FEBRUARY 2024

KLU KÜHNE LOGISTICS UNIVERSITY

CHORD CENTER FOR HUMANITARIAN LOGISTICS AND REGIONAL DEVELOPMENT

WREC FINAL REPORT

MEASURING THE GREENHOUSE GAS EMISSIONS & WASTE OF HUMANITARIAN SUPPLY CHAINS

A QUANTITATIVE RESEARCH STUDY ON THE ENVIRONMENTAL IMPACTS OF HUMANITARIAN DISASTER RESPONSE

In collaboration with:

WREC Environmental Sustainability in Humanitarian Supply Chain · LOGISTICS CLUSTER · DRC DANISH REFUGEE COUNCIL · IFRC · Save the Children · WFP

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Our study in short

Climate change is a top driver of humanitarian needs. Humanitarian organizations (HOs) face the complex task of scaling up operations in response to more frequent and severe natural disasters and chronic climate change consequences, while simultaneously reducing the environmental impacts of their supply chain to break this vicious cycle. **Can humanitarian disaster response also be environmentally sustainable or is the clash between humanitarian imperatives and environmental sustainability too strong? We addressed this question with the help of three case studies focused on humanitarian disaster response.**

This study employed an interdisciplinary approach to measure and evaluate the short- and long-term environmental impacts of humanitarian response, with a focus on **greenhouse gas (GHG) emissions and waste**. We used **three case studies** selected together with humanitarian organizations (HOs) to feed this research, including tarpaulins delivered to Mozambique following tropical cyclones and flooding in 2019, tarpaulins delivered to Pakistan following monsoon rains and flooding in 2022, and Super Cereal Plus (CSB++) delivered to Chad following catastrophic flooding in 2022.

We used **Life Cycle Assessment (LCA)** to analyze the impacts of these operations and calculate the GHG emissions of each step of the supply chain. These results were then combined with data collected on waste generated, response time, and financial costs to develop a **system dynamics model** that captured the impacts of these operations not just as static activities, but with long-term effects. In addition to modeling the current situation we also tested the potential to reduce the environmental impacts of supply chains through **transport, inputs, renewable energy, and waste management alternatives.**

MAIN TAKEAWAY

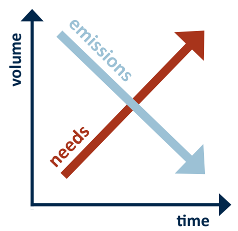
While there is no "one-size-fits-all" approach for environmentally sustainable humanitarian supply chains, focus areas can include: promote green procurement, reduce the use of air travel, increase renewable energy, opt for lower-impact inputs (e.g., plant-based or recycled materials), improve planning and preparedness, and shift towards recycling, reusing, and repurposing.

The results indicate that there are some general conclusions that can be taken when it comes to environmentally sustainable humanitarian supply chains. Firstly, **procurement plays a key role in setting the tone for the rest of the supply chain**. High impact products or materials not only contribute to increased emissions, but also may pose challenges for waste management or other downstream processes. Additionally, while **air transport offers reduced response time, it comes with a big environmental price tag**. In other words, when possible, HOs should opt for international distribution by sea, which may require additional planning. On that note, **preparedness and prepositioning in close proximity to disaster-prone areas** can be pivotal in balancing environmental (e.g., GHG emissions and waste), social (e.g., response time), and economic (e.g., response cost) perspectives.

Preparedness is also an increasingly important topic for many HOs, and the majority are investing in improving supply chain capabilities[1]. Additionally, the **energy source for storage and operations also is an important consideration, and renewable energy sources,** such as solar, have the potential to reduce GHG emissions and costs while also providing a reliable, decentralized source of energy. Finally, **repurposing and recycling** are crucial in lowering the environmental footprint of end-of-life management.

Through the combination of LCA and system dynamics, we illustrated the complex dynamics at play within the context of the end-to-end disaster response. The outcomes and learnings from this study can be used to support HOs in making **informed, evidence-based decisions** towards a greener future of humanitarian response.

1 CHORD (2023)



Humanitarian organizations face the complex task of **reducing the volumes of emissions and other environmental impacts** resulting from their operations, while also **scaling up these operations** in response to increasing climate change consequences. Meeting these two objectives will require a **transformative approach.**

List of abbreviations

CHORD	Center for Humanitarian Logistics and Regional Development
CLD	Causal loop diagram
CO_2	Carbon dioxide
CSB++	Super Cereal Plus
GHG	Greenhouse gas
GLC	Global Logistics Cluster
HDPE	High density polyethylene
HO	Humanitarian organization
HSC	Humanitarian supply chain
ICRC	International Committee of the Red Cross
IFRC	International Federation of Red Cross and Red Crescent Societies
KLU	Kühne Logistics University
kg	Kilogram
km	Kilometer
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LDPE	Low density polyethylene
MB	Masterbatch
SDG	Sustainable Development Goal
UN	United Nations
UNHCR	United Nations Refugee Agency
WFP	World Food Programme
WREC	Waste management and measuring, Reverse logistics, Environmentally sustainable procurement and transport, and Circular economy project

INTRODUCTION

Section 1 in short

Climate change and environmental degradation are top drivers of humanitarian needs. As disasters become more frequent and severe, humanitarian organizations (HOs) need to scale up their operations, which may contribute to emissions and environmental impacts long-term. Can HOs effectively incorporate environmental sustainability into their fundamental objectives, or is the clash between immediate humanitarian imperatives and the broader goals of long-term environmental preservation too strong? This study sought to answer that question by measuring the environmental impacts of humanitarian response and illustrating how data-driven approaches can support informed, evidence-based decision-making. Next, we describe the motivation, goal, and approach of this study, and identify how this endeavor fits into the current state of research on environmental sustainability in humanitarian supply chains (HSCs).

1.1 | MOTIVATION AND GOAL OF THIS STUDY

The goal of the study was to assess the environmental consequences associated with the humanitarian supply chain (HSC) and to work towards mitigating these impacts effectively, as part of the larger WREC project focused on environmental sustainability in humanitarian logistics. HSCs refer to the management of the flow of goods, services, and information aimed at delivering humanitarian aid[2], and are indispensable to those in need. However, these operations often unintentionally generate environmental impacts (e.g., waste and greenhouse gas (GHG) emissions) which can negatively effect the communities that humanitarian organizations (HOs) serve long-term, in addition to the supply chain assets and infrastructure at both local and global levels that are vital to reach these communities. This study sought to raise awareness among HSC practitioners and encourage a coordinated and scalable approach to measuring and reducing environmental impacts. Additionally, this study can be used to support HSC practitioners in the future to reduce their environmental impacts not only during direct activities, but also before and after, encompassing the entire supply chain.

To achieve these objectives, this research study conducted by the Center for Humanitarian Logistics

2 Van Wassenhove (2006)

and Regional Development (CHORD) at the Kühne Logistics University (KLU) quantitatively measured the environmental impacts across HSCs using three case studies conducted with HOs. The study also evaluated the effectiveness of existing and potential solutions for reducing this impact. It was built upon a qualitative analysis initiated by the Hanken School of Economics[3] to understand the motivations, current activities, and constraints in implementing environmentally sustainable practices in HSC operations. The findings are intended to measure, communicate, and support the development of guidance towards environmentally sustainable logistics and supply chain activities. This includes promoting circular economy principles (e.g., recycling) within the humanitarian sector and making case studies of solutions available for replication and scalability. Furthermore, the study aims to facilitate evidence-based decision-making for relevant stakeholders, such as donors or suppliers, and to promote environmental protection and management within the humanitarian sector.

1.2 | STATE OF RESEARCH RELATED TO THE PROJECT

Despite a clear commitment to the Sustainable Development Goals (SDGs)[4], there has historically been a strong focus on saving lives in the short run, and less attention has been given to the environmental sustainability of relief responses[5]. With climate change being widely recognized as one of the top drivers of humanitarian activities today, HOs have identified the need to integrate environmental sustainability into their programmatic and operational strategies. This emphasis on environmental sustainability is particularly relevant since many regions most vulnerable to climate change are also areas where HOs are most active. Consequently, understanding the long-term impacts of their operations is essential to disrupting the vicious cycle of climate change, environmental degradation, humanitarian needs, response efforts, and the resulting emissions and environmental consequences (Fig. 1).

To undergo a transformative shift towards more environmentally sustainable humanitarian responses, special attention needs to be given to supply chain operations which contribute to significant environmental impacts (e.g., GHG emissions or waste and pollution). HSCs are compelled to respond swiftly, often without sufficient time and funding for thorough preparation and planning, which can lead to excessive waste generation and emissions. This can cause long-term harm to the environment and the affected communities[6]. The centrality of the supply chain underscores its critical role in the pursuit of integrating environmental sustainability into humanitarian operations.

Widespread implementation of environmentally sustainable HSCs in practice, however, involves several constraints (e.g., costs, knowledge, capacity, and infrastructure) and is still in its infancy. Specifically, there is a lack of standardization, systematic methods, and fact-based evidence to reduce the environmental impacts of humanitarian activities[7]. This also reduces the ability of HSCs to reach sustainability goals and implies the need to address the gap between humanitarian efforts and environmental responsibility in both research and practice, where environmental sustainability is often considered at odds with humanitarian priorities[8].

3 Tuomala et al. (2022)
4 United Nations (2018)
5 Corbett et al. (2022)

6 Besiou et al. (2021)
7 Laguna-Salvadó et al. (2019)

According to a survey conducted by the Global Logistics Cluster (GLC) in September 2022[9], just 26% of organizations represented had implemented waste and pollution management policies to improve environmental aspects. Simultaneously, 91% did not have mechanisms in place to measure waste volumes. Just 28% of respondents belonged to organizations which measured GHG emissions, and 35% had emission reduction strategies in place. Furthermore, a survey conducted by CHORD[10] found that organizational leaders increasingly recognize the significance of environmental sustainability in HSCs, yet the implementation of a rewards system for green sustainable practices lagged behind. Additionally, the data revealed that less than half of the more than 2,000 respondents believed their organization was pursuing sustainability practices in their supply chain between 2021 and 2022. These survey findings showed a strong demand for change within the humanitarian system. They also helped to drive our motivation to address and contribute to the identified practical gaps through this study, and emphasized the need for collaborative efforts, such as those materialized in the WREC project.

The critical question is how to make humanitarian operations more sustainable. Our research sought to address this by: 1) investigating the environmental impacts of HSC activities; 2) identifying potential solutions; 3) exploring other aspects of sustainability through a data-driven approach; and 4) supporting the wider humanitarian sector with informed, evidence-based decision-making.

8 Zarei et al. (2019)
9 Log Cluster (2022)
10 CHORD (2023)

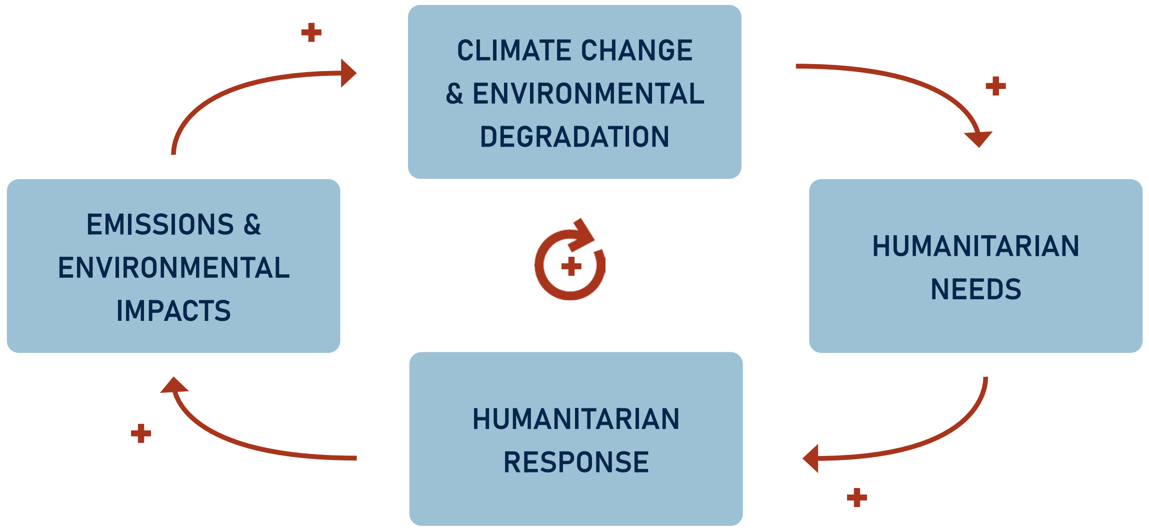


Fig. 1: Vicious cycle of climate change and environmental degradation, humanitarian needs, response, and emissions and environmental consequences.

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APPROACH AND METHODS

Section 2 in short

Quantitative analyses are key to support evidence-based decision-making. This is especially crucial in humanitarian response, where decisions often need to be made quickly, with little consideration of the long-term effects. In this study, we combined Life Cycle Assessment (LCA) with system dynamics modeling to capture the GHG emissions and waste associated with the end-to-end supply chain according to three case studies on disaster response. In this section, we describe our approach, methodologies used, and the suitability of these methodologies to reach the objective of supporting environmentally sustainable HSCs.

2.1 | APPROACH

This study utilized an interdisciplinary approach to calculate the short- and long-term environmental impacts of end-to-end HSCs with a focus on GHG emissions and waste. First, we captured the GHG emissions and waste associated with the selected case studies using Life Cycle Assessment (LCA) and calculated the total emissions[1] of each step of the supply chain. This was combined with data collected on waste and fed into a system dynamics model to capture the total GHG emissions and waste of these operations not just as static activities, but also with long-term effects. In addition to modeling the current situation (i.e., baseline supply chain), we tested the potential to reduce the environmental impacts of operations through transport (e.g., ship vs. plane), inputs (e.g., ingredients), energy (e.g., solar vs. diesel generator), and end-of-life (e.g., recycling vs. open dump) alternatives. To model other priorities for HOs and highlight trade-offs of environmental interventions, we calculated the financial costs and response time associated with each scenario.

1 While LCA measures a wide range of environmental impacts to air, land, and sea, in this study we focus on GHG emissions.

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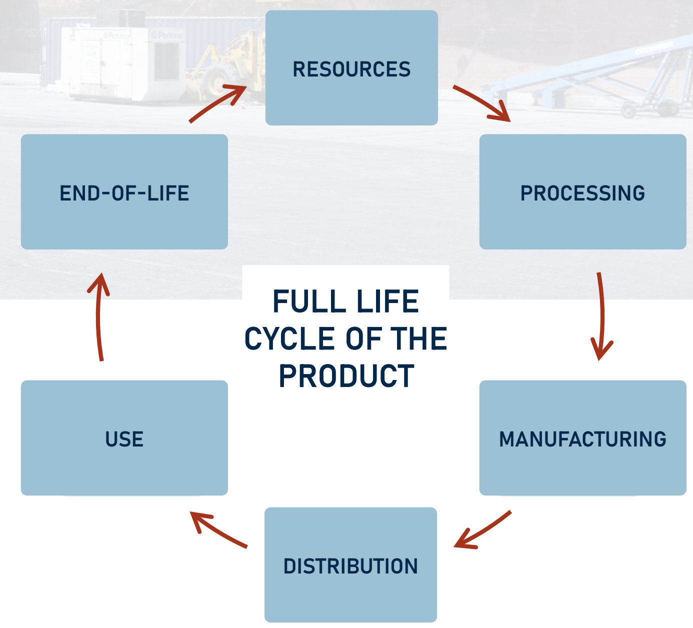

Fig. 2: Product life cycle steps that can be considered as part of an LCA.

2.2 | LIFE CYCLE ASSESSMENT (LCA)

LCA is a methodology used to measure the environmental footprint of products (or services) considering their entire life cycle, from raw material extraction to the use and end-of-life management of the product itself (Fig. 2). LCAs can consider multiple environmental dimensions (e.g., GHG emissions, land use, terrestrial acidification, freshwater eutrophication, etc.), or they can be used to also capture single categories such as GHG emissions. In our case, we used LCA to measure the GHG emissions associated with the end-to-end supply chain. Organizations also typically perform LCAs to identify environmental "hotspots" in the life cycle of their products and act upon these, or to compare the environmental performance of similar products. An LCA consists of four main steps: (1) goal and scope definition, (2) inventory analysis, (3) life cycle impact assessment, and (4) results interpretation.

DEFINING THE GOAL AND SCOPE

The first step is to define the goal and scope of the study to develop a model that mirrors reality as closely as possible. The goal outlines the objective of the analysis, while the scope defines the functional unit and system boundaries. The functional unit describes the product and the function it is intended to fulfill (e.g., in Case Studies 1 and 2, a tarpaulin delivered by the HO to people affected by crisis). The system boundaries define which steps of the life cycle to be considered (e.g., the transportation of the tarpaulin from the manufacturer to the prepositioning warehouse), as well as the enabling inputs to these processes (e.g., the ship and fuel required to transport the tarpaulin).

INVENTORY ANALYSIS

The second step of an LCA is to model the life cycle steps including all of the inputs as defined in the scope and their corresponding outputs. Inputs can come from the technosphere (e.g., trucks or electricity) or the biosphere (e.g., land or water). Outputs are the direct environmental consequences of the inputs, such as emissions to air, land, and water, as well as the depletion of natural resources.

Input data must be gathered for each step within the system boundaries, either as foreground or background data. Foreground data is specific to the study and typically gathered directly with the relevant actors (e.g., supplier or HO). Background data refers to generic processes (e.g., traveling 100 kilometers (km) in a 40' container truck) and comes from specialized databases (checked for quality and accuracy) embedded into the LCA software. We used the *EcoInvent* database and *SimaPro* LCA software. Background data can also be defined at different spatial aggregation levels (e.g., the average energy to produce maize in France vs. the average energy to produce maize globally). Input data is used to build the model in the LCA software, which then converts this into output data (e.g., *x* kg CO_2 emissions) based on a corresponding emission factor[2].

IMPACT ASSESSMENT

The third step is to translate output data (e.g., emissions) to environmental impacts. The impact assessment methodology defines which environmental challenges (referred to as *impact categories*) are considered as part of the LCA. The methodology also defines which output element contributes to which impact category and to what extent (e.g., which emissions to air contribute to global warming and the extent of their contribution based on the global warming potential of each emission type). We used *ReCiPe 2016* as the impact assessment methodology, as it is one of the most widely used[3]. Additionally, ReCiPe also considers a broad range of environmental impact categories. Although we only considered GHG emissions in this study, the data gathered on other impacts can be used to generate future research.

RESULTS INTERPRETATION

The fourth step of LCA is to interpret the results. This includes identifying hotspot areas and operations within the life cycle of the product. In our case, we used the results of the LCA to feed the system dynamics model and although this was the last step of the LCA, it was first step for the overall objective.

2 Output data could also directly be collected, but that is generally the case only with highly specialised LCAs.
3 Huijbregts et al. (2017)

2.3 | SYSTEM DYNAMICS

System dynamics is a methodology for understanding the behavior of complex systems characterized by multiple stakeholders that interact and have different objectives and time delays. It is particularly suitable for studying humanitarian operations, given the dynamic complexity resulting from uncertainty, constraints, trade-offs, unfamiliar contexts, conflicting goals, and counter-intuitive behaviors[4]. The modeling approach involves several key steps: (1) problem formulation and conceptualization; (2) data collection and equation development; (3) model calibration; (4) sensitivity and scenario analyses; and (5) model validation[5]. Each of these steps is integral to the systematic and holistic understanding of complex systems, which is a cornerstone of system dynamics, enabling data-driven decision-making and the formulation of effective strategies and policies.

PROBLEM FORMULATION AND CONCEPTUALIZATION

The first step of system dynamics is problem formulation and conceptualization, where the system structure of interest is defined, and its key components, variables, and relationships are identified. During this step, causal loop diagrams (CLDs) may also be developed. By establishing a clear problem statement and conceptual framework, one lays the foundation for a systematic analysis of the system's dynamics. This is similar to the goal and scope step of LCA. In our case, we calculated the emissions of the functional unit within the defined system boundaries of the LCA to represent a static "snapshot" of the emissions associated with each step in the baseline and alternative scenarios. This was fed into the system dynamics model (in addition to data on waste, time, and financial costs associated with each step) to measure the GHG emissions, waste generated, response time, and financial costs of the entire system, as well as to test for the change in the system when using an alternative solution (e.g., solar energy instead of a diesel generator).

4 Besiou and Van Wassenhove (2015)
5 Sterman (2002)

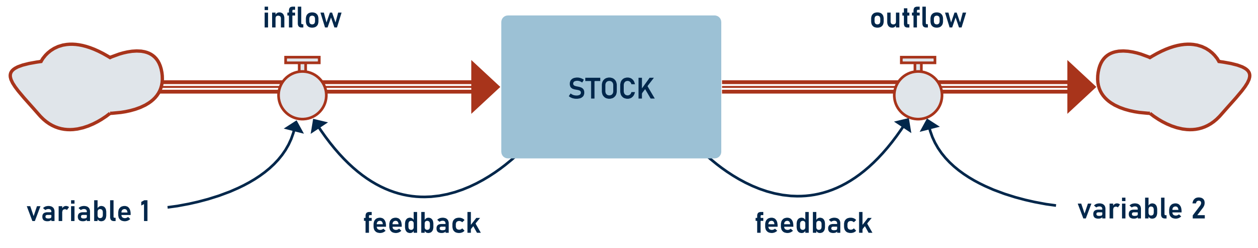

Fig. 3: Stock and flow diagram in which the flow is the rate of accumulation of the stock.

DATA COLLECTION AND EQUATION DEVELOPMENT

The second step is data collection and equation development to create a model that represents the system's behavior. This is where historical data or expert insights are gathered to inform the model's parameters and initial conditions. In our case, we collected data directly from the relevant suppliers, HOs, and literature to feed the model. This conceptual model is then translated into a set of mathematical equations that describe how the system evolves over time. These equations help formalize the relationships among system variables. This is also when critical stock and flow diagrams (Fig. 3) and feedback loops (Fig. 4) are developed.

MODEL CALIBRATION

The third step is model calibration to ensure that the system dynamics model accurately reflects real-world behavior. It involves adjusting the model's parameters and initial conditions to make the output align with historical data. Calibration fine-tunes the model to be an accurate representation of the system under study. A simulation software is used to run the model and observe system dynamics over time. We used *Powersim Studio*.

SENSITIVITY AND SCENARIO ANALYSES

The fourth step is sensitivity and scenario analyses to explore how parameter changes impact the system's behavior. These analyses help identify critical variables and assess how different conditions or interventions affect the system's dynamics. By running various scenarios, potential outcomes and responses of the system to different inputs can be investigated.

MODEL VALIDATION

The fifth step is model validation, a crucial step in system dynamics to ensure model accuracy. It entails comparing the model's simulation results with real-world data and observations. This process verifies the model's accuracy and its ability to replicate actual system behavior. Any disparities between the model and reality are addressed to improve the model's predictive capabilities. The process is iterative, with ongoing refinement of the model as more data becomes available and the system evolves. This step may also include expert panel reviews of the model's impact on variables and relationships.

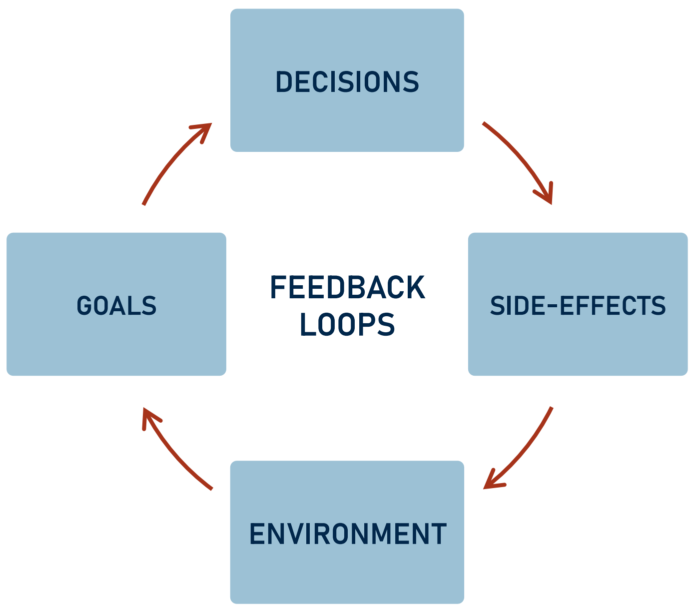

Fig. 4: Feedback loops in which output routes feed back to the chain as an input to feed the overall system.

2.4 | SUITABILITY OF APPROACH

Several factors led us to combine LCA with system dynamics to analyze the environmental impacts of case study responses in the humanitarian sector.

EVIDENCE-BASED SUPPORT

Research and practice are increasingly calling for more data-driven studies to support evidence-based decision-making in the humanitarian sector[6]. HOs need evidence based on real (context-specific) data on where and in what volumes emissions are embedded within end-to-end supply chains, as well as the impact of those operations over time. This is especially relevant to support environmentally sustainable disaster response. By using LCA and system dynamics to model complete HSCs using real data on real-world disaster response, we illustrated how HOs can identify key drivers and factors that impact the environmental sustainability of their operations based on quantitative data, such as transportation routes and resource allocation.

UNINTENDED CONSEQUENCES

By modeling environmental impacts within the complex dynamics of cost and response time, we also showed how this approach can help HOs to identify potential unintended consequences of their actions (e.g., increasing the number of vehicles used for transportation may seem like a good way to improve delivery times, but it can also lead to rising emissions and negative impacts on the environment). We illustrated how modeling the system and interactions, identifying hotspot areas, and testing different scenarios, can help to effectively plan and take steps to improve environmental performance.

COMPLEX SYSTEMS

HSCs involve complex systems with multiple variables and feedback loops that can be difficult to understand and manage. System dynamics provides a framework for modeling and analyzing these complexities and their interactions.

6 Besiou et al. (2021), Corbett et al. (2022), Van Wassenhove (2019), GHA (2022)

MULTIPLE STAKEHOLDERS

The complexity of HSCs, characterized by a high level of interconnectedness among various actors[7], dynamic, rapidly-changing conditions on the field, and numerous uncertainties[8], makes it challenging to address multiple stakeholder perspectives. Through this approach, we illustrated how decisions affect the whole system from multiple perspectives (environment, time, costs) and thus are able to account for diverse goals.

SCENARIO ANALYSIS

By using scenario analysis, we showed how HOs can identify potential problems and test different solutions before implementing them (e.g., the potential to reduce GHG emissions and waste with increased recycling). This included testing how choices made from different perspectives effect the system as a whole over time, which can be used to identify the most effective strategies to reduce the HOs environmental impact and optimize their operations for long-term sustainability.

RESOURCE OPTIMIZATION

HSCs involve the allocation of limited resources (e.g., personnel, supplies, and transportation) in a way that maximizes the impact of aid. This study illustrated how system dynamics models can help HOs optimize the allocation of these resources by identifying bottlenecks, inefficiencies, and areas where resources can be better utilized.

CONTINUOUS IMPROVEMENT

Finally, supply chain planning is an ongoing process that requires continuous improvement. By using LCA results and other quantitative data to model the system of HSCs, we developed a baseline that can be used to monitor and evaluate logistics operations over time, identify areas for improvement, test different strategies to plan, monitor progress, and effectively balance environmental sustainability with costs and response time.

7 Guzmán Cortés et al. (2022)
8 Van Wassenhove (2006)

DATA COLLECTION AND MODEL DEVELOPMENT

Section 3 in short

Data is a significant challenge to support quantitative studies in many regions where HOs are most active. To address this gap, we worked directly with two international HOs to develop three case studies and collect data along the end-to-end supply chain. This data was used to run the LCA and develop a system dynamics model that captures the complex dynamics of humanitarian disaster response and measures GHG emissions, waste, response time, and costs over time. In the next sections, we define the case studies, describe the steps for data collection, and outline model development.

3.1 | CASE STUDIES

Three case studies on disaster response were selected to support this analysis (please see right):

1. **Tarpaulins** delivered to Mozambique following floods and tropical cyclones by IFRC[1] in 2019
2. **Tarpaulins** delivered to Pakistan following monsoon rain and floods by IFRC in 2022
3. **Super Cereal Plus (CSB++)** delivered to Chad following floods by WFP[2] in 2022

IFRC is the world's largest humanitarian network, supporting local Red Cross and Red Crescent action in more than 191 countries. WFP is part of the United Nation's (UN) system, and the world's largest HO addressing hunger and promoting food security. By working with HOs that have large internal supply chain networks, we were able to collect necessary data in a more centralized and efficient way than would be possible from HOs with many external supply chain partners, and thus many potential collection points. This also allowed us to ensure more consistent primary data collection methods.

1 International Federation of Red Cross and Red Crescent Societies (IFRC)
2 World Food Programme (WFP)

CASE STUDY 2

IFRC

TARPAULINS DELIVERED TO PAKISTAN FOLLOWING MONSOON RAIN AND FLOODS (2022) BY IFRC

In mid-June 2022, unprecedented monsoon rain caused devastating floods in Pakistan, impacting one-third of the country's territory, and affecting around 33 million people[1]. The worst floods to hit Pakistan in a decade destroyed crops, livestock, infrastructure, and millions of homes. The areas hit the hardest were some of the country's most vulnerable and roughly 300,000 people were living in relief camps[2].

1 IFRC (2023a)
2 IFRC (2023b)

Aftermath of Flooding in Islamabad, Pakistan (2022)
© Pakistan Red Crescent Society

CASE STUDY 3

WFP

SUPER CEREAL PLUS (CSB++) DELIVERED TO CHAD FOLLOWING FLOODS (2022) BY WFP

In October 2022, Chad was hit with catastrophic flooding – the worst in decades. Over 1.3 million people in N'Djamena and 19 provinces were directly affected between 2022 and 2023. The situation was compounded by the fact that Chad was already grappling with a significant food and nutrition crisis, affecting millions of people, including 1.8 million acutely malnourished children in 2022 to 2023[3]. The floods further exacerbated this situation, pushing more individuals into the risk of food insecurity.

3 IPC (2023)

CASE STUDY 1

IFRC

TARPAULINS DELIVERED TO MOZAMBIQUE FOLLOWING FLOODS AND TROPICAL CYCLONES (2019) BY IFRC

According to the IFRC, "Cyclones Idai and Kenneth were the worst natural disasters to hit Southern Africa in at least two decades, wreaking havoc in the spring of 2019, killing at last 1,000 people and displacing some 2.2 million people"[4]. This resulted in widespread damage, causalities, displacement of thousands of people, and an urgent need for humanitarian aid. In total, over 750,000 hectares of standing crops were destroyed[5].

4 IFRC (2023c)
5 IFRC (2019)

Harvest loss in Chad following flooding (2022)
© WFP/Evelyne Fey

Aftermath of Cyclone Idai in Beira, Mozambique (2019)
© IFRC Climate Centre/Denis Onyodi

Fig. 5: Main body of tarpaulin for Case Studies 1 and 2 without packaging.

Fig. 6: One bag CSB++ in its primary packaging for Case Study 3.

3.2 | DATA COLLECTION

Both LCA and system dynamics are data-intensive approaches, which can be especially challenging for studies that focus on regions with a lack of reliable and accessible data. To provide context-specific insights on the complexities of environmental sustainability in humanitarian response, we collected this data directly at the HOs and suppliers.

The research involved three steps for data collection: (1) identify suitable products and disaster scenarios; (2) develop a questionnaire to gather relevant data; and (3) collect data on operations, waste, time, and costs from the target organizations (WFP and IFRC).

IDENTIFY SUITABLE PRODUCTS AND DISASTER SCENARIOS

In the first step, we worked with the relevant HOs to identify suitable product(s) and disaster(s) to model (i.e., they fit the context and there was enough data available). We selected two products (Fig. 5 and Fig. 6) and corresponding disasters, defined as Case Studies 1, 2, and 3.

The items and disasters were selected for several reasons. Tarpaulins were selected as a non-food relief item due to their critical role in providing vital shelter. Tarpaulins offer a safe and secure space that shields affected individuals from harsh weather conditions, preserves their privacy, and upholds their dignity, enabling them to recover and rebuild their lives. Furthermore, the fortified maize-soy blend, aka Super Cereal Plus (CSB++) was selected as a food item because it is commonly distributed by WFP and other HOs to treat and prevent malnutrition (e.g., over 700,000 packages for the selected case study). In countries like Chad, which suffers from severe malnutrition, it is considered a disaster relief item. Please see Tables 1 and 2 for a breakdown of the inputs. More details are provided in the assumptions and limitations.

DEVELOP QUESTIONNAIRE TO GATHER RELEVANT DATA

After defining the disasters and items, we developed a questionnaire in Excel to gather the required data for our joint objectives (measure GHG emissions, waste creation, response time, and costs, as well as to develop a system dynamics model to capture these over time). The survey covered each step of the supply chain to ensure a comprehensive overview and allowed us to identify specific points in the supply chains which significantly contribute to negative long-term consequences. In general, different data was required for the LCA (e.g., transport mode to calculate GHG emissions) than for the system dynamics model (e.g., lead time or financial costs). In some cases, data points fed both analyses (e.g., storage duration to capture the time aspect for the system dynamics model as well as to calculate the energy required for storage at that supply chain step in the LCA). The questionnaire was developed to capture all of this data within one file. Due to the extent and complexity of the required data, we worked with WFP and IFRC to revise the first version of the survey by clarifying specific points to facilitate ease of use for respondents (e.g., in-country offices). The revised file also included example responses and an accompanying description file, which explained the rationale behind each row and column.

Table 1: Material inputs and composition of the tarpaulin and packaging used for Case Studies 1 and 2.

	MATERIAL INPUTS	WEIGHT (KG)	SHARE OF TOTAL WEIGHT
TARPAULIN	High Density Polyethylene (HDPE) granulate	2.654	54.0%
	Low Density Polyethylene (LDPE) granulate	1.496	30.4%
	Masterbatch (MB) additives (white and grey)	0.290	5.9%
	Calpet	0.241	4.9%
	Calcium carbonate	*0.212*	*4.3%*
	HDPE granulate	*0.014*	*0.3%*
	LDPE granulate	*0.014*	*0.3%*
	Masterbatch (MB) additives (UV protection)	0.097	2.0%
	MB additives (black)	0.049	1.0%
	TARPAULIN WEIGHT (PER UNIT)	**4.825**	**98.2%**
PACKAGING	Pet straps	0.010	0.2%
	HDPE granulate	0.080	1.6%
	PACKAGING WEIGHT (PER UNIT)	**0.900**	**1.8%**
	TOTAL WEIGHT	**4.915**	**100%**

Table 2: Material inputs and composition of the CSB++ and packaging used for Case Study 3.

	MATERIAL INPUTS	WEIGHT (KG)	SHARE OF TOTAL WEIGHT
CSB++	Maize flour	0.822	47.8%
	Soybean flour	0.353	20.5%
	Dried skim milk powder	0.120	7.0%
	Refined soybean oil	0.045	2.6%
	Sugar	0.135	7.9%
	Fortification products	0.026	1.5%
	CSB++ WEIGHT (PER UNIT)	**1.500**	**87.2%**
PACKAGING*	Polyethylene (PE) packaging film	0.147	8.5%
	Aluminum	0.017	1.0%
	Cardboard	0.056	3.2%
	PACKAGING WEIGHT (PER UNIT)	**0.220**	**12.8%**
	TOTAL WEIGHT	**1.720**	**100%**

*Note: for the purpose of the study, packaging materials have been simplified to represent a metalized plastic (PE) packaging. In reality, the materials are a combination of three layers: (1) polyethylene terephthalate (PET); (2) metalized polyethylene terephthalate (met PET) which implies integrating metal in the PET layer (metalization); and (3) polyethylene (PE).

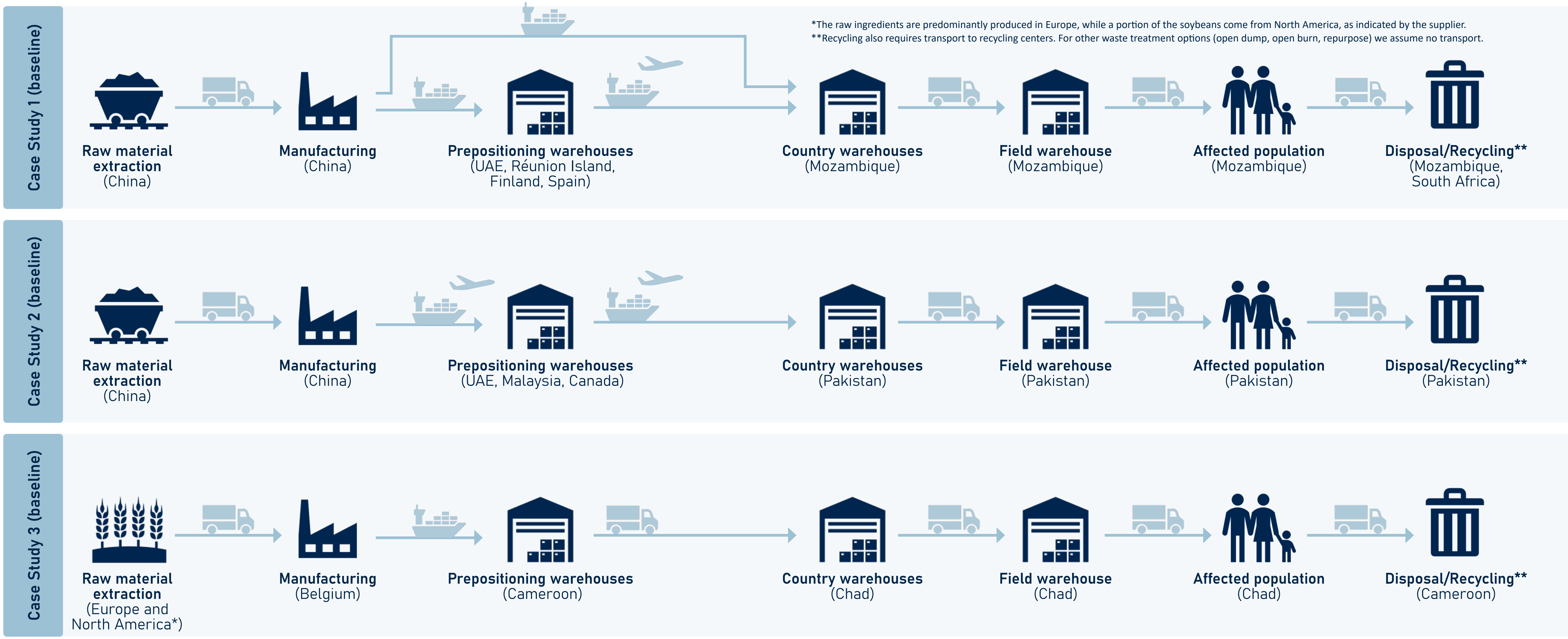

Fig. 7: Supply chains' steps for the baseline scenarios of Case Studies 1, 2, and 3.

COLLECT DATA ON OPERATIONS, WASTE, TIME, AND COSTS

Using the questionnaire, we collected data on the supply chains' steps and waste generated through specific disaster relief efforts to calculate GHG emissions, waste, and capture the dynamic relationship between variables within the response itself (e.g., lead time or frequency of shipment) for the selected case studies. We collected this data directly from suppliers (to model production and manufacturing of the items and packaging) and the HOs (to model transport, storage, and end-of-life). To calculate GHG emissions, we combined data on the operations (e.g., transporting the item 100 km with a 40' container truck) with the background data from the LCA database (EcoInvent) to measure the impact of the specific process, as described in Section 2. Essentially, the responses in the questionnaire on specific operations (foreground data) described which processes (background data) to model in the LCA to capture GHG emissions. Please see Figure 7 for an illustration of the baseline scenario for the end-to-end supply chain of each case study, which guided data collection requirements.

Starting at production and procurement, we gathered data differently for the two items. For the tarpaulin delivered by IFRC (Case Studies 1 and 2), we used the data generated by the "Eco-Design Tarpaulin Project," a joint initiative between the International Committee of the Red Cross (ICRC), the IFRC, and the UN Refugee Agency (UNHCR)[3]. The supplier that provided data for that project is the same which IFRC used for Case Studies 1 and 2. For CSB++, we used data on production and processing collected from a major European supplier of CSB++ for WFP (Case Study 3) that was gathered for a previous study[4]. Based on discussions with WFP, this was a suitable assumption for a supplier in the selected disaster, although this may not be generalizable to each case in the region. Data for the production of the items included the raw materials, energy, and required inputs to produce each item. For the tarpaulin, this consisted mostly of virgin plastics and energy used for production and storage (Table 1). For CSB++ this included agricultural production of the raw ingredients (assumed to be carried out under average industrialized production methods), inputs such as fertilizers, pesticides, seeds, water, and land, as well as the energy used on the farm and at the supplier for processing and storage. We also collected data on packaging materials and processes to model the production of packaging for both items. Furthermore, we collected data on the transport from raw material extraction/agricultural production to the suppliers.

3 Log Cluster (2023)
4 CHORD (2022)

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Following production, items were transported to different locations on their journey along the supply chain. To model transport, we collected data on the transport mode, capacity, distance traveled, lead time, and frequency of shipment. We also collected data on the cost per unit (e.g., 1 tarpaulin and its packaging) following the procurement of the item by the organization. Costs were not collected for the production and manufacturing, as this is embedded into the cost of the item in the further steps.

Once the items arrived at the various warehouses, they were stored for a specific number of days. To model these processes we collected data on the number of days products were stored, the energy source, and the number of items present in the warehouse at the time of the disaster. We modeled the electricity consumption for storage based on the average electricity required to store the item each day (kWh per m^2) multiplied by the number of days[5]. In the case of prepositioning this can be up to two years. Additionally, as with transport, we also collected data on the cost to store each unit for the indicated time duration. When the items reach the affected population they are used. Data collection for this process varies depending on the item. In the case of a non-food item, this may imply that there are no further inputs required to use the item (e.g., tarpaulins), and thus no data needs to be collected. For other items (e.g., lamps, stoves) the inputs of use may include fuel, electricity, or natural resources. Food items, on the other hand, will usually imply some sort of preparation or cooking. In the case of CSB++, we asked WFP about current cooking processes and took the assumption it was heated over open fire. Finally, at the end of the product's life cycle it reaches the end-of-life phase. Again, data collection for this step may vary depending on non-food vs. food item. For non-food items, we can assume that the item (or a portion of it) must be disposed of in addition to the packaging. For food items, we can assume that the food is consumed by the user and thus only the packaging requires end-of-life management.

We developed several scenarios to collect data on different disposal options: (1) open burning, (2) open dumping, (3) repurposing, (4) recycling. Open dumping refers to the disposal of waste in open areas, typically in uncontrolled or unauthorized locations, while open burning involves burning waste in the open air, often in uncontrolled or unregulated areas. For repurposing, no further data was required. Although we did not directly collect data on these processes from the HOs (as in reality the items have not yet reached the end-of-life phase) we confirmed that these could be reasonable assumptions for end-of-life management. We also collected data on the cost of recycling based on the literature[6]. Furthermore, we surveyed the HOs on the amount of waste generated in the supply chain (reported as a percentage of the total weight of the shipment) from procurement to the end-of-life to estimate the total waste volumes.

5 Lewczuk et al. (2021)

6 Bening (2022)

3.3 | MODEL DEVELOPMENT

In the next step, we calculated the GHG emissions of the operations according to the defined scope of the case studies using LCA, and fed this data into the system dynamics model, in addition to data on waste creation, lead times, and costs. The next paragraphs describe the model development steps using Case Study 2 (Pakistan) as an example.

First, our system started with the production of raw materials, including any inventory needed for the raw materials and respective inputs. Once the raw materials were extracted and produced, they were transported to the tarpaulin manufacturer based on procurement orders. After the tarpaulins were manufactured, they were packaged and prepared for transport. Packaging is important to prevent damage during transport and storage, but in the end, it becomes waste. Tarpaulins were also stored in the manufacturer's warehouses.

Next, the tarpaulins were procured by IFRC and transported to their warehouses (prepositioning, international, national, and local) using various modes of transportation (e.g., trucks, ships, or airplanes). Each mode of transport has different emission factors, so it was important for the model to differentiate between them. Furthermore, every warehouse consumes energy for storage, in which emissions needed to be calculated. We modeled each of these steps and their corresponding time, and costs. In terms of waste creation, both transportation and warehousing also contributed to waste and were considered in the model.

After distributing the tarpaulins to the affected population and passing its life span, the items reached the end-of-life phase (i.e., waste management). We modeled waste management in various ways (open dump, open burn, repurpose, or recycle). Each has different resultant emissions and trade-offs. Open burning, open dumping, and recycling implied some emissions, time, and cost associated with the waste treatment process (e.g., GHG emissions associated with burning). However, recycling also created recycled materials which can be used instead of virgin ones, potentially reducing emissions from production. For repurposing, no emissions, time, or costs was assumed as the waste is not transformed from its original state, but application may also be limited. We considered potential recycling centers in the countries or neighboring ones to measure the GHG emissions of recycling, and then compared it with other scenarios like open dump and open burn. For example, in Pakistan, there are several recycling plants that facilitate the recycling of items, like tarpaulins, made from HDPE (High Density Polyethylene) and LDPE (Low Density Polyethylene). These recycling centers can be found in the Plastic Recycling Plants in Pakistan, as listed in the ENF Recycling Directory[7]. We assumed that there are suitable recycling centers in the provinces of Punjab and Sindh and modeled that the tarpaulins were sent to one of these facilities after serving a useful lifespan of up to five years providing shelter[8].

It is important to remember that the lifespan of the tarpaulin is five years and the actual tarpaulins in these case studies have not yet reached the end-of-life phase. The scenarios were intended to represent what the inevitable impact would be according to potential waste treatment options of the specific disaster responses considering the ten-year scope of the system dynamics model (for the tarpaulins). We also confirmed with IFRC that they were suitable assumptions. For the CSB++, we modeled open dump, open burn, and repurpose[9] for the primary packaging (metalized plastic packaging film), while all four options were modeled for the secondary packaging (cardboard box) under the 700 day scope of Case Study 3. Unfortunately, the primary packaging of the CSB++ is not recyclable due to the complexities of separating the metal from the plastic[10], and thus this was not considered.

7 ENF (2023)
8 The tarpaulin is designed to last a minimum of 2 years. In many cases some have a lifespan of 10 years or more. We considered the average of five years after discussions with IFRC.
9 WFP (2023)
10 Joint Initiative (2023)

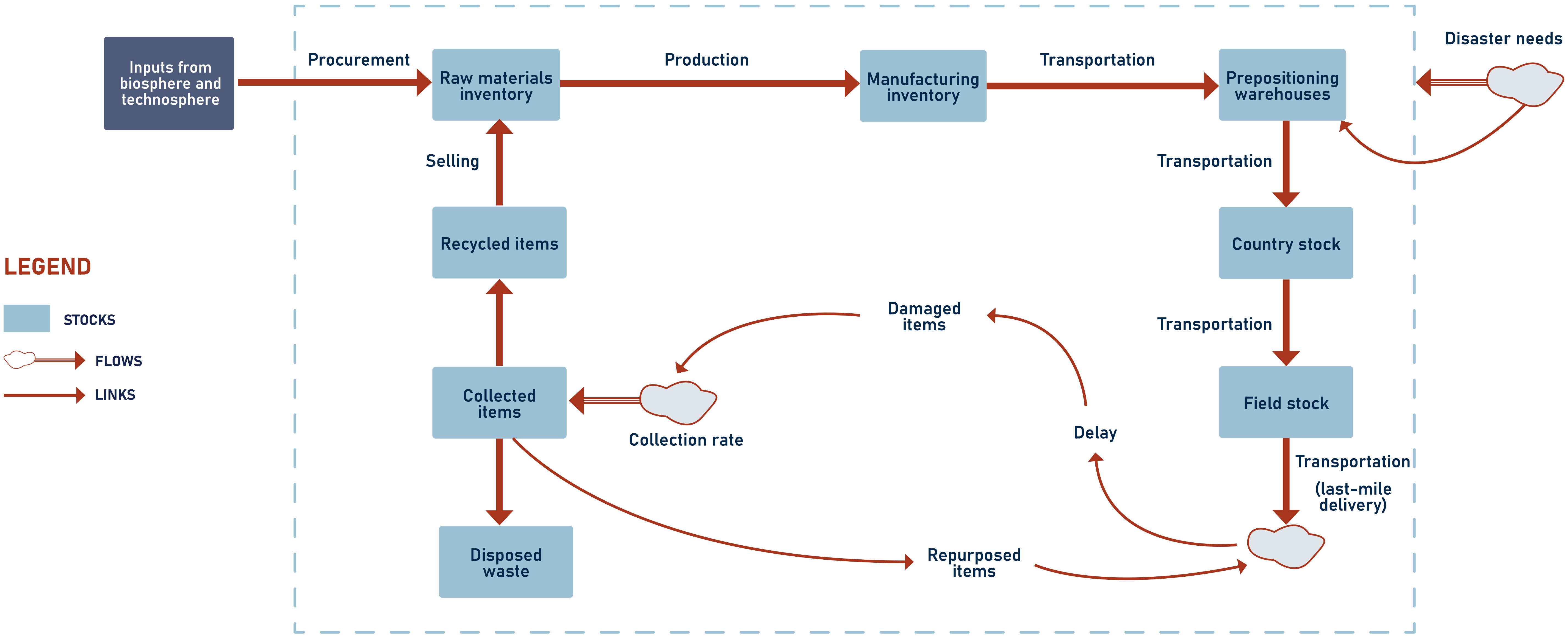

Fig. 8: Simplified representation of the structure of the system.

We modeled open burning and dumping to illustrate the emissions associated with waste management when there is a lack of infrastructure, and thus this step did not require transport to recycling centers. Although recycling is not currently practiced for the case study scenarios, we modeled this to provide insights on the potential for recycling to reduce environmental impacts. For Case Studies 1 (Mozambique) and 3 (Chad), we could not locate recycling centers in-country, and thus modeled the transport to recycling centers in neighboring countries in addition to the recycling process. For repurpose, we assumed no transportation to waste treatment and no disposal processes.

To better understand the dynamics of the supply chain, Fig. 8 illustrates a simplified representation of the system, which encompasses several key activities: procurement of raw materials, manufacturing, transportation, warehousing (e.g., prepositioning, global, national, or local), product use, collection of used products, recycling, and end-of-life. Stocks represent an accumulation of a quantity over time. Arrows represent links, which connect variables and indicate the direction of influence. By default, these are information links, representing the flow of information between variables, but they can also fill other functions such as that of a delayed link (described in Fig. 10). Flows connect levels and represent quantities transported between them. A flow has a source and a destination. If an end is unconnected, it has a cloud symbol at one end, indicating the source of the flow is outside the scope of the diagram or model. The upstream supply chain consisted of five levels: the raw material inventory, manufacturers' inventory, preposition centers' inventory, and country and local warehouses' inventory. We also assumed that the producers' demand for raw materials of non-food items is met through inputs from the bio- and technosphere, procured from external suppliers (procurement rate), and recycled materials were obtained from the recycling operations (recycling rate). By considering the interdependencies and feedback loops within the system, this methodology enabled us to model and analyze the behavior of the supply chain.

The causal loop diagram (CLD) in Fig. 9 illustrates the relationships between demand, order backlog, inventory, transportation, GHG emissions (CO_2 equivalent), waste, and the end-of-life fate of items in the context of the HSC. The red arrows have no difference from the blue arrows, except for facilitating the demonstration of larger loops (described later). The model begins with a disaster event and the affected population, which generates demand for humanitarian aid. The demand flows into the system, initiating a chain of interactions. The availability of emergency items in the field warehouses plays a crucial role in meeting the demand of the affected areas. If the inventory in the field warehouses is insufficient to meet the demand, it leads to an increase in the order backlog of the country's stock. To address this shortage, available items are transferred from country warehouses to field warehouses, refilling their inventory. However, these transportation activities contribute to GHG emissions and waste generation, with different modes implying varying emissions. Country warehouses, in turn, maintain their own inventory

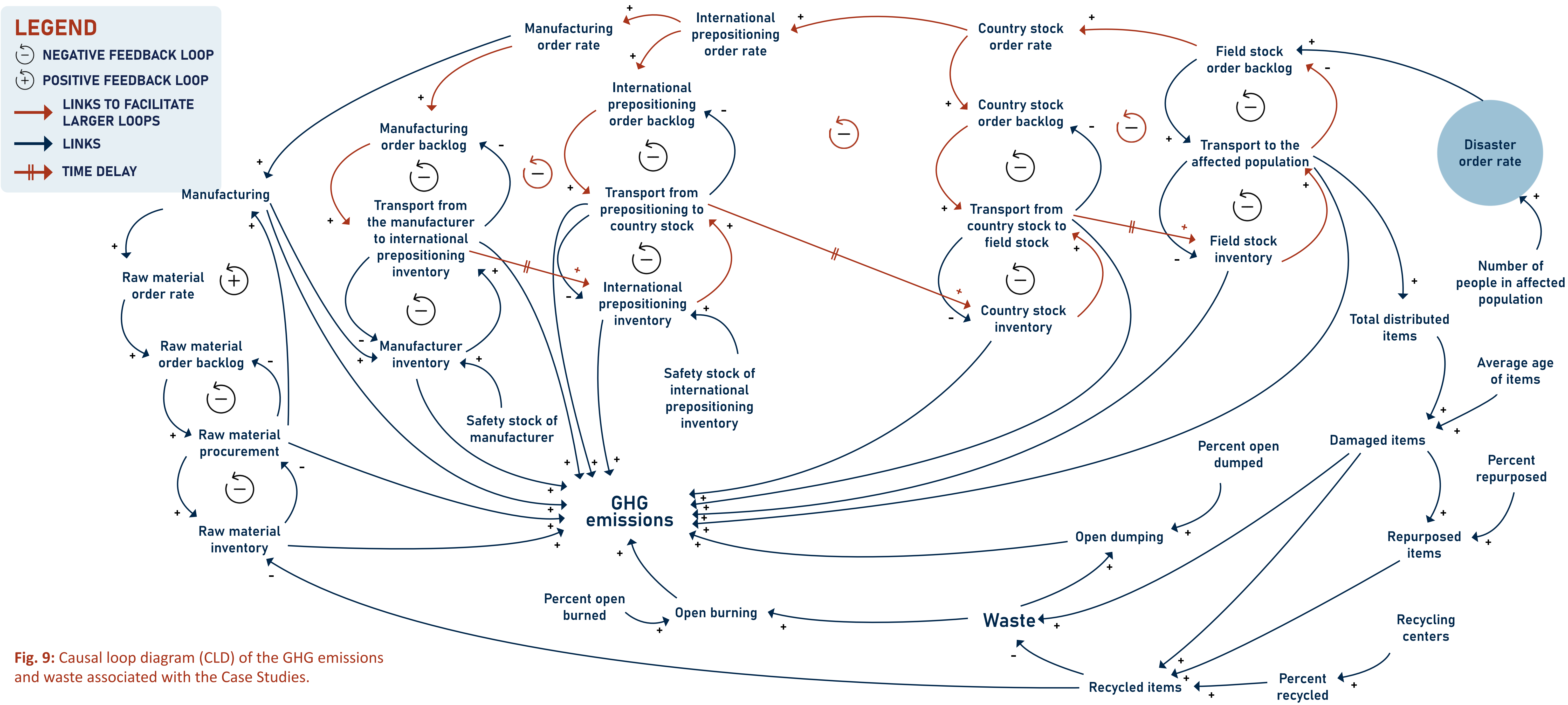

Fig. 9: Causal loop diagram (CLD) of the GHG emissions and waste associated with the Case Studies.

management and have their order backlog. When the demand from the field warehouses exceeds their inventory, it adds to their order backlog. To bridge the gap, they place orders to prepositioning warehouses to obtain the necessary items. The transportation and warehousing activities involved in fulfilling these orders contribute to GHG emissions and waste generation. Likewise, the prepositioning warehouses maintain and manage their inventory and order backlog. If their inventory is insufficient to meet the demand, the excess demand contributes to their order backlog. To fulfill the requirements, they place orders to manufacturing warehouses, which produce the needed items. Again, the transportation and manufacturing processes result in GHG emissions and waste generation. The manufacturing warehouses also have their inventory and order backlog. If there is a shortage of raw materials required for production, they must place orders to acquire the necessary materials. The transportation of raw materials and the manufacturing processes contribute to GHG emissions and waste generation. Different materials will also imply different environmental impacts.

At the end-of-life, items face different scenarios. Some options include repurposing the items for other uses, thus extending their life span and reducing waste. Unfortunately, many of these items may end up in environmentally harmful disposal practices like open burning or being discarded in open dump sites, contributing to pollution and health hazards. Another option at the end-of-life is recycling. Some portions of these items can be sent to recycling centers, where they are processed to extract valuable materials to use in the manufacturing of new products. This approach helps conserve resources, reduce the need for raw materials, and minimize the environmental footprint associated with extracting and processing virgin materials. Consideration of these options also implies several steps.

These relationships form feedback loops within the system, allowing for adjustments in inventory levels and order backlogs based on demand fluctuations and resource availability at each stage of the supply chain. The larger feedback loops depicted in the CLD illustrate the interconnected process of demand fulfillment and inventory replenishment across different levels of warehouses (field, country, international) and manufacturing facilities. This process is initiated by demand at the field warehouse level, which, if unable to be met by current inventories, triggers a chain of orders upstream, from country warehouses to international warehouses, and finally to manufacturers. Each step involves transportation activities that are necessary to replenish stocks and reduce order backlogs but also contribute to GHG emissions and waste.

Together, the feedback loops highlight the critical balance between operational efficiency in responding to humanitarian needs and the environmental impact of supply chain activities. They underscore the importance of strategic inventory management and the adoption of sustainable logistics practices to mitigate environmental impacts while ensuring timely aid delivery to affected populations. The significance of these loops also lies in their illustration of the supply chain's dynamics and the environmental challenges inherent in humanitarian logistics. By mapping out the relationships between demand, inventory levels, transportation, and environmental impacts, the CLD encourages a holistic view of humanitarian operations and facilitates a comprehensive understanding of the sustainability challenges in HSCs. In addition, the CLD also explores strategies to minimize GHG emissions and waste while also effectively meeting the needs of the disaster response.

Figures 10 and 11 illustrate the stock and flows related to the GHG emissions generated by waste treatment (Fig. 10) and the waste generated by recycling and waste treatment (Fig. 11). The diagrams consist of two main components: stocks and flows. Stocks represent the quantities of resources that are stored in various locations (e.g., warehouses or distribution centers). Flows represent the movement of resources between these locations and the factors that affect this movement (e.g., material and information delays). Tarpaulins, for example, typically have a lifespan of roughly five years, after which they require collection and management. A portion of these aging tarpaulins can be repurposed for other uses, extending their lifespan. Currently, many end up being improperly disposed of through methods like open burning or open dumping.

Our research explored various scenarios to assess the consequences of these choices on the tarpaulins' afterlife, with a focus on sustainability and responsible waste management. The rest of the stock and flow diagrams can be found in the Appendix, which provides a snapshot of the model and illustrates the stock and flow diagrams of GHG emissions associated with the rest of the steps along the end-to-end supply chain, including prepositioning, international and local procurement, warehousing, and last-mile delivery.

3.4 | MODEL TESTING AND VALIDATION

To validate the accuracy and reliability of the developed model, we conducted several tests, as recommended in the system dynamics literature[11]. These tests included checking the model's dimensional consistency to ensure that all equations were dimensionally coherent. Additionally, extreme-condition tests were performed to assess the model's behavior under large shocks and extreme scenarios. For example, we examined the model under conditions where there was no demand from the affected population, meaning no disaster and no return of used items. Furthermore, we simulated the model using historical data to verify its ability to replicate past system behavior. The results of these tests demonstrated that the model successfully replicated the observed behavior of the system.

For IFRC data, the simulations spanned 3650 days, equivalent to ten years, factoring in the average five-year lifespan of tarpaulins, and for the WFP data, the simulations spanned 700 days, encompassing the entire life cycle from the procurement of raw materials, through consumption, and concluding with the process of sending packages to recycling facilities. Moreover, since the shortest time constant in the model is set to 1 day and standard practice in system dynamics suggests that the integrating time step (DT) should be a maximum of 0.25 of the shortest time constant in the model[12], we set the DT initially at 0.2 days and ran the model. Then we cut the DT in half and ran the model again. The results did not significantly change, which confirmed the validity of modelling.

11 Bayer (2004)
12 Georgiadis and Besiou (2008)

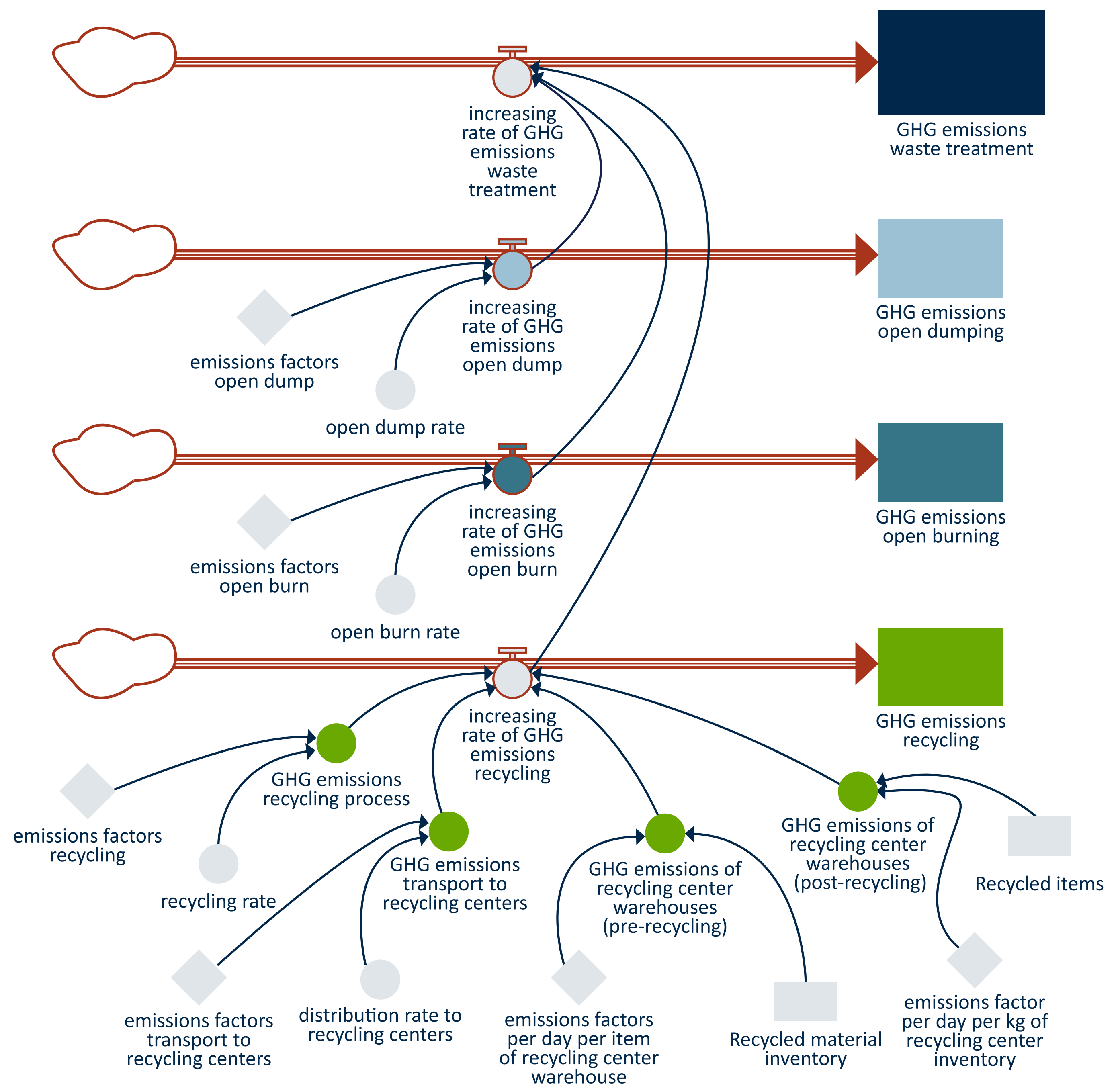

Fig. 10 Stock and flow diagram of the GHG emissions associated with waste.

LEGEND

STOCKS (LEVELS) | Accumulations of a quantity over time. They represent variables like population, capital, or inventory. Here, they represent GHG emissions (kg CO_2 eq.).

AUXILIARY VARIABLES | Used to encapsulate intermediate or calculated variables within a model. They are not part of the core stocks, flows, or constants but serve to perform calculations or transformations on these core variables for modeling and analysis.

CONSTANTS | Values that don't change over time, like parameters or fixed inputs.

FLOWS | Flows (rates) indicate the rate of change in a stock over time.

LINKS | Connect variables and indicate the direction of influence, and can show how changes in one affect the other. This can also be information flows.

TIME DELAY | Represent time lags in the system, where the effect of one variable on another is delayed.

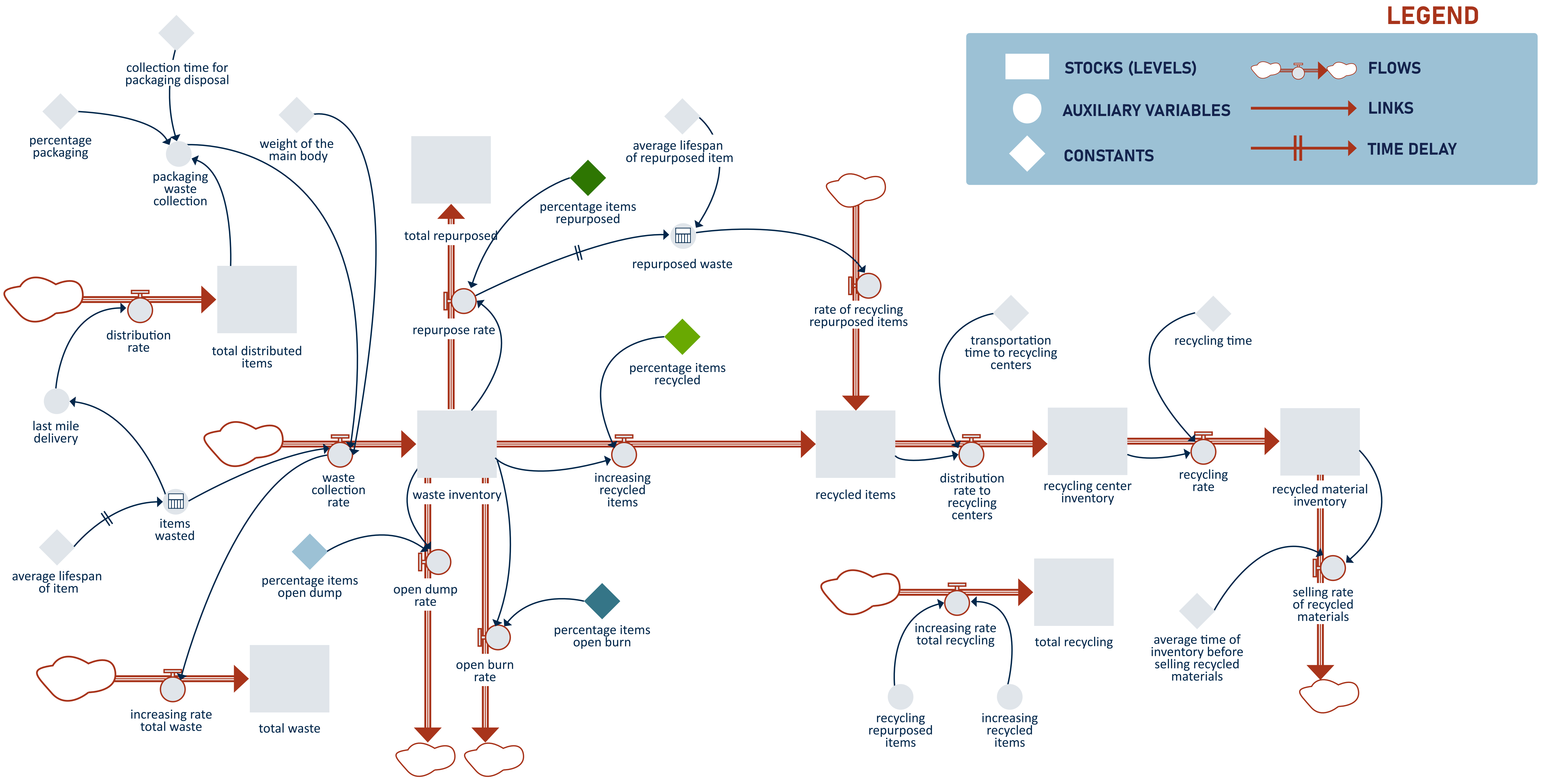

Fig. 11 Stock and flow diagram of the recycling and waste treatment section of the model.

This figure represents the **dynamics at play** when it comes to **waste generation and management** in humanitarian response. Although this is just one step of the supply chain, it serves to illustrate the **multitude of factors and feedback loops** that affect the overall performance of the system.

RESULTS AND DISCUSSION OF KEY FINDINGS

Section 4 in short

Understanding the potential to reduce GHG emissions and waste generated by humanitarian response is a key step to breaking the vicious cycle of humanitarian needs and climate change. In this section, we report the results of each case study according to different perspectives (GHG emissions, waste, response time, and costs) across multiple scenarios. Furthermore, we illustrate the potential for alternative operations to improve the environmental sustainability of response (e.g., transport mode, energy source, waste management strategies) and identify key trade-offs and considerations to support evidence-based decision-making.

4.1 | RESULTS

In the following sections we present the results of the various scenarios for each of the case studies. First, we report the results of the baseline scenario which represents the actual supply chain operations according to the identified processes (e.g., transporting the tarpaulins by air from Malaysia to Pakistan). Next, we describe several scenarios to illustrate the effect on GHG emissions, response time, financial costs, and waste generated when opting for alternatives. These include direct delivery from the manufacturer, increased prepositioning, integrating renewable energy (in most cases solar energy, except for the use of wind energy in Finland in Case Study 1) as a replacement for the local electrical grid or diesel generator during storage, substituting a plant protein (soy protein concentrate) for animal protein (dried skim milk power), in the case of the CSB++[1], as well as recycling or repurposing waste. It should be noted here that while we tested the effect of replacing diesel generators or the local electrical grid

1 Animal proteins generally have a higher environmental impact than plant-based versions. In the case of CSB++, the dried skim milk powder accounts for 80% of GHG emissions of the product, despite being just 8% of the weight.

with solar panels this may not be the best decision in some cases. Namely, in situations where the local electrical grid is reliable and comes predominantly from renewable energy (e.g., Kenya) it would most likely not have a large effect and imply unnecessary costs or emissions (to produce solar panels). In reality, investments in decentralized renewable energy would be better targeted to locations where diesel generators are relied on for a high percentage of energy demand. This was the case in regards to the in-country distribution for the three case studies. When we tested for the effects of recycling or repurposing, we assumed that 100% of the items are sent for the designated treatment (this was used to establish the upper bound of what is possible). For the tarpaulin, we modeled recycling the used tarpaulin and packaging. For the CSB++, we modeled recycling only the secondary packaging, while the primary packaging was repurposed.

Furthermore, there are various costs presented in the following sections. The "prepositioning cost" includes both the expense of transporting goods from the factory to the prepositioning warehouses and the cost of storing items in these warehouses, but does not cover the cost of purchasing the items. The broader context of "total cost," accounts for various elements, including purchasing cost of items, prepositioning costs (as described above), expenses related to national and field warehouses, transportation costs to the national and field warehouses, last-mile delivery, distribution costs, and recycling costs. For simplification, we omitted the detailed costs of national and field warehouses, as these remain relatively constant. Additionally, transportation costs are not explicitly listed in the table but can be derived by subtracting prepositioning, recycling, and fixed costs of national and field warehouses from the total.

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TOTAL NUMBER OF TARPAULINS DISTRIBUTED: **33,528**

CASE STUDY 1 SCENARIOS AND RESULTS

IFRC

TARPAULINS DELIVERED TO MOZAMBIQUE FOLLOWING FLOODS AND TROPICAL CYCLONES (2019)

Scenario 1 represented the baseline scenario in which 18% of the items were sent directly from the manufacturer in China to Mozambique. The rest of the items were distributed from the manufacturer by sea to prepositioning warehouses, where the tarpaulins were stored[1] before being sent to the country warehouse in Mozambique by the following modes and quantities: Dubai, UAE by air (27%), Réunion Island, FR by sea (21%), Tampere, FI by air (27%), and Las Palmas, ES by sea (7%). Once in country, the items were stored at the country warehouses for an average of 3 days before being sent to field warehouses and the affected population. Although data on disposal was limited, we assumed that 95% of the tarpaulins and packaging were sent to an open dump, while 5% to open burn. The total GHG emissions is 1,201,801 kg CO_2 eq. This scenario fulfilled 90% of the needs in 58 days, the total cost of the disaster response was 1,748,283 EUR, and the total waste of this scenario was 140,386 kg.

1 Prepositioning time is on average 485 days, but varies by location. Energy source is the local electrical grid.

Scenario 2 follows the same steps as the baseline scenario, except we tested the impact of recycling the entire tarpaulin and packaging instead of open dumping and burning. This leads to a 25% reduction in GHG emissions compared to the baseline scenario with little change to cost.

Scenario 3 substitutes solar panels for current energy sources used for storage (grid and diesel generators) which results in a 4% reduction in GHG emissions compared to the baseline scenario, and a slight increase in cost. The increase in cost takes into account both the up-front installation expenses and the reduction in energy costs of solar panels.

Scenario 4 models the potential to reduce GHG emissions if all items are transported exclusively by ship, leading to a 43% reduction in GHG emissions compared to the baseline scenario. It is important to note that this increases the response time by 29% and thus would also require improved planning, although costs are also reduced by 10%.

Scenario 5 tests the opposite, where all items are transported exclusively by air. This increases GHG emissions and costs by 40% and 9%, respectively, and reduces response time by 65%.

In **Scenario 6** direct transportation from the manufacturer in China to Mozambique is done by sea rather than air, resulting in a 40% reduction in GHG emissions and 67% reduction in costs. However, response time increases 89%, to 110 days

Scenario 7 is the same as Scenario 6, but also introduces recycling, resulting in a 64% reduction in GHG emissions compared to the baseline scenario.

Scenario 8 is also aligned with Scenario 6, except it models solar energy in addition to sea transport, resulting in a 40% reduction in GHG emissions compared to the baseline scenario (i.e., little impact with no prepositioning).

Scenario 9 models that all items are sent directly from the manufacturer in China to Mozambique by air. This increases GHG emissions significantly, but reduces response time and costs by 56% and 33%, respectively. It's essential to note that this scenario is only viable if the manufacturer has the necessary safety stock on hand and is willing to maintain the inventory for an extended period in case of a disaster.

Scenario 10 is aligned to Scenario 9, except that it also includes recycling practices, which still results in a large increase in GHG emissions.

Scenario 11 is similar Scenario 9, but with the addition of solar energy. Due to limited prepositioning in this new scenario, the impact of solar is minimal.

In **Scenario 12** the tarpaulins are delivered directly from the manufacturer, but 50% are transported by ship, while the remaining 50% are transported by air. This results in an increase in GHG emissions and response time, 33% and 35% respectively, but a 50% reduction in cost.

Scenario 13 is similar to Scenario 12, but also introduces recycling. This combination still results in an increase in GHG emissions, though now 9%, while response time and costs increase similar to the previous scenario.

Scenario 14 is aligned with Scenario 12, but includes solar energy to replace current sources. This provides little change compared to Scenario 12, as storage time is limited, similar to Scenario 11.

Scenario 15 models distribution exclusively through prepositioning warehouses, where 25% of the items are sent to each of the four locations (Dubai, Réunion Island, Tampere, and Las Palmas) by ship, and from these locations, they are transported by air to the disaster-affected country, leading to a 26% increase in GHG emissions but significant 63% reduction in response time.

Scenario 16 is similar to Scenario 15, but introduces recycling, which essentially cancels out the added impact of air transport as GHG emissions only increase by 1% compared to the baseline. Response time decreases by 63%, while costs increase by 22%.

Scenario 17 is also similar to Scenario 15, but introduces solar energy for storage, resulting in a 22% increase in GHG emissions and similar reduction in response time and costs as the previous scenario.

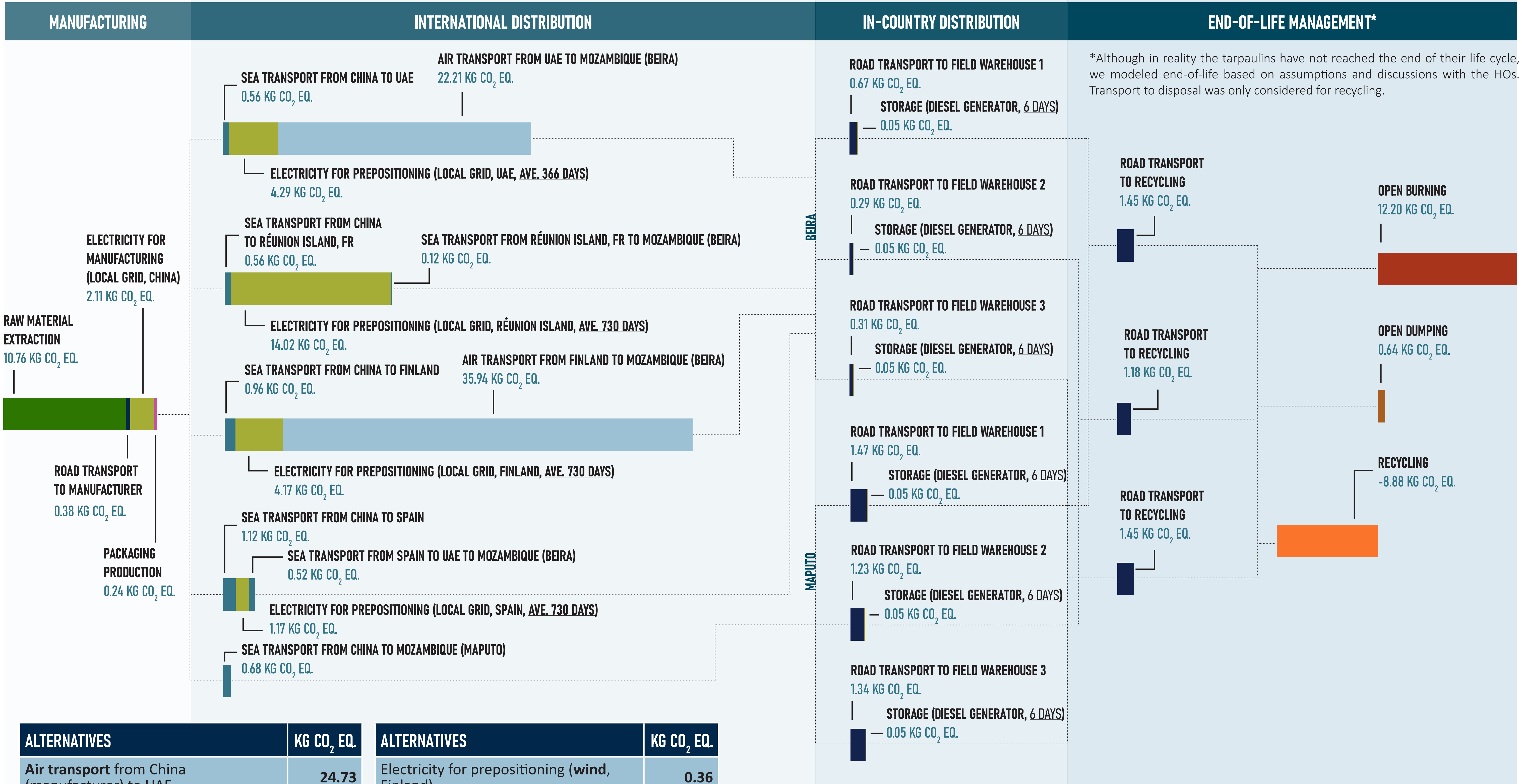
Scenario 18 is like Scenario 15, but items are also sent to Mozambique from the prepositioning warehouses by sea instead of air. This strategy results in a 43% reduction in GHG emissions, but response time increases by 41%. Costs stay relatively unchanged.

Scenario 19 is similar to Scenario 18, but this scenario introduces recycling, leading to a 68% reduction in GHG emissions compared to the baseline scenario. It combines prepositioning and recycling for a significant emissions reduction. However, it increases response time by 41%.

Scenario 20 is also aligned to Scenario 18, but with the implementation of solar energy, resulting in a 48% reduction in GHG emissions compared to the baseline scenario. Here, response time also increases by 41%, and costs by 8%.

Scenario 21 is similar to the baseline but includes substituting air transport for sea, and incorporating recycling, and solar energy (for storage). GHG emissions are reduced by 71% while response time increases by 29% and costs slightly increase by 3%.

Fig. 12 Total GHG emissions for one tarpaulin and packaging (total weight 4.92 kg) according to Case Study 1.



ALTERNATIVES	KG CO$_2$ EQ.
Air transport from China (manufacturer) to UAE	24.73
Electricity for prepositioning (**solar**, UAE)	0.51
Sea transport from UAE to Mozambique (Beira)	0.32
Air transport from China to Réunion Island, France	31.96
Electricity for prepositioning (**solar**, Réunion Island, France)	1.51
Air transport from Réunion Island, FR to Mozambique (Beira)	13.17
Air transport from China to Finland	27.26

ALTERNATIVES	KG CO$_2$ EQ.
Electricity for prepositioning (**wind**, Finland)	0.36
Sea transport from Finland to Mozambique (Beira)	0.77
Air transport from China to Spain	45.67
Electricity for prepositioning (**solar**, Spain)	1.30
Air transport from Spain to Mozambique (Beira)	30.12
Air transport from China to Mozambique (Beira)	52.95
Electricity for in-country storage (**solar**, **Mozambique**)	0.01

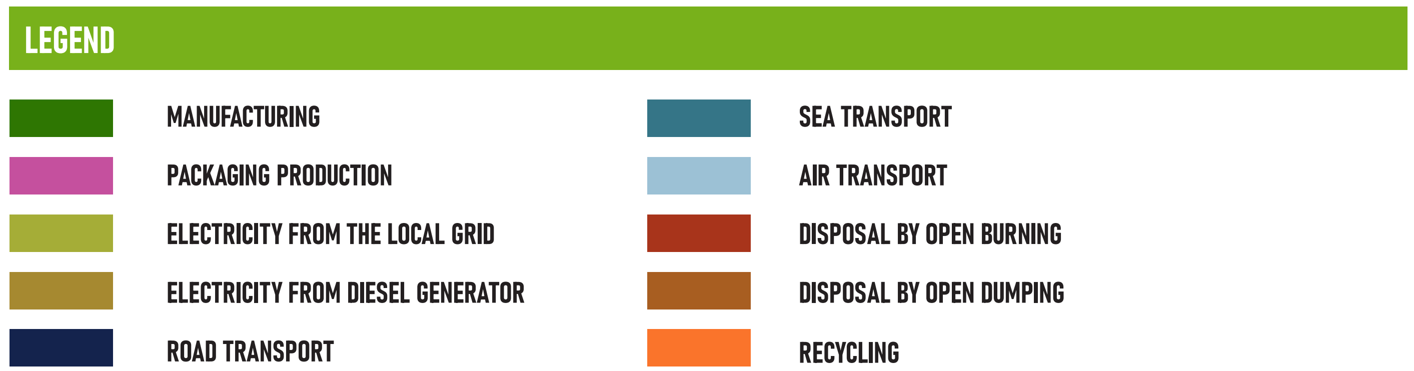


Table 3: GHG emissions, response time, and cost associated with scenarios developed for Case Study 1.

#	SCENARIO	GHG EMISSIONS (KG CO2 EQ.)	RESPONSE TIME (DAYS)	TOTAL COST (EURO)	PREPOSITIONING COST (EURO)	RECYCLING COST (EURO)	COMPARED TO THE BASELINE SCENARIO: REDUCTION IN GHG EMISSIONS	REDUCTION IN RESPONSE TIME	REDUCTION IN COST	REDUCTION IN WASTE
1	Baseline scenario	1,201,801	58	1,748,283	1,001,482	-				
2	Baseline scenario + recycling	907,156	58	1,790,333	1,001,482	116,662	25%	0%	-2%	100%
3	Baseline scenario + solar energy	1,155,111	58	1,827,585	1,078,688	-	4%	0%	-5%	0%
4	Baseline scenario + international transport by sea	685,450	76	1,577,576	1,002,846	-	43%	-29%	10%	0%
5	Baseline scenario + international transport by air	1,677,746	21	1,908,303	1,000,683	-	-40%	65%	-9%	0%
6	All items sent directly from manufacturer by sea	724,330	110	583,303	-	-	40%	-89%	67%	0%
7	Scenario 6 + recycling	430,224	110	625,273	-	116,428	64%	-89%	64%	100%
8	Scenario 6 + solar energy	723,525	110	585,400	-	-	40%	-89%	67%	0%
9	All items sent directly from manufacturer by air	2,475,135	26	1,170,814	-	-	-106%	56%	33%	0%
10	Scenario 9 + recycling	2,180,256	26	1,212,898	-	116,764	-81%	56%	31%	100%
11	Scenario 9 + solar	2,474,330	26	1,172,911	-	-	-106%	56%	33%	0%
12	Scenario 9, but 50% by sea and 50% by air	1,599,969	79	877,058	-	-	-33%	-35%	50%	0%
13	Scenario 12 + recycling	1,305,477	79	919,086	-	116,596	-9%	-35%	47%	100%
14	Scenario 12 + solar	1,599,164	79	879,155	-	-	-33%	-35%	50%	0%
15	All items sent to prepositioning (25% each) by air	1,514,483	22	2,097,473	1,222,586	-	-26%	63%	-20%	0%
16	Scenario 15 + recycling	1,219,567	22	2,139,563	1,222,586	116,781	-1%	63%	-22%	100%
17	Scenario 15 + solar	1,463,491	22	2,193,663	1,316,678	-	-22%	63%	-25%	0%
18	All items sent to prepositioning (25% each) by sea	679,351	82	1,798,681	1,225,017	-	43%	-41%	-3%	0%
19	Scenario 18 + recycling	384,974	82	1,840,691	1,225,017	116,546	68%	-41%	-5%	100%
20	Scenario 18 + solar energy	627,754	82	1,895,061	1,319,301	-	48%	-41%	-8%	0%
21	Baseline scenario + ship + recycling + solar	344,054	76	1,699,006	1,080,160	116,573	71%	-29%	3%	100%

TOTAL NUMBER OF TARPAULINS DISTRIBUTED: **10,500**

CASE STUDY 2 SCENARIOS AND RESULTS

TARPAULINS DELIVERED TO PAKISTAN FOLLOWING MONSOON RAIN AND FLOODS (2022)

IFRC

Scenario 1 represented the baseline scenario, where 90% of the tarpaulins were sent by sea from the manufacturer in China to prepositioning centers in Dubai, UAE (20%) and Port Klang, MY (70%). The last 10% were provided as in-kind donations from Ottawa, CA directly to Pakistan by air. We assumed the tarpaulins were sent from the same manufacturer in China to Canada, and then directly on to Pakistan without any significant storage in Canada. This was confirmed with IFRC. The items in Dubai were prepositioned for 48 days before being sent by sea to Pakistan. In Port Klang, they were prepositioned for 503 days before being flown in. Once in Pakistan, the tarpaulins were stored for 3 days before being sent to field warehouses, and then finally the affected population by road. As with Case Study 1, we assumed 95% of the tarpaulins and packaging were sent to an open dump, while 5% were sent to an open burn. The total GHG emissions was 275,686 kg CO_2 eq., response time was 63 days, the total cost of the disaster response was 557,559 EUR, and the total waste of the baseline scenario was 44,100 kg.

Scenario 2 is similar to Scenario 1, but introduces recycling, which reduces GHG emissions by 35%, leaving costs and response time relatively unchanged.

Scenario 3 is aligned to Scenario 1 but integrates solar energy for storage, leading to a reduction in GHG of 8%.

Scenario 4 involves direct transportation from China to Pakistan by air, without prepositioning. This results in a significant increase in GHG emissions, more than doubling those of the baseline scenario. However, it reduces response time by 66%. As with the previous case study, this is viable only if manufacturers can maintain safety inventory for extended periods in case a disaster happens. The reduced cost is due to the absence of prepositioning warehouses for HOs.

Scenario 5 is the same as Scenario 4, but includes recycling. Costs and response time improve, but GHG emissions significantly increase by 92%.

Scenario 6 is aligned to Scenario 4, but solar energy is considered. However, the impact on GHG emissions reduction is limited, as there is no prepositioning, and thus shorter storage times.

Scenario 7 assumes all tarpaulins are sent from China to Pakistan by ship, including in-kind donations. The result is a 20% reduction in GHG emissions and significant 67% reduction in costs.

Scenario 8 is similar to Scenario 7, but this scenario also introduces recycling. GHG emissions and costs are reduced by 54% and 65% respectively.

Scenario 9 is similar to Scenario 7, but this scenario introduces solar energy for storage. Since there is a limited inventory, the impact of solar panels on GHG emissions reduction is minimal.

Scenario 10 is aligned to Scenario 7, but 50% of are shipped and 50% are transported by air directly from China to Pakistan. Costs and response time are reduced, but GHG emissions increase by 53%.

Scenario 11 is the same as Scenario 10, but includes recycling. Even with recycling, the high usage of air transportation over long distances cannot fully compensate for GHG emissions, which increase 19%.

Scenario 12 is similar to Scenario 10, but with solar energy for storage. Again, with no prepositioning, the impact of solar energy is minimal.

Scenario 13 involves prepositioning 50% of items in Dubai and 50% in Port Klang by sea, followed by air transportation to Pakistan. While response time decreases by 78%, costs and GHG emissions increase by 25% and 24%, respectively.

Scenario 14 is like Scenario 13, but includes recycling. With recycling, GHG emissions reduce by 10% compared to the baseline with a similar change in costs and response time as in Scenario 13.

Scenario 15 is similar to Scenario 13, but with solar energy for storage. The total GHG emissions still increase, though less than in Scenario 13.

Scenario 16 is aligned with Scenario 13, but assumes that the tarpaulins are also sent by sea from the prepositioning warehouses to Pakistan. This results in a 21% and 14% decrease in GHG emissions and response time, respectively

Scenario 17 is the same as the previous scenario but also includes recycling, resulting in a significant 56% reduction in GHG emissions.

Scenario 18 is also aligned to Scenario 16, but includes solar energy for storage, resulting in a 29% reduction in GHG emissions.

In **Scenario 19**, 40% of items are prepositioned in Dubai, 40% in Port Klang, and 20% are in-kind donations from Ottawa, all transported by air to Pakistan. GHG emissions increases by 49%, primarily due to air transportation, especially from Canada. The response time decreases by 75%, however.

Scenario 20 is similar to Scenario 19, but includes recycling practices. Recycling compensates for air transportation but is not enough to fully offset GHG emissions compared to the baseline scenario.

Scenario 21 is also aligned to Scenario 19, but introduces solar energy. While solar panels have an impact, recycling offers a greater reduction in GHG emissions with a smaller investment.

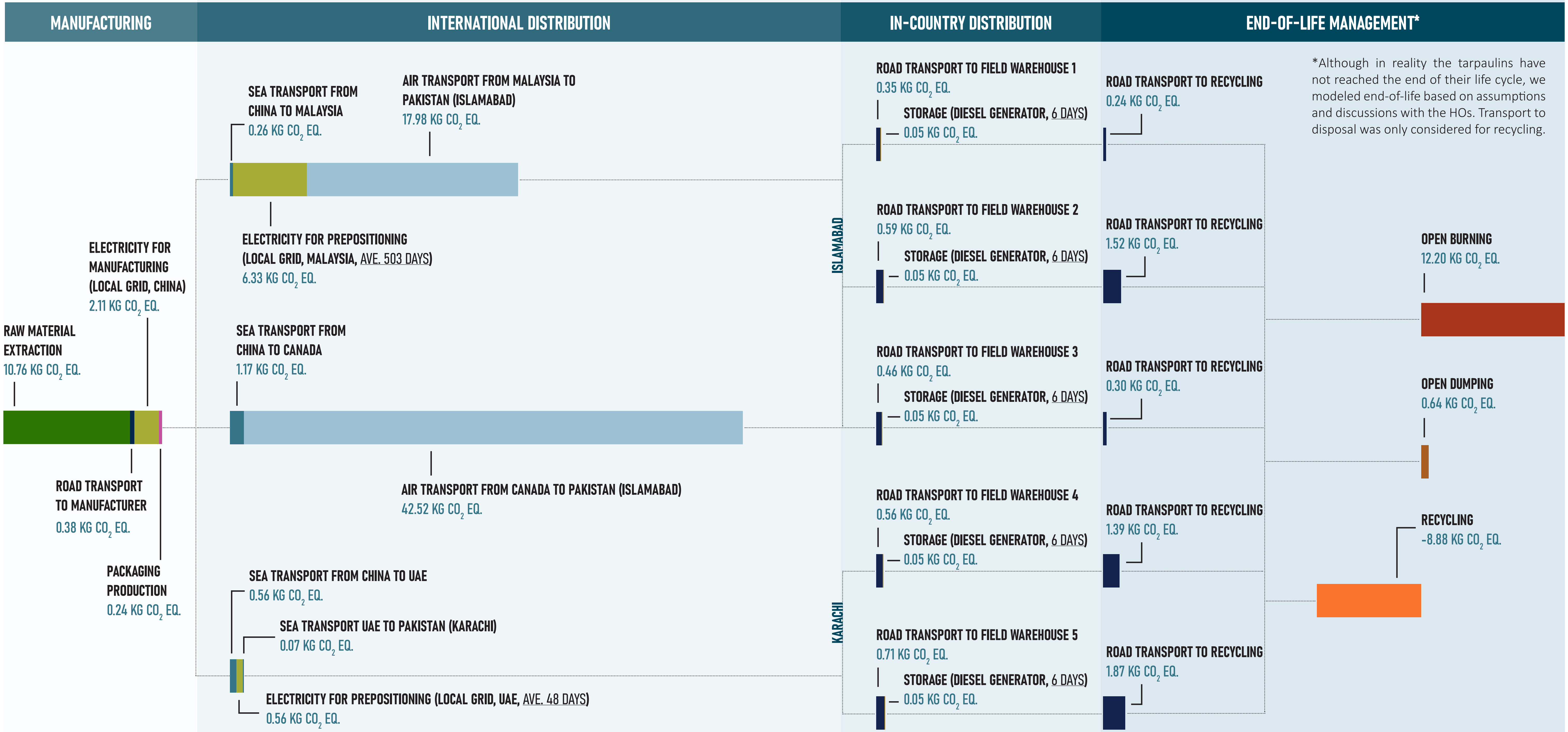
Scenario 22 is the same as Scenario 19, but all items are sent by ship instead of air. GHG emissions are reduced by 20%, while the costs and response time also improve by 12% and 4%, respectively.

Scenario 23 is similar to Scenario 22, but this scenario incorporates recycling. The combination of shipping items from long distances and prepositioning reduces GHG emissions by 54%.

Scenario 24 is also aligned to Scenario 22, but this scenario introduces solar energy for storage, which results in a 27% decrease in GHG emissions.

Scenario 25 is similar to the baseline scenario, but substitutes only with sea transport and includes recycling and solar energy. GHG emissions are reduced by 63%, while response time and costs slightly increase.

Fig. 13 Total GHG emissions for one tarpaulin and packaging (total weight 4.92 kg) according to Case Study 2.



ALTERNATIVES	KG CO_2 EQ.
Air transport from China (manufacturer) to Malaysia	16.52
Electricity for prepositioning (**solar**, Malaysia)	1.04
Sea transport from Malaysia to Pakistan (Karachi) + **road transport** to Islamabad	1.53
Air transport from China to Canada	42.99
Sea transport from Canada to Pakistan (Karachi) + **road transport** to Islamabad	2.06
Air transport from China to UAE	24.73
Electricity for prepositioning (**solar**, UAE)	0.11
Air transport from UAE to Pakistan (Karachi)	5.46
Sea transport from China to Pakistan (Karachi)	0.51
Air transport from China to Pakistan (Karachi)	20.63
Electricity for in-country storage (**solar**, Pakistan)	0.01

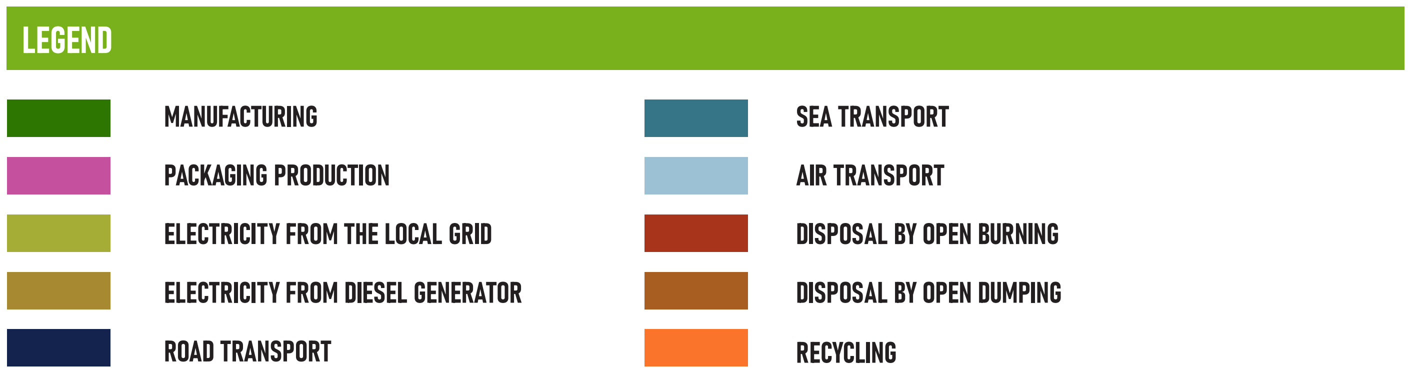


Table 4: GHG emissions, response time, and cost associated with scenarios developed for Case Study 2.

#	SCENARIO	GHG EMISSIONS (KG CO2 EQ.)	RESPONSE TIME (DAYS)	TOTAL COST (EURO)	PREPOSITIONING COST (EURO)	RECYCLING COST (EURO)	COMPARED TO THE BASELINE SCENARIO: REDUCTION IN GHG EMISSIONS	REDUCTION IN RESPONSE TIME	REDUCTION IN COST	REDUCTION IN WASTE
1	Baseline scenario	275,686	63	557,559	353,993	-				
2	Baseline scenario + recycling	180,304	63	570,756	353,993	36,685	35%	0%	-2%	100%
3	Baseline scenario + solar energy	254,066	63	585,802	381,579	-	8%	0%	-5%	0%
4	All items sent directly from manufacturer by air	624,254	21	363,441	-	-	-126%	66%	35%	0%
5	Scenario 4 + recycling	528,859	21	376,640	-	36,691	-92%	66%	32%	100%
6	Scenario 4 + solar energy	624,002	21	364,098	-	-	-126%	66%	35%	0%
7	All items sent directly from manufacturer by sea	221,419	67	182,568	-	-	20%	-6%	67%	0%
8	Scenario 7 + recycling	126,041	67	195,765	-	36,684	54%	-6%	65%	100%
9	Scenario 7 + solar energy	221,167	67	183,225	-	-	20%	-6%	67%	0%
10	Scenario 7, but 50% by sea and 50% by air	422,836	48	273,005	-	-	-53%	23%	51%	0%
11	Scenario 10 + recycling	327,450	48	286,203	-	36,687	-19%	23%	49%	100%
12	Scenario 10 + solar energy	422,584	48	273,662	-	-	-53%	23%	51%	0%
13	All items sent to prepositioning (50% each) by air	342,454	14	696,470	389,440	-	-24%	78%	-25%	0%
14	Scenario 13 + recycling	247,057	14	709,655	389,440	36,692	10%	78%	-27%	100%
15	Scenario 13 + solar energy	321,711	14	727,473	419,786	-	-17%	78%	-30%	0%
16	All items sent to prepositioning (50% each) by sea	216,924	54	572,003	391,272	-	21%	14%	-3%	0%
17	Scenario 16 + recycling	121,541	54	585,200	391,272	36,686	56%	14%	-5%	100%
18	Scenario 16 + solar energy	195,839	54	603,149	421,761	-	29%	14%	-8%	0%
19	80% sent to prepositioning, 20% in-kind by air	410,126	16	592,500	311,580	-	-49%	75%	-6%	0%
20	Scenario 19 + recycling	314,730	16	605,699	311,580	36,692	-14%	75%	-9%	100%
21	Scenario 19 + solar	389,290	16	617,434	335,857	-	-41%	75%	-11%	0%
22	80% sent to prepositioning, 20% in-kind by sea	221,689	60	492,927	313,047	-	20%	4%	12%	0%
23	Scenario 22 + recycling	126,307	60	506,124	313,047	36,685	54%	4%	9%	100%
24	Scenario 22 + solar	200,540	60	517,977	337,439	-	27%	4%	7%	0%
25	Baseline scenario + ship + recycling + solar	101,660	68	576,029	381,686	36,684	63%	-7%	-3%	100%

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TOTAL NUMBER OF CSB++ DISTRIBUTED: **735,956**

CASE STUDY 3 SCENARIOS AND RESULTS

SUPER CEREAL PLUS (CSB++) DELIVERED TO CHAD FOLLOWING FLOODS (2022)

Scenario 1 is the baseline scenario, where all items were sent from the supplier in Belgium to Cameroon by ship. The CSB++ was stored in Cameroon for 60 days before being delivered by road to Chad. Once in country, it was stored for 15 days before being sent to field warehouses by road. It was then stored for an additional 30 days before being distributed by road to the affected population. The energy source for storage needs in the country warehouse was the electrical grid, while diesel generators were used in the field warehouses. The contents of the CSB++ was cooked over open wood fire and the packaging was sent to end-of-life. We assumed 95% was sent to open dump and 5% to open burn. The total GHG emissions was 5,133,522 kg CO_2 eq., the response time, 120 days, the total cost of the disaster response was 12,814,923 EUR, and the total waste (primary and secondary packaging) was 169,875 kg.

Scenario 2 is the same as Scenario 1, except that the primary packaging is repurposed (as mentioned previously) and the secondary packaging is recycled. This results in a 97% reduction in waste. The 3% of leftover waste was generated during earlier steps of the supply chain and not eligible for recycling or repurpose in-country.

Scenario 3 is the same as Scenario 1, but includes solar energy instead of the electrical grid and diesel generators for storage, leading to a reduction in GHG emissions by 7% and increase in costs by 7%, as well.

Scenario 4 evaluates the potential to reduce the GHG footprint when substituting the dried skim milk powder in the CSB++ (which results in significant GHG emissions) with a soy protein concentrate. This substitution results in a remarkable 43% reduction in GHG emissions, highlighting the potential environmental benefits of substituting plant-based proteins for animal proteins. In this case, response time and waste remain the same. We were able to find information on global prices for dried skim milk powder, but this was much more complex for soy protein concentrate, and thus the price change was not included in the model. More details are provided in the assumptions and limitations.

Scenario 5 combines all three alternatives: solar, soy protein concentrate, and recycling and repurposing. This leads to a 50% reduction in GHG emissions, and 97% reduction in waste.

In **Scenario 6** all items are sent from the supplier in Belgium to Cameroon by ship (as in the baseline), but then sent by air from Cameroon to Chad. We modeled this option because the current lead time from Cameroon to Chad by road is 50 days. This scenario results in a 21% and 29% increase in GHG emissions and costs, respectively, but a significant 86% reduction in response time.

Scenario 7 is the same as Scenario 6, but also includes recycling and repurposing the packaging. The results on GHG emissions, response time, and costs minimally change from the previous scenario, but waste is reduced by 97%.

Scenario 8 is similar to Scenario 6, but includes solar energy. Costs and response time remain aligned to Scenario 6, but GHG emissions are slightly reduced, resulting in an increase of 15%, instead of 21%.

Scenario 9 is also aligned with Scenario 6, but the soy protein concentrate is substituted for the dried skim milk powder. This results in a 21% decrease in GHG emissions and 86% decrease in response time.

Scenario 10 is the same as Scenario 6, but combines all three alternatives: solar, soy protein concentrate, and recycling and repurposing. This results in a 28% reduction in GHG emissions, 86% reduction in response time, and 97% decrease in waste compared to the baseline. Costs, however, do increase by 36%.

Scenario 11 models direct distribution from the supplier in Belgium to Chad by air. This results in a 9% increase in GHG emissions, but 77% and 73% decrease in response time and costs, respectively.

Scenario 12 is the same as Scenario 11, but includes recycling and repurposing. This leads to minimal change from the previous scenario, except that waste is reduced by 100% (air travel had no waste).

Scenario 13 is the same as Scenario 11, but includes solar energy for storage and little change from Scenario 11 due to the limited storage time.

Scenario 14 is the same as Scenario 11 but includes the substitution of the soy protein concentrate for the dried skim milk powder. This results in a notable 34% reduction in GHG emissions, and a 77% and 73% reduction in response time and costs, respectively.

Scenario 15 is also the same as Scenario 11 but combines all three alternatives: solar, soy protein concentrate, and recycling and repurposing. This option results in a 34% decrease in GHG emissions, 77% reduction in response time, 72% decrease in costs, and 100% reduction of waste.

Scenario 16 assumes that 50% of items are sent through prepositioning in Cameroon and 50% are sent directly by air to Chad. This results in a 5% increase in GHG emissions, but a 29% and 37% reduction in response time and costs, respectively.

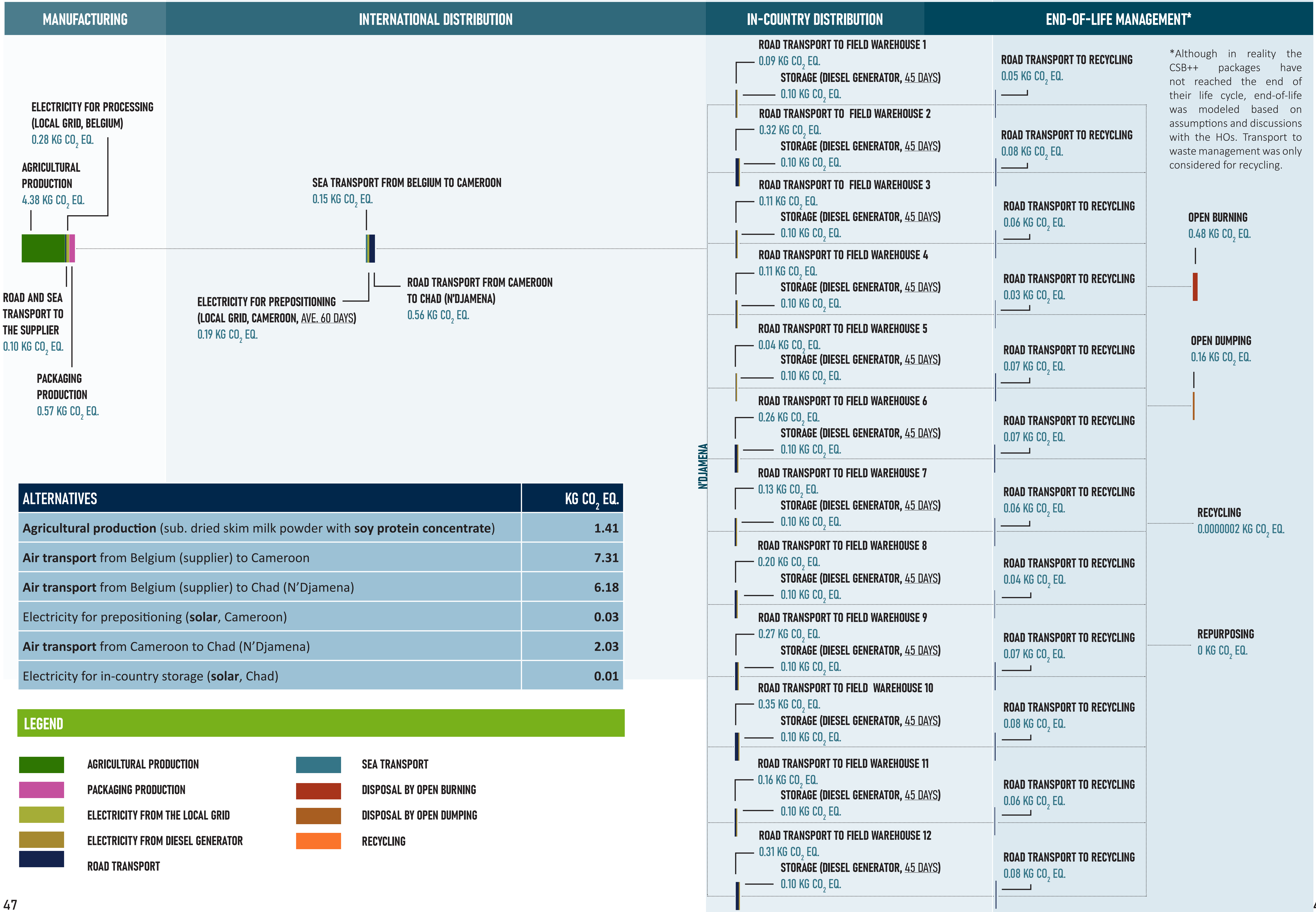
Scenario 17 is aligned with Scenario 16, but includes recycling and repurposing, resulting in little change compared to the previous scenario except a 98% reduction in waste.

Scenario 18 is the same as Scenario 16, but incorporates solar energy. GHG emissions are slightly reduced compared to the previous scenario.

Scenario 19 is also aligned with Scenario 16, but the soy protein concentrate is substituted for the dried skim milk powder. The GHG emissions, response time, and costs decrease by 39%, 29%, and 37%, respectively.

Scenario 20 is the same as Scenario 16, but combines all three alternatives: solar, soy protein concentrate, and recycling and repurposing waste. This results in a 42% decrease in GHG emissions, 29% reduction in response time, 33% decrease in costs, and 98% decrease in waste compared to the baseline scenario.

Fig. 14 Total GHG emissions for one unit CSB++ and packaging (total weight 1.72 kg) according to Case Study 3.



ALTERNATIVES	KG CO_2 EQ.
Agricultural production (sub. dried skim milk powder with **soy protein concentrate**)	1.41
Air transport from Belgium (supplier) to Cameroon	7.31
Air transport from Belgium (supplier) to Chad (N'Djamena)	6.18
Electricity for prepositioning (**solar**, Cameroon)	0.03
Air transport from Cameroon to Chad (N'Djamena)	2.03
Electricity for in-country storage (**solar**, Chad)	0.01

Table 5: GHG emissions, response time, and cost associated with scenarios developed for Case Study 3.

#	SCENARIO	GHG EMISSIONS (KG CO2 EQ.)	RESPONSE TIME (DAYS)	TOTAL COST (EURO)	PREPOSITIONING COST (EURO)	RECYCLING COST (EURO)	COMPARED TO THE BASELINE SCENARIO: REDUCTION IN GHG EMISSIONS	REDUCTION IN RESPONSE TIME	REDUCTION IN COST	REDUCTION IN WASTE
1	Baseline scenario	5,133,522	120	12,814,923	10,847,359	-				
2	Baseline scenario + recycling + repurpose	5,122,700	120	12,863,163	10,847,359	134,830	0.31%	0%	0%	97%
3	Baseline scenario + solar energy	4,788,845	120	13,697,668	11,711,007	-	7%	0%	-7%	0%
4	Baseline scenario + soy protein concentrate (SPC)	2,946,221	120	12,814,923	10,847,359	-	43%	0%	0%	0%
5	Baseline scenario + recycling + repurpose + solar + SPC	2,590,721	120	13,745,908	11,711,007	134,830	50%	0%	-7%	97%
6	Baseline scenario + air from Cameroon to Chad	6,223,055	17	16,561,950	10,818,708	-	-21%	86%	-29%	0%
7	Scenario 6 + recycling + repurpose	6,212,229	17	16,610,264	10,818,708	135,360	-21%	86%	-30%	97%
8	Scenario 6 + solar energy	5,882,946	17	17,442,410	11,680,064	-	-15%	86%	-36%	0%
9	Scenario 6 + SPC	4,035,754	17	16,561,950	10,818,708	-	21%	86%	-29%	0%
10	Scenario 6 + recycling + repurpose + solar + SPC	3,684,818	17	17,490,724	11,680,064	135,360	28%	86%	-36%	97%
11	All items sent directly from supplier by air	5,574,929	28	3,490,505	-	-	-9%	77%	73%	3%
12	Scenario 11 + recycling + repurpose	5,564,103	28	3,538,817	-	135,341	-8%	77%	72%	100%
13	Scenario 11 + solar	5,569,778	28	3,509,609	-	-	-8%	77%	73%	3%
14	Scenario 11 + SPC	3,387,742	28	3,490,505	-	-	34%	77%	73%	3%
15	Scenario 11 + recycling + repurpose + solar + SPC	3,371,764	28	3,557,921	-	135,341	34%	77%	72%	100%
16	50% to prepositioning by sea, 50% direct by air	5,365,183	85	8,108,459	5,379,424	-	-5%	29%	37%	1%
17	Scenario 16 + recycling + repurpose	5,354,359	85	8,156,737	5,379,424	135,109	-4%	29%	36%	98%
18	Scenario 16 + solar	5,190,012	85	8,555,843	5,807,708	-	-1%	29%	33%	1%
19	Scenario 16 + SPC	3,152,647	85	8,108,459	5,379,424	-	39%	29%	37%	1%
20	Scenario 16 + + recycling + repurpose + solar + SPC	2,966,651	85	8,604,121	5,807,708	135,109	42%	29%	33%	98%

4.2 | DISCUSSION OF KEY FINDINGS

The results indicate numerous interesting key findings. Across all case studies, it's clear that focusing on improving one perspective (e.g., GHG emissions) may have a negative impact on others (e.g., costs or response time). Understanding how these decisions are interconnected within the dynamic and complex environment of disaster response is key to supporting evidence-based decision-making and a long-term strategy to reduce the environmental impacts of HSCs, while also considering social (e.g., saving lives through faster response) and economic (e.g., reducing financial costs) sustainability.

Furthermore, it is important to note that the disaster context, item delivered (e.g., food vs. non-food item), and supply chain structure also have a significant impact on the results. Thus, identifying what solutions fit best to the specific context is also a crucial step and there is not necessarily a "one-size-fits-all" approach to environmental sustainability. Figures 15, 16, and 17 illustrate the change in GHG emissions, response time, cost, and waste for the scenarios with the greatest reduction in GHG emissions and waste compared to the baseline scenario. You may notice that while GHG emissions and waste dramatically decrease for all three case studies, response time and costs don't always follow. In the next sections, we discuss the results considering these different perspectives and identify key considerations for the various approaches.

GHG EMISSIONS

GHG emissions are embedded in nearly every step of the supply chain. The only exception in our case is the use phase for the tarpaulins and the repurposing of the CSB++ primary packaging, as we assume no additional processes take place during these steps. However, some operations clearly contribute to significantly higher GHG emissions than others. Starting at procurement, in Case Study 3 we tested for the potential to reduce GHG emissions by substituting the high impact (animal-based) dried skim milk powder for a (plant-based) soy protein concentrate. Despite representing just a small percent of the weight (7%), the dried skim milk powder contributed to 80% of the overall GHG emissions associated with producing the raw agricultural items for the CSB++. In this case, opting for the soy protein concentrate and keeping all other supply chain operations the same resulted in a 43% reduction in GHG emissions compared to the baseline (Scenario 4). Thus, HOs should also consider the impact of the ingredients chosen for food response during procurement. However, this should always be taken with consideration to nutritional requirements. Understanding the potential for lower impact ingredients to meet these demands in addition to reducing the environmental footprint of operations is a key step moving forward, as hunger is also continuously on the rise. The role of plant-based ingredients, which generally have a lower environmental impact (e.g., GHG emissions, soil degradation, and water and land use) than animal-based ones, should be further explored.

Moving along the supply chain, air transport implies much greater emissions than sea transport. In Case Study 1, for example, sea transport is used in the baseline scenario to deliver the tarpaulins from the manufacturer in China to the prepositioning warehouses in Dubai, UAE, Réunion Island, FR, Tampere, FI, and Las Palmas, ES. However, if air transport is used for these routes instead of sea, GHG emissions increase by a multiple of 44 (Dubai), 57 (Réunion Island), 28 (Tampere), and 31 (Las Palmas), according to the LCA results. Along the same logic, using sea transport instead of air offered significant reductions in GHG emissions for both Case Studies 1 and 2 (air transport was not used in the baseline scenario for Case Study 3). When possible, HOs should opt for sea transport over air, as this can be a low-hanging fruit to reduce GHG emissions (in addition to saving costs). However, this may require increased planning as response times generally also rise with sea transport.

Planning plays a key role in reducing the GHG emissions associated with response, especially in the case of crises. Discussions with the HOs suggest that better planning involves ensuring enough items are in prepositioning warehouses for swift shipping, a factor already considered in the scenarios. The scenarios specifically examine the difference in GHG emissions when utilizing shipping for prepositioning with sufficient warehouse stock compared to a scenario where everything is sent by air from the factory. However, due to insufficient data, alternative planning strategies from other potential warehouses or factories have not been included in the study (to measure GHG emissions we need data on the location of potential warehouses, the weight of cargo, etc.).

Furthermore, location planning also plays a role in reducing the distance the items need to travel throughout their life cycle and has the potential to reduce GHG emissions as illustrated in Scenario 6 in Case Study 1 and Scenario 7 in Case Study 2, where we model the direct distribution of the tarpaulins to the disaster country by sea and do not include distribution to various prepositioning or regional warehouses. Thus, localizing response also can be an effective tool to reduce overall GHG emissions, but this needs to be considered within the context of the local market (e.g., the impact of producing the item locally vs. internationally).

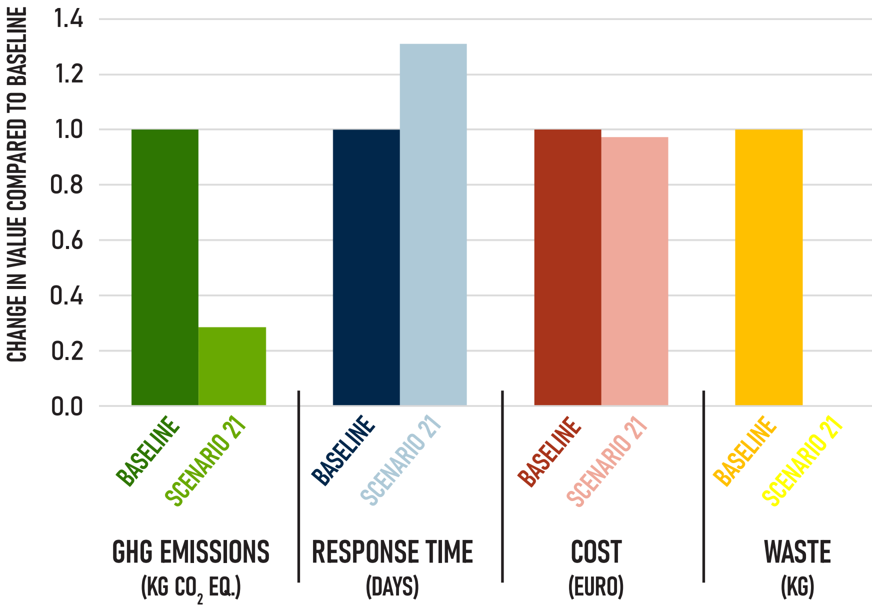


Fig. 15 Comparison of baseline scenario to Scenario 21 (Baseline + ship + recycling + solar) in Case Study 1.

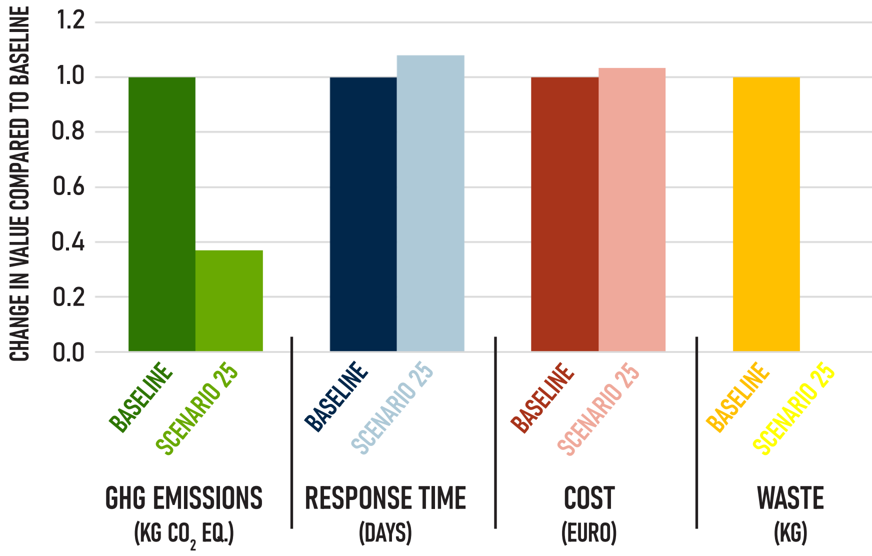


Fig. 16 Comparison of baseline scenario to Scenario 25 (Baseline + ship + recycling + solar) in Case Study 2.

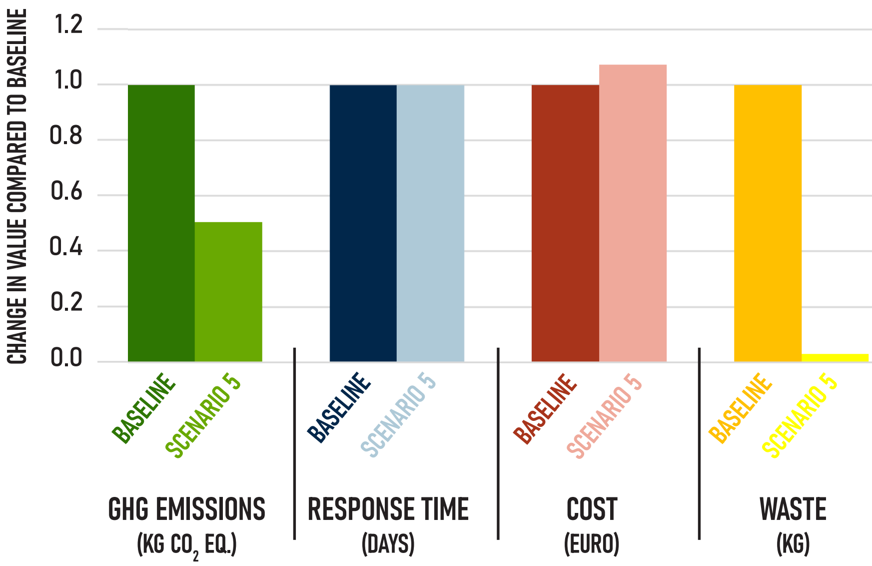


Fig. 17 Comparison of baseline scenario to Scenario 5 (Baseline + recycling + repurpose + solar + SPC) in Case Study 3.

Energy is also a key component in reducing the environmental footprint of HSCs. Energy is required throughout the supply chain (e.g., producing items or storing them in prepositioning warehouses). In our case, electricity was the primary source of energy required. This was often met through the local electrical grid, but that was not always the case. In areas with unstable or inaccessible electrical grids, diesel generators remain the go-to alternative. Comparing the GHG emissions of the electrical grid and diesel generators is not so straight-forward. Some electrical grids are comprised predominantly of fossil fuel sources, which may have a higher impact than the diesel generator due to less losses along the distribution network. This is highly contextual. However, in comparison to renewable energy, the electrical grid and diesel generators imply higher GHG emissions. In our case, we modeled the use of solar energy for storage (and wind only for prepositioning in Finland) as it offers the benefit of having a lower carbon footprint, in addition to providing a decentralized energy source. Implementing solar panels has the potential to play a vital role in reducing the GHG emissions of disaster response supply chains, but the degree of their effectiveness increases with higher electricity requirements. For scenarios where the item moves more quickly through the supply chain, such as direct delivery from the manufacturer (and thus a lower inventory of items), the impact of solar is smaller. The story changes with increased demand for electricity (e.g., to meet cold chain requirements). Although not explored in this research, maintaining the cold chain can result in significant GHG emissions, exacerbated by unsustainable energy sources such as fossil fuels. As the demand for energy increases in the supply chain, the role of renewable sources to reduce the impact of operations also rises. Along the same lines, while we did not deal explicitly with the potential change of suppliers from the local grid to renewable energy, this is an important step to understand the result if HOs request that suppliers adopt renewable sources or work with local governments to improve the composition of the national grid.

The end-of-life phases also contributes to significant GHG emissions. In Case Studies 1 and 2 recycling was consistently the most effective strategy for reducing the GHG emissions of the disaster response. This was due to the potential to recycle the entire tarpaulin and its packaging. Recycling the tarpaulins also reduces the need for virgin plastics during the production phase. It should be noted that recycled materials may also impact the durability of items, and thus should be tested before implementation.

The Eco-Design Tarpaulin project, for example, tested multiple scenarios, including locally-procured recycled materials to support increased durability and UV protection when using recycled materials[1].

In Case Study 3, only the secondary packaging could be recycled, which offered limited benefits. However, if an item and/or packaging can be repurposed (in close proximity), this provides even more advantages to reduce GHG emissions, as no transport to recycling centers is necessary and emissions from disposal (e.g., landfill) are avoided. Investing in recycling and repurposing strategies also provides the additional reward of replacing other waste management options (e.g., open burn or open dump) which imply greater GHG emissions, as well as supporting a transition to the circular economy. This is especially relevant in areas with little or no waste infrastructure, where waste may also lead to pollution if it is dumped and contribute to negative effects on the environment (beyond GHG emissions) and human health (e.g., hazardous waste). The adoption of more environmentally friendly practices, coupled with careful material selection for items plays a substantial role in lowering GHG emissions associated with the humanitarian response.

When considering the overall reduction in GHG emissions when a combination of alternatives are used, it's clear that there is potential for big savings. In Case Study 1, using sea transport instead of air, investing in recycling, and opting for solar energy instead of the electrical grid or diesel generators for storage resulted in a 71% reduction in GHG emissions compared to the baseline scenario. For Case Study 2, the same actions resulted in a decrease of 63%. In Case Study 3, recycling and repurposing packaging, using solar energy for storage, and substituting the soy protein concentrate for the dried skim milk powder offered a 50% savings in GHG emissions. Air transport was not included in the baseline scenario for Case Study 3, and thus the alternative sea transport did not need to be modeled.

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RESPONSE TIME

Different supply chain operations also imply trade-offs in response time. More specifically, transporting items by air often significantly reduces response time compared to sea or road transport, as illustrated in Scenarios 5, 4, and 6 for Case Studies 1, 2, and 3, respectively. Opting for air transport instead of sea to the prepositioning centers in Case Study 1, for example, resulted in a 65% reduction in response time. This is significant considering faster responses also often mean saving more lives, a key objective of humanitarian response. However, this should also be balanced with environmental and cost perspectives. Opting for air travel, while quicker, will typically imply higher GHG emissions and financial costs compared to sea or road transport, in addition to other challenges.

Furthermore, it should be noted the model does not consider constraints in the capacity to receive, import, and distribute relief items. In reality, there are cases in which HOs are limited in the quantities of items that can be handled. There are many examples by different organizations where goods are quickly transported by air, and later that inventory stays in country (usually in a warehouse close to the entry point) for some days or weeks until it is transferred downstream because warehousing, transport, and distribution to final users is limited, especially during the early phases of a new emergency operation. Therefore, the option of transporting "as much as possible" by air is not efficient in many cases, even from a response time perspective.

Finally, careful planning and prepositioning (coupled with the timely availability of funds) also have the potential to further improve response time and reduce GHG emissions and costs associated with quicker response. Prepositioning items in closer proximity to disaster-prone areas, for example, implies shorter distances the item needs to travel to reach the affected populations. This may also mean that items can be sent by sea or road, without compromising response time. In terms of disaster response, localizing has the potential to offer great benefits, but this is highly contextual and depends on the specific conditions of the region and the choice of transportation mode. Decisions should be made considering the long-term impacts of the response and the specific constraints of the operation. Additionally, effective response is not always about quantity but also accurate forecasting of items that will be required in-country. This is linked to efficient communications practices between partners, including those in-country.

COSTS

Costs are a crucial aspect of disaster response. HOs work with limited budgets and spending more to reduce environmental impacts should not compromise saving lives. Transport mode influences the cost of the operation, and while air transport is often faster than sea, it typically implies higher per unit costs. Reducing the distance the items need to travel also plays a role. Direct delivery from the manufacturer to the disaster country, for example, can also help save costs related to transport and storage. On the other hand, investing in more environmentally sustainable alternatives, such as solar panels or recycling initiatives may imply higher costs up-front. However, these types of investments may end up costing less over time considering the long-term perspective. For example, the initial cost of solar panels often yields long-term cost-effectiveness, especially with expanded operations and substantial warehouse inventories. This is particularly relevant in areas which have an unstable energy source or experience fluctuating energy prices. Having a reliable, decentralized energy source also means you can stay operational even if the local grid is down, a huge benefit in areas with extensive diesel generator use. This may imply cost savings (depending on the operation) and is especially relevant for items with temperature requirements. Furthermore, while recycling may require up-front investments, recyclable materials can also be sold back into the supply chain to recoup initial costs. In this case, all costs associated with recycling, such as transport to the recycling centers, should be considered in addition to potential benefits.

Figures 15, 16, and 17 illustrate the trade-offs of prioritizing alternatives to reduce GHG emissions of supply chains. In Case Study 1, costs are slightly reduced, namely due to the cheaper price per unit of sea transport than air. In Case Study 2, this balance is not fully achieved, mainly because of the shorter distances from the prepositioning warehouses, and thus less room to improve. In Case Study 3, costs are slightly higher. This is partly due to the investment in solar panels, as well as the lack of air transport in the baseline scenario (and thus no potential cost savings for using sea instead of air transport). It should be noted that the data on costs used in this research was based on estimations from the HOs and current industry reports. Further research is necessary to provide more specific recommendations to HOs on exact costs. Additionally, financial investment should always be considered in the long-term scope of the potential cost savings over time, as well as those associated with reduced GHG emissions, response time, and waste. This also includes increased costs in responding to the consequences of climate change.

WASTE

Waste is also a major challenge for humanitarian response. Firstly, waste generated along the supply chain before it reaches the affected population is not only one less relief item, but also a waste of resources and resultant emissions from the production of the item itself. In the case of GHG emissions, this has a global impact. Though the waste in the case studies generated along the supply chains is small compared to the total waste at the end of the life cycle, it is still an important aspect to consider. This is especially true for parts of the supply chain that may be more vulnerable to increased waste, such as flood-prone areas that pose a higher risk of items being damaged. Additionally, reducing waste along the supply chain is also a critical aspect for products with a short shelf-life (i.e., a high risk of waste if

expired or quality decreases over time) or those with specific temperature requirements (e.g., cold chain). In these cases, proper inventory management is crucial to avoid generating significant amounts of waste before reaching end users.

In this research we illustrated the potential for different waste treatment options to not only reduce the total waste involved, but also the environmental impact associated with waste management. These processes were modeled based on discussions with the HOs, as there was no specific data on the end-of-life phase for the case studies (either because this had not happened yet, or data was not collected). Thus, the results illustrate the potential to reduce waste substantially through recycling and repurposing initiatives. To model potential recycling processes based on what is possible with the current infrastructure, we assumed that the waste is sent to the nearest recycling facility, which is on average more than 1,000 km for Case Studies 1 and 3. Developing strategies for recycling may also imply the need to organize solutions to work as efficiently as possible, such as through joint waste collection or a circular economy approach. In addition, the informal recycling sector may also have a key role to play here. This is particularly relevant for remote areas or those which require long distances to recycling centers. In these cases, the informal recycling sector plays a vital role in collecting, aggregating, and transporting waste. Building strategies based on the informal sectors' capacities may also help to reduce organizational costs and support sustainable livelihoods for the informal recycling sector.

Furthermore, it is necessary to consider the entire life cycle of the product or packaging when discussing waste. For example, the primary packaging of the CSB++ is not recyclable due to the material composition. This limits waste management to disposal, reuse, or repurpose and negates any potential environmental or cost benefits associated with recycling. During procurement, decision makers should consider the impact of specific materials at the end of their life cycle in addition to the necessary budget and plan for the management of items and waste (e.g., collection, storage, transportation, equipment, personnel, and monitoring costs).

CONCLUSIONS, ASSUMPTIONS, LIMITATIONS, & FUTURE STEPS

Section 5 in short

What do the results of this study mean for HSC practitioners? Understanding the potential of different supply chain operations to contribute to GHG emissions and waste is a key step towards improving the environmental sustainability of supply chains. Improvements can be made along each step of the supply chain and future steps should focus on how to scale up studies like these to support evidence-based decisions as standard practice. In this section we summarize the main findings, provide recommendations for practitioners, and identify future steps for research and practice.

5.1 | SUMMARY CONCLUSIONS

In this study, we analyzed the impacts of HSCs from several perspectives (GHG emissions, waste, response time, and financial costs) and illustrated the role of alternative approaches to enhance environmental sustainability, especially their potential to reduce GHG emissions and waste associated with disaster response. From these results, several recommendations can be made. Firstly, procurement plays a key role in setting the tone for the rest of the product's life cycle. When selecting items and packaging, HOs should consider the entire life cycle of the product, including how it will be disposed of at the end-of-life, and the potential impact of those operations within the local humanitarian context. This is especially relevant for areas with little to no waste management infrastructure. For example, increasing attention towards materials that can easily be recycled, reused, or repurposed is a step in this direction. Additionally, HOs should also aim to promote procurement of items with a lower environmental footprint. This will require developing a procurement strategy which systematically incorporates environmental sustainability into decision-making. It is also key that program teams are aligned to this mindset and work with procurement to identify the best options in the market considering what is available with their suppliers either globally or locally. Collaboration between the different areas of the organization is key to make these changes.

In terms of distribution, HOs should avoid air transport when possible and instead opt for sea or road travel, which has significantly lower GHG emissions. In some cases, direct delivery from manufacturers may be the most sustainable in terms of GHG emissions and waste reduction due to fewer steps in between production and the end user. This requires that the manufacturer has sufficient inventory to meet the needs of the disaster response, however. On the other hand, localization may also be considered as a potential means to reduce environmental impacts, but this should always be evaluated within the local context and ensure that items are also produced locally (i.e., not procured internationally and sold by a local supplier).

Additionally, reducing transport distances through well-designed planning and prepositioning in close proximity to disaster-prone areas may offer benefits for environmental, economic, and social sustainability such as reduced GHG emissions, costs, and response time. From an environmental perspective, however, increasing prepositioning should also be taken in consideration with energy sources for storage. This is especially relevant for items which have special conditions, such as the cold chain. Investing in renewable energy sources such as solar has the potential to reduce GHG emissions and costs while also providing a reliable, decentralized source of energy and increasing the resilience of humanitarian operations and response.

At the end of the life cycle, waste management can also be a main factor for environmentally sustainable humanitarian response. Investing in recycling, reusing, and repurposing strategies can play a pivotal role in waste reduction and lowering the environmental footprint of end-of-life management.

5.2 | ASSUMPTIONS AND LIMITATIONS

Assumptions are designed to simplify complex reality and make the research manageable while still yielding valuable insights. They also contribute to limitations of the study (in addition to other factors such as data availability), as real-world conditions may be more context-specific and/or vary. In the next paragraphs, we summarize the main assumptions and limitations of the study, as described in detail in the previous sections.

ASSUMPTIONS

Case Study 1: Mozambique

- All tarpaulins are produced by a single manufacturer in China to maintain consistency in production-related environmental impacts.
- 95% of waste is sent to open dumping and 5% to open burning during the end-of-life phase in the baseline scenario.
- During the use phase for tarpaulins, there are no additional processes that would affect the environmental assessment.
- Recycling waste is transported to the nearest recycling facility, which is on average more than 1,000 km away from the point of collection.
- Recycling necessitates transportation to recycling centers, but not for other waste treatment options such as open dumping or open burning.
- In the case of recycling, 100% of the items are sent for the designated treatment without deviation.

Case Study 2: Pakistan

- All the same assumptions as Case Study 1 except recycling takes place closer (in the provinces of Punjab and Sindh).

Case Study 3: Chad

- Agricultural production of raw ingredients is conducted under average industrialized production methods.
- The food is consumed by the recipients, and thus, only the packaging requires waste management.
- 95% of waste is sent to open dumping and 5% to open burning during the end-of-life phase in the baseline scenario.
- Recycling waste is transported to the nearest recycling facility, which is on average more than 1,000 km away from the point of collection.
- Recycling necessitates transportation to recycling centers, but not for other waste treatment options such as open dumping or open burning.

LIMITATIONS

Exclusion of other environmental impacts

In reality, there are many other critical environmental aspects to consider, such as water use, pollution, land degradation, or resource scarcity. To simplify the results, our study focuses on GHG emissions and waste. Diving deeper into other environmental impacts is a key step for future research.

Exclusion of social or economic factors

Although this study was limited to the environmental perspective, we also included response time and financial costs to illustrate trade-offs between different sustainability perspectives and enrich the overall analysis without delving deeply into these specific areas. We used response time as a measure for social perspectives, but future research should expand to other areas such as the equitable distribution of resources, the empowerment of vulnerable groups, and the long-term social consequences of humanitarian interventions. Additionally, we included the direct financial costs of the disaster response, but did not factor in other components relevant for economic sustainability. These can include economic resilience, long-term financial viability, local economic development, or employment generation.

Challenges in implementing sustainable alternatives

While we tested several alternative scenarios, implementing environmentally sustainable solutions in practice requires further analysis and involves several constraints (e.g., financial costs, capacity, and infrastructure). Creating pathways to pilot some of the alternatives presented in this study should be a future step for research and practice.

Data availability constraints

Data collection was a significant challenge for this research. Both LCA and system dynamics are data-intensive methodologies, and we faced several challenges to obtain sufficient primary data for the model. In other cases, data was not available because the activity did not happen in reality (e.g., recycling or implementation of solar panels). In response, we discussed these limitations with the HOs (and noted this in the report) and made informed assumptions. Additionally, we also consulted reports and scientific literature to fill in data gaps for scenario analysis. This allowed for the completion of the model, but increased uncertainty for specific points such as costs for recycling or solar panels. Furthermore, while we found reliable data on the cost of dried skim milk powder, it was challenging to find a comparable value for soy protein concentrate (prices were for not available for large quantities or only related to those for animal feed). Thus, this calculation was left out of the model, but is a step for future research.

Limited generalizability

While the model reflects the operations of three different case studies, they also represent a particular subset of a much wider range of humanitarian activities within a specific context. Therefore, while the findings and models developed are valuable and can be generalized to an extent, they do not capture every aspect of the diverse and complex landscape of humanitarian operations globally. It's important to consider this context when applying the report's conclusions, as they offer a snapshot that contributes to, but does not fully define, the whole picture of humanitarian efforts. For example, the


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data collected for each case study on production and manufacturing was gathered from a specific supplier. Gathering data from a different supplier may change the results as this would imply differences in the origin of inputs, transportation distances, etc. We did not test for the impact of this change.

Furthermore, the products we selected for the case studies were dependent on several factors, in addition to generalizability. For example, we selected CSB++ together with WFP as a focus for Case Study 3 due to the fact that it is commonly used in the humanitarian sector, in addition to the fact that data had already been collected for a previous study on the upstream processes at the supplier used for the disaster that was selected. It's important to keep in mind that there are several factors which increase the impact of the production of CSB++ that may not be applicable to items WFP and other HOs primarily procure (e.g., staple foods): 1) CSB++ has animal ingredients; 2) it is a processed commodity; 3) it requires much more packaging than average (staple) food commodities; 4) it is more susceptible to losses and damages than average commodities.

5.3 | FUTURE STEPS

Through this research, we illustrate the potential for a data-driven approach to provide clear, evidence-based support for humanitarian supply chain actors. We hope these results help to support HOs in several ways. Firstly, we hope this research increases awareness among humanitarian logistics practitioners about the environmental impact of operations. Future steps for research and practice should aim at developing a coordinated, scalable, and sustainable approach to measuring the environmental impacts of end-to-end supply chains and extend to a more comprehensive scope of impact categories (e.g., water use, pollution, resource scarcity).

Next, we hope this research provides support for HSC practitioners to take action based on the findings (e.g., try to reduce the use of air travel or animal-based ingredients). This also includes the potential to use this model to run further simulations and support HOs to evaluate and compare changes in their current supply chain strategies. This would require up-front investments, such as hiring or training staff on models, as well as to collect more accurate data to support analyses.

In this study, we highlight the importance of the entire supply chain – from procurement to transport, storage, use, and finally, end of life – in reducing the environmental impact of humanitarian logistics and illustrate the potential for alternative operations to achieve this goal. Implementing this into practice may not be an easy step, but it is a necessary one when considering the vicious cycle of humanitarian needs and climate change consequences. Future steps should also aim at highlighting best practices and sharing knowledge between practice and academia towards a greener future. This study is one step towards that goal.

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APPENDIX: SYSTEM DYNAMICS MODEL

Fig. A System dynamics model of the full supply chain related to case studies.

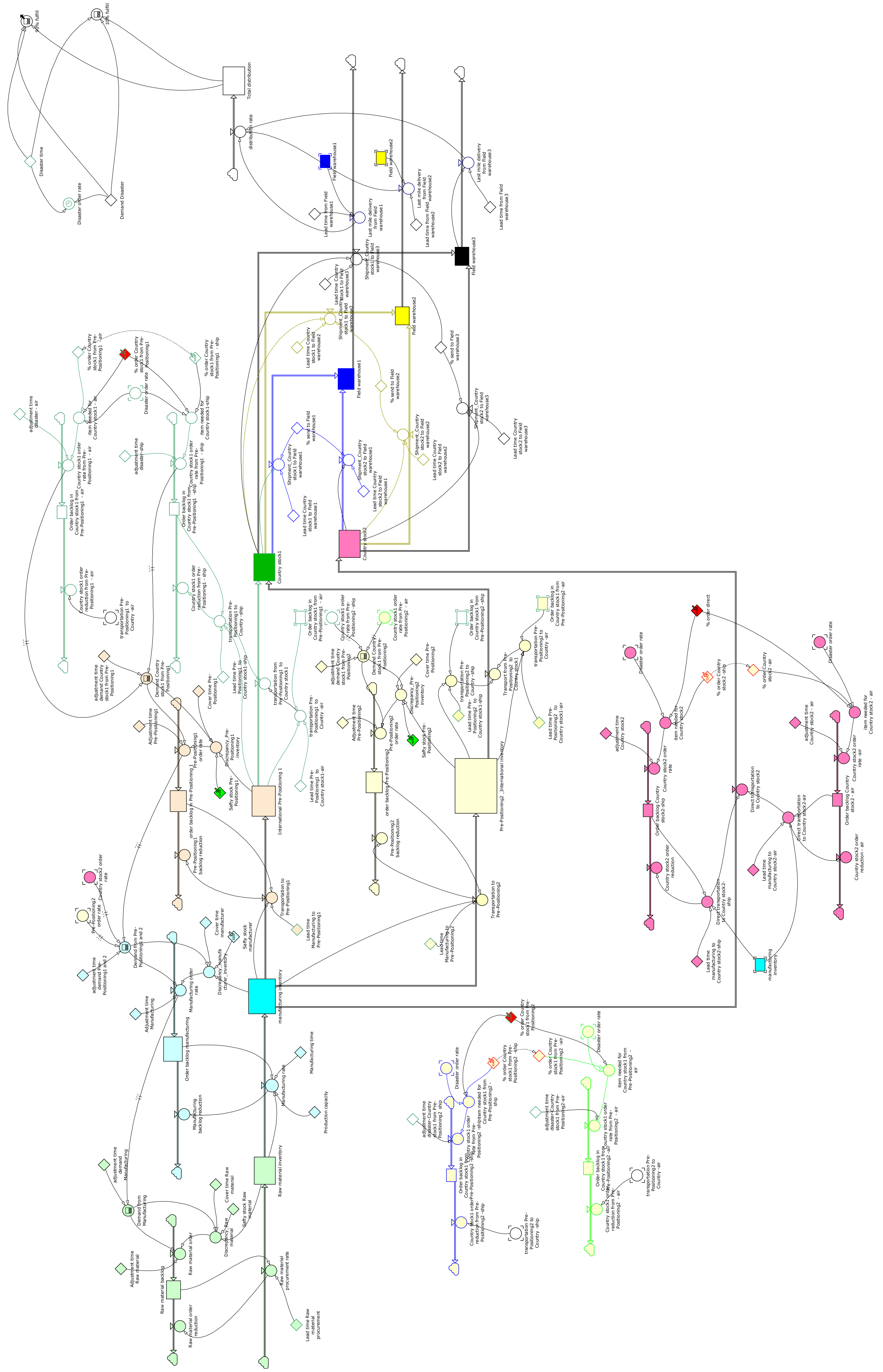


Fig. B System dynamics model to calculate GHG emissions related to case studies.

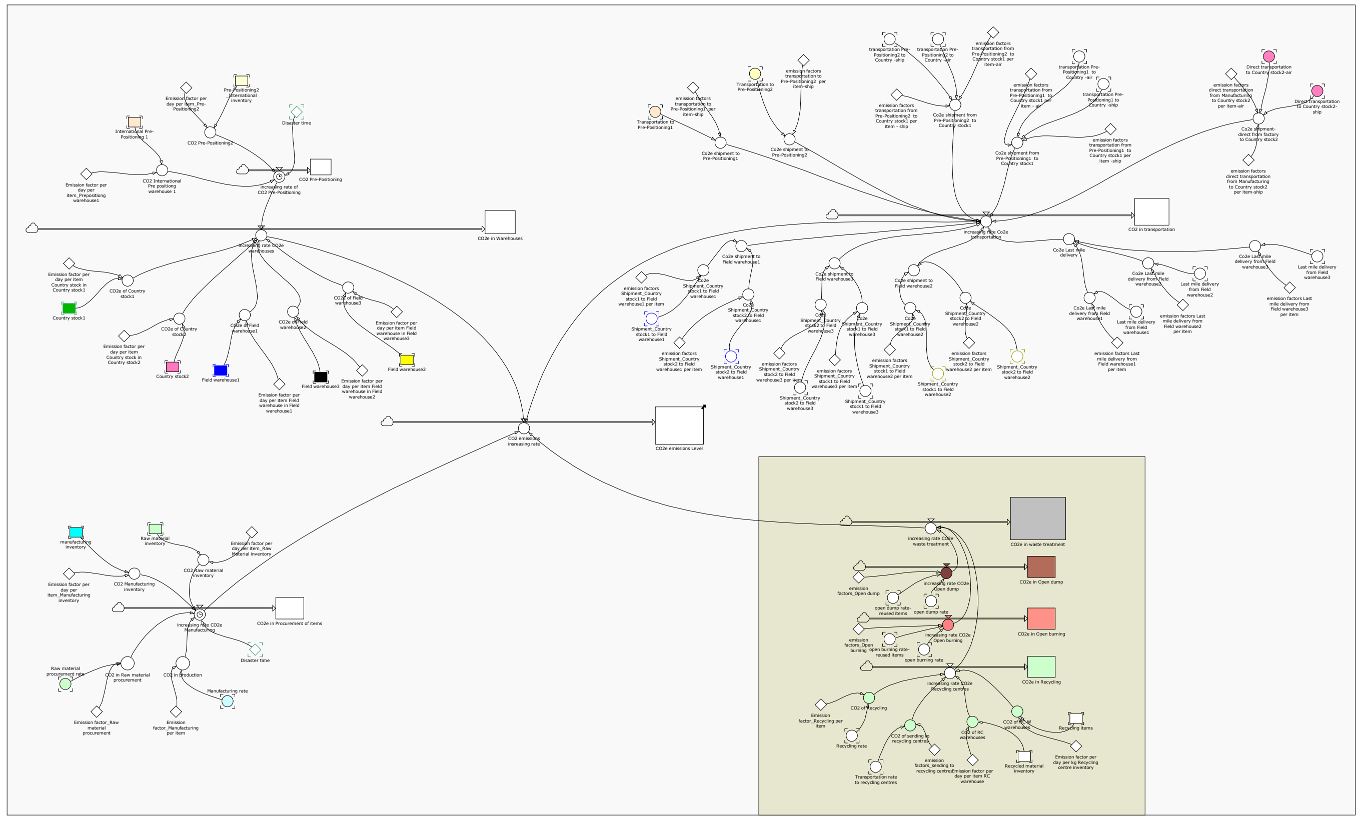


Fig. C System dynamics model to calculate financial costs related to case studies.

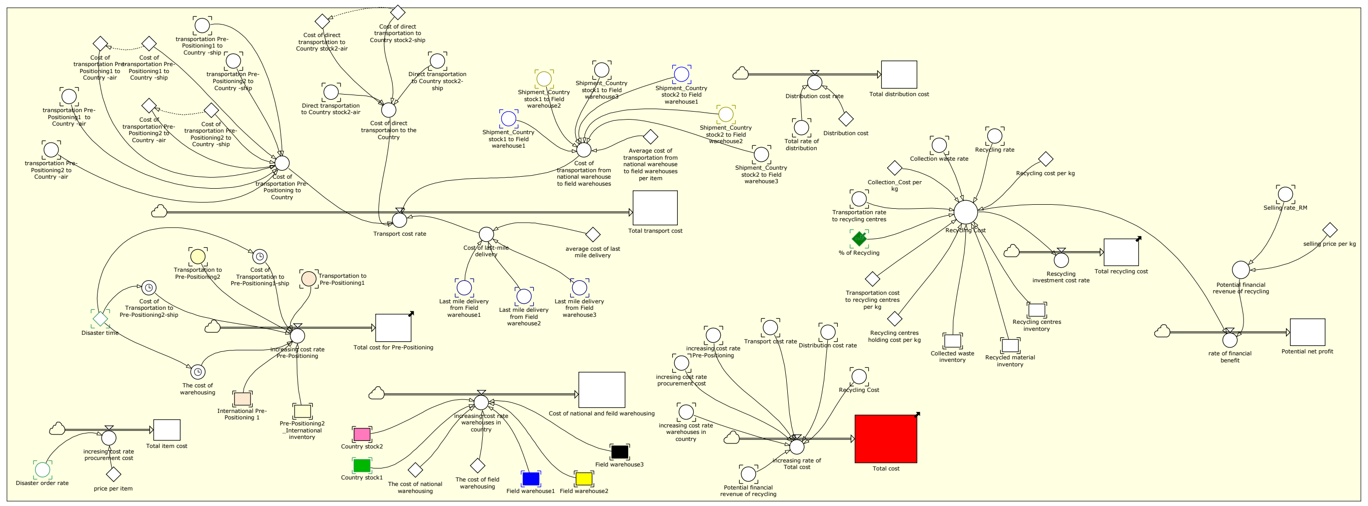
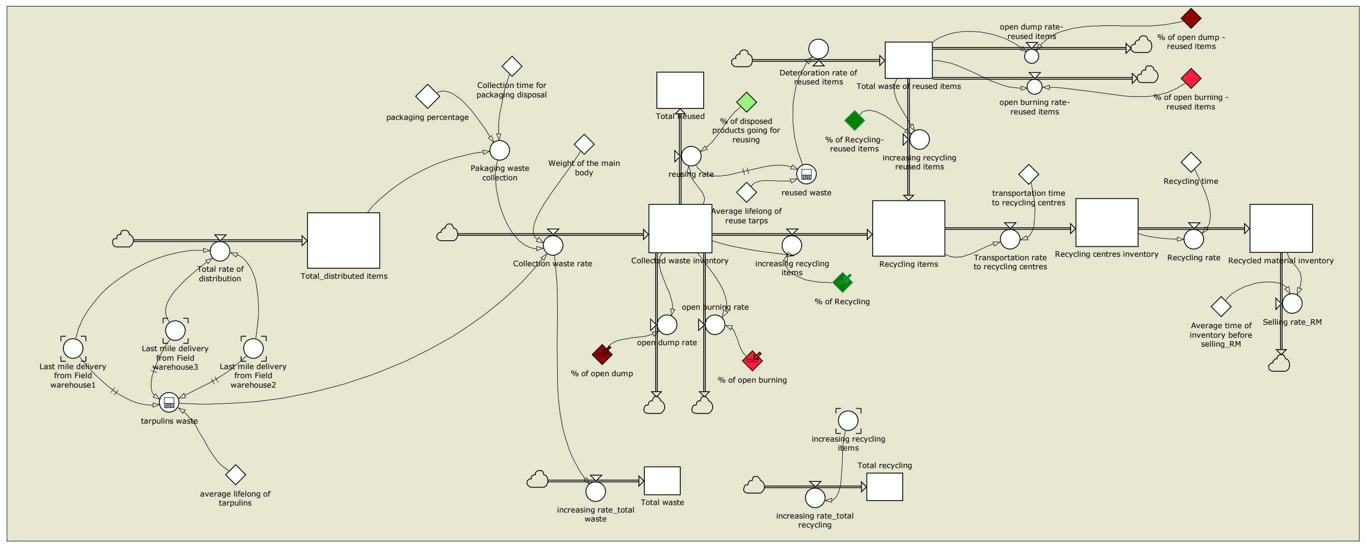


Fig. D System dynamics model to calculate waste related to case studies.



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We would like to thank our counterparts at IFRC, WFP, and their respective suppliers, who together made this report possible. A special thank you to the field office respondents in Mozambique, Pakistan, and Chad who kindly provided us with the data required for this study.

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