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ORIGINAL PAPER

Environmental life cycle analysis of manufacturing options for humanitarian supplies: drinking water containers

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Abstract

The purpose of this life cycle assessment study was to determine the life cycle impacts for production and distribution of a humanitarian supply item under various supply chain paradigms in order to illustrate the potential environmental benefits of organizing production and supply operations for these items in novel ways. To do this, a case study is used on a family-size water storage and dispensing bucket, such as the 14 L capacity polyethylene bucket commonly produced by Oxfam International. The LCA is a cradle to gate including production and transportation of PE plastic feedstock, fabrication of the water bucket, and transportation of the bucket to a common distribution site representative of a humanitarian aid location. Three different humanitarian aid locations are used to illustrate the range of potential impacts for each processing and supply system: Nepal, South Sudan, and Peru. Six processing and supply scenarios were investigated: (1) centralized Oxfam traditional system, (2) centralized commercial Chinese supply and distribution, (3) quasi-centralized Field Ready supply and distribution, (4) distributed supply and distribution system with 3-D printing, (5) distributed supply and distribution system with 3-D printing and local waste feedstock, and (6) distributed supply and distribution system with extrusion molding and local waste feedstock. The results found the major contribution to total GHG emissions are electricity usage for manufacturing and shipping feedstock and final product. Among Systems 1–3, System 1 and System 2 are environmentally poor as the electricity emissions in Pakistan and China are high. System 3 was an improvement as the products are manufactured locally. Decentralized supply and distribution system with 3-D printing (System 4) is less compatible with regions of high grid emissions. In System 5, the same equipment has been used, but with local waste feedstock, which shows an improvement of 67.7% for Nepal and 65.5% for Peru because of the reduced shipping emissions, even if the manufacturing emission is the highest among all of the systems. System 6 is feasible for all three locations. It is concluded that manufacturing should be prioritized on grids where the electricity emission is lower using local waste feedstock as it is the most efficient approach; however, a further study should be done on operating the FPF/FGF 3-D printer or extrusion molding systems powered with distributed photovoltaic systems in order to complement this process and produce the most environmentally responsible production.

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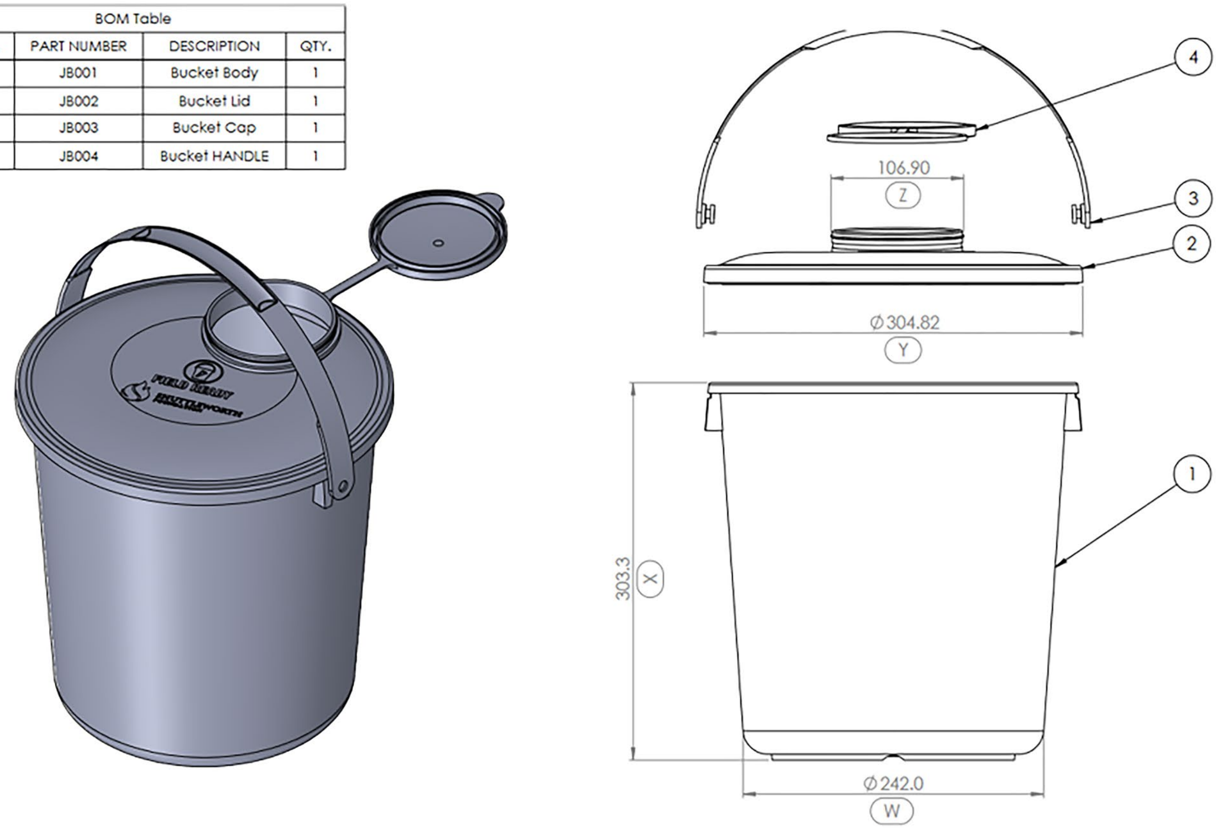
Graphical Abstract

BOM Table			
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	JB001	Bucket Body	1
2	JB002	Bucket Lid	1
3	JB003	Bucket Cap	1
4	JB004	Bucket HANDLE	1



Keywords Distributed manufacturing · Life cycle assessment · Humanitarian supplies · Additive manufacturing · Local manufacturing · Humanitarian aid · 3-D printing

Introduction

With a both a large number and severity, a combination of crises has resulted in a record 339 million people that will need humanitarian assistance in 2023: one in every 23 people (UN OCHA 2022). For example, acute food insecurity has grown to at least 222 million people and need urgent assistance, while 45 million people are at risk for starvation (UN OCHA 2022). There is thus an urgent need for effective humanitarian responses to disasters as they occur, which can be focused on the logistical efforts to move goods (e.g., food or supplies) from where they are available to where people need them (Van Wassenhove 2006; Kovács and Spens 2007; Banomyong, et al. 2019). The field of supply chain logistics for humanitarian responses is complex because it is challenging to forecast the demand because of the timing and location of a future disaster being unknown and the supply of aid as it is constrained by manufacturing potential and often funded by donations. (De la Torre et al. 2016). Unfortunately, there can be a mismatch between both the quantity, type, and timing of supplies delivered and the supplies that are needed in a given crises (Loy et al. 2016; James and Gilman 2016). More than half of aid money is used to purchase these materials, so the mismatch wastes critical funds as well as negatively impacting the long-term economics of the regions suffering the disasters (James and Gilman 2016).

With the open-source release of the self-replicating rapid prototyper (RepRap) 3-D printer (Sells et al. 2010; Jones et al. 2011; Bowyer 2014) and the rapid innovation that ensued (De Jong and De Bruijn 2012), the costs of additive manufacturing have decreased enough to make distributed manufacturing a threat to disrupt global value chains (Laplume et al. 2016). In fact, the costs have been reduced enough to make it viable in resource-constrained contexts like those found in impoverished communities, the developing world, or during a crisis (Pearce et al. 2010). Thus, an approach to partially solve humanitarian aid issues gaining attention in humanitarian logistics circles is the concept of rapid manufacturing on site using 3-D printing (Tatham et al. 2015; James and Gilman 2016; Loy et al. 2016; De la Torre et al. 2016; Mohammed et al. 2019; Corsini et al. 2022; Sniderman et al. 2023).

Distributed additive manufacturing can reduce time and money for procurement of common consumer goods (Wittbrodt et al. 2013; Petersen and Pearce 2017; Pearce and Qian 2022) by reducing the amount of capital required for manufacturing locally. Distributed manufacturing also allows for customization (Gwamuri et al. 2014; Wittbrodt et al. 2015). This form of manufacturing for local needs during a disaster response, waste is eliminated as the only materials that need to be shipped to the disaster site are 3-D printers and feedstock, which need less space for storage and transport, are more durable and eliminate most packaging in a disaster response (Loy et al. 2016; James et al. 2016; Sniderman et al. 2023). New 3-D printers have been designed specifically for humanitarian use (Savonen et al. 2018; Lipsky et al. 2019). In addition, by only manufacturing what is needed on site, the mismatch that results in relief organizations shipping thousands of items that are not required and missing thousands of others that are required.

Perhaps even better than shipping 3-D printing feedstock to an area needing humanitarian aid would be using local materials and then only needing to ship the equipment, which includes 3-D printers and recyclebots (waste plastic extruders that make filament for fused filament-based 3-D printers) (Baechler et al. 2013; Zhong et al. 2017; Woern et al. 2018a, b; Mohammed et al. 2018a; b; 2022). This approach has been proved successful with a range of common plastics including acrylonitrile butadiene styrene (ABS) (Mohammed et al. 2017; Zhong and Pearce 2018), high density polyethylene (HDPE) (Baechler, et al. 2013; Chong et al. 2017; Mohammed et al. 2017; 2019), linear low-density polyethylene (LLDPE) and low-density polyethylene (LDPE) (Hart et al. 2018), polypropylene (Pepi et al. 2018; Zander et al. 2019), and PET (Lee et al. 2013). In addition, there are open-source printers that can directly 3-D print ground plastic waste from a wide range of materials using fused particle fabrication/fused granular fabrication (FPF/FGF) at both the small-scale (Volpato et al. 2015; Whyman et al. 2018; Alexandre et al. 2020) and the large-scale Cartesian based systems (Woern et al. 2018b; Byard et al. 2019; Reich et al. 2019; Little et al. 2020) and hangprinter/cable robot (Petsuik et al. 2022). Finally, for materials which are hard to fit into the distributed recycling and additive manufacturing (DRAM) method (Sanchez et al. 2017; 2020), it is possible to 3-D print a mold and then extrusion mold into it (Dertinger et al. 2020). For these reasons, 3-D printing appears to be particularly well-suited for humanitarian responses for everything from malnutrition identification bands (Michaels and Pearce 2017) and

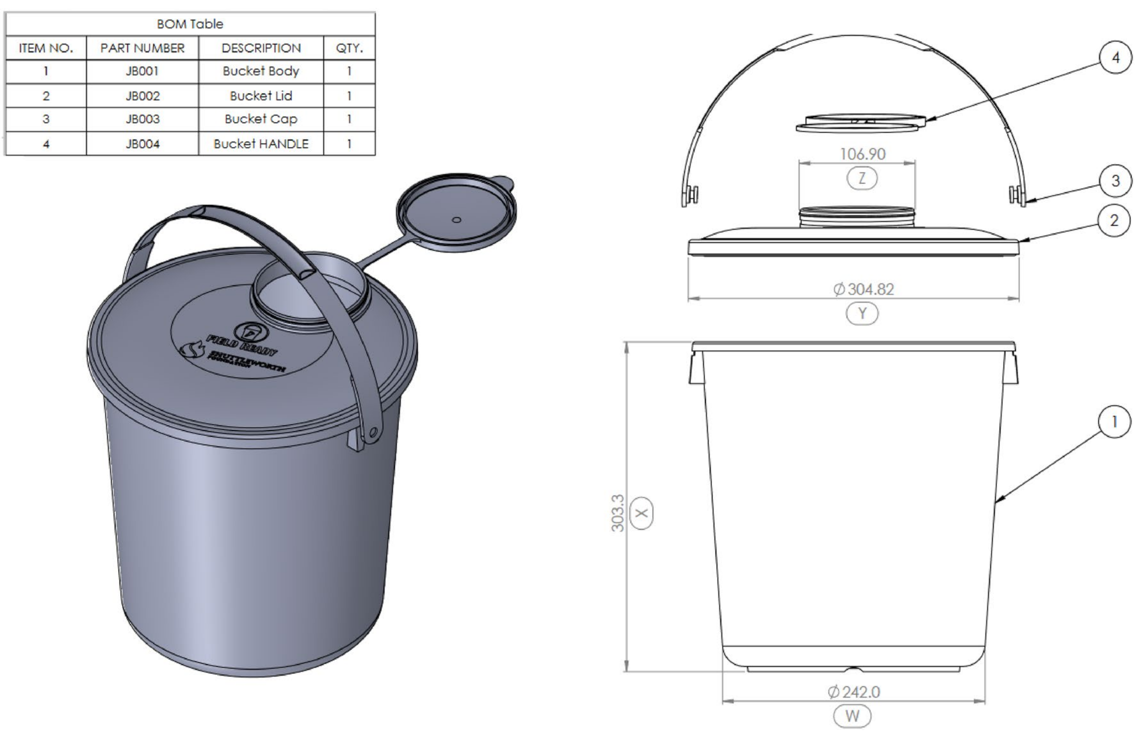


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Fig. 1 A field ready 14 L bucket design

housing (Gregory et al. 2016) to vehicle repair (De la Torre et al. 2016), surgical tools (Angela and Khan 2015) and even surgical tables (Bow et al. 2022). Humanitarian relief nonprofit organizations are using this technique now including Refugee Open Ware (ROW) (Wharton et al. 2018), who 3-D prints prosthetics (Ramadurai et al. 2019) and Field Ready, which 3-D prints medical devices (Saripalle et al. 2016) like umbilical cord clamps (Dotz 2015) and also has a long list of other approaches that are on the spectrum of full distributed manufacturing to localized central manufacturing (James and Gilman 2016). These approaches include those that could be considered "do-it-together" where the success of the Do-It-Yourself (DIY) phenomenon is transferred to small and medium-sized enterprises (SMEs) (Dupont et al. 2021). In this approach networks of makerspaces, hackerspaces, factories, FabLabs, or other spaces (e.g., libraries, schools, or community centers) equipped with digital manufacturing tools like 3-D printers have enabled distributed production based on commons-based peer production off of open-source designs in the 2022 digital commons (Fox 2013; Pearce 2014; Kohtala and Hyysalo 2015; Dupont 2019; 2022). Although all these mechanisms to produce humanitarian goods are technically possible, both the economics and environmentally most responsible solutions have not been determined. This study aims to fill that knowledge gap in relation to the environmental benefits of one approach to another, which will provide insight into the long-term most sustainable approach.

The goal of this life cycle assessment (LCA) study was to determine the life cycle impacts for production and distribution of a humanitarian supply item under various supply chain paradigms in order to illustrate the potential environmental benefits of organizing production and supply operations for these items in novel ways. To do this, a case study is used on a family-size water storage and dispensing bucket, such as the 14 L capacity polyethylene (PE) bucket commonly produced by Oxfam International. The system boundary for this study is cradle to gate and includes the production and transportation of PE plastic feedstock, fabrication of the water bucket, and transportation of the bucket to a common distribution site representative of a humanitarian aid location. Three different humanitarian aid locations are used to illustrate the range of potential impacts for each processing and supply system: Nepal, South Sudan, and Peru. Six processing and supply scenarios were investigated, which are described in more detail below: (1) centralized Oxfam traditional system, (2) centralized commercial Chinese supply and distribution, (3) quasi-centralized Field Ready supply and distribution, (4) distributed supply and distribution system with 3-D printing, (5) distributed supply and distribution system with 3-D printing and local waste feedstock, and (6) distributed supply and distribution system with extrusion molding and local waste feedstock. The results are presented and discussed in terms of the environmental impact, logistics, and applications and future work.

Methods

Goal and scope definition: case study humanitarian aid product

Case study humanitarian aid product selected was the OXFAM Jerry Bucket, which is normally supplied by UNICEF for USD$5.34 as a 14 L bucket with cap, and smooth handle (UNICEF 2023). The bucket was designed primarily for the storage, transport, and dispensation of drinking water. It is made from virgin high density polyethylene (HDPE) and the lid is made from virgin low-density polyethylene (LDPE), according to EN1186-3-9 standard (iTeh 2002). The materials were selected to be tough, durable, UV-resistant, and food safe. The 14L bucket dimensions consist of a height of 300 mm, top diameter of 300/310 mm ± 5%, bottom diameter of 240 mm ± 5%, and a wall thickness of 1.3 mm. Both the inside and outside of the bucket must be smooth: The gloss finish and curved inside surface prevents dirt and bacteria accumulation and eases cleaning and the outside smooth surface ensures comfort when carried on the head (UNICEF 2023). The lid is meant to be tight-fitting lid with rim-lock design,

Table 1 Electricity grid mix assumptions used in this study (IEA 2022), and GWP impacts

Country	Electricity assumptions
China	Coal (67%), Nat. Gas (3%), Hydro (18%), Solar (4%), Wind (6.5%), Biofuels (1.5%), 5.5% transmission losses assumed within Ecoinvent – 771 g CO_{2eq}/kWh
Nepal	Hydro (100%) for internal electricity, but 15% imported from coal-dominant India, 10.5% transmission losses assumed within Ecoinvent – 258 g CO_{2eq}/kWh
Pakistan	Coal (20%), Nat. Gas (12%), Oil (24%), Hydro (33%), Solar/Wind (5%), Nuclear (7%), 7.5% transmission losses assumed within Ecoinvent – 545 g CO_{2eq}/kWh
South Sudan	Oil (100%), 10.5% transmission losses assumed within Ecoinvent – 991 g CO_{2eq}/kWh
Peru	Nat. Gas (35%), Oil (1%), Hydro (58%), Solar/Wind (5%), 7.5% transmission losses assumed within Ecoinvent – 240 g CO_{2eq}/kWh

Table 2 Life cycle input data for Nepal location scenarios

Item	Amount	Comments
System 1		
Material	189.2 kg	Virgin PE, 90% HDPE, 10% LDPE
Material transit	2520 km truck	Mumbai (India) to Lahore (Pakistan)
Manufacturing	189.2 kg	Injection Molding, 10% loss assumed
Bucket shipping	1184 km truck 11021 km ship 107 km UK truck 107 km UK truck 13251 km ship 1950 km truck	Lahore to Karachi, Pakistan Karachi to Southampton (UK) Southampton to Oxford (UK) Oxford to Southampton Southampton to Mumbai (India) Mumbai to Kathmandu (Nepal)
System 2		
Material	189.2 kg	Virgin PE, 90% HDPE, 10% LDPE
Material transit	200 km truck	From PE production in China to manufacturer in Hong Kong
Manufacturing	189.2 kg	Injection Molding, 10% loss assumed
Bucket shipping	5700 km boat 900 km truck	Hong Kong to Kolkata Kolkata to Kathmandu
System 3		
Material	195.8 kg	Virgin PE, 90% HDPE, 10% LDPE, Field Ready buckets weigh slightly more than Oxfam buckets
Material transit	2000 km truck	From PE production in China to manufacturer in Kathmandu
Manufacturing	195.8	Injection Molding, 10% loss assumed
Bucket shipping	0 km	Already in Kathmandu
System 4		
Material	179.8 kg	Virgin PE, 90% HDPE, 10% LDPE
Material transit	2000 km truck	From PE production in China to manufacturer in Kathmandu
Manufacturing	1190.8 kWh	3-D printing, 6.69 kWh/kg assumed (Byard et al. 2019), 1% loss assumed
Bucket shipping	0 km	Already in Kathmandu
System 5		
Material	179.8 kg	Local waste PE, 90% HDPE, 10% LDPE
Material transit	50 km truck	Local waste PE in Kathmandu
Manufacturing	1232 kWh	0.23 kWh/kg (grinding) and 6.69 kWh/kg (3-D printing) assumed (Byard et al. 2019), 1% loss assumed
Bucket shipping	0 km	Already in Kathmandu
System 6		
Material	179.8 kg	Local waste PE, 90% HDPE, 10% LDPE
Material transit	50 km truck	Local waste PE in Kathmandu
Manufacturing	83.7 kWh	0.23 kWh/kg (grinding) and 0.24 kWh/kg (recycle bot extrusion molding) assumed (Woern et al. 2018a), 1% loss assumed
Bucket shipping	0 km	Already in Kathmandu

to prevent it from being removed, but it has a clip-on 100 mm ± 5% cap for filling with hand pumps and cleaning. Various humanitarian organizations produce these 14 L buckets. A rendering of the Field Ready version of the bucket is shown in Fig. 1 and is used here throughout the analysis. The bucket weighs 0.86 kg and the handle weighs 40 g.

This study was conducted in a manner that is consistent with best practices in LCA (ISO 2006). Although a cradle-to-grave LCA was considered it is not used as the primary purpose of this, LCA is to compare the manufacturing processes of the bucket not to do a full LCA of the bucket. To be a fair comparison of the manufacturing processes, it is assumed that the buckets will all be disposed of in the same way. Thus, in this cradle-to-gate analysis, the use of the water bucket and final disposal of the bucket are not included in the system boundary of this study, because these phases of the item life cycle will be common across all of the scenarios under study and therefore would not contribute to the differences observed in supply and production operations.

Global Warming Potential (GWP) is the environmental impact of interest in this study. The functional unit used for comparing scenarios will be the production and transportation of 200 buckets each with a 14 L capacity to a

Table 3 Life cycle input data for Peru location scenarios

Item	Amount	Comments
System 1		
Material	189.2 kg	Virgin PE, 90% HDPE, 10% LDPE
Material transit	2520 km truck	Mumbai (India) to Lahore (Pakistan)
Manufacturing	189.2 kg	Injection Molding, 10% loss assumed
Bucket shipping	1184 km truck 11021 km ship 107 km UK truck 107 km UK truck 11500 km ship 600 km truck	Lahore to Karachi, Pakistan Karachi to Southampton (UK) Southampton to Oxford (UK) Oxford to Southampton Southampton to Lima (Peru) Lima to Ayacucho (Peru)
System 2		
Material	189.2 kg	Virgin PE, 90% HDPE, 10% LDPE
Material transit	200 km truck	From PE production in China to manufacturer in Hong Kong
Manufacturing	189.2 kg	Injection Molding, 10% loss assumed
Bucket shipping	17,500 km boat 600 km truck	Hong Kong to Lima (Peru) Lima to Ayacucho (Peru)
System 3		
Material	195.8 kg	Virgin PE, 90% HDPE, 10% LDPE, Field Ready buckets weigh slightly more than Oxfam buckets
Material transit	6000 km ship	From PE production in Houston (USA) to manufacturer in Lima
Manufacturing	195.8	Injection Molding, 10% loss assumed
Bucket shipping	600 km	Lima to Ayacucho (Peru)
System 4		
Material	179.8 kg	Virgin PE, 90% HDPE, 10% LDPE
Material transit	6000 km ship	From PE production in Houston to manufacturer in Lima
Manufacturing	1190.8 kWh	3-D printing, 6.69 kWh/kg assumed (Byard et al. 2019), 1% loss assumed
Bucket shipping	600 km	Lima to Ayacucho (Peru)
System 5		
Material	179.8 kg	Local waste PE, 90% HDPE, 10% LDPE
Material transit	50 km truck	Local waste PE in Lima
Manufacturing	1232 kWh	0.23 kWh/kg (grinding) and 6.69 kWh/kg (3-D printing) assumed (Byard et al. 2019), 1% loss assumed
Bucket shipping	600 km	Lima to Ayacucho (Peru)
System 6		
Material	179.8 kg	Local waste PE, 90% HDPE, 10% LDPE
Material transit	50 km truck	Local waste PE in Lima
Manufacturing	83.7 kWh	0.23 kWh/kg (grinding) and 0.24 kWh/kg (recycle bot extrusion molding) assumed (Woern et al. 2018a), 1% loss assumed
Bucket shipping	600 km	Lima to Ayacucho (Peru)

humanitarian aid location, which is the number of buckets assumed to fit on a common pallet for shipping (Field Ready 2023a).

Life cycle inventory data

To estimate the differences of electricity impacts in each manufacturing location, the local grid mixes were represented in the electricity profile for each country (Table 1) using data from the International Energy Agency (IEA 2022). Life cycle input data and commentary for each supply and distribution system are shown in Tables 2, 3, 4. Life cycle inventory data comes from the Ecoinvent version 3 database (Wernet et al. 2016) unless otherwise noted. Data from Google Earth was used to estimate the shipping distances between port cities for transportation and cities for manufacturing and distribution in all the countries in the study, in addition to the existing information on the typical Oxfam supply chain system (Field Ready 2023b). A standard injection molding process was used from the Ecoinvent database (1.48 kWh electricity, 4.4 MJ heat per kg of molded plastic) to model typical manufacturing impacts for Systems 1–3, with modifications to the electricity inputs to reflect country grid mixes as described in Table 1. The FPF/FGF

Table 4 Life cycle input data for South Sudan location scenarios

Item	Amount	Comments
System 1		
Material	189.2 kg	Virgin PE, 90% HDPE, 10% LDPE
Material transit	2520 km truck	Mumbai (India) to Lahore (Pakistan)
Manufacturing	189.2 kg	Injection Molding, 10% loss assumed
Bucket shipping	1184 km truck 11021 km ship 107 km UK truck 107 km UK truck 10500 km ship 2400 km truck	Lahore to Karachi, Pakistan Karachi to Southampton (UK) Southampton to Oxford (UK) Oxford to Southampton Southampton to Mogadishu (Ethiopia) Mogadishu to Joba (South Sudan)
System 2		
Material	189.2 kg	Virgin PE, 90% HDPE, 10% LDPE
Material transit	200 km truck	From PE production in China to manufacturer in Hong Kong
Manufacturing	189.2 kg	Injection Molding, 10% loss assumed
Bucket shipping	10000 km boat 2400 km truck	Hong Kong to Mogadishu Mogadishu to Joba
System 3		
Material	195.8 kg	Virgin PE, 90% HDPE, 10% LDPE, Field Ready buckets weigh slightly more than Oxfam buckets
Material transit	3600 km ship 2400 km truck	From PE production in Mumbai to Mogadishu Mogadishu to Joba
Manufacturing	195.8	Injection Molding, 10% loss assumed
System 4		
Material	179.8 kg	Virgin PE, 90% HDPE, 10% LDPE
Material transit	3600 km ship 2400 km truck	From PE production in Mumbai to Mogadishu Mogadishu to Joba
Manufacturing	1190.8 kWh	3-D printing, 6.69 kWh/kg assumed (Byard et al. 2019), 1% loss assumed
System 5		
Material	179.8 kg	Local waste PE, 90% HDPE, 10% LDPE
Material transit	50 km truck	Local waste PE in Joba
Manufacturing	1232 kWh	0.23 kWh/kg (grinding) and 6.69 kWh/kg (3-D printing) assumed (Byard et al. 2019), 1% loss assumed
System 6		
Material	179.8 kg	Local waste PE, 90% HDPE, 10% LDPE
Material transit	50 km truck	Local waste PE in Joba
Manufacturing	83.7 kWh	0.23 kWh/kg (grinding) and 0.24 kWh/kg (recycle bot extrusion molding) assumed (Woern et al. 2018a), 1% loss assumed

3-D printing and extrusion manufacturing processes come from experimental data on the typical performance of these systems (Byard et al. 2019; Little et al. 2020). Manufacturing losses were estimated at 10% for injection molding and 1% for both of the decentralized 3-D printing and extrusion recyclebot-based processes. Additional scenarios will explore the impacts of manufacturing efficiency assumptions. Oxfam-produced buckets are slightly lighter than the decentralized buckets produced by Field Ready according to available information (172 kg vs. 178 kg for the same 200-bucket functional unit), and each collection of 200 buckets is moved on a 17 kg pallet (Field Ready 2023a).

IPCC 100a Global Warming Potential (GWP) method was used to determine the amount of CO_2-equivalent greenhouse gas (GHG) emissions as the environmental impact of interest for this study, in units of kg CO_{2eq}. Life cycle assessment modeling was performed in the SimaPro LCA modeling platform.

Life cycle impact assessment and scenarios

Three countries were selected because of historic disasters requiring humanitarian aid (1) Nepal for the 2017 flooding (Relief 2017), (2) South Sudan for sporadic violence, chronic food insecurity, and the devastating impact of major flooding in 2021 (UNHCR 2023), and (3) Peru for floods, landslides, and mudslides in 2011 (Relief 2015). A prominent location in each of the three countries was used for each representative location for humanitarian aid distribution, which will be described in more details in each scenario.

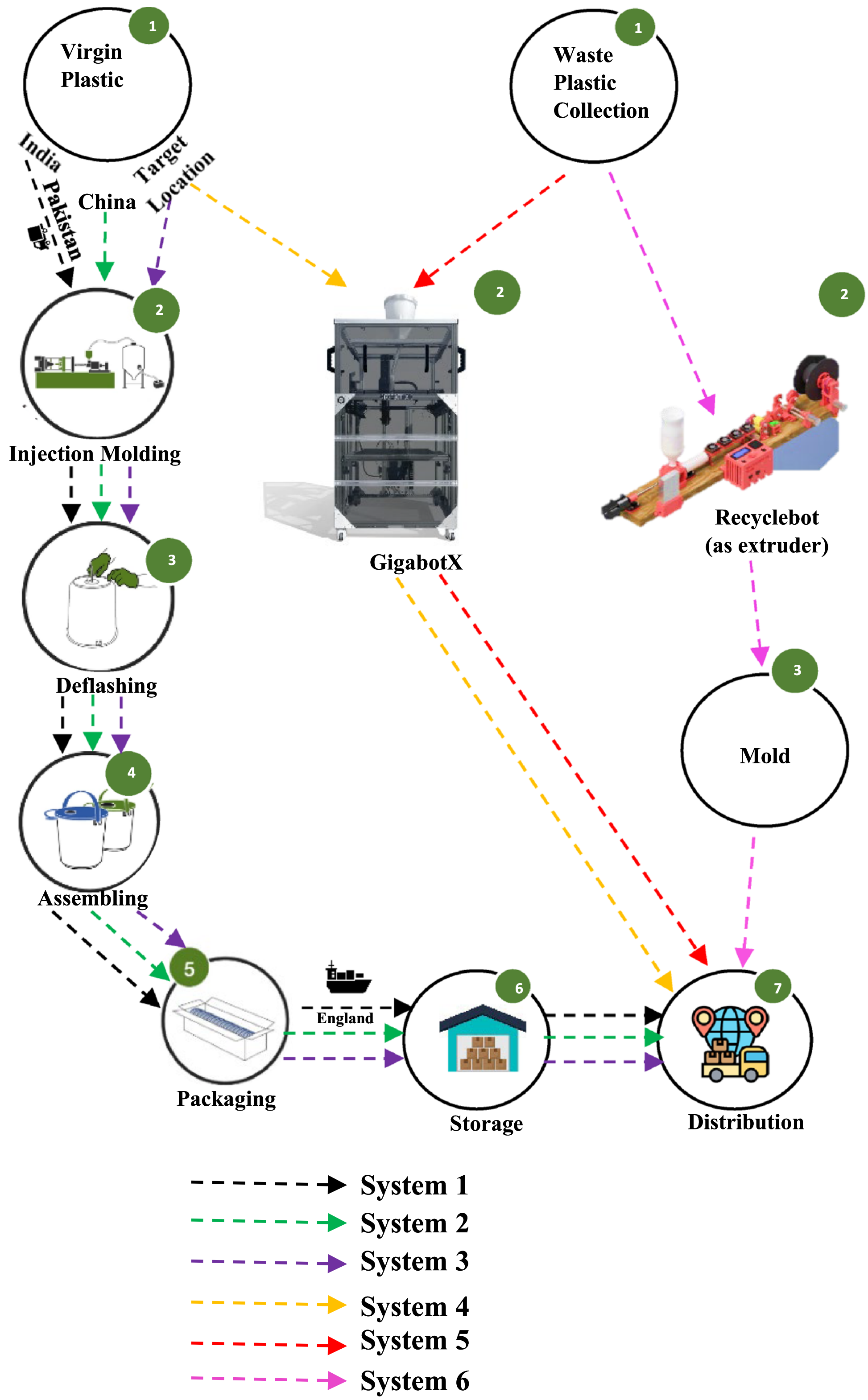


Fig. 2 Summary of the six types of production of humanitarian aid products

The six processing and supply scenarios are described briefly below and summarized in Figs. 2 and 3.

System 1 Oxfam traditional system. In Oxfam's traditional system of supply delivery, the buckets are manufactured in a low-cost location, such as India, and are transferred to a centralized distribution warehouse. The Oxfam Central facility in Oxford, England, serves as the central single supplier for re-shipping (Field Ready 2023b). Virgin PE is sourced in

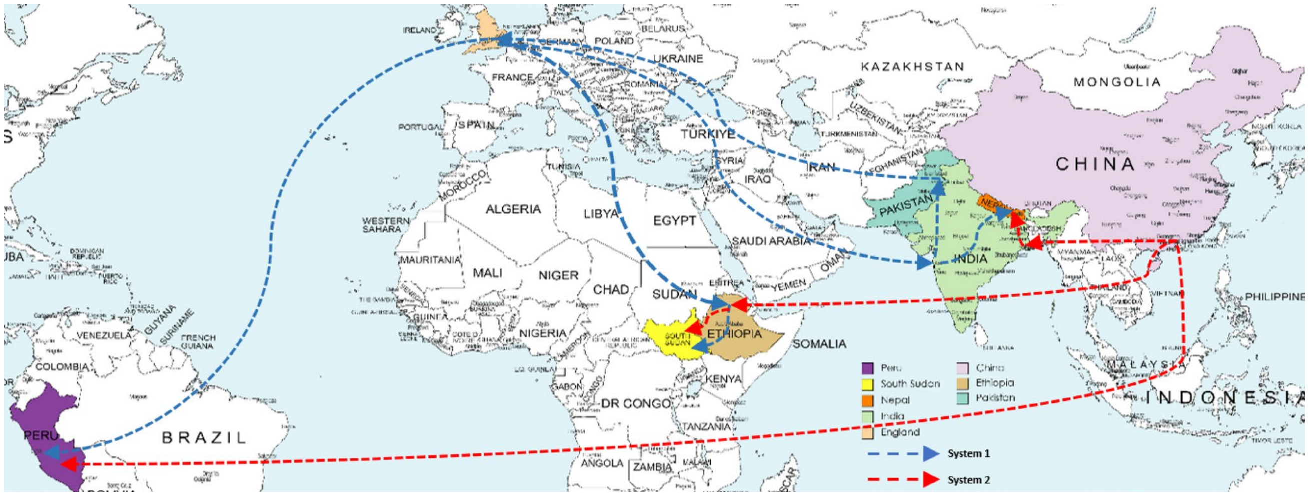


Fig. 3 Map of feedstock collection to distribution of final product to targeted locations for System 1 and 2

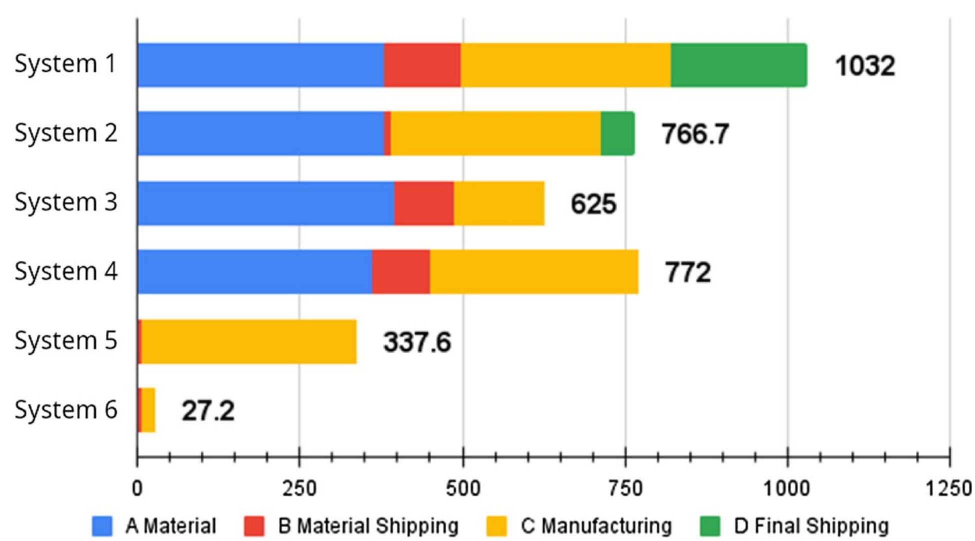
India, buckets are manufactured using conventional injection molding in Pakistan, and then shipped to Oxford, England. When a humanitarian crisis occurs, buckets are shipped to the location of the crisis from England. Because of the large international shipping distances required, a combination of marine, rail, and road transport is used.

System 2 Chinese supply and distribution. An alternative option for centralized production and transport would remove Oxfam international and do PE sourcing, bucket manufacturing using injection molding, and intermediate storage in the same general location. So, for example, Alibaba.com provides several sources of buckets ordered with a minimum of several thousand. For this system, a location in eastern China was assumed to serve as the course for PE supply, bucket assembly, and storage.

System 3 Field Ready supply and distribution system (https://www.fieldready.org/buckets). In this more decentralized supply system, conventional virgin PE pellets are sourced from suppliers within the region of the country of interest, and local bucket manufacturing using injection molding is established at a key strategic location within the country of interest, eliminating one critical leg of transportation which is typically long, costly, and slow.

System 4 Decentralized supply and distribution system with 3-D printing. In this system, the decentralized method of virgin PE sourcing and bucket manufacturing is adopted similar to System 3, but now it is assumed that the bucket manufacturing process is accomplished using FPF 3-D printing tools (Byard et al. 2019) instead of injection molding systems, which are utility-intensive in comparison with 3-D printing. The printer assumed is the open-source GigabotX,

Fig. 4 LCA results (kg CO_{2eq}) for Nepal



which is a commercial large format 3-D printer capable of printing the entire bucket. (Many desktop 3-D printers do not have the manufacturing volume capacity to print the 14 L buckets.) In addition, as it is FPF/FGF printer, only ground waste plastic or pellets is needed already sourced in the country.

System 5 Distributed supply and distribution system with 3-D printing and local waste feedstock. In this system, the decentralized distribution system and 3-D manufacturing processes are similar to System 4, but it is assumed that the PE feedstock for 3-D printing comes from local waste PE such as drink bottles and is mechanically recycled into 3-D printing PE feedstock using well-established existing processes for DRAM. For this process, the waste plastic would need to be cleaned, dried, and shredded before putting into the FPF/FGF printer (Little et al. 2020).

System 6 Distributed supply and distribution system with extrusion molding and local waste feedstock. This decentralized system utilizes locally sourced waste plastic HDPE/LDPE, but replaces 3-D printing with an even lower-intensity manufacturing process, extrusion molding using a recyclebot as the extruder (Dertinger et al. 2020).

Limitations

There are several limitations to this study. First, although the primary data was collected for Systems 4, 5, and 6 for other products it was published previously, and the cited data was used for the inputs for the processing. There were no other primary data used in this study/only secondary data were thus used. The focus of this study is on only on the global warming potential indicator as this is the most

Fig. 6 LCA results (kg CO_{2eq}) for South Sudan

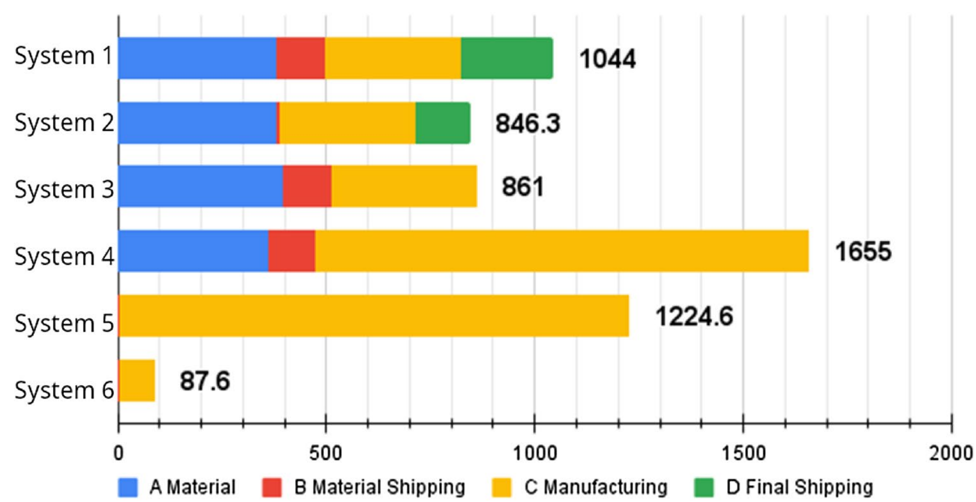
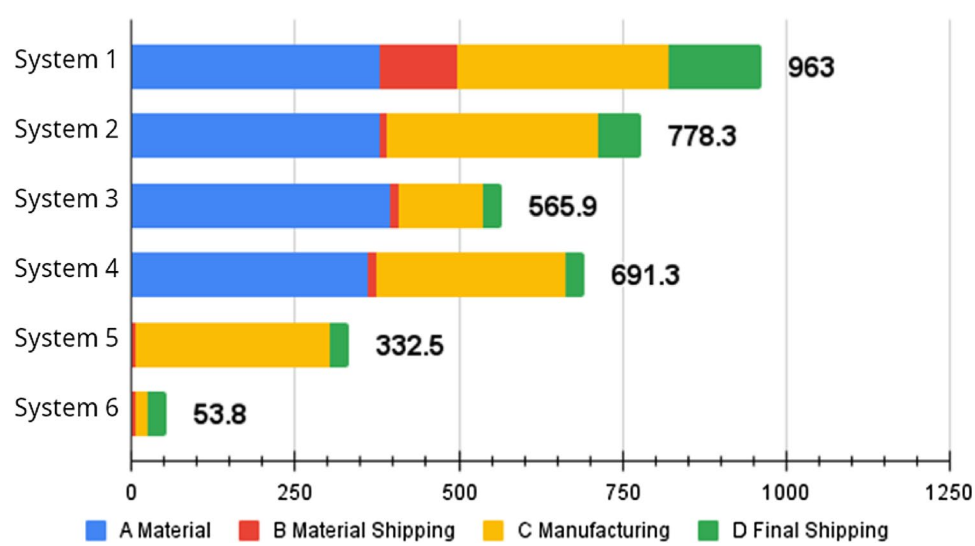


Fig. 5 LCA results (kg CO_{2eq}) for Peru



valuable comparison metric and other LCA indicators like ecotoxicity were not used. As this study is focusing only on the method of manufacture, it is assumed that the case study product is used and disposed of in the same way. This system boundary for the LCA study was selected on purpose because the primary point of this analysis is to understand the impacts of the manufacturing. Thus, the system boundary study does not include use and the various types of potential disposal are not studied (e.g., centralized recycling, DRAM, incineration, landfilling, or any type of upcycling). As all of the 3-D printing scenarios 4, 5, and 6, have been demonstrated in detail for other products with far more challenging manufacturing specifications (Shahrubudin et al. 2019) including watertight systems for chemical research (Gelhausen et al. 2018) and even vacuum systems (Mayville et al. 2022), the technical viability was not considered an issue and tested. Future work could follow up the results of this LCA to test the technical viability in the field of these types of distributed systems.

LCA results, interpretation, and discussion

The LCA results are shown in Figs. 4, 5, and 6 for the GWP of the six supply and production scenarios, for each of the three target locations in the study, respectively. Appendix contains Tables 5, 6, 7, which compile the numerical results. Several common observations can be seen across the results for all three locations, although the specifics of shipping and utility use in each location also give rise to different impacts. For System 1 and 2 where shipping of large quantities of buckets was considered, 1 pallet could hold 200 buckets and weighed 172 kg.

In general, System 2 (Chinese supply and distribution) performs better than System 1 (Oxfam typical process) due to the large reductions in shipping distance, even though the majority of that shipping distance is from relatively low-emissions marine shipping. For System 2, however, there would be concern among aid organization that is too scared out reliability/delivery time from ordering under disaster-related contexts at a site like Alibaba. For this model to work, the NGOs would need to do some pre-ordering and testing, but there is an economic barrier of having to order thousands (e.g., 5,000) at a time.

Transitioning from System 2 to System 3 (local injection molding) typically results in lower overall emissions by trading off higher material shipping impacts for lower manufacturing emissions, in Nepal and Peru, due to the lower embodied emissions associated with electricity. This is not the case in South Sudan, where electricity production produces even more GHGs than in China due to the reliance on oil for electricity. This conversion to more distributed production indicates the importance of the local electricity supply.

System 4 (local 3-D printing of virgin plastic) typically results in higher emissions than System 3, due to the reliance on electricity for FPF/FGF 3-D printing. This underscores the importance of the emissions intensity of the grid for choosing an ideal location to do manufacturing. Locations with low emissions (e.g., Quebec) would systematically do better. In addition, it is straightforward to power the 3-D printing devices with solar photovoltaic technology so that rapid manufacturing can take place on site without reliable power with no emissions (King et al. 2014; Gwamuri et al. 2016; Khan et al. 2018). Future work is needed to investigate this scenario, which may be realistic in the case of humanitarian crises. It also points to areas of future work to improve

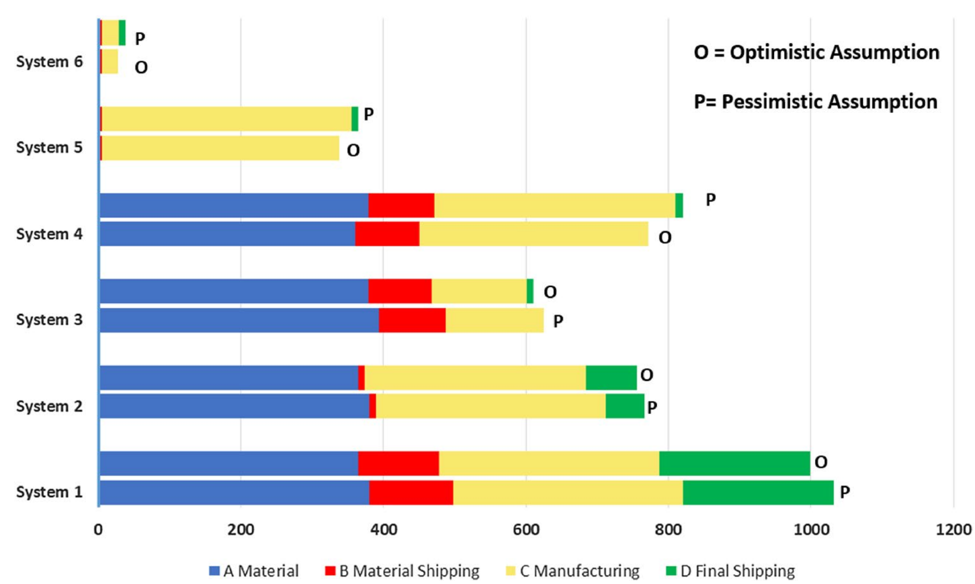


Fig. 7 LCA comparison (kg CO_{2eq}) between optimistic and pessimistic scenarios for Nepal

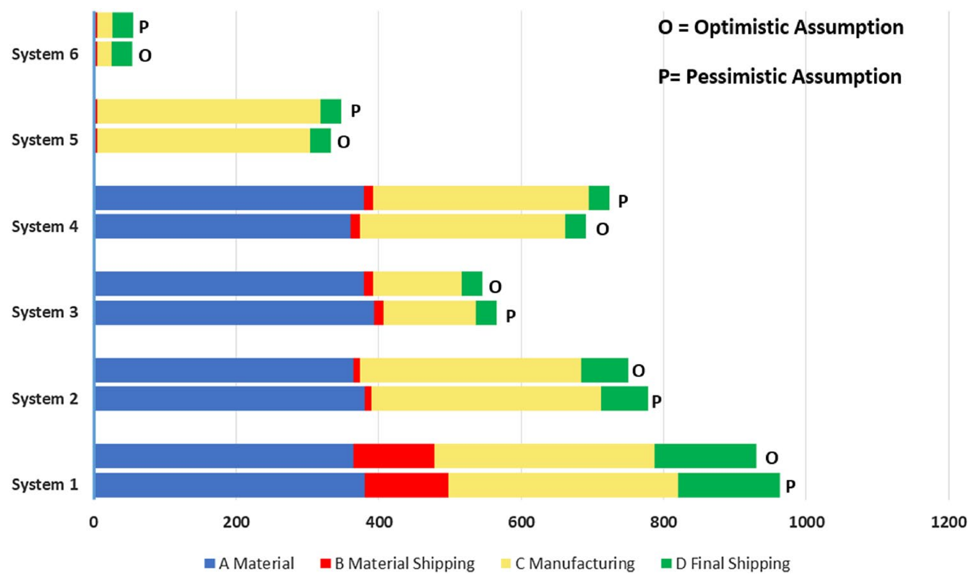


Fig. 8 LCA comparison (kg CO_{2eq}) between optimistic and pessimistic scenarios for Peru

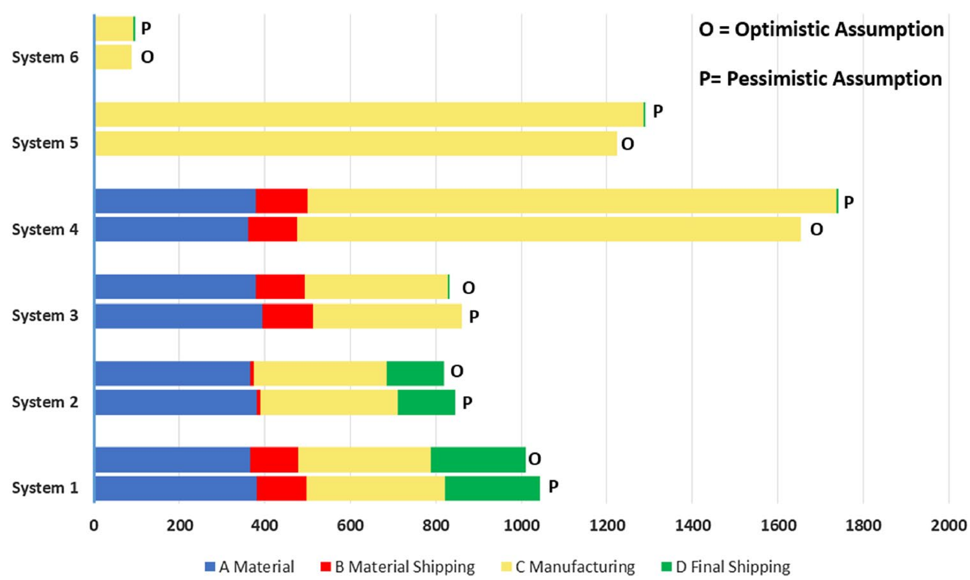


Fig. 9 LCA comparison (kg CO_{2eq}) between optimistic and pessimistic scenarios for South Sudan

printing speed, throughput, multi-nozzle 3-D printing and other areas that could enable more rapid and more efficient manufacturing with 3-D printing.

The real benefit of local 3-D printing, however, starts to be realized in the DRAM System 5 (waste plastic local FPF 3-D printing), due to the elimination of the emissions associated with virgin plastic, assuming that all of the necessary plastic can be recovered within a 50 km radius of the manufacturing location—quite likely, this supply radius is a very conservative estimate and material supply impacts could be even lower. The South Sudan scenarios for System 4 and 5 still appear worse than the System 1 baseline, however, due to the extremely large electricity emissions in that country. Again, any country that wants to be favored for manufacturing from those seeking low-embodied emissions should be aggressively eliminating fossil carbon sources from the supply.

Even further emissions reductions are possible with the transition to extrusion molding with the recyclebot extrusion molding system (System 6), which offers a 95% reduction in manufacturing electricity usage compared to 3-D printing. This system change is enough to drive the GHG emissions for the Nepal and Peru scenarios to greater than 94%, and also brings the South Sudan case back to being largely environmentally favorable, with a 90.9% GHG emissions reduction compared to System 1. This path is also perhaps the most realistic as for humanitarian products like a bucket, where they are relatively large 3-D prints and many identical ones would be adequate the extrusion molding system can make use of DRAM (e.g., 3-D printing the molds onsite in high temperature plastics like poly carbonate) and then manufacturing products rapidly with lower melting temperature plastics. Substantially more technical work is needed in this area to get open-source designs adapted to this method and optimized with experimental testing.

Critics may point out that low errors were used for the distributed processes and thus low sources of waste. This would appear likely after experience is gained, but before that 3-D printing errors can be as high as 10% or more (Wittbrodt et al. 2013). To illustrate the impacts of manufacturing efficiency in this system, an alternate set of LCA results are shown in Figs. 7, 8, and 9 and are presented in Appendix Table 8, where the manufacturing efficiency for regular injection molding was changed from 10% down to 5%, and the manufacturing failure rate of 3-D printing was increased from 1 to 10%. This impacts the amount of raw material that is required to be produced, shipped, and transformed during the manufacturing phase, but should not affect the final shipping stage of this LCA study. This does have the effect of lowering the GHG emissions associated with supply Systems 1, 2, and 3 and increasing the emissions of systems 4, 5, and 6, but the overall results are still consistent with the general observations discussed above that significant GHG emissions reductions are possible from distributed manufacturing and local procurement of waste feedstock. Changes in overall results are generally less than 5% due to these changes in assumed manufacturing efficiency. This effect is similar for the Peru target location (Appendix Table 9) and the South Sudan location (Appendix Table 10), although the impacts of changing manufacturing efficiency in situations where manufacturing is being performed in South Sudan do have more of an impact due again to the large emissions associated with electricity production.

Future work can consider the economics of the various scenarios with a sensitivity run on labor costs and location, as well as a more detailed sensitivity analysis of the key parameters that will ultimately influence economic and environmental impacts. It is well documented that distributed manufacturing particularly of recycled materials has economic benefits (Byard et al. 2019), but these benefits are highly dependent on labor costs. LCA input items such as shipping distances and burdens, electricity grid assumptions, and manufacturing energy inputs are all items that can have the potential to influence the outcomes of this study, but the overall conclusions in the paper can be seen to demonstrate the potential of this approach to delivering services in a novel way.

Conclusions

This study examined the effects of manufacturing and distributing an Oxfam Jerry Bucket, a family-size water storage, and dispensing bucket with a 14 L capacity, in Nepal, Peru, and South Sudan under six distinct supply chain models. During the LCA, it has been observed that two factors have the major contribution to total GHG emissions: (i) electricity usage for manufacturing and (ii) shipping feedstock and final product. Among System 1–3, System 1 and System 2 are environmentally poor as the electricity emission in Pakistan and China is quite high. Emissions from System 2, however, is marginally lower overall than System 1 due to the significant reduction in shipping distance. On the other hand, System 3 showed convenience as the products are manufactured locally. Nepal and Peru's electricity mix includes more than 50% of hydropower; therefore, almost 57%–60% of emission reduction can be observed in manufacturing.

Nevertheless, a 7% increase has been perceived in the South Sudan location, as 100% of their total electricity production relies on oil. There a decentralized supply and distribution system with 3-D printing (System 4) seems less compatible due to the massive contribution of nearly 72% of GHG emissions associated with manufacturing. The FPF/FGF GigabotX 3-D printer relies on local electricity makes it one of the less appropriate methods for the three targeted locations for now, even considering the optimistic assumptions. In System 5, the same equipment has been used, but with local waste feedstock, which shows an improvement of 67.7% for Nepal and 65.5% for Peru because of the reduced shipping emissions, even if the manufacturing emission is the highest among all of the systems. Yet, System 5 shows the worst scenario for South Sudan. System 6 (distributed supply and distribution system with extrusion molding and local waste feedstock) is feasible for all three locations, with reductions in GWP of 90.9%-97.4% compared to the baseline System 1. Even with a more pessimistic assumption of manufacturing material loss (Appendix, Table 8), the results for System 6 only increase by less than 1%.

System 4 and 5 seem less feasible for locations with heavy fossil fuel percentages on the grid because of their reliance on electricity from the manufacturing location. If manufacturing could be done where the electricity emission is lower, i.e., Quebec, these systems can be feasible. Furthermore, it has been vividly seen that using local waste feedstock is the most efficient approach; however, a further study should be done on operating the FPF/FGF 3-D printer or extrusion molding systems powered with distributed photovoltaic systems in order to complement this process and produce the most environmentally responsible production.

Appendix

See Table 5, 6, 7, 8, 9, 10

Table 5 LCA results (kg CO_{2eq}) for Nepal target location

	System 1	System 2	System 3	System 4	System 5	System 6
Material	Virgin PE	Virgin PE	Virgin PE	Virgin PE	Waste PE	Waste PE
Source	India	China	Nepal	Nepal	Local	Local
Mfg	Pakistan IM	China IM	Nepal IM	Nepal 3DP	Nepal Grind + 3DP	Nepal Grind + Recyclebot EM
Distribution	To UK and Out	China out	Nepal local	Nepal local	Nepal local	Nepal local
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
A Material	380	380	394	361	0	0
B Material Shipping	118	9.3	93	89	4.6	4.6
C Manufacturing	323	323	138	322	333	22.6
D Final Shipping	211	54.4	0	0	0	0
Total	1032	766.7	625	772	337.6	27.2
Percent Improvement from System 1	0.0%	25.7%	39.4%	25.2%	67.3%	97.4%

Table 6 LCA results (kg CO_{2eq}) for Peru target location

	System 1	System 2	System 3	System 4	System 5	System 6
Material	Virgin PE	Virgin PE	Virgin PE	Virgin PE	Waste PE	Waste PE
Source	India	China	Peru	Peru	Local	Local
Mfg	Pakistan IM	China IM	Peru IM	Peru 3DP	Peru Grind + 3DP	Peru Grind + Recyclebot EM
Distribution	To UK and Out	China out	Peru local	Peru local	Peru local	Peru local
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
A Material	380	380	394	361	0	0
B Material Shipping	118	9.3	13	12.4	4.6	4.6
C Manufacturing	323	323	130	289	299	20.3
D Final Shipping	142	66	28.9	28.9	28.9	28.9
Total	963	778.3	565.9	691.3	332.5	53.8
Percent Improvement from System 1	0.0%	19.2%	41.2%	28.2%	65.5%	94.4%

Table 7 LCA results (kg CO_{2eq}) for South Sudan target location

	System 1	System 2	System 3	System 4	System 5	System 6
Material	Virgin PE	Virgin PE	Virgin PE	Virgin PE	Waste PE	Waste PE
Source	India	China	S Sudan	S Sudan	Local	Local
Mfg	Pakistan IM	China IM	S Sudan IM	S Sudan 3DP	S Sudan Grind + 3DP	S Sudan Grind + Recyclebot EM
Distribution	To UK and Out	China out	S Sudan local	S Sudan local	S Sudan local	S Sudan local
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
A Material	380	380	394	361	0	0
B Material Shipping	118	9.3	120	114	4.6	4.6
C Manufacturing	323	323	347	1180	1220	83
D Final Shipping	223	134	0	0	0	0
Total	1044	846.3	861	1655	1224.6	87.6
Percent Improvement from System 1	0.0%	12.1%	10.6%	−71.9%	−27.2%	90.9%

Table 8 LCA Results (kg CO_{2eq})—Scenarios with alternative manufacturing losses, for the Nepal target location

	System 1	System 2	System 3	System 4	System 5	System 6
Material	Virgin PE	Virgin PE	Virgin PE	Virgin PE	Waste PE	Waste PE
Source	India	China	Nepal	Nepal	Local	Local
Mfg	Pakistan IM	China IM	Nepal IM	Nepal 3DP	Nepal Grind + 3DP	Nepal Grind + Recyclebot EM
Distribution	To UK and Out	China out	Nepal local	Nepal local	Nepal local	Nepal local
	System 1	System 2	System 3	System 4	System 5	System 6
A Material	365	365	379	379	0	0
B Material Shipping	113	9	89	93	4.8	4.8
C Manufacturing	310	310	133	338	350	24
D Final Shipping	211	72	10	10	10	10
Total	999	756	611	820	364	38
Percent Improvement (Original % Improvement)*	3.2% (0.0%)	26.8% (25.7%)	40.8% (39.4%)	20.5% (25.2%)	64.7% (67.3%)	96.3% (97.4%)

*The original percent improvement values in parentheses are reproduced here from Table 5 to facilitate easy comparison. The System 1 GHG emissions value from Table 5 is still used as the baseline in all cases

Table 9 LCA Results (kg CO_{2eq})—Scenarios with alternative manufacturing losses, for the Peru target location

	System 1	System 2	System 3	System 4	System 5	System 6
Material	Virgin PE	Virgin PE	Virgin PE	Virgin PE	Waste PE	Waste PE
Source	India	China	Peru	Peru	Local	Local
Mfg	Pakistan IM	China IM	Peru IM	Peru 3DP	Peru Grind + 3DP	Peru Grind + Recyclebot EM
Distribution	To UK and Out	China out	Peru local	Peru local	Peru local	Peru local
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
A Material	365	365	379	379	0	0
B Material Shipping	113	9	13	13	4.83	4.83
C Manufacturing	310	310	125	303	314	21
D Final Shipping	142	66	29	29	29	29
Total	930	750	545	724	348	55
% Improvement	3.4%	22.1%	43.4%	24.8%	63.9%	94.3%

Table 10 LCA Results (kg CO_{2eq})—Scenarios with alternative manufacturing losses, for the South Sudan target location

	System 1	System 2	System 3	System 4	System 5	System 6
Material	Virgin PE	Virgin PE	Virgin PE	Virgin PE	Waste PE	Waste PE
Source	India	China	S Sudan	S Sudan	Local	Local
Mfg	Pakistan IM	China IM	S Sudan IM	S Sudan 3DP	S Sudan Grind + 3DP	S Sudan Grind + Recyclebot EM
Distribution	To UK and Out	China out	S Sudan local	S Sudan local	S Sudan local	S Sudan local
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
A Material	365	365	379	379	0	0
B Material Shipping	113	9	115	120	4.83	4.83
C Manufacturing	310	310	334	1239	1281	87
D Final Shipping	223	135	5	5	5	5
Total	1011	819	833	1743	1291	97
% Improvement	3.1%	14.9%	13.5%	−81.0%	−34.0%	90.0%

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Author contributions J.M.P. conceived the study. R.M.H and R.R. performed the LCA and made the figures. All authors reviewed and wrote the manuscript.

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Data availability All data is available upon request.

Declarations

Conflict of interest The authors have no conflict of interest.

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