetration of devices is

so low in this market, very few organizations outside this pilot had sufficient knowledge about mRDTs to provide reasonable responses. Thus, our case study considered a small but knowledgeable portion of the market and was complete in its consideration of the entire supply chain. Piloting a new supply chain is a complex problem spanning multiple agents, each with their own objectives and value trade-offs (Keeney, 1982). Multi-attribute value analysis (MAVA) was used to elicit: (i) which criteria are relevant in making decisions regarding how many, if any, mRDTs to keep in stock, (ii) the relative importance (weights) of the criteria, and (iii) the marginal value that increases in performance would generate for agents for each criterion. This study adapted MAVA elicitation protocols to be applicable in the Ugandan context and understandable to the agents who participated in the study.

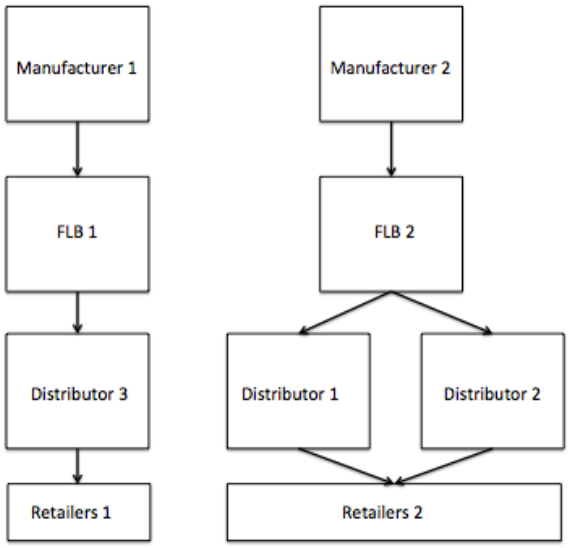

Figure 1. Supply chain of mRDTs in Uganda in this study.

4.3 Methods

The research team met individually with five first-line buyers and distributors, all of which were participants in the HO's pilot. All but one of the interviews was performed in-person in Uganda and one was on Skype because the distributor was out of town while the data was being collected (see Online Appendix A). Follow up questions were addressed to first line buyers through email or Skype. After giving consent, interviews began with an introduction to the study, a brief background on the importance of collecting this information, and a few general questions about their business. It was important to provide some context and explain that the questions were hypothetical in nature and therefore may be abstract. The interviewees were assured that it may be confusing and they should not hesitate at all to ask for clarification. The goal of this was to ensure that respondents were actually understanding the question and providing accurate information that reflected their true opinions and thoughts.

Additionally, we provided a variety of tangible and culturally relevant examples to facilitate understanding (see Online Appendix B).

Information from the retailers was gathered through two three-hour focus group discussions with a total of 28 retailers (see Online Appendix C). A group discussion in multi-criteria value analysis enabled participants to discuss and debate criteria. Moreover, in a focus group discussion, it was possible to get the reasonably undivided attention of a group of retailers for a block of time, as opposed to a survey that solicits information from an individual during work hours.

However, a traditional focus group setting had drawbacks because the respondents were a mix of genders, business levels, experience, and retail types. This diversity led to some situations where some individuals were much more vocal than others. Especially in this particular cultural context, the women in the group were much less outspoken. In order to ensure input from all parties, the focus group included a survey component. Respondents were asked to fill out a piece of paper to rank their "happiness" for different attribute values and the overall weighting for attributes. For both interviews and focus groups, culturally appropriate examples were used to clarify the questions.

The researchers led the focus group discussions with assistance from a Ugandan moderator. This individual was briefed on the project ahead of time to provide necessary background to effectively facilitate the focus group discussion. The native facilitator was a very important aspect of the research framework. For example, although all respondents spoke fluent English, the facilitator could clarify concepts in the local language. He could add nuance to what was being asked of the group. Additionally, if the respondents were uncomfortable asking questions to the researchers, they had the option to speak to the facilitator first. In this way, the accuracy of responses was strengthened.

We also elicited value functions from the agents, which represent the marginal value in gaining performance on a given attribute. A sensitivity analysis was performed on both weights and input assumptions on value functions.

4.4 Decision criteria and weights

Through a literature review and from interviews and focus group discussions with the respondents, researchers identified 17 criteria (C_{ij}) as factors that agents in the supply chain considered when making decisions about stocking mRDTs (Table 1; see also Online Appendix D). Most criteria were determined in advance through five expert interviews (ranging from international development professionals to malaria disease control experts) and literature, though some emergent criteria raised by respondents during interviews and focus groups were also included. The two emergent criteria from the second group (opportunities and time to complete a sale) were not rated by the first focus group due the

infeasibility of tracking down participants. Emergent criteria that came up in the interviews were followed up with previous interviewees through email or skype.

The checks on the objectives, described in Section 3, were done by consulting with cultural and international development professionals. The humanitarian organization offering the bundled service confirmed the completeness of the objectives and international development professionals from Uganda confirmed the objectives were non-redundant and understandable. Moreover, the objectives were verified during each interview with the distributors and first-line buyers (FLBs).

Checks for preferential and weak-difference independence conditions were made to ascertain if we could employ a simple weighted sum aggregation. For example, there were checks whether the value difference between the lowest (0 mins) and highest (60 mins) time to complete a sale would remain the same if the administrative work per week were 0 hours or 60 hours. Conversely, we checked whether the value difference between 0 hours and 60 hours of administrative work per week if the time to complete a sale were 0 mins or else 60 mins. These checks were made between each pair of criteria and no preferential dependence was detected.

Determining the weights of the criteria, which represent value trade-offs, is critically important in a multi-attribute value analysis framework and should always be elicited in relation to the ranges of the attributes as well as the relative importance of such ranges. In this study, the criteria weights (w_{ij}) were elicited by employing the swing weights methods (see von Winterfeldt & Edwards, 1986). Respondents were asked to consider a decision option that ranked the *lowest* in all of the attributes previously defined. Respondents were then asked to think about their most important swings, ranging from the *lowest* to the *highest* level of each attribute, when making the decision on whether or not to stock mRDTs and whether to participate in the bundled service. The first swing was anchored at 100 and the subsequent ones judged against this first swing. These swing weights were normalized (Table 1) and aggregated for retailers and the median value was taken. The distributors and FLBs weights were not aggregated. Blanks in Table 1 represent criteria that were not expressed as relevant or important to that particular agent. Note that profit is included as a criterion in addition to cost and price to reflect respondents' preferred responses.

Overall, there is a variation in the spread of weights between the supply chain agents. Retailers have a narrow range, from 7.4% to 10.8%, while the FLBs have a wide range from less than 5% to over 20%. Some criteria, such as cross sales of other products (e.g., malaria treatments), are critical for almost all agents. Other criteria vary by role in the supply chain. For example, training is relatively important for the retailers providing the patient service; however, it is only the cost of training that is important for the distributors who provide this service. The relative weights for each agent reveal the most salient

aspects in their business decisions and how much they value performance on each criterion, as discussed next.

Table 1. Decision criteria and normalized weights (%) for supply chain agents; all weights are normalized to 100.

Criteria	Retailers (based on median value, n=28)	Distributor 1	Distributor 2	FLB 1	FLB 2
Training	10.8				
Time per sale	10.5				
Awareness/ads	9.6				
Customer satisfaction	9.6				
Time to delivery	9.6				
Quality	9.0			20.9	19.8
Price of device	9.0			23.3	15.4
Cost of device	8.4	16.5	13.0	7.0	22.0
Sales of other products (Cross sales)	8.4	11.6	13.0		17.6
Other opportunities	7.8				
Volume of sales	7.4	16.5	16.3		
Expiration date		14.9	15.4		
Efficiency (of distribution)		14.9	14.6		
Profit		14.0	13.0	4.6	11.0
Cost of training		11.6	14.6		
Relationship with NGO				23.3	12.1
Administrative time				20.9	2.2

Note: Cost is defined as the amount paid by the agent to procure the device and price is the amount received by the agent upon sale.

4.5 Value functions

In addition to the relative importance across criteria revealed by the weights, it was important to consider the level of performance that agents seek within each criterion. Such preferences are revealed by eliciting a value function ($v_{ij}(x_i)$) for each x_i-th attribute, where value represents the satisfaction that an agent derives from various levels of attribute performance. In this study, the primary method employed was direct rating, which requires respondents to apply a score to various points of the attribute considering the lowest and highest attribute levels as anchors. Respondents provided a numerical value for points on a continuum between the upper and lower performance bounds, which were assigned the highest value (5) and lowest value (1) respectively. Piecewise linear interpolation was used to create a continuous value function and cross-checking questions were employed to confirm the functions.

The value functions reveal the range of performance that is desired by agents and also the marginal gain in value with increases in performance, which is not always constant. For example, consider the bottom right chart in Figure 2 where value is plotted as a function of the profit margin for first line buyers

(FLB). Clearly, a profit margin of 0% has minimal value, but the marginal value is distinct by agent: FLB 1 gives a maximal value at 50% margin while FLB 2 seeks 100%. The marginal increase is greater on the low end for both, with the marginal value dropping notably at 10% margin for FLB 1 and dropping slightly at 30% margin for FLB 2. The ability to understand different valuations over an attribute for similar agents, which may explain their behavior, is a major benefit of eliciting these individual value functions.

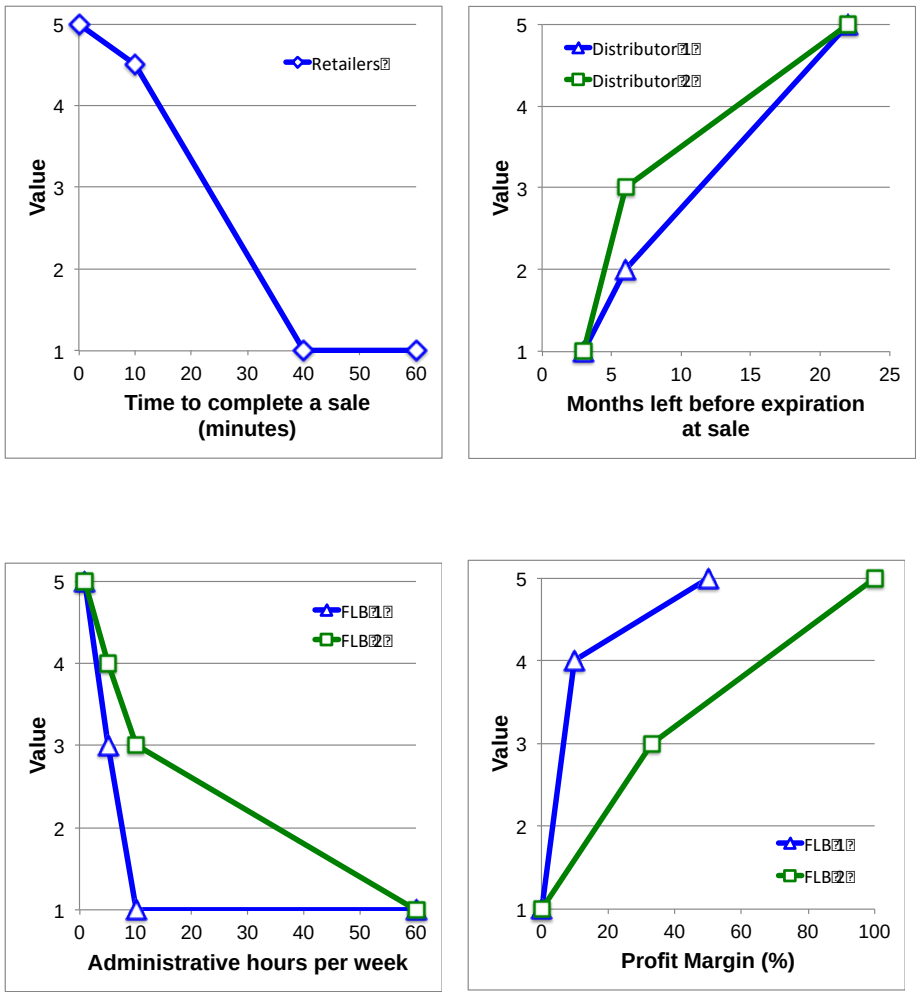

Figure 2 – Value functions for various agents and criteria

The range of values agents seek along with the inflection points in marginal value are very useful when designing a business model or bundled service to maximize value for different supply chain agents. The range of values can be used to set targets for each criterion and inflection points represent the nuance in preferences among agents. We next discuss our findings regarding the case study and reflect on the use of the multi-attribute value analysis in this context.

4.6 Value evaluation of existing and new options

The value of various options combining subsidies and services can be determined for each agent in the private sector supply chain using Eq. 1. We consider thirteen different options (see Table 2). There were four original options, which were actually available to the decision makers in the case study (A, B, C and E) and nine hypothetical options (D, F to M) that were subsequently designed to evaluate potential interventions the health organization could consider. The first three original options (A-C) are available to all agents without HO involvement: not sell mRDTs, sell non-WHO approved devices, and sell WHO approved devices with no HO services. The fourth original option is the specific enhanced malaria RDT bundle introduced in the pilot by the HO (Option E). Option D considers the most common health intervention of subsidies alone (as discussed in the literature review).

The piloted option (E) combines a subsidy with a bundle of services, which we break out into three subpackages: training to retailers, biohazard disposal with barcoding of devices, and advertising.

Table 2. Description of the options evaluated.

Option A	Do not sell malaria rapid diagnostic tests
Option B	Sell non-WHO approved devices
Option C	Sell WHO-approved devices with no HO services
Option D	Subsidy with no HO services
Option E	Subsidy with HO services of advertising, biohazard/barcoding, training (the "enhanced bundle" in the case study pilot)
Option F	HO services of training only; no subsidy
Option G	HO services of advertising only; no subsidy
Option H	HO services of biohazard/barcoding only; no subsidy
Option I	HO services of advertising and training; no subsidy
Option J	HO services of biohazard/barcoding and training; no subsidy
Option K	HO services of advertising and biohazard/barcoding; no subsidy
Option L	HO services of advertising, biohazard/barcoding, and training; no subsidy
Option M	Sell malaria rapid diagnostic tests as part of a "malaria service" model, no HO services

To identify more sustainable private sector solutions that do not rely on long-term financial incentives, we were particularly interested evaluating various service subpackages without subsidies. Options F-L in Table 2 (along with Option C, which serves as a "control" with no services) consider the complete combinatorial enumeration of the three service subpackages with prevailing market prices. Finally, Option M is defined based on the observation that retailers fundamentally view the mRDT as a service, with time associated, rather than a product (see below). The "malaria service" model requires more retailer time than Option C, but offers higher customer satisfaction along with a slightly higher price and sales volume. Further evaluation of this retailer service model along with various HO services could

also be analysed, but we did not enumerate these for brevity. Table 3 shows the structure of each bundle with the components of an option.

Table 4 shows the overall value for each agent per option based on Eq. 1 as well as the ordinal rank of each option for the three agents. The specific parameters used for each option are provided in the Online Appendix E and an explanation on how performance inputs were estimated is provided in the Online Appendix F. Opting out of the mRDT market (Option A) is very unappealing for all agents, which is fortunate for health outcomes. However, distributors are surprisingly interested in the market for non-WHO approved devices, in part because they do not value client or HO relationships as much as their upstream and downstream partners.

Table 3. Structure of the bundles for the options evaluated.

Option	WHO approved devices	Subsidy	Training	Advertising	Biohazard + Barcoding	Retailer Business Model
A	No	No	No	No	No	Do not sell RDTs
B	No	No	No	No	No	Same
C	Yes	No	No	No	No	Same
D	Yes	Yes	No	No	No	Same
E	Yes	Yes	Yes	Yes	Yes	Same plus services
F	Yes	No	Yes	No	No	Same plus services
G	Yes	No	No	Yes	No	Same plus services
H	Yes	No	No	No	Yes	Same plus services
I	Yes	No	Yes	Yes	No	Same plus services
J	Yes	No	Yes	No	Yes	Same plus services
K	Yes	No	No	Yes	Yes	Same plus services
L	Yes	No	Yes	Yes	Yes	Same plus services
M	Yes	No	No	No	No	Sell RDTs as a service

Table 4. Overall value for supply chain agents from 1 (low) to 5 (high); overall rank of the values from 1 (best) to 13 (worst). Note: the two distributors' and first line buyers' results are averaged.

	Values			Combined Value Supply Chain (= $V_F + V_D + V_R$)	Ranks		
	FLB (V_F)	Distributor (V_D)	Retailer (V_R))		FLB	Distributor	Retailer
Option A	2.04	2.11	2.14	6.29	13	13	12
Option B	2.41	3.06	1.86	7.33	12	3	13
Option C	2.97	3.06	2.80	8.83	7	5	10
Option D	2.82	2.97	2.79	8.58	9	8	11
Option E	**3.77**	2.57	3.57	9.91	**1**	12	3
Option F	2.75	2.69	3.28	8.72	11	11	5
Option G	2.79	3.05	3.12	8.96	10	6	7
Option H	3.16	3.02	2.87	9.05	5	7	8
Option I	3.02	2.72	3.61	9.35	6	9	2
Option J	3.39	2.70	3.36	9.45	4	10	4
Option K	3.44	3.07	3.21	9.72	2	2	6
Option L	3.43	**3.09**	**3.79**	**10.31**	3	**1**	**1**
Option M	2.97	3.06	2.86	8.89	7	3	9
Minimum	*2.04*	*2.11*	*1.86*				
Median	*2.97*	*3.02*	*3.12*				
Maximum	*3.77*	*3.09*	*3.79*				

Retailers highly value the full combination of HO services, with Options E and L (Table 4) both ranking in their top three. They particularly value training and advertising, as that combination ranks second; and the largest drop in value (3.12 to 2.87) occurs between the single service options of advertising only and biohazard/barcoding. Option M does not carry very high value alone (2.86), but could be higher with the right HO support in establishing the business model.

First line buyers (FLBs) value the piloted option (E) highest. The combination of subsidies and services is critical to them, since the value drops from 3.77 to 3.44 for the second-best option, which does not include the subsidy. Surprisingly, they slightly prefer a smaller combination of services (Option K) to one that also includes training (Option L). Training and advertising alone are among the FLBs' least valued options (F and G), likely because they did not identify sales volume as a key attribute.

HOs looking to identify the best option would want to consider the combination of agents' values, $V_{SC} = V_F + V_D + V_R$ (Table 4). Alternatively, a weighted sum could be also employed, $V_{SC} = w_F V_F + w_D V_D + w_R V_R$, with $w_F + w_D + w_R = 1$, in which weights reflect the relative significance of each agent (in Table 4 we assumed equal weights of 33.3% each). Option L, which offers the full package of HO

services but without the subsidy, is the highest combination of values (V_{SC} = 10.31). Second is the piloted option (E), which is attractive to retailers and FLBs, but was very unappealing to distributors. This indicates that the piloted effort may not be far from the best intervention, but that the introduction of a subsidy and related conditions affected a key agent in the multi-echelon supply chain. Such misalignment could cause the entire supply chain intervention to fail. A sensitivity analysis on the weights in the overall supply chain value (as above, $V_{SC} = w_F V_F + w_D V_D + w_R V_R$) shows that these results are robust to variations of significance of each agent (see Online Appendix G).

5 Discussion

We discuss our findings from the case study to illustrate applications of the framework. First, we use the specific values and tradeoffs elicited to develop insights that could explain the low availability of diagnostics in the private sector of developing countries. Second, we consider how HOs can use value functions and criteria weights for agents engaged in humanitarian supply chains to assess engagement options. Finally, we consider how multi-attribute value analysis (MAVA) can be used as a framework for quantifying the objectives and priorities of agents at various levels of the supply chain. We stress the tentative nature of these findings, which were based on a single in-depth case study.

5.1 Developing insights regarding agent business models

Considering the criteria weights and value functions together, insights for the various agents in the case study emerge.

5.1.1 Retailers value training and are most concerned about time to complete a sale

The highest weighted criterion for retailers in our analysis was training on how to administer the devices (10.8% in Table 1), which indicates an interest in providing diagnosis. This sentiment was echoed in the focus group discussion with retailers. It is reasonable that training is ranked highest since it is a fundamental requirement enabling retailers to offer diagnostic services.

Interestingly, this study discovered that the next most valuable criterion for retailers was the amount of time required to complete a sale (10.5%), with a relative weight greater than typical business objectives of profits or sales volume. The sales transaction is not simple since the retailer needs to explain the importance of diagnosis, administer the mRDT, wait for the results, and then provide appropriate treatment (either an antimalarial or other medicine); this process can take up to 60 minutes. In the meantime, other sales may be lost if customers enter and find the retailer occupied. Value functions show that retailers were generally fine spending up to 10 minutes with a customer; they were completely dissatisfied with sales taking 40 minutes (Figure 2 – upper left graph). The relative importance of this

criterion indicates that retailers view the mRDT as a service that requires a time investment, rather than a product with a simple sales transaction.

5.1.2 Stock risk is a critical factor

The criteria weights reveal the risk structure of this supply chain. In this pilot, the distributors owned most of the stock and, thus, faced the greatest losses for unsold products that expire. For them, expiration date (14.9% and 15.4%, for distributor 1 and 2 respectively – Table 1) and sales volume (16.5% and 16.3%, idem) were weighed among the most valuable criteria. The value function shows that products with 3 months of shelf life have minimal value for distributors and the value only increases slightly with 6 months. This factor was a key part of the discussion in interviews with distributors. They emphasized that it was very concerning that they had to bear the risk of so much stock.

The retailers could place small orders from the distributors to avoid expiration risk; as a result, expiration date was not even considered a concern for retailers and sales volume received the lowest weight among the criteria considered (7.4% in Table 1). The first line buyers consider neither expiration date nor sales volume since they did not bear financial risk once the sales transaction to distributors was completed.

5.1.3 Agents playing the same role may have different business strategies

Criteria weights show that relative priorities between the first line buyers differ, which may point to distinct business strategies. FLB 1 puts much higher weights on NGO relationships (23.3%) and administrative time (20.9%), and is unwilling to invest more than 10 hours per week on managing mRDTs. In contrast, FLB 2 puts more weight on profits (11.0%) and cross sales (17.6%), with a value function indicating a desire for much higher profit margins (Figure 2 – bottom right graph); yet FLB 2 is willing to invest more time in achieving these financial results. It is possible, especially for FLBs who may have closer relationships with donors, that there is a divergence between reported and actual behavior. Access to transactional data would be an ideal solution, but many of these businesses do not even record sales data that could be shared. However, the data may also suggest that agents playing the same role of the supply chain may have different preferences that may be important to consider when designing business models.

5.2 Assessing the impact of hypothetical options

The weights and value functions can be combined to assess hypothetical options to engage the supply chain. Such assessment can help HOs avoid options that may be generally favourable but fail at one echelon. For example, the distributors' low willingness to stock mRDTs under Option E could cause the entire supply chain to fail, despite the good fit with retailers and FLBs.

HOs can also see certain aspects of an engagement strategy emerge across the supply chain. For example, Option H with biohazard/barcoding is the highest rated single service option across the board. It is somewhat surprising that "back of house" services like biohazard disposal and barcoding are the most broadly attractive service package, even above advertising.

Finally, hypothetical options can point to the most sustainable HO engagement with the private sector, which in this case is counterintuitive. One of the most surprising results is that Option L, which offers all support services but no subsidies, is more attractive than the same package with subsidies included (Option E). Even Option M, with neither financial incentives nor service support, has a reasonable value proposition and is (also surprisingly) more attractive than subsidies (Option D). This suggests that the right support upfront to establish a new business model could be fairly sustainable without ongoing HO investment. The lower valuation of options that include long-term subsidies is not necessarily intuitive and could have important ramifications for sustainable development. The potential of this insight begs for further study to provide external validity.

5.3 Considerations for implementing the framework

To encourage further implementation of the framework and provide external validity, we develop some practical considerations from our experience to help HOs operationalize efforts. Multi-attribute value analysis might be perceived by respondents as complex, despite the simple mathematical model. The data collection process has subtleties such that, even among well-educated respondents, common mistakes and biases may occur and influence the results. To combat potential mistakes and biases, we employed well-established checks and implementation protocols. There are step-by-step guidelines on how multi-attribute value models should be built, which can help humanitarian logistics researchers and practitioners implement the framework in practice (e.g. Montibeller & Franco, 2007). It is important that facilitators are familiar with the relevant literature and engage a well-trained individual to support the process, as needed (Keeney, 2002; Montibeller & von Winterfeldt, 2015).

In addition to rigorous protocols, the framework may require adaptation to fit the local context, especially in humanitarian contexts where business practices may not align with the norms in global supply chains. In our effort, a Ugandan moderator and local development experts assisted with our research design. One adaptation was use of the "happiness" scale used to elicit value functions (see Appendix C). Development experts have used this type of direct ranking and respondents were comfortable providing answers in this format. Another adaptation was explanation of the approach using examples relevant to respondents' lives. One particularly effective situational example was a shirt purchase where the ranges and trade-offs among various criteria (cost, quality, fit, color, etc.) were considered. Other applications of multi-criteria decision analysis in Africa, for policy-related decisions, also report the importance of adapting it to the local context (e.g. Stewart et al., 2010). Problem

structuring methods can also help in further engaging with these diverse stakeholders (Franco and Montibeller, 2010b; Ferretti, 2016; Marttunnen et al., 2017).

Altogether, the framework employed in this case study required thoughtful planning by decision science experts and an experienced HO in Uganda, but was not onerous for two graduate students and a local moderator to implement over a three-week period. The approach could be further operationalized by development of a toolkit that describes elicitation protocols (with some useful contextual examples) and directs the implementation with a step-by-step guide tailored to HOs. This framework may be most useful when employed in a pilot since the sample size is smaller, accessibility to different agents is more manageable, and the results can inform and refine an intervention prior to large-scale resource deployment.

Once developed, these multi-criteria models can be turned into user-friendly decision support tools for humanitarian organizations and policy makers; this is exemplified by the system developed for the UK Department of Environment, Food and Rural Affairs (DEFRA) for the prioritization of emerging animal health threats (Vilas et al., 2013). From incremental appraisal of new options to full design of private sector engagement, users could easily input the performance levels of various options into the decision support tool and analyze the results for insights. This may be particularly useful for application in emergencies where evidence regarding agents' preferences that is relevant to the context is available; vulnerable contexts should be prioritized for further efforts to develop such evidence. In addition, such tools can be embedded into organizational processes for monitoring and evaluation of humanitarian programs. HOs engaged in continuous aid and development activities would benefit from such efforts.

6 Conclusions and Directions for Further Research

Private sector actors involved in humanitarian supply chains may have different motivations for engaging in such endeavors, ranging from short-term profit maximization to long-term growth based on a strong relationship with the HO. To achieve humanitarian outcomes, which may not be aligned with short-term profits, HO decision makers must understand the distinct objectives and priorities of agents across the supply chain when designing engagement with private sector.

In this paper, we explore how multi-attribute value analysis (MAVA), with a strong theoretical foundation in decision theory and measurement theory, can be a useful framework to represent the objectives and priorities of private sector agents. MAVA has well-developed elicitation procedures, which are psychometrically valid and minimize the cognitive biases that may affect judgments. However, to our knowledge, this is the first time that multi-attribute value analysis has been employed to understand the values of all agents in an integrated multi-echelon supply chain.

We employed the framework in collaboration with a health development HO pilot aiming to increase private sector stock of malaria diagnostics in Uganda. Applying MAVA was feasible in this context, but relied on the combined expertise of researchers and local experts to develop rigorous yet culturally appropriate ways of asking questions. We offered some practical considerations that may help HOs adopt the framework more easily.

The case study highlighted potential benefits that HOs could gain in doing so. The criteria weights and value functions helped the organization evaluate the pilot and hint at business model insights for agents across the diagnostic supply chain. The most impactful may be the retailers' emphasis on the time to complete a sale, perhaps suggesting that diagnostics be positioned as a paid service and not as a product sale. Retailers' emphasis on training indicates interest in providing diagnosis. A paid service could include medical treatment with a positive test result and counseling or referral if negative. The analysis also enabled assessment of hypothetical options based on combinations of products, services, and subsidies. Surprising results indicated that investment in subsidies may not only be wasteful, but perhaps detrimental to private sector adoption. Further studies to validate the results from this single case are essential, but this pilot illustrates how MAVA could improve the productivity of humanitarian funding by avoiding poor investment.

As in any case study, there are several limitations. First, external validity is limited in this first attempt to apply MAVA in this setting; further studies are required before confidently applying insights, though these insights may offer useful considerations in those decision settings. Second, the MAVA model makes strong assumptions about the nature of preferences, such as preferential independence among criteria and the ability of decision makers to provide quantitative preference information. While checks were made to assess if such assumptions were held and decision makers were able to provide the information required, this might not be always the case for other interventions. Third, we opted for an in-depth elicitation process, where the research team was directly involved with the group of agents in eliciting their preferences. Although we facilitated the meetings and provided procedural justice during the workshops, avoiding vocal leaders monopolizing the discussion, there is a risk that dysfunctional group dynamics occur in such elicitation processes. Fourth, we made the simplifying assumption, common in real-world MCDA applications and given the scope of the study, that the performances were deterministic thus value functions could be employed to represent the preferences.

This research indicates that MAVA might be a promising approach to understand the objectives of agents in multi-echelon supply chains, and particularly may help to engage the private sector in achieving humanitarian outcomes. However, further research is needed to confirm the early findings from a single case study. We suggest some avenues now. First, analysis of multiple cases is needed to validate the feasibility and generalizability of the framework we suggested and of the findings that we discovered. Second, assessment of the suitability of the MAVA axioms and the feasibility of elicitation

protocols may yield guidance on the appropriate level of complexity for decision rules and elicitation protocols in different contexts. Third, further development of guidelines to facilitate elicitation, especially for application and adaptation in various cultural contexts, is needed. Fourth, extension to elicit utility functions could model not only marginal value but also the risk attitude of agents, which may better address the uncertainty in humanitarian contexts. In addition, uncertainty about performance of alternatives could be analyzed with Monte-Carlo simulation, in which distributions would replace single-point estimates, to further assess the robustness of results.

Concluding, we hope the preliminary results from implementing MAVA in this case study may help to demonstrate the benefits to donors and HOs of employing rigorous protocols to understand the behavior of agents in supply chains. We also hope that this paper stimulates interest in the research community to validate and further develop the framework proposed for modeling the value of agents in multi-echelon supply chains, which might result in better private sector engagement to achieve humanitarian outcomes.

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7 References

Albu, M. (2010). *Emergency market mapping and analysis toolkit*. Oxfam GB.

Altay, N., & Green, W. G. (2006). OR/MS research in disaster operations management. *European Journal of Operational Research, 175*(1), 475-493.

Amexo, M., Tolhurst, R., Barnish, G., & Bates, I. (2004). Malaria misdiagnosis: Effects on the poor and vulnerable. *The Lancet, 364*(9448), 1896-1898.

Awor, P., Wamani, H., Bwire, G., Jagoe, G., & Peterson, S. (2012). Private sector drug shops in integrated community case management of malaria, pneumonia, and diarrhea in children in Uganda. *The American Journal of Tropical Medicine and Hygiene, 87* (Suppl), 92-96.

Balcik, B., Beamon, B. M., Krejci, C. C., Muramatsu, K. M., & Ramirez, M. (2010). Coordination in humanitarian relief chains: Practices, challenges and opportunities. *International Journal of Production Economics, 126*(1), 22-34.

Baltussen, R., & Niessen, L. (2006). Priority setting of health interventions: The need for multi-criteria decision analysis. *Cost Effectiveness and Resource Allocation, 4*(1), 1.

Barcus, A., & Montibeller, G. (2008). Supporting the allocation of software development work in distributed teams with multi-criteria decision analysis. *Omega*, 464-475.

Barrett, C. B., Bell, R., Lentz, E. C., & Maxwell, D. G. (2009). Market information and food insecurity response analysis. *Food Security, 1*(2), 151-168.

Bastian, N., Griffin, P., Spero, E., & Fulton, L. (2016). Multi-criteria logistics modeling for military humanitarian assistance and disaster relief aerial delivery operations. *Optimization Letters, 10*(5), 921-953.

Beamon, B. (1998). Supply chain design and analysis: Models and methods. *International Journal of Production Economics, 55*(3), 281-294.

Belton, V., & Stewart, T. (2002). *Multiple criteria decision analysis: An integrated approach.* Norwell, MA: Springer.

Bendoly, E., Donohue, K., & Schultz, K. (2006). Behavior in operations management: Assessing recent findings and revisiting old assumptions. *Journal of Operations Management, 24*(6), 737-752.

Berenguer, G., Feng, Q., Shanthikumar, J. G., & Xu, L. (2017). The effects of subsidies on increasing consumption through for-profit and not-for-profit newsvendors. *Production and Operations Management*, 26(6), 1191-1206.

Besiou, M., & Van Wassenhove, L. N. (2015). Addressing the challenge of modeling for decision-making in socially responsible operations. *Production and Operations Management, 24*(9), 1390-1401.

Bornstein, C., & Rosenhead, J. (1990). The role of operational research in less developed countries: A critical approach. *European Journal of Operational Research, 49*(2), 156-178.

Bradley, B. D., Jung, T., Tandon-Verma, A., Khoury, B., Chan, T. C., & Cheng, Y. L. (2017). Operations research in global health: A scoping review with a focus on the themes of health equity and impact. *Health Research Policy and Systems, 15*(1), 32.

Branke, J. (2008). *Multiobjective optimization interactive and evolutionary approaches.* Berlin: Springer-Verlag.

Cameron, A. R., Ewen, M., Mantel-Teeuwisse, A. K., Leufkens, H. G., & Laing, R. O. (2011). Differences in the availability of medicines for chronic and acute conditions in the public and private sectors of developing countries. *Bulletin of the World Health Organization, 89*(6), 412-421.

Cameron, A., Ewen, M., Ross-Degnan, D., Ball, D., & Laing, R. (2009). Medicine prices, availability, and affordability in 36 developing and middle-income countries: A secondary analysis. *The Lancet, 272*(9659), 240-249.

Cameron, A., Roubos, I., Ewen, M., Mantel-Teeuwisse, A. K., Leufkens, H. G., & Laing, R. O. (2011). Differences in the availability of medicines for chronic and acute conditions in the public and private sectors of developing countries. *Bulletin of the World Health Organization, 89*(6), 412-421.

Chandler, C. I., Hall-Clifford, R., Asaph, T., Pascal, M., Clarke, S., & Mbonye, A. K. (2011). Introducing malaria rapid diagnostic tests at registered drug shops in Uganda: Limitations of diagnostic testing in the reality of diagnosis. *Social Science and Medicine, 72*(6), 937-944.

Clark, A. J., & Scarf, H. (1960). Optimal policies for a multi-echelon inventory problem. *Management Science, 6*(4), 475-490.

De Meyer, A., Cattrysse, D., Rasinmäki, J., & Van Orshoven, J. (2014). Methods to optimise the design and management of biomass-for-bioenergy supply chains: A review. *Renewable and Sustainable Energy Reviews, 31*, 657-670.

Dong, J., Zhang, D., & Nagurney, A. (2004). A supply chain network equilibrium model with random demands. *European Journal of Operational Research, 156*(1), 194-212.

Dyer, J. (1990). Remarks on the analytic hierarchy process. *Management Science, 36*, 249-258.

Dyer, J., & Sarin, R. (1979). Measurable multiattribute value functions. *Operations Research, 27*, 810-822.

Edwards, W., Winterfeldt, D. v., & Moody, D. (2008). Simplicity in decision analysis: An example and a discussion. In D. R. Bell, *Decision Making* (pp. 443-464). Cambridge: Cambridge University Press.

Eisenhardt, K. M., & Graebner, M. E. (2007). Theory building from cases: Opportunities and challenges. *Academy of Management Journal*, 50(1), 25-32.

Ernst, R. (2003). The academic side of commercial logistics and the importance of this special issue. *Forced Migration Review, 18*(1), 5-8.

Eskandarpour, M., Dejax, P., Miemczyk, J., & Péton, O. (2015). Sustainable supply chain network design: An optimization-oriented review. *Omega, 54*, 11-32.

Ewen, M., Zweekhorst, M., Regeer, B., & Laing, R. (2017). Baseline assessment of WHO's target for both availability and affordability of essential medicines to treat non-communicable diseases. *PloS One, 12*(2), e0171284.

Ferretti, V. (2016). From stakeholders analysis to cognitive mapping and multi-attribute value theory: An integrated approach for policy support. *European Journal of Operational Research*, 253(2), 524-541.

Ferretti, V., & Montibeller, G. (2016). Key challenges and meta-choices in designing and applying multi-criteria spatial decision support systems. *Decision Support Systems, 84*, 41–52.

Franco, L., & Montibeller, G. (2010a). Facilitated modelling in operational research. *European Journal of Operational Research, 205*, 489–500.

Franco, L. A., & Montibeller, G. (2010b). Problem structuring for multicriteria decision analysis interventions. *Wiley Encyclopedia of Operations Research and Management Science*.

Galindo, G., & Batta, R. (2013). Review of recent developments in OR/MS research in disaster operations management. *European Journal of Operational Research, 230*(2), 201-211.

Gibbert, M., Ruigrok, W., & Wicki, B. (2008). What passes as a rigorous case study? *Strategic Management Journal*, 1465–1474.

Gralla, E., Goentzel, J., & Fine, C. (2014). Assessing trade-offs among multiple objectives for humanitarian aid delivery using expert preferences. *Production and Operations Management, 23*(6), 978-989.

Greco, S., Ehrgott, M., & Figueira, J. (2016). *Multiple criteria decision analysis: State of the art surveys; International series in operations research & management science* (2nd Edition ed.). New York: Springer.

Guerin, P., Olliaro, P., Nosten, F., Druilhe, R., Laxminarayan, F., Binka, F., . . . White, N. (2002). Malaria: Current status of control, diagnosis, treatment, and a proposed agenda for research and development. *Lancet Infect. Dis, 2*(9), 564-573.

Gutjahr, W. J., & Nolz, P. C. (2016). Multicriteria optimization in humanitarian aid. *European Journal of Operational Research, 252*(2), 351-366.

Harland, C. (1996). Supply chain management: Relationships, chains and networks. *British Journal of Management, 7*(S1), S63-S80.

Ho, W., Xu, X., & Dey, P. (2010). Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. *European Journal of Operational Research, 202*(1), 16-24.

Jones, D., & Tamiz, M. (2010). *Practical goal programming.* New York; London: Springer.

Keeney, R. (1982). Decision analysis: An overview. *Operations Research, 30*, 803-838.

Keeney, R. (1996). *Value-focused thinking: A path to creative decisionmaking.* Cambridge, MA: Harvard University Press.

Keeney, R. (2002). Common mistakes in making value trade-offs. *Operations Research, 50*, 935-945.

Keeney, R. (2013). Identifying, prioritizing, and using multiple objectives. *EURO Journal on Decision Processes, 1*(1-2), 45-67.

Keeney, R., & Gregory, R. (2005). Selecting attributes to measure the achievement of objectives. *Operations Research, 53*(1), 1-11.

Keeney, R., & Raiffa, H. (1993). *Decisions with multiple objectives: Preferences and value trade-offs.* Cambridge, U.K.: Cambridge University Press.

Keeney, R., & von Winterfeldt, D. (2007). Practical value models. In W. M. Edwards, *Advances in decision analysis: From foundations to applications* (pp. 232-252). New York, NY: Cambridge University Press.

Kovács, G., & Spens, K. M. (2007). Humanitarian logistics in disaster relief operations. *International Journal of Physical Distribution & Logistics Management, 37*(2), 99-114.

Kovács, G., & Spens, K. M. (2011). Trends and developments in humanitarian logistics–a gap analysis. *International Journal of Physical Distribution & Logistics Management, 41*(1), 32-45.

Krantz, D., Luce, R., Suppes, P., & Tversky, A. (1971). *Foundations of measurement.* New York, NY: Academic Press.

Kunz, N., & Reiner, G. (2012). A meta-analysis of humanitarian logistics research. *Journal of Humanitarian Logistics and Supply Chain Management, 2*(2), 116-147.

Lee, H., & Billington, C. (1993). Material management in decentralized supply chains. *Operations Research, 41*(5), 835-847.

Lee, H., & Whang, S. (1999). Decentralized multi-echelon supply chains: Incentives and information. *Management Science, 45*(5), 633-640.

Levi, R., Perakis, G., & Romero, G. (2016). On the effectiveness of uniform subsidies in increasing market consumption. *Management Science, 63*(1), 40-57.

Ma, J., Scott, N., DeGloria, S., & Lembo, A. (2005). Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. *Biomass and Bioenergy, 28*(6), 591-600.

Marttunen, M., Lienert, J., & Belton, V. (2017). Structuring problems for multi-criteria decision analysis in practice: A literature review of method combinations. *European Journal of Operational Research.*

Marsh, K., Dolan, P., Kempster, J., & Lugon, M. (2013). Prioritizing investments in public health: A multi-criteria decision analysis. *Journal of Public Health, 35*(3), 460-466.

Mbonye, A. K., Turinde, A., Magnussen, P., Clarke, S., & Chandler, C. (2010). The feasibility of introducing rapid diagnostic tests for malaria in drug shops in Uganda. *Malaria Journal, 9*(1).

Mbonye, A., Lal, S., Cundill, B., Hansen, K., Clarke, S., & Magnussen, P. (2013). Treatment of fevers prior to introducing rapid diagnostic tests for malaria in registered drug shops in Uganda. *Malaria Journal, 12*(1), 1.

Mendoza, G., & Martins, H. (2006). Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms. *Forest Ecology and Management, 230*(1), 1-22.

Miettinen, K. (2013). *Nonlinear multiobjective optimization.* Springer Verlag.

Montibeller, G. (2007). Action researching multiple criteria decision analysis interventions. *49th Operational Research Society Conference Keynote Papers* (pp. 106-123). Birmingham: British Operational Research Society.

Montibeller, G., & Franco, L. A. (2007). Decision and risk analysis for the evaluation of strategic options. In Frances O'Brien & Robert Dyson (eds.) *Supporting strategy: Frameworks, methods and models* (pp. 251-284). Chichester, UK: John Wiley & Sons.

Montibeller, G., & von Winterfeldt, D. (2015). Cognitive and motivational biases in decision and risk analysis. *Risk Analysis, 35*(7), 1230-1251.

Ndyomugyenyi, R., Magnussen, P., & Clarke, S. (2007). Diagnosis and treatment of malaria in peripheral health facilities in Uganda: Findings from an area of low transmission in south-western Uganda. *Malaria Journal, 6*(1), 1.

Nutt, D., King, L., & Phillips, L. (2010). Drug harms in the UK: A multicriteria decision analysis. *The Lancet, 376*(9752), 1558-1565.

Oloruntoba, R., & Gray, R. (2006). Humanitarian aid: An agile supply chain? *Supply Chain Management: An International Journal, 11*(2), 115-120.

Pai, N., Wilkinson, S., Deli-Houssein, R., Vijh, R., Vadnais, C., Behlim, T., . . . Wong, T. (2015). Barriers to implementation of rapid and point-of-care tests for human immunodeficiency virus infection. *Point Care, 14*(3), 81–87.

Park, T., & Kim, K. (1998). Determination of an optimal set of design requirements using house of quality. *Journal of Operations Management, 16*(5), 596-581.

Rezaei, J. (2015). A systematic review of multi-criteria decision-making applications in reverse logistics. *Transportation Research Procedia, 10*, 766-776.

Roy, B. (1996). *Multicriteria methodology for decision aiding.* Springer.

Rutebemberwa, E., Pariyo, G., Peterson, S., Tomson, G., & Kallander, K. (2009). Utilization of public or private health care providers by febrile children after user fee removal in Uganda. *Malaria Journal, 8*(1), 1.

Ryckembusch, D., Frega, R., Silva, M. G., Gentilini, U., Sanogo, I., Grede, N., & Brown, L. (2013). Enhancing nutrition: A new tool for ex-ante comparison of commodity-based vouchers and food transfers. *World Development, 49*, 58-67.

Saaty, T. (1980). *The analytic hierarchy process: Planning, priority setting, resource allocation.* New York: McGraw-Hill.

Sanyal, B., Frey, D., Graves, S., de Weck, O., Brine, D., Goentzel, J., et al. (2015). Experimentation in product evaluation: The case of solar lanterns in Uganda, Africa.

Siggelkow, N. (2007). Persuasion with case studies. *The Academy of Management Journal, 50*, 20-24.

Sivakumaran, S. (2011). Market analysis in emergencies. *Cash Learning Partnership, Oxford*.

Smith, D. (2008). A bibliography of applications of operational research in West Africa. *International Transactions in Operational Research, 15*(2), 121-150.

Sodhi, M. S., & Tang, C. S. (2014). Buttressing supply chains against floods in Asia for humanitarian relief and economic recovery. *Production and Operations Management, 23*(6), 938-950.

Srivastava, S. (2007). Green supply-chain management: A state-of-the-art literature review. *International Journal of Management Reviews, 9*(1), 53-80.

Stewart, T., Joubert, A., & Janssen, R. (2010). MCDA framework for fishing rights allocation in South Africa. *Group Decision and Negotiation, 19*(3), 247-265.

Swaminathan, J., Smith, S., & Sadeh, N. (1998). Modeling supply chain dynamics: A multiagent approach. *Decision Sciences, 29*(3), 607-632.

Taylor, T. A., & Xiao, W. (2014). Subsidizing the distribution channel: Donor funding to improve the availability of malaria drugs. *Management Science, 60*(10), 2461-2477.

Thomas, D. J., & Griffin, P. (1996). Coordinated supply chain management. *European Journal of Operational Research, 94*(1), 1-15.

Tomasini, R. M., & Van Wassenhove, L. N. (2009). From preparedness to partnerships: Case study research on humanitarian logistics. *International Transactions in Operational Research, 16*(5), 549-559.

Van Wassenhove, L. N. (2006). Humanitarian aid logistics: Supply chain management in high gear. *Journal of the Operational Research Society, 57*(5), 475-489.

Vega, D., & Roussat, C. (2015). Humanitarian logistics: The role of logistics service providers. *International Journal of Physical Distribution & Logistics Management, 45*(4), 352-375.

von Winterfeldt, D., & Edwards, W. (1986). *Decision analysis and behavioral research.* New York, NY: Cambridge University Press.

Wang, F., Lai, X., & Shi, N. (2011). A multi-objective optimization for green supply chain network design. *Decision Support Systems, 51*(2), 262-269.

Wang, J., Jing, Y., Zhang, C., & Zhao, J. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews, 13*(9), 2263-2278.

Wang, X., & Triantaphyllou, E. (2008). Ranking irregularities when evaluating alternatives by using some ELECTRE methods. *Omega, Special Issue Section: Papers presented at the INFORMS conference, Atlanta, 2003, 36*, 45-63.

White, L., Smith, H., & Currie, C. (2011). OR in developing countries: A review. *European Journal of Operational Research, 208*(1), 1-11.

World Health Organization. (2011). Global plan for artemisinin resistance containment.

Wu, Z., & Pagell, M. (2011). Balancing priorities: Decision-making in sustainable supply chain management. *Journal of Operations Management, 29*(6), 577-590.

Xia, Y., Zu, X., & Shi, C. (2015). A profit-driven approach to building a "people-responsible" supply chain. *European Journal of Operational Research, 241*(2), 348-360.

Yin, R. (2008). Case study research: Design and methods. *SAGE Publications*.

C. Carland, J. Goentzel and G. Montibeller (2018). Modeling the values of private sector agents in multi-echelon humanitarian supply chains. European Journal of Operational Research. (https://doi.org/10.1016/j.ejor.2018.02.010)

Zhu, Q., & Sarkis, J. (2004). Relationships between operational practices and performance among early adopters of green supply chain management practices in Chinese manufacturing enterprises. *Journal of Operations Management, 22*(3), 265-289.

Zopounidis, C., & Doumpos, M. (2002). Multi-criteria decision aid in financial decision making: Methodologies and literature review. *Journal of Multi-Criteria Decision Analysis, 11*(4-5), 167-186.

Zyck, S. A., & Kent, R. (2014). Humanitarian crises, emergency preparedness and response: The role of business and the private sector. *Humanitarian Policy Group, Overseas Development Institute*.