Carbon footprinting

in humanitarian construction

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Carbon footprinting in humanitarian construction

What are the CO_2 emissions and how to mitigate them?

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Abstract

Climate change has become a key driver of humanitarian disasters and forced migration. Its impacts are seen globally but the greatest vulnerability is experienced in the cities of the less developed countries. Although the built environment is globally accountable for around 30% of greenhouse gas emissions, the research of its impact in humanitarian construction is very thin and recommendations for optimising the carbon footprint of transitional shelters or reconstruction are extremely hard to find.

Life cycle assessment is often considered to be the most suitable tool for the science-based evaluation of the greenhouse gas emissions of buildings or building products. However, its implementation in the iterative design and decision-making processes is rather difficult. In order to include carbon footprinting in building design, simplifications are needed, especially in the field of humanitarian operations.

In this dissertation, the knowledge gaps related to carbon footprint estimation and simplified methods are presented. First the background is presented: climate-related disasters, environmental assessment in humanitarian construction and the existing, standardised methods for estimating the environmental impacts of buildings. Secondly, a series of case studies from different countries reveal the carbon footprint and primary energy demand of transitional shelters and reconstruction projects. Thirdly, novel methods are proposed for setting the benchmark levels of an acceptable carbon footprint in humanitarian construction and for cross-comparing carbon footprint, energy efficiency and construction costs. Finally, the findings are summarised into practical recommendations and a low-carbon humanitarian construction project model.

The carbon footprint in humanitarian construction seems to be very material related. Bio-based materials enable low greenhouse gas emissions. In addition, focusing on energy efficiency seems to be relevant in the refugee camps of cold climates, especially if the energy infrastructure is damaged in a humanitarian disaster. Several further research needs are recognised for improving the reliability of life cycle assessment in humanitarian construction. Embedding environmental accountability into the development of core humanitarian standards and guidelines is recommended.

Climate change

is a key driver for humanitarian crises.

The mitigation of climate change is almost excluded in the environmental guidelines for humanitarian construction.

The construction sector is globally accountable for 40% of primary energy demand and 30% of greenhouse gas emissions.

Transitional shelters may cause very large overshoots to national per capita greenhouse gas emissions.

Do no harm! Humanitarian aid should not further accelerate climate-related disasters.

Changes in planning, funding and evaluation of humanitarian aid **are required.**

CO_2

Humanitarian construction projects should include clearly defined maximum greenhouse gas peaks.

Shelters have short service lives. Therefore the sustainability of their construction materials is essential for mitigation of greenhouse gas emissions.

Encourage the use of bio-based, sustainably-sourced construction materials.

Wood and bamboo shelters have clearly lower carbon footprint than those made of other materials.

Favour clustered shelters in cold regions. Clustering improves energy and resource efficiency.

The recycling of construction materials can cause larger or smaller emissions in comparison to virgin materials. The environmental feasibility depends on the intended end use and context.

The carbon efficient project model gives humanitarian operators a frame of reference for mitigating the emissions of construction projects.

The overall sustainability of humanitarian construction may be obtained by cross-comparing carbon footprint, energy demand and costs.

Leading a sustainable human life should be considered as an

emerging human right.

Preface

This thesis is an attempt to draw a picture of carbon footprinting in the context of humanitarian construction. First we ask the fundamental question of why this is relevant. Then we will go through methodological aspects and introduce the existing means for assessing the environmental impacts of buildings. The theoretical principles are further illustrated with the help of the case studies of several shelter and reconstruction projects. The case studies are followed by new proposals for adjusting the constant environmental assessment methods for humanitarian use. Finally, a practical project model is introduced for mitigating the carbon footprint of humanitarian construction projects.

There seems to be very little research or examples from the applied scientific field of humanitarian construction and the environmental assessment of buildings. Therefore this thesis is primarily aimed at humanitarian professionals who are interested in sustainable construction but are not experts in life cycle assessment. Because of this focus, the study does not cover all the details of life cycle or environmental impact assessment. Because of this limitation I hope that the contents will inspire other scientists and practitioners to add their contribution to the environmental assessment of humanitarian operations.

Sustainable living should not be a privilege of the rich and educated minority of the world. It should be considered a human right, especially in our era that requires all hands on deck to combat our behavioural tendency to cause climate change.

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I would like to thank my supervisor, professor Toni Kotnik from Aalto University, and my tutors, professor Pekka Heikkinen (Aalto) and professor Stefan Winter (TU München) for their continuous support, experienced guidance and constructive approach to my work. Professor Annette Hafner (Ruhr University Bochum), professor Esther Charlesworth (RMIT University) and professor Aoife Houlihan Wiberg (Norwegian University of Science and Technology) have provided very valuable comments and feedback.

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I would like to extend my gratitude to my relatives as well. As I learnt to walk, my grandfather took me to building sites and introduced me to the world of construction. Later, my father took me along on his field trips and showed me what research looks like. As teachers, my mother, sister and aunts have surrounded me with good examples of the importance of education.

Finally, I wish to thank my family for their patience during my commitments. When travelling all around the world and working in disaster areas I have understood how privileged I have been to be able to live in a safe country with my beautiful wife and four lovely children. Academic merits or professional achievements can never compare to that. I am humbly grateful for each of these days that I have been blessed with.

Matti Kuittinen, architect

Lohja, 30 March 2016

What is the use of a house

if you haven't got a tolerable planet to put it on?

- Henry Thoreau

Contents

Definitions

These are the definitions for the terms used in this book in thematic order. Other definitions may exist for the same terms in other sources.

Disaster

"A sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses that exceed the community's or society's ability to cope using its own resources. Though often caused by nature, disasters can have human origins" (IFRC, 2014).

Natural hazard

"Naturally occurring physical phenomena caused either by rapid or slow onset events which can be geophysical (earthquakes, landslides, tsunamis and volcanic activity), hydrological (avalanches and floods), climatological (extreme temperatures, drought and wildfires), meteorological (cyclones and storms or wave surges) or biological (disease epidemics and insect or animal plagues)" (IFRC, 2014).

Man-made or technological hazard

"Events that are caused by humans and occur in or close to human settlements. This can include environmental degradation, pollution and accidents (IFRC, 2014). Technological or man-made hazards include "complex emergencies or conflicts, famine, displaced populations, industrial accidents and transport accidents" (IFRC, 2014).

Disaster preparedness

"Measures taken to prepare for and reduce the effects of disasters" (IFRC, 2014).

Humanitarian action or **aid** or **assistance**

"The objectives of humanitarian action are to save lives, alleviate suffering and maintain human dignity during and in the aftermath of man-made crises and natural disasters, as well as to prevent and strengthen preparedness for the occurrence of such situations" (Good Humanitarian Donorship, 2013).

Humanitarian construction

The design, production and assembly or building of emergency shelters, transitional shelter or reconstruction work, carried out after natural or man-made disasters. Needs for humanitarian construction may occur in developing or developed countries and for any socio-economic group.

Emergency shelter

Shelter which is provided immediately after a disaster and that ensures protection from weather. Usually a tent or room in a grouped accommodation centre.

Transitional shelter

"Shelter which provides a habitable covered living space and a secure, healthy living environment, with privacy and dignity, to those within it, during the period between a conflict or natural disaster and the achievement of a durable shelter solution" (Corsellis & Vitale, 2005, p. 11). Transitional shelters may be individual shelter buildings, a room with a host family or grouped accommodation in existing buildings.

Transitional settlement

"Settlement and shelter resulting from conflict and natural disasters, from emergency response to durable solutions" (Corsellis & Vitale, 2005, p. 11).

Reconstruction phase

The design, production and construction of permanent buildings and infrastructure after natural or man-made disasters.

Vulnerability

"The diminished capacity of an individual or group to anticipate, cope with, resist and recover from the impact of a natural or man-made hazard" (IFRC, 2014).

List of abbreviations and symbols

ACT	Action by Churches Together
aLCA	Attributional Life Cycle Assessment
BEM	Building Energy Model
BIM	Building Information Model
CAD	Computer-aided design
CEAP	Community-based Environmental Action Planning
CEN	European Committee for Standardization
cLCA	Consequential Life Cycle Assessment
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DRM	Disaster risk management
DRR	Disaster risk reduction
EC	European Commission
ECHO	Directorate-General for Humanitarian Aid and Civil Protection
EIA	Environmental Impact Assessment
EIO	Economic Input-Output analysis
EN	Europäische Norm (European Standard)
EPD	Environmental Product Declaration
EU	European Union
FCA	Finn Church Aid
FSC	Forest Stewardship Council
GHG	Greenhouse gas
GPP	Green Public Procurement
GWP	Global Warming Potential
HAP	Humanitarian Accountability Partnership
HFA	Hyogo Framework for Action
IASC	Inter-Agency Standing Committee
IDP	Internally Displaced People
IEA	International Energy Agency
IFRC	International Federation of Red Cross and Red Crescent Societies
INEE	Inter-Agency Network for Education in Emergencies
IO	Input-output analysis
IOM	International Organization for Migration
ISO	Internation Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCEA	Life Cycle Energy Assessment
LCIA	Life Cycle Impact Assessment
LRRD	Linking Relief, Rehabilitation and Development
MDG	Millenium Development Goals
MFA	Material Flow Analysis
NFI	Non-food item
NGO	Non-governmental Organisation
OCHA	Office for Coordinating Humanitarian Affairs
OECD	Organization for Economic Cooperation and Development
PCR	Product Category Rules
PE	Primary Energy
REA	Rapid Environmental Impact Assessment in Disasters
TLS	Transitional Learning Space
T-shelter	Transitional Shelter
UN	United Nations

UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UN-Habitat	United Nations Human Settlements Programme
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children´s Fund
UNITAR	United Nations Institute for Training and Research
UNOPS	United Nations Office for Project Services
UNOSAT	UNITAR´s Operational Satellite Applications Programme
WBCSD	World Business Council for Sustainable Development
WFP	World Food Programme
WWF	World Wildlife Fund

Part 1

Research

1 Climate change and humanitarian crises

1.1 Change is natural but the current speed of change is not

During the past 10 000 years, we have experienced a relatively stable climate that has supported the development of our civilisations (Rioual et al., 2001; Rockström et al., 2009). However, in longer timescales, change seems to be a normal state: our planet has experienced considerably colder periods (Allen & Etienne, 2008) and warmer periods (Röhl et al., 2000) than today. Compared to these extremes, the observed increase of mean surface temperature (GISTEMP Team, 2015; Hansen et al., 2010) does not appear extraordinary.

If this is the case, why should one worry about the role of man in climate change, which is a natural phenomenon? The primary problem is not the change but its speed and the challenges that the change causes to our societies and well-being. After the industrial revolution, the amount of greenhouse gases (GHGs) released into the atmosphere has increased at a speed that is faster than the natural fluxes of the same gases, thus disturbing climate sensitivity (Hansen et al., 2011) and causing anthropogenic climate change (Hansen et al., 2013). This speed of emission surpasses the natural mechanisms of our planet that balance and mitigate these changes. As a result, we have caused the climate to change faster than previously experienced and the speed is likely to increase in the 2020s (Smith et al., 2015). With the current rate of emissions, the internationally agreed goal of the Copenhagen Accord (UNFCC, 2009), limiting global warming to 2°C, may already be exceeded around 2039 (University of Oxford, 2014; Allen et al., 2009).

The changing climate is already causing significant stress to life on earth. Both flora and fauna are suffering from the change (Parmesan & Yohe, 2003). As habitats are changing, land and sea animals are migrating towards poles at a rate of approximately 100 km per decade (Burrows, et al., 2011). The change of habitats also causes forced human migration that may result in a further one billion refugees by 2050 (Christian Aid, 2007). Thus, climate change has already become a key driver behind the coming humanitarian crises (Walker et al., 2012). Today's flow of refugees from the Middle East and Africa to Europe gives an example of the type of humanitarian, economic and political problems this new era of climate-related mass-migration may bring.

1.2 Humanitarian disasters related to climate change

There are several types of disasters that can either fully or in part be account for the climate change with a very high level of confidence. These include increased precipitation that may increase flooding, more intense storms, drought, sand storms, heat waves and wildfires. The warming climate holds the potential to cause more climate related disasters (IPCC, 2014, p. 6), and the increasing population (Seto et al., 2014), especially in urban settlements, makes communities more vulnerable to them (Hansen, 2010; Walker et al., 2012; OCHA & UNEP, 2012). The impacts of these natural disasters often cause cascade effects and may affect critical infrastructures (Berariu et al., 2015). The classification of disasters and their relation to climate change are presented in figure 1.1.

The amount of disasters changes on a yearly basis. Between 2002 and 2011 there were over 400 disasters linked to natural hazards, which resulted into more than 1.1 million deaths and financial losses of almost 1.2 trillion USD (UNISDR, 2012). However, the year 2013 presented a decrease in the amount of disasters, mainly due to a decrease in climatological disasters, leaving 24.5% less victims than in 2012 (Guha-Sapir et al., 2013). Still, 51.2 million people were displaced in 2013 and natural disasters alone caused 22 million displacements (UNHCR, 2013). Climate change is causing crises that have complex linkages to each other (Walker et al., 2012) and it has been argued that the impact of climate change as a driver of, for example, forced migration should not be over-emphasized but studied together with other reasons, for example, socio-economic pressures (Hartmann, 2010).

The annual statistics of the International Disaster Database (Centre for Research on the Epidemiology of Disasters, 2016) show that floods, droughts and storms cause the highest human impacts, as illustrated in figure 1.2. These disaster types are linked to changes in the weather system but also to increased vulnerability. There are relatively high annual variations in the impacts of different disaster types. For instance, the earthquakes of Haiti (2010) and Japan (2011) caused a significant peak in the impacts of seismic disasters. Otherwise storms as single disaster type hold the leading position for human impacts.

The El Niño and La Niña weather pattern, resulting from natural changes in the water temperatures of the Pacific Ocean, amplifies certain weather-related disaster types, such as hurricanes and droughts. The impacts of this pattern on weather have been observed from at least the 17th century (Pielke & Landsea, 1999). However, global warming seems to change both the El Niño (Cai et al., 2014) and La Niña (Cai et al., 2015) phases towards becoming "devastating weather events". Indeed, the frequency and impact of storms are recently reported to have increased due to warming oceans and rising sea levels (UNISDR, 2016).

All countries are prone to disasters. However, less developed countries have been found to be more vulnerable to natural hazards than more developed countries. For example, between 1991 and 2001 there were 1 052 deaths per disaster in less developed countries, whereas the same figure for more developed

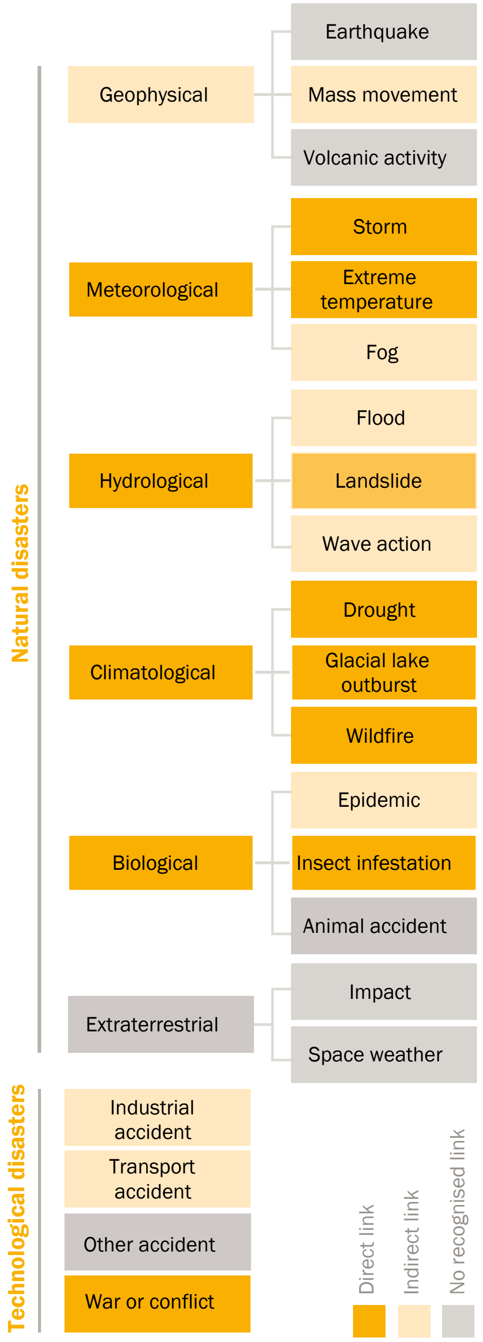


Figure 1.1 (left). The classification of disasters according to EM-DAT (2009) and their relation to climate change (by author).

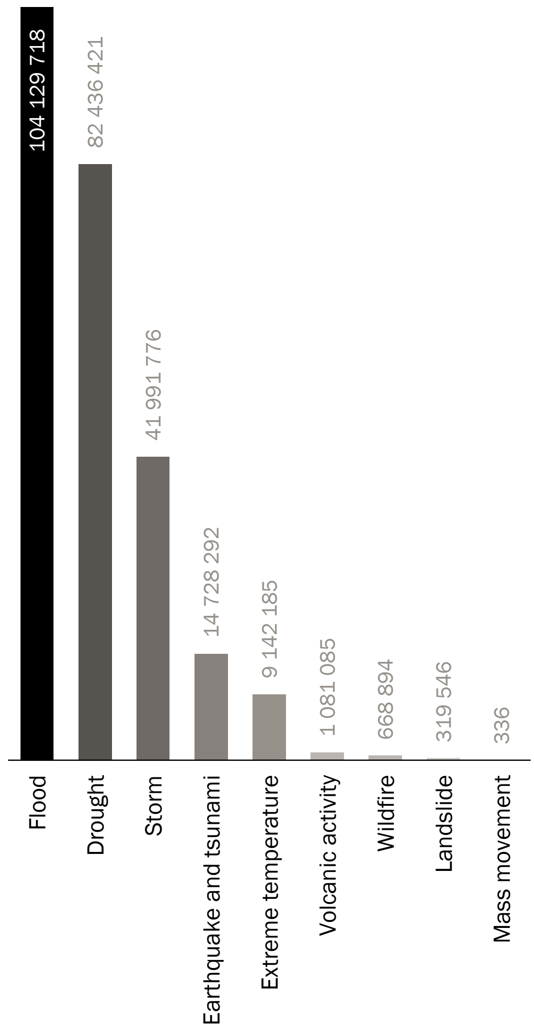


Figure 1.2 (below). Human impacts by disaster type. The annual average over ten years (2005–2015). Based on the data of UNISDR (2016).

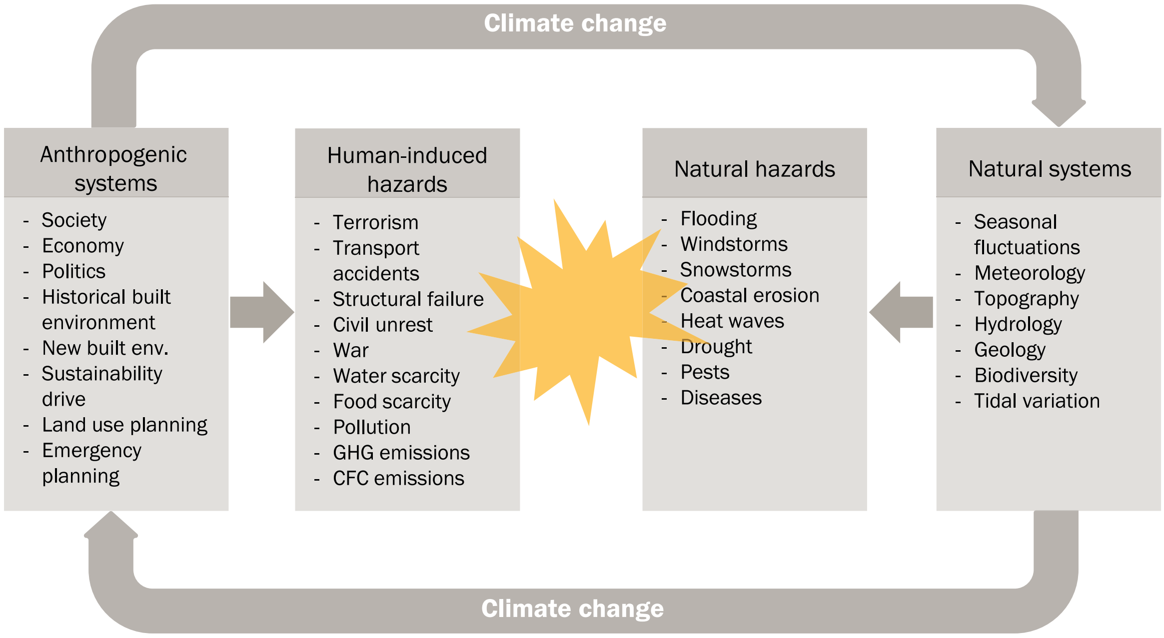
countries was only 23 (O´Brien et al., 2006), mostly because of their better institutional and financial capacity for mitigating the impacts of disasters. Low-income countries are well aware of the risks, but only 15% reported success in planning land use and urban development for reducing disaster vulnerability (UNISDR, 2012).

If the temperature rise keeps within 2 °C, the amount of climate related migration may not differ much from today's rates (Walker et al., 2012). However, if the emissions continue to grow and more warming occurs, the migration will increase considerably, particularly from low-lying coastal areas near the equator. It has been estimated (Brown, 2008) that warming in the range of 2 to 4 °C would increase the migration by 250 million people and warming over 4 °C would lead to the forced migration of at least 400 million people (Brown, 2007), although the consequences of such catastrophic levels of warming are difficult to model. In dystopic scenarios, civil society would fall apart and the world – at least in some regions – would fall into an anarchic battle for resources and survival (Hansen, 2010; Greer, 2009).

Estimations of the possible amounts of forced migration differ based on the source. However, migration is only one, if extreme, form of adaptation. It requires another area to which one can migrate. Thus, only looking at the numbers of predicted migration does not give the full picture of the humanitarian crises that may be caused by global warming.

Due to the anthropogenic climate change, we seem to be entering a new era in which the changing climate causes constant stress to mankind, and therefore better preparation is required (O´Brien et al., 2006). This also calls for changes in the planning, funding and evaluation of the response. Humanitarian NGOs face the need to change their operative profile from that of external actors to forming locally linked networks.

Figure 1.3. Potential relationships between climate change and natural and human-induced hazards, according to Bosher et al. (2007).



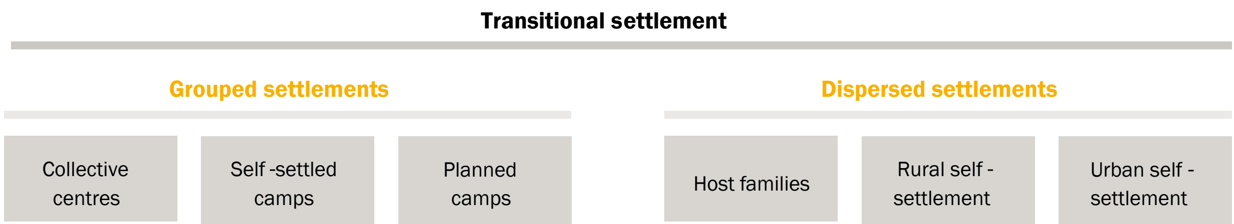


Figure 1.4. The types of transitional settlement, based on Corsellis and Vitale (2005).

1.3 Typologies of humanitarian construction

Providing the survivors of crises with shelter is an integral part of humanitarian aid. It is essential for maintaining human dignity but may also be highly important for saving lives, especially in cold climates. There are a number of forms of humanitarian construction depending on which stage of the response is considered. The main types include an emergency shelter, a transitional shelter and reconstruction. In reality the diversity of self-settled and self-made responses to acute housing needs is broader. The typologies of transitional settlement are described in figure 1.4.

Emergency shelters are provided directly after the disaster. They are usually tents, but also existing buildings, such as sport halls or offices, can be converted into emergency shelters and equipped with partition walls (Miyazaki et al., 2013, pp. 36–41) or other means of providing privacy.

A transitional shelter is often the standard solution to housing needs. However, it is not always an ideal solution. Sanderson et al. (2014) investigated transitional shelter projects in Haiti after the 2010 earthquake. They stated that there is need for a more diverse typology of shelters than the typical “transitional” one that may be inappropriate for poor households and does not take into account varied forms of housing, such as multi-occupancy, tenancy or squatting. Thus there is a need to develop alternatives to transitional shelters and to integrate the methods of urban planning into post-disaster recovery.

1.4 The relevance of carbon footprinting in the humanitarian sector

1.4.1 What is carbon footprint?

A carbon footprint is a metric for measuring the “sum of greenhouse gas emissions and removals in a product system, expressed as

Figure 1.5. *Examples from Haiti: emergency shelter (top), transitional shelter (middle) and reconstruction (bottom).*

CO_2 equivalent and based on life cycle assessment" (ISO, 2013). In technical terms it is thus a subset of a life cycle assessment (LCA) analysis (see chapter 3) or the results of "streamlined LCA" (Crawford 2011, p. 98). Carbon footprinting can provide an essential understanding of how our production, consumption and operations affect to the sum of GHGs, which cause global warming.

Carbon footprinting is an emerging field of practice in the environmental assessment of buildings and construction products. Its use as one of the environmental "key indicators" has been discussed at the European Commission (EC) (Ilomäki, 2013). In everyday building design and construction, carbon footprinting is still rare, although the latest versions of building information model (BIM) design tools already give possibilities for systematically estimating the accumulation of carbon footprint through automated bills of the quantities that are linked to material-specific GHG emission factors (see chapter 6).

1.4.2 Reasons for carbon footprinting in humanitarian construction

The relevance of carbon footprinting in humanitarian operations and construction can be argued from several viewpoints.

1. We should not accelerate climate-related humanitarian crises

As described in earlier sections, climate change is a key driver for humanitarian crises and the construction sector may play an important role in the mitigation of anthropogenic GHGs. While assisting refugees, we should not do further harm. It is inevitable that providing material help causes some environmental, economic and social impacts. However, these impacts should be minimised or turned into positive effects. Although the overall impact of humanitarian work may be small on a global scale, the volume of the work is expected to increase and this increases its impact as well. In addition, the example that is given to local communities through humanitarian aid may influence the construction and consumption choices they make in the future.

2. Humanitarian work also needs environmental accountability

Accountability in humanitarian work has been advocated through the 2010 Humanitarian Accountability Partnership (HAP) Standard in Accountability and Quality Management (HAP International, 2010) and is currently being extended into a Core Humanitarian Standard (Groupe HRD, HAP International, People in Aid, the Sphere Project, 2014). Accountability can be understood as "the means through which power is used responsibly" (HAP International, 2010, p. 1). Traditionally accountability has been focused on finance and human rights. However, the Humanitarian Core Standard refers to environmental considerations in several of its key actions, for example: "Environmental assessments are vital to understand the impact of construction and rehabilitation activities as well as how to mitigate negative environmental impact through transportation, packaging and disposal" (Groupe HRD, HAP International, People In Aid, the Sphere Project, 2015).

The next step of accountability seems thus to incorporate environmental considerations into the existing fields of economic and social accountability. In this respect the definitions of accountability and sustainability may be seen as different viewpoints on the same areas of interest.

The "triple bottom line" approach (Elkington, 1999) has been promoted in the corporate world for three decades. It stands for corporate accounting that includes economic, social and environmental aspects. Because of the ethical nature of humanitarian work, the accountability should be broadened to include environmental aspects – such as the carbon footprint – as well.

3. Per capita GHG emissions

Per capita emissions stand for the national average GHG emissions, normalised per all residents. Estimations of per capita emissions are carried out by, for example, the World Bank. Emissions range from almost zero metric tons per capita (e.g. Chad) to over 40 (e.g. Qatar) (The World Bank, 2015). International negotiations for lowering these emissions continue. Therefore humanitarian assistance should be developed to take into account the efforts to mitigate per capita emissions. This calls for enhancing "the scientific and technical work on disaster risk reduction and its mobilization through the coordination of existing networks and scientific research institutions at all levels and in all regions" (UN, 2015).

It may be argued that this has only marginal impacts. However, as will be shown in this study (see section 5.3), some shelter projects may increase the per capita GHG emissions dramatically and cause GHG peaks due to the large number of shelters built. Furthermore, it can be argued that in addition to security, nutrition, health and shelter, leading a sustainable life should be considered as an emerging human right.

4. Normative development

The rules for Green Public Procurement (GPP) apply to governmental organisations that provide humanitarian assistance in and from the European Union (EU). As described in section 1.5, these norms are developing and the pricing of externalities is possible in the revised procurement directive 2014/24/EU (European Parliament, 2014). The manufacturers of products already have to take into account the future needs for Environmental Product Declarations (EPDs). Thus the norms steer towards the inclusion of environmental merits in procurement decisions. For humanitarian construction this acts in two ways. First it makes it possible to require environmental information from the producers who offer their products for procurers who should follow the GPP rules. Secondly, the environmental awarding of construction products and services will become the new normal. This will inevitably be diffused into the segment of humanitarian construction as well. Grasping this potential calls for understanding the significance of carbon footprinting in humanitarian work.

1.5 How is the environment taken into account in humanitarian construction?

1.5.1 Climate change and the built environment in humanitarian research

Climate change is commonly discussed in humanitarian literature. It is mainly considered from the viewpoint of causing migration and requiring new means to answer to the complex problems it arises. Its impact to the built environment is seldom touched on in the articles and scientific discussion about how humanitarian construction should be developed in order to lessen its climate impacts was not found. In a review of the key scientific journals[1] from the fields of humanitarian operations and emergency response the following could be observed:

- Between 1977 and 2015 there have been 1145 articles that mention climate change in relation to humanitarian operations.
- Of these, only 65 (6%) consider the impacts of climate change in the built environment.
- No articles were found that discussed the mitigation of climate change in the built environment in humanitarian literature.
- One article was found that directly addresses the issue of the environmental impacts of the construction materials of shelters. This case, however, is not humanitarian scientific literature.

1) Journals:
- Asian Journal of Environment and Disaster Management
- Disaster Advances
- Disaster Prevention and Management
- Disasters
- International Journal of Disaster Resilience in the Built Environment
- International Journal of Disaster Risk Reduction
- International Journal of Disaster Risk Science
- International Journal of Mass Emergencies and Disasters
- Journal of Contingencies and Crisis Management

O´Brien et al. (2006) outlined the linkages between climate change and disaster management. They explain how the humanitarian sector may be driven by the need to show results and may not operate on both disaster response and development projects in the same area. Thus in complex settings it may be difficult to evaluate if an operation was successful in the short term, long term or both. They call for a new approach that includes the mitigation of vulnerability through enhancing governance and resilience.

Bosher et al. (2007) emphasised the vulnerability of the built environment in the changing climate. They suggest systematic emergency management that includes hazard mitigation through more active collaboration with the construction sector. They further argued (2007b) that the construction sector does not sufficiently play its role in integrated disaster risk management (DRM).

Cavan and Kingston (2012) developed a GIS-based climate change risk and vulnerability assessment tool for urban areas. The tool may improve disaster preparedness by visualising the most vulnerable areas of the studied region. The proposed tool does not directly address climate-mitigating construction but seems very relevant for disaster preparedness planning for a more sustainable disaster response.

Rivera and Wamsler (2013) have studied how climate change adaptation and disaster risk reduction (DRR) are integrated into urban planning policies in Nicaragua. They conclude that urban authorities should review their policies in intersectoral participative work so that synergies can be utilised and gaps filled.

"You don´t have to take more time to take environmental issues into account when you are responding to a disaster."

Melagarejo and Lakes (2014) studied how public infrastructure can be used as temporary shelters during river floods in Columbia. They developed a screening tool for transitional shelters and local adaptation planning. In this way there is less need for building temporary shelters and the corresponding environmental impacts can be avoided. This would be a very low-threshold approach to avoiding the GHG emissions resulting from the construction and logistics of temporary shelters. If screening could also be used for identifying potential unused spaces that can be refurbished into residential use in the possible reconstruction phase, the impacts on sustainability would likely be even more positive.

Anh, Phong and Mulenga (2014) investigated the process of community consultation for developing climate-resilient, post-disaster housing in Vietnam. They found that self-built houses, when compared to donor-built examples, may have a more adaptable use of space, which increases their resilient use. If this finding holds true in other areas as well, the functional performance of buildings in relation to their climate impacts should be developed in tighter collaboration with the end users. Still, the study found needs for programmes to raise public awareness of climate risks.

Clarke and de Cruz (2014) developed recommendations for "climate-compatible" practices for humanitarian NGOs. They state that the old practices can no longer continue, that relief efforts will become the new normal in several countries and that collaboration with governments and multilateral organisations will be critical. The recommendations are primarily aimed at development projects, but the urge is clear: "A climate-compatible approach to development requires a new lens through which to view current development practice that will take into account a range of contextual changes, including climate change" (p. 25).

Iftekhar (2010) gave an overview of post-disaster permanent housing reconstruction in developing countries. He notes that there are considerable gaps in linking aspects of post-disaster recovery and the mitigation of environmental impacts. Salvaging materials for lowering the environmental impacts is given as an example of reducing environmental impacts. In some cases, however, (see section 4.3) this may have adverse effects.

Abrahams (2014) investigated the barriers to environmental sustainability in the implementation of transitional shelters in Haiti. He studied the procurement practices for timber and concrete and concluded that environmental sustainability is not generally integrated into shelter programmes, mostly because of either prioritisations hindering environmental sustainability or organisational barriers. Abrahams reported that including environmental considerations is often perceived to slow down the disaster response. Interestingly, however, one interviewed expert who is specialised in both disaster response and environmental issues argued that "you don´t have to take more time to take environmental issues into account when you are responding to a disaster" (p. 37). Furthermore, it was found out that one of the identified barriers for including sustainability into humanitarian action was the "humanitarian sector´s slow rate of adaptation to new practices" (p. 36).

Zea Escamilla and Habert (2015) compared the sustainability of local and imported construction materials for 20 transitional shelter designs. They found that local materials, on average, seem to have better possibilities for ensuring low environmental impacts and costs, whereas imported "global" materials were more likely to produce higher technical performance. The actual comparison of sustainability was carried out with the IMPACT 2002+ evaluation method (Jolliet et al., 2003) and the results were presented as the sum of four categories: disability-adjusted life years, ecosystem quality, the global warming potential (GWP) and energy demand. The results for either the carbon footprint or primary energy (PE) demand cannot be disaggregated from these sums.

The referred studies underline the need to include climate change adaptation and mitigation into humanitarian operations. Strong and authoritative voices are raised for including climate change mitigation into humanitarian work. The studies also recognise how difficult it may be to change the current disaster response priorities: "[the] climate-compatible approach to development is a bleak shift from current orthodox positions and will be a major challenge to international humanitarian NGO's" (Clarke & Cruz, 2014, p. 21).

However, from the studies referred to (or from the lack of studies) it can be concluded that assessment of environmental sustainability in humanitarian construction is extremely marginal. Thus it does not seem likely to enter into mainstream practice unless required by either norms or donors. The reported barriers are mostly understandable, as the main focus of disaster response has conventionally been tightly focused to the mandate of each operator. The exemplified calculations, which include summed-up indicators for multiple aspects of sustainability, present the state-of-the-art of environmental sciences. However, in the light of the reported and perceived barriers, these sophisticated methods seem to primarily serve the interests of the academic audience.

Much work is therefore needed for implementing the scientific methods in humanitarian context and then interpreting the findings into practical recommendations for both humanitarian operators and policy-makers. A possible channel for introducing environmental assessment into humanitarian construction may be found by improving the collaboration of humanitarian NGOs and construction enterprises. Haigh and Sutton (2012) studied strategies for engaging multi-national construction companies in post-disaster construction projects. They found that these companies could provide many projects with much-needed technical expertise. As environmental assessments are commonly conducted in conventional construction projects, their inclusion might be one of the benefits of such closer collaboration.

1.5.2 The environment in operative humanitarian guidelines

The commonly used handbooks and guidelines for humanitarian operations and construction include some environmental considerations or recommendations. These considerations are briefly described regarding the following guidelines:

- *Handbook for Emergencies* by the United Nations High Commissioner for Refugees (UNHCR)
- *Minimum Standards for Humanitarian Response* by the Sphere Project
- *Camp Management Toolkit* by the Norwegian Refugee Council (NRC)
- *Transitional settlement* guidebooks by the Shelter Centre
- The guidebook by the United Nations Development Programme (UNDP) *Preparing Low-Emission Climate-Resilient Development Strategies*

UNHCR Handbook for Emergencies

The third version of UNHCR's Handbook for Emergencies (2007) includes environmental aspects in several of its recommendations. The environment is advised to be taken into account at an early stage of emergencies, including not only the impacts caused by the operation and refugees but also "strengthening the institutional capacity to deal with environmental matters in the field" (pp. 21–23). The nature of the handbook is not to present detailed technical recommendations and therefore it only briefly mentions specific technical issues related to environmental impacts, for example, energy-saving through the insulation of shelters (p. 217). However, throughout the handbook the importance of environmental considerations is constantly referred to.

Sphere Handbook

The Sphere Handbook (Sphere Project) provides guidance on minimum standards in humanitarian response. The standards are divided into five sections:

- Core Standards
- Water supply, sanitation and hygiene promotion
- Food security and nutrition
- Shelter, settlement and non-food items
- Health action

The Core Standards recommend using "environmentally sustainable materials" whenever feasible. There is no exact definition or criteria for sustainability.

The minimum standards for shelter and settlement include a section for environmental impacts. These standards recommend collaboration with environmental agencies to ensure the mitigation of long-term environmental impacts or assessing the environmental impacts of sourcing construction materials. Checklists are provided for obtaining appropriate information for the humanitarian response. However, no recommendations on the exact assessment schemes are given in the current version of the Core Standards. The sources referred to for further environmental information include the guidelines and checklists of Kelly (2005a, 2005b), UNHCR (2002) and the World Wide Fund for Nature (WWF) (2010).

The Core Standards are being updated into Humanitarian Core Standards in collaboration with Groupe HRD, HAP International and People In Aid (2014). The consultation drafts of this standard include recommendations for environmental assessments (Groupe HRD, HAP International, People In Aid, the Sphere Project, 2015, p. 17).

Transitional Settlement

The fundamental works of Tom Corsellis and Antonella Vitale include "Transitional settlement: displaced populations" (2005) and "Transitional Settlement and Reconstruction After Natural Disasters" (2008). There are several general references to environmental considerations in these books, for example, those regarding the recycling of construction materials (Corsellis & Vitale, 2008, p. 49), the environmental impacts arising from the choice of construction materials (p. 206), the energy required to transport materials and that embodied in construction materials (2005, p. 59), the heating values of alternative fuels (p. 338) and planning the environmental rehabilitation measures of refugee camps (pp. 400–401).

The above listed environmental issues are presented on a general level and instruction for the practical assessment of their impacts is not within the scope of these guidelines.

The Camp Management Toolkit

The Camp Management Toolkit (Ashmore et al., 2008) is prepared by the NRC in collaboration with other NGOs for improving the management of refugee camps and for a holistic approach. It presents an environmental management framework titled the "Community-based Environmental Action Plan" (CEAP) (see subsection 1.3.2). The toolkit suggests commissioning specialized environmental staff or at least delegating such responsibility to a focal person. The environmental considerations of the toolkit cover a wide range of topics, including shelter, water and sanitation, domestic energy, erosion, agriculture, livelihoods and livestock (pp. 170–179). Strategies for saving energy in refugee camps are well described. However, climate change, the carbon footprint or global warming are neither mentioned nor discussed.

UNDP´s guidebook on Preparing Low-Emission Climate-Resilient Development Strategies

UNDP promotes low emissions development through its guidebook (2011). The focus of the guide is on development projects, not on the humanitarian response. However, the five steps of the guidebook for preparing a low-emission, climate-resilient development strategy can well be considered in disaster preparedness planning:

1. Developing a multi-stakeholder process
2. Preparing climate change profiles and vulnerability scenarios
3. Identifying strategic options that lead to low-emission climate-resilient development trajectories
4. Identifying policies and financing options to implement priority climate change actions
5. Preparing a low-emission climate-resilient development roadmap

The third step includes assessment of existing GHG emissions and alternative scenarios for their development based on business-as-usual or alternative scenarios. These scenarios are further described in the level of alternative technologies in UNDP's Technology Needs Assessment Handbook (UNDP, 2010). The focus of the latter handbook is also on the development context, not the humanitarian context. Nevertheless, UNDP's detailed strategic guidance and principles lend themselves to disaster preparedness planning.

1.5.3 Existing environmental assessment methods for humanitarian construction

There are only a few methods or practices for assessing any environmental impacts in the field of humanitarian construction. They are briefly described in the following. Existing conventional certifications schemes for sustainable construction are presented in chapter 2. The focus of the description of existing humanitarian environmental assessment methods is in looking at how the existing methods or practices answer to the needs of taking climate change mitigation seriously in humanitarian construction.

This chapter briefly presents the following assessment tools that have been developed with the humanitarian context in mind: Aspire, CEAP, the Checklist-Based Guide, environmental needs assessment (ENA), the Flash Environmental Assessment Tool (FEAT), Rapid environmental impact assessment in disasters (REA) and Quantifying Sustainability in the Aftermath of Natural Disasters (QSAND).

Aspire

Aspire is developed by Arup and Engineers Against Poverty (2009) for evaluating the sustainability of infrastructure projects in developing countries. It is based on the classical three pillars of sustainability and includes over 90 detailed indicators for environment, society, economics and institutions. The goals for environmental sustainability include integrating the principles of sustainable development into country policies and programmes (target 1), reducing biodiversity loss (target 2), access to safe drinking water and basic sanitation (target 3) and improving the lives of 100 million slum dwellers (target 4). The steps of the assessment process are grouped into the stages of initiating the assessment, data collection and entry, review and reporting. The tool had been tested in nine projects across the globe prior to its launch. Although Aspire is directly intended for development use, not humanitarian use, its approach may serve disaster response as well. The concepts of climate change and low carbon economy are mentioned, but Aspire does not provide further guidance for mitigating them.

Checklist-Based Guide to Identifying Critical Environmental Considerations in Emergency Shelter Site Selection, Construction, Management and Decommissioning

This guide has been developed by Charles Kelly (2005b) with the aim to "provide an easy-to-use way to assess whether environmental issues have been appropriately addressed in emergency shelter efforts". The document presents four categories for assessment: site selection, site construction, site management and site decommissioning. These include 57 individual environmental criteria. Around nine percent of these criteria have a direct impact on mitigating GHG emissions (Kuittinen & Kaipainen, 2011).

Community-based Environmental Action Plan

The CEAP (UNHCR, 2009) emphasises the role of participatory environmental needs assessment and planning. After its core document, regional guidance documents have been published, for example, for the contexts of Sudan and Darfur (UNEP and ProAct, 2013). They include templates and instructions for arranging participatory environmental planning sessions and exemplify tools for participatory evaluation and monitoring, as well as tips for facilitating participatory events. As the scope of CEAP is to build community participation, specific environmental themes such as global warming are not discussed.

Environmental Needs Assessment in Post-Disaster Situations

The ENA guide (UNEP, 2008) is built upon the typical environmental impacts or hazards that are associated with different disaster types (e.g. soil contamination after a tsunami). The ENA guide describes an assessment process for a team that starts with baseline data gathering, followed by team training, analysing the situation, performing stakeholder consultation, drafting reports, disseminating the strategy and a follow-up phase. The ENA documentation includes ready questionnaires that include several predefined questions, for example, for shelter, energy or water and sanitation. Among these questions are several that have a direct or indirect impact on climate change through GHG emissions. Again, emissions, climate change and global warming are not mentioned in the ENA guide.

There are only a few methods or practices for assessing any environmental impacts in the field of humanitarian construction.

Flash Environmental Assessment Tool

FEAT (UNEP and OCHA, 2009) is intended for prioritizing the activities of relief and risk management teams but not for producing definitive scientific assessments. It is based on the method and case study of van Dijk et al. (2009) and its use is further presented by Nijenhuis and Wahlström (2014). FEAT is primarily intended for use in disaster conditions for identifying acute environmental risk factors, such as hazardous chemicals, or long-term impacts, such as soil contamination or erosion. The process of FEAT begins with identifying the required assessment process from pre-defined modules (First Alert Module FM1, Priorities Scan Module FM2, Facilities and Objects Assessment Module FM3), then collecting information from within the framework of the chosen module and finally producing output reports and possible follow-up actions. FEAT includes comprehensive lists of potential hazards that may be caused from different types of infrastructure, for example, the leakages or emissions from chemical industry, textile industry or a wood treatment plant after a disaster. As the focus of FEAT is mainly in mapping hazardous substances, long-term climate impacts or the GWP of various substances are not included.

Rapid Environmental Impact Assessment in Disasters

The REA method was developed by Charles Kelly (2005a) and is aimed at non-professional use, supplementing the process of environmental impact assessment (EIA) in a humanitarian context. It includes four modules for (1) organisation level assessment, (2) community level assessment, (3) consolidation and analysis, and (4) the green review of relief procurement. The process enables the assessor to cover a variety of environmental topics. In the module of green procurement, REA refers generally to UNEP's resources regarding life cycle considerations. Climate change mitigation, global warming, carbon footprinting, GHG emissions and LCA are not mentioned in REA guidelines.

Quantifying Sustainability in the Aftermath of Natural Disasters

Developed by the Building Research Establishment (BRE) and the International Federation of Red Cross and Red Crescent Societies (IFRC), QSAND is a self-assessment tool for humanitarian NGOs for adopting sustainable reconstruction practices (BRE and IFRC, 2015). It includes the categories of shelter and community, settlement, materials and waste, energy, water and sanitation, the natural environment, communications and cross-cutting topics.

QSAND differs from all other humanitarian environmental tools by referring several times to material or energy related specifications that may have an impact on the carbon footprint of the shelter: the reusability and recyclability of materials (BRE and IFRC, 2014, p. 23), the use of alternative or renewable energy sources and reducing energy consumption (pp. 41, 140–151, 243), the reuse of temporary shelters on-site or off-site (p. 69), reducing the life cycle impacts of construction materials (p. 104), minimising raw material consumption and requesting an LCA report from the suppliers of materials (p. 107). The approach of QSAND is reminiscent of the Building Research Establishment Environmental Assessment Methodology (BREEAM), a green building certification tool developed by BRE and used globally. However, although the life cycle impacts of construction materials and energy are mentioned, guidance on their assessment or carbon footprinting is not mentioned or referred to. Still, QSAND offers the most science-based approach to the environmental assessment of humanitarian construction of the studied alternative systems for humanitarian use.

1.5.4 Building back better

The concept of "building back better" is often referred to in humanitarian practice. The phrase implies that the construction efforts should include improvements. But as no official definition exists, the term "better" is highly prone to subjective interpretations. Especially, who has the right to define what is "better" and for whom?

Clinton made ten propositions for defining the concept (2006), which cover broad themes (such as equity, accountability, livelihoods and resilience) and also includes considerations of effective and fair collaboration between operative stakeholders. Justification for including climate change mitigation into building back better can be found from the third proposition "Governments must enhance preparedness for future disasters" and from the tenth proposition "Good recovery must leave communities safer by reducing risks and building resilience". Mitigating climate change by already avoiding its root causes (namely anthropogenic GHG emissions) in humanitarian construction has a small but clear positive consequence that acts towards lowering future risks and building resilience.

Kennedy et al. (2008) further analysed the propositions of Clinton based on field reports and evidence from post-tsunami recovery projects in Aceh and Sri Lanka. They found out that the interpretation of "better" indeed varied highly depending on stakeholder and the focus of the operation. A well-built house could be part of an inadequately planned settlement and, while providing good living conditions in the short term, might expose the area to environmental degradation. The study concluded that the word "better" may be problematic, as it is understood differently depending on the stakeholder and therefore suggest that "building back safer" would be a clearer definition. Safety is a highly important aspect in humanitarian construction, but it is not the only one.

Although the question of what "better" actually means and who defines it is to large extent open, it can be argued that including the mitigation of climate change should fit into the definition as well. This is because of the proven linkages between our built environment and man-made GHG emissions. If temporary homes, reconstruction and repairs are conducted in a manner that does not further accumulate climate change and associated weather events, the outcome should be less harmful for present and future generations. Indeed, all of the preceding reasons for including carbon footprinting in humanitarian construction fit under the umbrella concept of building back better, this time extending the interpretation to include climate change mitigation as well. Sometimes, as pointed out by Amaratunga and Haigh (2011), disasters can be seen as an opportunity for improving the built environment and its economic, ecological and social sustainability.

1.5.5 Green procurement and humanitarian operations

It is not only the planning of humanitarian construction that ensures that it will become ecologically sustainably. The procurement of the actual construction products and implementation of the built infrastructure may differ from the plans for a number of reasons. The desired materials may not be available, there may be cheaper but perhaps less ecological solutions or the constructor prefers a product that he or she is familiar with. Furthermore, corruption and nepotism may alter the plans in the implementation phase considerably. Green procurement criteria can be used as a tool for ensuring that the planned environmental performance is actually realised.

Green procurement can be understood as "purchasing products and services which are less environmentally damaging" (OECD, 2002). The principles and practices of green procurement are widely advocated, especially in the public sector. The concept of green procurement can already be found in the reports of the UN's Brundtland commission (1987). The Organization for Economic Cooperation and Development (OECD) recommends "Improving the Environmental Performance of Public Procurement" (OECD, 2002) and promotes good practices both amongst its members (OECD, 2013) and jointly with the United Nations Environment Programme (UNEP) (OECD, 2012), including several examples of how environmental standards have been used in procurement. UNEP is promoting the potential of public procurement to advance sustainability through the Sustainable Public Procurement Initiative (SPPI), launched in Rio in 2012.

EU countries follow the procurement directive 2014/24/EU. In its recast form (European Parliament, 2014) new articles were added for enabling public procurers to better include criteria for environmental and social sustainability into the awarding of tenders. European EN standards have been proposed (European Commission, 2008) as a good way to benchmark the environmental performance of procured products. The construction sector standard EN 15804 (CEN, 2014) gives specifications for creating Environmental Product Declarations (EPDs) for building products. These standardised EPDs will help procurers to compare the environmental performance of the products they wish to procure.

The majority of the funding for humanitarian responses come from the OECD countries (Walker et al., 2012). Thus it is logical that the principles of green procurement are implemented in humanitarian operations as well. UNEP promotes "mainstreaming the environment into humanitarian action" through guidelines (UNEP, 2011) and the Directorate-General for Humanitarian Aid and Civil Protection (ECHO) has published guidelines for humanitarian procurement (European Commission, 2011). The United Nations Office for Project Services (UNOPS) provides training for improving the knowledge of sustainable procurement (UNOPS, 2015).

However, among the GPP recommendations for humanitarian use, the coverage of climate change mitigation seems to be limited. In UNEP's collection of guidelines the only construction-related publications deal with the sustainable procurement of timber (Fowler & Ashmore, 2006; WWF, 2005). The focus of these recommendations is on ensuring that sustainability certifications, such as the Forest Stewardship Council (FSC), are met. ECHO refers to the EU´s GPP guidelines (European Commission, 2008), which, for the sector of construction, suggest using either voluntary sustainability certification schemes (e.g. Leadership in Energy and Environmental Design [LEED] or BREEAM) or applying EN standards prepared by CEN/TC350 that deal with sustainable construction. However, "the challenge of green procurement in emergency response is to manage the process of selecting a greener product or service in a way which does not delay the provision of assistance" (Kelly, 2005a, p. 37).

Studies (Alhola, 2012) reveal that many public procurers hesitate to place environmental criteria into public procurement. This is partly due to difficulties in setting relevant criteria and in comparing the different tender documents. Especially in the field of ecological design and construction, procurers often do not have sufficient knowledge of the awarding criteria (Sporrong & Bröchner, 2009). Therefore LCA has been proposed (EU, 2011) as a science-based and international approach for assessing the environmental performance of compared goods. But performing LCA is time consuming and seldom in the expertise of the procuring bodies.

There is a considerable gap between the recognition of climate-related disasters and any guidance for mitigating them in humanitarian construction.

The humanitarian sector, especially when bound to follow the procurement directive or other GPP regulation, may apply the environmental recommendations for conventional construction products and utilise the EPDs that are made according to corresponding standards, such as EN 15804 (CEN, 2012). However, the suitability of conventional environmental recommendations in disaster response – where humanitarian aid is a priority – may prove difficult. Therefore, the humanitarian sector may develop further environmental specifications that take into account the context and practicalities of humanitarian operations. Such documents are referred as "product category rules" (PCRs) and are based on LCA in accordance to standards such as ISO 14040 (ISO, 2006) or EN 15804. The strength of PCRs lies in internationally developed, tested and acknowledged environmental standards. In order to build a solid platform for environmental assessment, the humanitarian sector should utilise the existing framework of international standards.

1.6 Summary

Climate change is a natural phenomenon that has been pushed out of its natural rhythm by the rapid accumulation of anthropogenic GHGs. Already the changes that are in the pipeline by the emitted amounts of, for example, CO_2 in the atmosphere will cause inevitable needs to adapt to changing weather and sea levels. These – together with population growth, urbanisation conflicts and wars – will increase mankind´s vulnerability to disasters.

Climate change is frequently discussed in humanitarian scientific literature. The viewpoint is dominantly adaptation to climate change in the fields of disaster risk preparedness, vulnerability, mapping, increased rates of natural or complex disaster and forced migration. However, only a small fraction of this literature examines climate change adaptation in the built environment. No literature was found regarding the methods and practices that may lower the GHG emissions from humanitarian construction operation, for example, low carbon reconstruction, energy efficiency or the carbon footprint of transitional shelters.

Practical guidance literature for humanitarian operations and construction, on the other hand, are consistent in recommending the consideration of the environmental impacts of humanitarian operations. However, there are only a few practical methods or tools for the environmental assessment of humanitarian operations or construction. None of them gives practical instructions for directly mitigating global warming.

Green procurement is a process that may offer a path for implementing environmental criteria into practice. Applying climate-mitigative awarding criteria, which are now further empowered through the EU´s revised procurement directive, may improve the environmental and social accountability of humanitarian construction. However, this may also add responsibilities for humanitarian procurement.

Concluding from both scientific and practice-based literature, there is a considerable gap between the recognition of climate-related disasters and any guidance on either theoretical or practical means for mitigating them in humanitarian construction. Therefore humanitarian operators need more information on how to mitigate climate change in their operations and how to use green procurement for implementing this information into projects.

To start filling in these knowledge gaps, chapter 4 of this study exemplifies how the carbon footprint of humanitarian construction accumulates and which features may help to decrease it. Chapters 5–6 give examples on how humanitarian construction can be carried out so that its potential in the mitigation of climate change is taken into account.

2 The research approach

2.1 The scope and focus of this study

2.1.1 The structure of the research

This research is built around three case empirical studies and two theoretical case studies that have been published in the form of scientific articles. These studies are included as annexes to this thesis, which summarises and concludes their findings. The structure of the research is presented in figure 2.1.

Case study methodology is a research approach that, according to Yin (2012), “desires to derive an up-close, in-depth understanding of a single or small number of cases in their real-world contexts”. The research questions are arranged around the context of climate change mitigation through assessing the causes of GHG emissions and the primary energy use of humanitarian construction. The research questions and corresponding methods are listed in table 2.1. The listed variants of the qualitative case study methodology are based on the classifications of Baxter and Jack (2008).

Humanitarian construction may be divided into four phases: emergency, transitional, reconstruction and preparedness phases. This research includes all of these apart from the emergency phase. Emergency structures, such as tents or tarpaulins, are excluded as they represent products rather than buildings.

In this research “humanitarian” construction refers to construction efforts that take place during or after a crisis or disaster that seek to “save lives, alleviate suffering and maintain human dignity” (Good Humanitarian Donorship, 2013). Therefore cases from both developed and developing countries are chosen to exemplify different approaches to humanitarian construction.

2.1.2 Materials and methods

The materials for the case studies are collected from humanitarian NGOs and presented in detail together with the description of the corresponding studies. The method for the case studies 1–3 is a streamlined, process-based attributional LCA (aLCA) method for the assessment of the carbon footprint, also referred to as GHG-LCA. The LCA method and its main variants are further described in chapter 3. In addition, energy simulation has been carried out for the Japanese case study (annex 3). The energy simulation process is described in annex 3.

2.1.3 Case studies

The case studies are made for 11 transitional shelters and 25 different structural alternatives of a school reconstruction project. These studies are descriptive in their nature. They seek to assess the buildings in detail and produce focused and articulated conclusions of their features. Some of the case studies are not linked to disasters that relate to climate change. Examples from Haiti and Japan, both responses to an earthquake, are however chosen because they provide a good example of the environmental impacts of humanitarian construction. Results from the case studies can be applied to actions for mitigating the climate change through carbon-efficient humanitarian construction.

Generalisations from these case studies are avoided in this research. Although the data indicates relatively clear trends, there are a number of uncertainties that cannot be eliminated, such as the uncertainty of the GHG factors in the production of construction materials in developing countries. These uncertainties are described in annexes 1–3 and in subsection 4.6.5. The conclusions and recommendations based on the present fidings are given in chapter 7.

Table 2.1. Research questions and the used methods.

Research questions	***Applied methods***	***Annexes***
1. What is the role of climate change in humanitarian crises and how is its mitigation considered in humanitarian construction?	Literature review	5
2. How can the methods developed for the carbon footprinting of conventional buildings be applied in a humanitarian context?	Developing and testing methods in instrumental case studies	1 and 4
3. How would these methods need to be developed in order to meet the needs of the humanitarian community?		4 and 5
4. How large are the carbon footprint and primary energy demand of the selected humanitarian constructions?	Performing LCA in descriptive case studies	1–3
5. How could the mitigation of the carbon footprint be taken into practice in humanitarian construction?		1–3, 5

2.1.4 Methodological development

Theoretical methods and practical applications for carbon footprinting in humanitarian construction projects are based mostly on instrumental case studies. First, a hypothetical model for choosing national per capita GHG values for a point of reference is formulated (annex 5). It is applied as an instrumental case study to the studied transitional shelters. The second instrumental case study is built around the concepts of carbon efficiency and carbon economy (annex 4). This theoretical study is carried out by investigating the carbon footprint of selected schools and kindergartens, and testing variable comparison methods. It is taken outside of the humanitarian context on purpose, as one of the aims of this research was to derive methods from "conventional" to humanitarian use. Thus the applicability and transferability of modern methods for assessing and analysing the environmental impacts of buildings can be tested.

The practical application for a carbon-efficient project model (chapter 6) is built on top of interviews, personal field and design experience, the development of a project model for a humanitarian NGO (Kuittinen & Kaipainen, 2013) and the author´s work with other scientists (Häkkinen et al., 2015).

2.2 Outcomes

Three case studies are complemented with two methodological studies and summarised in scientific conclusions and practical recommendations, which are exemplified through a humanitarian construction project in Syria.

The outcomes include

- reference carbon footprint and primary energy values for a set of humanitarian buildings (chapter 4),
- a proposal for a minimum system boundary for LCAs in humanitarian construction (section 5.1),
- a method for setting benchmark levels for the carbon footprint utilising the per capita GHG emissions targets (section 5.2),
- a method for measuring the carbon efficiency and carbon economy of buildings (section 5.3) and
- exemplifying how these can be taken into practice in transitional shelter or reconstruction projects (chapter 6).

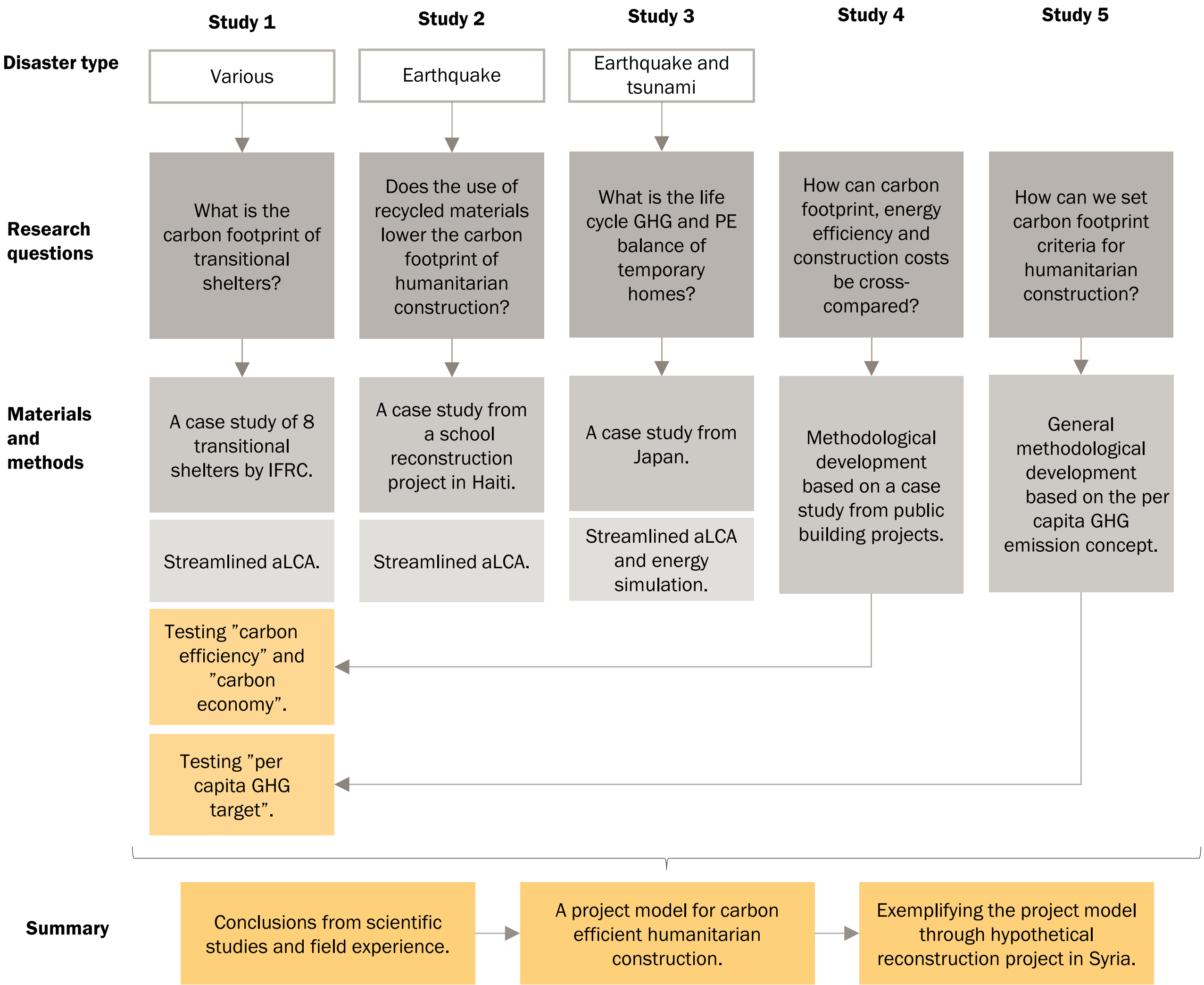
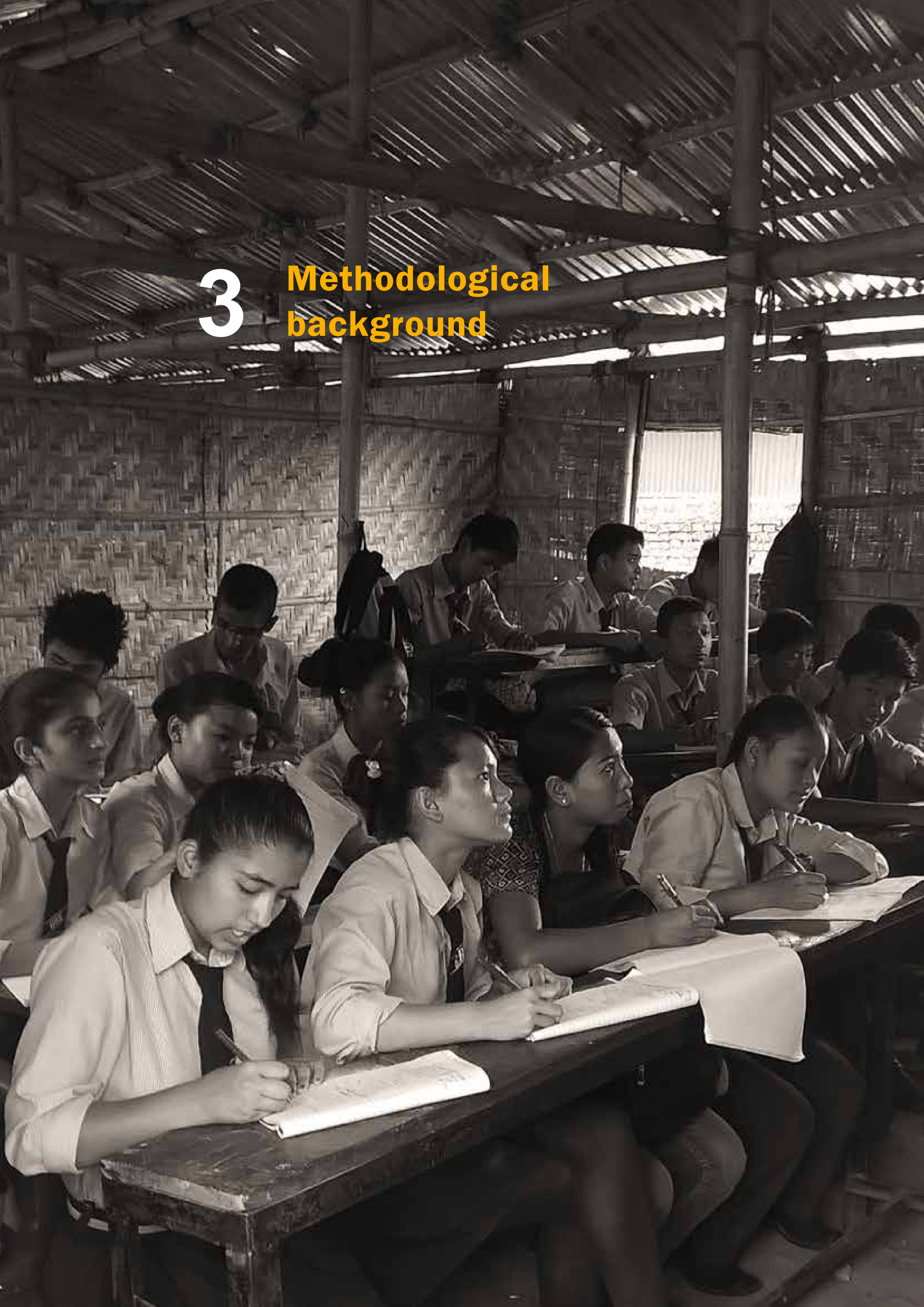


Figure 2.1. The structure of the research.

3 Methodological background



3.1 The concept of sustainability

3.1.1 Measuring sustainability

Sustainability is commonly mentioned as a goal for construction. However, it is a very wide concept that includes several subcategories or viewpoints that sometimes have conflicting agendas. The term sustainable development was first documented by the UN´s Brundtland commission in the report "Our Common Future" (1987). The classical definition of sustainability includes three pillars: ecological, economic and social sustainability (United Nations, 1992). Culture was later suggested as the fourth domain of sustainability (United Cities and Local Governments, 2002). The multiple aspects of sustainable development are shown in figure 3.1.

The focus of this research falls into the category of ecological or environmental sustainability in the context of the built environment. This category consists of several fields of environmental impacts that may be assessed. For example, material use, energy, different types of emissions into the air, land or water may be assessed.

The methods for measuring the ecological sustainability are several. LCA is a widely used and internationally standardised tool. Other approaches include various types of environmental risk analyses, material flow analysis (Brunner & Rechberger, 2004), multi-criteria decision-making methods (Bell et al., 2003) and environmental footprinting (Wackernagel, 1991). In the formal process framework of EIA several of these assessment methods may be applied (Senécal et al., 1999).

LCA was chosen as a method for this study because of its wide international use, standardised process (ISO, 2006) and its argued critical importance among the tools available today (Crawford, 2011, p. 36). The LCA method is applied in this study in its "streamlined" form (see figure 3.4). New methods are developed as a part of this study (see chapters 5–6) based on the LCA results and important observations along the design phases of humanitarian buildings and their assessment process. These developments build on the existing practice of streamlined LCA but improve its applicability by adding reference carbon footprint target values (annex 5) and widen the use of results by cross-comparing them to use of energy and money (annex 4).

3.1.2 Environmental assessment methods for buildings

The environmental assessment for buildings can be divided into standardised and voluntary schemes. Standardised schemes are guided via international or regional standards, such as ISO and EN. The key standards related to the environmental assessment of building are shown in figure 3.2.

Standards are technical documents designed to be an instruction, decree or definition and are either quantitative or qualitative in nature. They are based on a common agreement and jointly designed with producers, consumers, experts and those enforcing them (Kuittinen & Linkosalmi, 2015).

Voluntary schemes are guided through the green building certification systems, such as LEED, BREEAM, DGNB, HQE or CASBEE. The methods for each scheme differ and they are not comparable to each other. Voluntary schemes are mostly qualitative, but may refer to quantified methods, such as LCA.

3.2 Life cycle assessment

Life cycle assessment (LCA) is a tool for the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). LCA is standardised in ISO 14040 and further defined in several standards presented in figure 3.2. The scientific basis of LCA can be found in system theory (König et al., 2010). The benefits of LCA are its holisticity to environmental assessment, consideration of wide range of possible impacts and the possibility to cover and document every stage of a product´s or building´s life (Crawford, 2011, p. 38).

As the name implies, LCA describes the environmental impacts along the life cycle, which is modularised (figure 3.4) for ease and clarity of communication of the results of LCA. The most condensed form of LCA usually covers the first module set, A1–3, or the production stage, and is called "cradle-to-gate" assessment. If

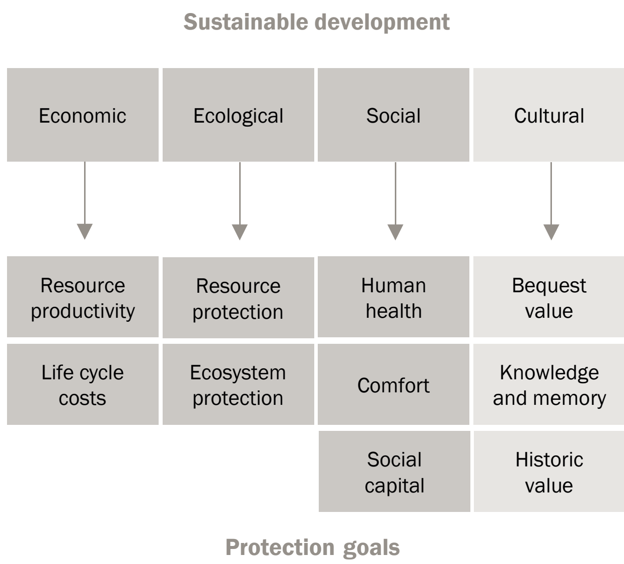


Figure 3.1. The domains of sustainable development, based on the work of König et al. (2010).

ISO 14040
Environmental management – Life cycle assessment – Principles and framework

ISO 14044
Environmental management – Life cycle assessment – Requirements and guidelines

Sustainability of buildings

ISO 21929 Sustainability in building construction – Sustainability indicators

ISO 21931 Sustainability in building construction – Framework for methods of assessment for environmental performance of construction works

EN 15643-1 Assessment of buildings - General framework

EN 15978 Assessment of environmental performance of buildings - Calculation method

Environmental Product Declarations
for building products

ISO 21930 Sustainability in building construction – Environmental declarations of building products

EN 15084 Environmental product declarations – Core rules for product category of building products

Product Category Rules

EN 16485 Environmental product declarations - Product category rules for wood and wood-based products for use in construction

Carbon footprint

ISO TS 14067
Carbon footprint of products

EN 16449 Calculation of sequestration of atmospheric carbon dioxide

Figure 3.2. Key standards related to life cycle assessment, environmental assessment of buildings and construction products.

A1-3	A4-5	B		C
PRODUCTION	**CONSTRUCTION**	**USE**		**END-OF-LIFE**
A1 Raw material supply	**A4** Transport to site	**B1** Use	**B5** Refurbishment	**C1** Deconstruction
A2 Transport to factory	**A5** Construction work	**B2** Maintenance	**B6** Operational energy use	**C2** Transport
A3 Manufacturing		**B3** Repair	**B7** Operational water use	**C3** Waste processing
		B4 Replacement		**C4** Disposal

D
ADDITIONAL

Benefits and loads beyond the system boundary

Figure 3.3. The life cycle stages of a building according to standard EN 15643 (CEN, 2012).

an LCA covers all modules, it is referred to as a "cradle-to-grave" assessment.

There are multiple paths through the process of an LCA. The main alternative methods include attributional LCA (aLCA) and consequential LCA (cLCA). The main difference between the aLCA and the cLCA methods lies in the scope. While aLCA aims to assess the direct emissions of a process or product, cLCA looks at the changes in total emissions as the result of several marginal changes in the production, consumption and disposal processes associated to the object of assessment (Brander et al., 2008; Crawford, 2011) and may be especially suitable for decision making, although the role of scenario modelling has been argued to require development (Zamagni et al., 2012). Therefore comparison of aLCA and cLCA is not very relevant, as they are not substituting but complementing each other (Rajagopal, 2012). Their applicability and uncertainties have been compared in a number of studies.

Brander et al. (2008, p. 3) argued that aLCA is more certain because the "relationships between inputs and outputs are generally stoichiometric" and because cLCA may suffer from double counting. Crawford concludes (2011, pp. 41–42) that aLCA is suitable for individual systems whereas cLCA is more appropriate for explaining to decision-makers the variety of options and their consequences. The choice between aLCA and cLCA is thus dependant on the goal and scope of the study.

According to ISO 14040 (ISO, 2006) the process of LCA includes the steps of (1) defining the goal and the scope of the assessment, (2) inventory analysis, (3) impact assessment and (4) interpretation of the results. These stages are carried out in an iterative manner. It should be underlined that different LCAs do not necessarily produce comparable results because of differing scopes and goals, methods applied or data used.

The multiple stages of the LCA process are illustrated in figure 3.4 and further described in box 1.

3.3 Green building certification schemes

There are several systems for the environmental certification of buildings or building products on the market today. These systems are voluntary and are used for a number of reasons, for example, for managing and improving the sustainability of the building design process, for reducing the environmental damage that the building may cause, for reducing operative costs (Braune & Sedlbauer, 2007), for marketing the "greenness" of the property or for meeting the corporate responsibility strategy of either clients, investors or insurers (Ebert et al., 2011).

Internationally green certification schemes are developed through a number of initiatives. The World Green Building Council (WGBC) was established in 1996 and is aiming at promoting sustainability on an international level and supports the work of national Green Building Councils. The WGBC also arranges the World Sustainable Building Conferences that take place around the globe. The Sustainable Building Alliance (SBA) is a network of academia, research institutions and the business sector aiming at developing sustainable building and the corresponding assessment tools. Furthermore, the International Initiative for a Sustainable Built Environment (iiSBE) aims at the development of a common, comparable assessment tool, although the attempt to create one comparable international tool failed due to too large differences in legislation, climate and building culture (Ebert et al., 2011, p. 27). In addition, UNEP has launched the Sustainable Buildings and Climate Initiative (UNEP-SBCI), which is intended for promoting energy efficiency and GHG mitigation worldwide. The outcomes of UNEP-SBCI are the Sustainable Building Index and Common Carbon Metric.

Currently several local and international market-based certification systems compete with each other. Among the most known are LEED (USA/int.), BREEAM (UK/int.), DGNB (Germany), HQE (France), CASBEE (Japan) and Green Star (Australia). Their certificates are not cross-comparable. For example, a comparison that certified the same office building resulted a high energy rating score with Green Star, a low rating with BREEAM and a failed certification with LEED due to differences in the assessment of energy performance (Roderick et al., 2009). Of all the voluntary green building certification schemes, LEED and BREEAM can be considered to be truly international and both have developed localised versions for regional use.

BREAAM and LEED and briefly described in box 2.

3.4 The suitability of life cycle assessment and green building certification schemes in humanitarian construction

3.4.1 Life cycle assessment in a humanitarian context

The use of LCA in the conventional building design process is still a rarity. Buildings are perhaps some of the most complicated objects of LCA as they consist of tens or hundreds of materials, which means that LCA takes longer to perform. Normal design processes seldom have the time or resources for iterative LCAs during the process (Crawford, 2011, p. 116; Häkkinen et al., 2015). Therefore building LCAs are often streamlined to only focus on a few key indicators, such as energy or GHG emissions.

Given this status in the field of conventional construction, full LCAs cannot yet be recommended for operative humanitarian construction projects. The priority in humanitarian operations should remain with disaster response and all other accountability or quality aspects are secondary. A disaster response is often hectic and stressful, and has chaotic elements (Virtanen, 2010). However, in disaster preparedness planning the use of LCA results may be viable. Before the acute response phase, NGOs (in theory) have more time to consider how to respond and where to source the required services and materials from. Especially in areas that are prone to natural disasters or political unrest, preparedness planning could be enhanced with environmental considerations.

In the context of reconstruction, the timeframe is typically longer than during the emergency or transitional phases. The use of LCAs in reconstruction projects depends on the context. For instance, developed countries have both the capacity and baseline data for making LCA-based choices for building back better with less climate impacts. Less developed countries, however, may lack institutional capacity, environmental governance and benchmark data for coordinating climate-mitigative reconstruction. In such cases the realistic potential for improving the reconstruction may be in the preparedness phase, in collaboration with environmental professionals.

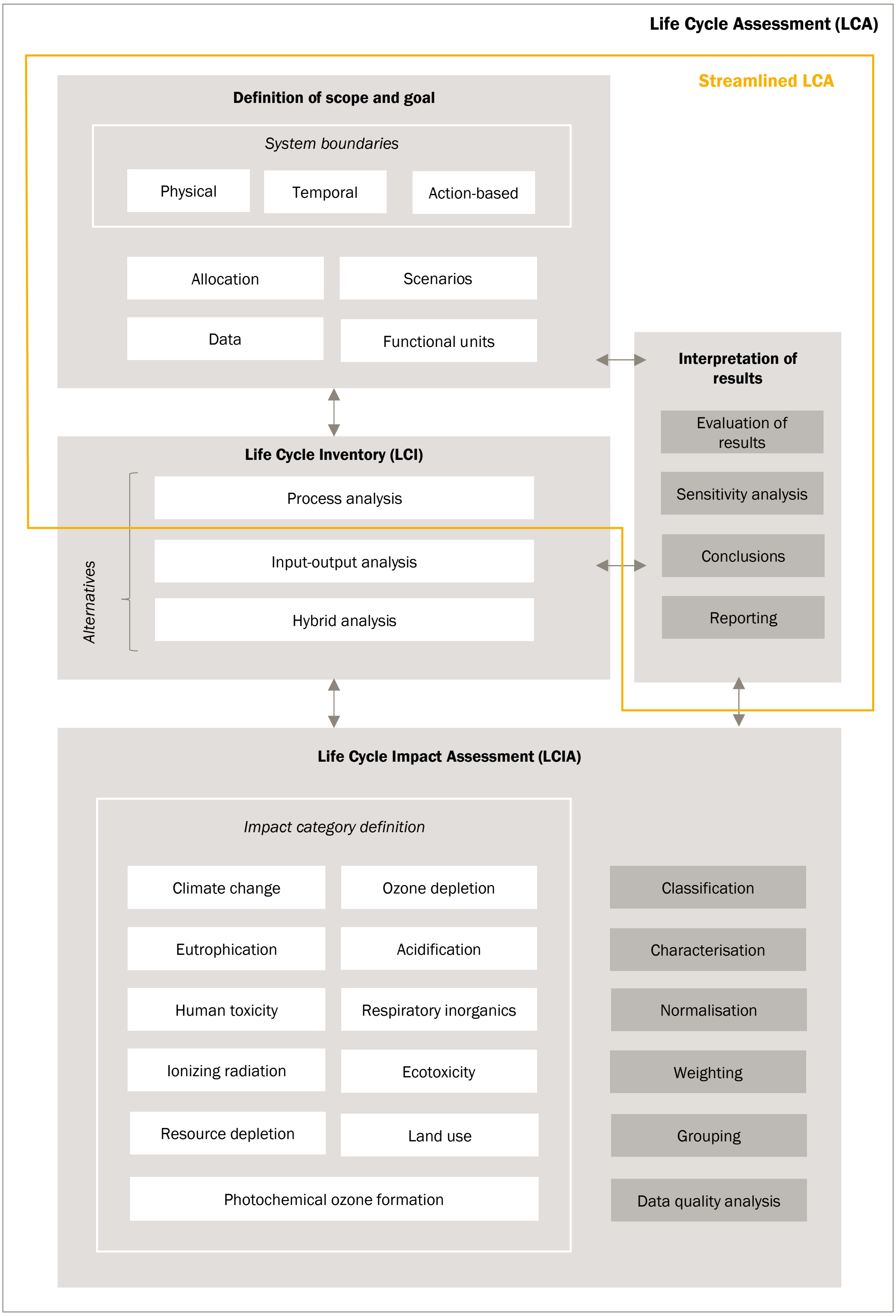


Figure 3.4. The structure and contents of the LCA process and the boundary for streamlined LCA. Optional stages of LCA marked with grey.

3.4.2 Green building certification in humanitarian construction

Typically green building certification schemes are localised, in other words they are adapted to be used in a certain country with its regulations and environment. Thus they do not necessarily lend themselves to other uses in an agile manner. Localisation is key to their existence, but it also makes them less agile for humanitarian use. It can be argued that, for example, the studied categories may not be relevant in the reconstruction projects of less developed countries (Kuittinen & Kaipainen, 2011). However, the QSAND tool is related to the logic of BREEAM and may thus be seen as an opening to green building certification in the humanitarian context. As shown earlier, it covers a wide range of issues, from environmental to social sustainability, and does not yet give any explicit means for mitigating climate change in humanitarian construction.

In the reconstruction phase green building certification may be fully relevant, depending on the context. If there are certification systems in use, their use may be continued as in conventional projects. If no certification systems have been localised or developed, it may be very laborious to adopt one along the reconstruction process. Still, reconstruction offers the potential to move away from infrastructure solutions that lock societies into carbon-intensive pathways and therefore the environment should be one of the priorities in reconstruction, regardless of the pre-disaster situation of green building certification.

3.5 Summary

The environmental assessment of buildings may be carried out through standardised methods or voluntary green building certification. LCA is the most commonly used, scientific tool for environmental assessment. It is based on international standards, such as ISO and EN. The results of an LCA study are mainly dependant on the selection of scope and goal, as well as the chosen methods for LCI and impact assessment. LCA offers a science-based framework for making comparable environmental assessments.

Green building certification schemes are voluntary and typically combine several aspects of environmental and social sustainability. Different certification schemes are not mutually comparable. None of the commonly used green building certification schemes were found to be directly applicable in the emergency or transitional phases of humanitarian construction.

Both LCA and green certification are time-consuming processes and therefore not ideal to be used simultaneously with disaster response. However, they may offer valuable input to disaster preparedness planning, which may have more time and resources available. The same applies for the reconstruction phase in less developed countries, whereas in developed countries the reconstruction stage and its environmental optimization may not differ from the conventional case.

In order to promote climate-mitigative humanitarian construction, emphasis should be placed on disaster preparedness planning with the help of proper and contextually relevant criteria. These criteria should be science-based. LCA can offer reliable information for setting criteria. Such criteria can also be used for green procurement.

If carbon footprinting is applied into humanitarian construction, simplifications are necessary. Such may include using streamlined LCA and focusing only on chosen key indicators, such as the carbon footprint and primary energy demand. These are directly linked to the acute global need for climate change mitigation. In addition, database values for the environmental profiles of different construction materials are essential for making any LCA comparisons in the humanitarian field possible. Furthermore, cross-comparison to construction costs and energy efficiency is essential for ensuring that multiple sides are understood in decision making. Finally, reference levels for what could be an “acceptable” carbon footprint in humanitarian construction are needed.

The proposed boundary for streamlined LCA is presented in chapter 4. New suggestions for setting reference carbon footprint levels and for the cross-comparison of key indicators are introduced in chapter 5.

Box 1. Stages of the LCA process

1. Definition of the scope and goal

Defining the scope and goal of an LCA is strategically an essential phase. At this stage the outline for the entire study is drawn. The definition of the goal and scope guides the whole LCA process and thus it should be carefully done. Important aspects that are included in the definition of the goal and scope include system boundaries, the functional unit, allocation, scenarios and data quality.

System boundaries define the borders of the assessment. A product or a building is a result of several inputs, outputs and processes. Depending on the goal of the LCA, they may not all be relevant. System boundaries are drawn so that the essential features of the assessed object are included and that the less relevant are excluded. Drawing tight boundaries may ease the LCA process but may also lead to biased results as not all relevant impacts can be foreseen before performing the life cycle inventory (LCI) and life cycle impact assessment (LCIA) stages. System boundaries may be physical, temporal or action-based.

The functional units describe the unit for which all impacts are given. Typically in buildings this unit is the square metres of the floor area or cubic metres of air volume. For building products the functional unit may be one kilogram, one metre, one square metre, one cubic metre or another relevant unit. If two alternatives are compared, setting the proper functional unit is essential. For instance, comparing the carbon footprint of one kilogram of steel to one kilogram of concrete is irrelevant, as one kilogram of either material yields very different amount of finished construction product. Instead, one should compare items that fulfil the same functional requirement, for example one square metre of external wall with the same thermal insulation and fire protection capacity.

Allocation is used for production processes that result in more than one end product. Its purpose is to describe how the environmental impacts of the production process are allocated to each of these products. Allocation is often subjective and should therefore be avoided. If it is unavoidable, the general allocation methods are physical allocation and economic allocation or allocation according to energy content (for fuels).

Scenarios are made for those parts of the life cycle that cannot be observed during the assessment. Typically these include the use of the building (i.e. the environmental impacts from use, repairs, renovations and refurbishments etc.), the technical or economic service lives of the used products and the end-of-life stage (deconstruction, waste management and waste disposal). As these happen in the future, it is not possible to know them accurately. Therefore scenarios are prone to errors, but describing them transparently enables the reader to understand what assumptions have yielded the results of the LCA.

Data quality refers to the background information that is used in the LCA. For environmental assessment of a building it is necessary to know the unit emissions of producing, for example, one kilogram of plywood or one solar panel. This information can be based either on an LCA study of the particular material or product, an EPD that the manufacturer issues for a certain product or retrieved from a database. EPDs describe the environmental impacts of a specific product better. However, if an LCA is performed in the design stage of a building, not all the product manufacturers are known. Two producers for the same product may not be comparable if one uses renewable hydro power and the other relies on fossil coal for producing energy for the factory. As EPDs are still voluntary in most countries, not all producers are issuing them. Therefore databases describe the average environmental impacts for common materials or products. However, there are differences between the databases as well (Takano, 2011), as the methods for collecting and aggregating data vary. This feature has been criticized as a fundamental problem of using databases (Crawford, 2011, p. 48), but there are seldom alternatives and in practice these error margins need to be accepted. The issue of the possibly poor quality of data becomes very clear in the context of humanitarian construction as the databases only describe the general environmental impacts of production in industrial countries and no databases exist for developing countries (Kuittinen & Kaipainen, 2011).

2. Inventory analysis (LCI)

The LCI phase consists of the quantification of emissions caused and resources used in the studied products. At the LCI stage the alternative methods include process analysis, input–output analysis and hybrid analysis.

Process analysis is comparable to a process flow chart and seeks to document each input and output of the described stage of the process. It follows a bottom-up approach starting from the process that is being studied and then approaching relevant upstream and downstream impacts.

Input–output analysis is based on a top-down economic technique and utilizes matrices that describe the inputs and outputs of industry sectors and their interdependencies. This approach is holistic and requires the availability of national input–output tables.

Process analysis is considered to be suitable for accurately analysing a single process or object, whereas the input–output method can produce more accurate results, due to a larger system boundary (Crawford, 2011). A *hybrid analysis*, however, is a combination of process and input–output analyses. It includes the comprehensive system boundary of the input–output analysis and the accurate process data of the certain processes that are being studied.

If the study is carried out for buildings and is limited to only a few environmental parameters (e.g. GHG emissions or energy) the process may proceed from the LCI phase directly to interpretation, and the LCIA phase may be excluded (Crawford, 2011, p. 98). Such a limited study is referred as *"streamlined LCA"*.

In this research a streamlined aLCA method has been applied. The basis for its selection lies in the focus of only looking at the GHG emissions and primary energy use of humanitarian construction. Furthermore, the economic matrices required for input–output or hybrid LCI analyses are very difficult to gather for humanitarian operations, which include materials from a variety of countries, including developing ones with limited data availability. In addition, the aim is to describe the steps of an LCA clearly linked to the process of building in order to increase understanding of the environmental impacts of the choices made in humanitarian construction. Further, narrowing the scope of an LCA can be justified as an attempt to limit the amount of speculative assumptions along the future stages of a life cycle of a building. Indeed, "completeness in the scope comes at the price of simplifications and uncertainties" (Hellweg & Milà i Canals, 2014).

3. Impact assessment (LCIA)

The LCIA phase consists of three mandatory and four optional elements (Baumann & Tillman, 2004). Mandatory elements include impact category definition, classification and characterisation. Optional elements include normalisation, grouping, weighting and data quality analysis.

The first mandatory element is *impact category definition*, in which the impact categories, their indicators and characterisation models are selected. Impact categories include climate change, ozone depletion, eutrophication, acidification, human toxicity, respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use and resource depletion. Depending on the case, the LCIA may include one or several of the categories and this selection leads to the selection of indicators.

The second mandatory element of LCIA is *classification*, during which the results from LCI are divided into the selected impact categories.

The third mandatory element, *characterisation*, consists of the calculation of the indicators. There are alternative methods for this. For instance, for calculating the factors for the indicator category of climate change, one can either calculate the impacts at a "mid-point level", (i.e. where the emissions are caused) or, alternatively, the indicator can describe the amount of harm that is caused to the climate at the "end-point level". The JRC recommends (European Commission JRC, 2011) the IPCC´s GWP method (IPCC, 2007) for calculating the mid-point indicator and either Eco-indicator 99 (Goedkoop & Spriensma, 2001; Steen, 1999), ReCiPe (Goedkoop et al., 2012) or LIME (Itsubo & Inaba, 2004) for the end-point indicator calculation. Different methods for midpoint or end-point calculation are available based on the impact category.

Normalisation is a recalculation of characterisation results so that they can be compared to, for example, the regional reference state of the environment.

Grouping may be done to ease the interpretation of results. In grouping, the indicators are arranged based on the priorities of the study, for example, according to the geographic distribution of the impacts or life cycle module of the process.

Weighting is a subjective and value-based conversion of the results of LCIA according to chosen priorities. For example, the acidification potential may be seen as more important than climate change for a certain region and on a certain timescale. Because of its subjective nature, weighting is not allowed for comparative LCAs that are communicated to the public (ISO, 2006).

Data quality analysis may be carried out for understanding the reliability of the LCIA results. This element may include consideration of uncertainties and sensitivity analysis, which are important if the aim is to compare alternatives.

4. Interpretation of results

After the LCI and LCIA phases are carried out, the results are interpreted according to the initial goal and scope of the LCA study. Interpretation may include evaluating the results based on the grouping done in the LCIA phase, conducting sensitivity analysis (if not included in the LCIA phase), drawing conclusions, reporting uncertainties and making recommendations according to the goals of the study. There is no fixed format for the communication of the results of an LCA study. If an LCA is used for making EPDs that are intended for business-to-customer markets, the results need to be verified by a third party who is not dependent on the client or whoever conducts the LCA.

Box 2. BREEAM and LEED green building certification schemes

BREEAM

Building Research Establishment Environmental Assessment Scheme (BREEAM) has given certifications to over 425.000 buildings across the globe. Developed by BRE in the UK, the scheme is further localised for the context of several countries.

The project categories vary slightly depending on country but may include new construction, communities, in-use, eco homes, refurbishment and code for sustainable homes (UK only). Within these project categories, there are several sub categories for e.g. management, health & wellbeing, energy, transport, materials, waste, water, land use & ecology, pollution and innovation. Certifications range from Outstanding (best) to Pass (passed).

Carbon footprinting in BREEAM is mainly focused to mitigation of GHG emissions from operational energy use and to certain extent to embodied emissions from building materials. Generic material-related data is available at BRE´s Green Guide, but accurate product-specific data on embodied emissions can be used as well. A specific "Green Guide To Specification" includes data for various structure types based on LCA´s that are carried out using the BRE´s Environmental Policy Methodology 2008 (BRE, 2008), which follows standards ISO 21930, ISO 14025, ISO 14040 and ISO 14044.

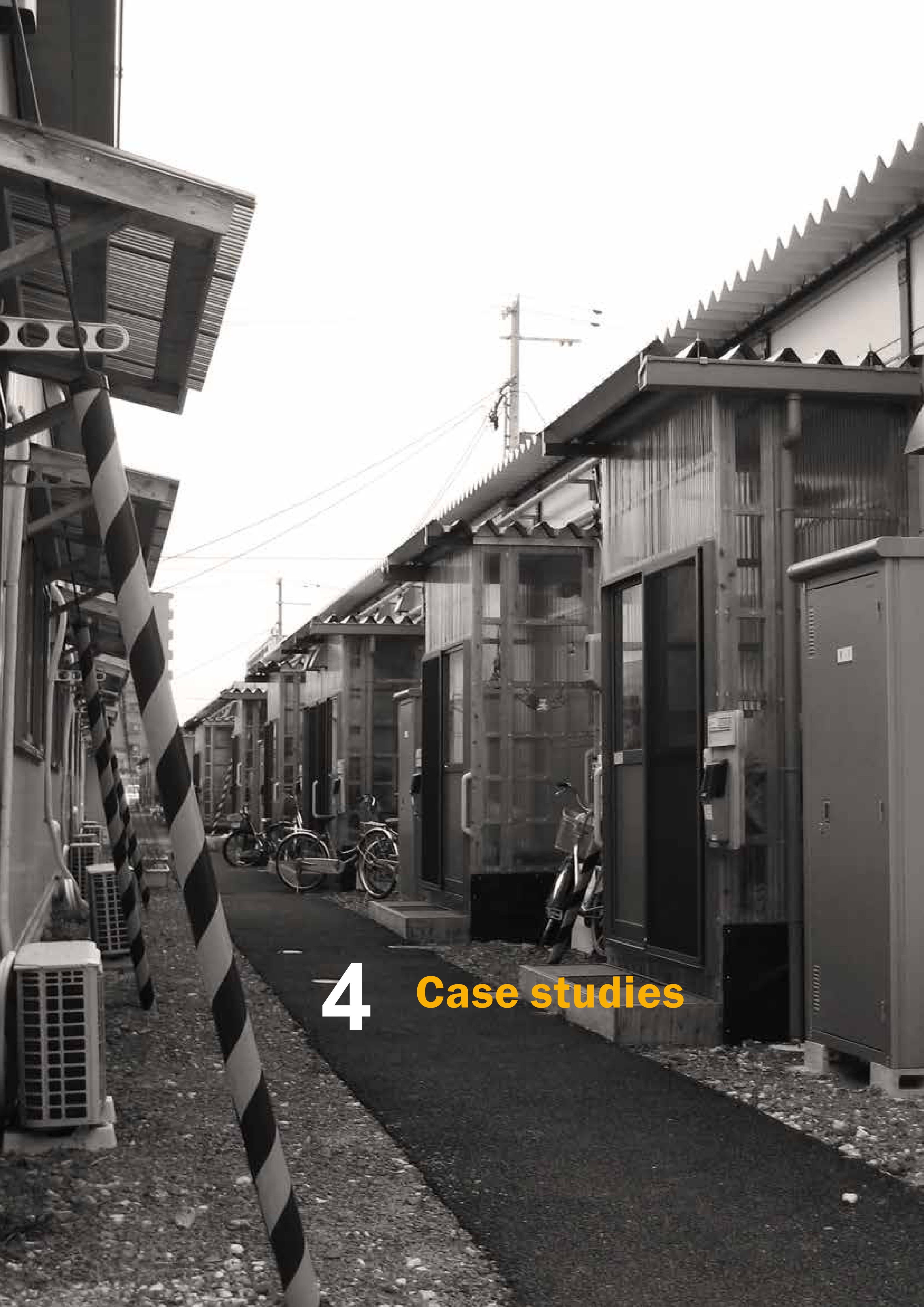
LEED

Leadership in Energy & Environmental Design (LEED) is a certifications scheme developed by United States Green Building Council. It is suitable for several types of conventional project types: building design & construction, interior design & construction, building operations & maintenance, neighbourhood developments and homes.

Each of LEED´s certification system is a compilation of several credit categories: integrative process, location & transportation, materials & resources, water efficiency, energy & atmosphere, sustainable sites, indoor environment quality, innovation, regional priorities, smart location & linkage, neighbourhood pattern & design and green infrastructure & buildings. Projects are scored from Platinum (best) to Certified (passed) levels.

One of the aims that LEED certified project should accomplish is "reverse contribution to climate change" (Owens, et al., 2013). This may be accomplished through e.g. building´s operations energy use or embodied energy from materials, but the focus is on the reduction of fossil-fuel based energy. Also carbon offsets are possible in LEED v4 through collaboration with Carbonfund.org (U.S. Green Building Council, 2013).

The impacts of average LEED certification have been criticised for probably not improving the energy efficiency of buildings: Office buildings in New York with rates "LEED Certified" or "LEED Silver" scored almost equally to non-certified offices in terms of GHG emissions and energy consumption (Scofield, 2013).



4 Case studies

4.1 Case studies and their methods

4.1.1 Background

This chapter presents three environmental, descriptive case studies of transitional shelters and a reconstruction project. The focus has been on quantifying their environmental impacts:

- The carbon footprint and primary energy demand of eight transitional shelter types (annex 1).
- The carbon footprint of alternative concrete structures in school reconstruction project in Haiti (annex 2).
- The energy efficiency and carbon footprint of temporary homes in Japan after the Great Eastern Tohoku Earthquake (annex 3).

The studies were made between 2010 and 2015 and included field visits. This chapter consists of summaries of the case studies. Detailed descriptions of each study are given in annexes 1–3. The case studies are further analysed for developing strategies for mitigation of the carbon footprint and optimising the performance of humanitarian construction in chapter 5.

4.1.2 Description and system boundaries

The objective of the studies

The objective of the studies has been to calculate the carbon footprint or primary energy demand of the chosen humanitarian constructions. More detailed objectives are described in the presentations of the case studies.

Methods

A streamlined, attributional life cycle assessment (aLCA) is used, based on the standard suite EN 15643 and the separate standards EN 15978, EN 15804, EN 16485, EN 16449 and ISO/TS 14067.

System boundaries and inventory

System boundaries and coverage of the inventory for the case studies are presented in tables 4.1–4.3. The boundaries differ in the studies because their contexts are very different. Further explanation of the choice of differing system boundaries is provided in the annexes.

Study period

The study period means the period of time for which the assessment is made. For transitional shelters it has been one to 10 years, as explained in the case studies. The assumed technical service life for the reconstruction project in Haiti is 50 years.

According to EN 15978 the difference of the reference study period (RSP), as defined in the LCA study, and the required service life (ReqSL) of the building, as given by the client or authorities, needs to be taken into account. If the RSP is shorter than the ReqSL, the impacts from the use phase (module B) have to be adjusted accordingly with a correction factor (CEN, 2011). In the case of temporary shelters this rule is difficult to apply. First of all, there are no common requirements for the service life of a temporary shelter. Secondly, temporary shelters often consist of unconventional materials, some of which may be vernacular (e.g. bamboo leaves, straw mats or compacted earth) and therefore lack designed service life definitions. As even short-term exposure tests may not be available for such components and the use of the "factor method" of ISO15686-8 (ISO, 2008) for service life estimation may be much too demanding in a humanitarian context, it may not be possible to compile the service life of a shelter "from the smallest elements, into an estimate for the whole building", as instructed in ISO 15686-1 (ISO, 2011).

Functional units

- Gross floor area (in m^2) for the allocation of the life cycle impacts of the building
- Construction costs for the estimation of carbon economy
- Technical service life (in years) for the estimation of annual impacts

The accuracy of the inventory and truncation criteria

An inventory is made from the bill of quantities or from technical drawings. Documentation on the real material consumption on the building site has not been available. Temporary structures – such as scaffolding, building site barracks and the weather protection of the building – and landscaping have been excluded.

The studies are focused on the production of construction materials and other selected life cycle stages differ case-by-case. The justification for this is that some of the transitional shelters are mostly located in warm climates with no building service technology at all. Other examples from Japan give an example of winterised temporary homes and in this case the operative energy efficiency is very important.

Life cycle stages that would have very high uncertainty are avoided in the calculations. It is likely that including them would distort the results. This applies to the exclusion of modules A4–5 and C in the cases of transitional shelters and Haiti school reconstruction. Furthermore, speculations on the reuse scenarios of used containers and temporary homes in Japan have been excluded.

Average unit values for windows, exterior doors and interior doors have been used as detailed drawings of these building parts were not available. Nails, screws, glue, seams, hinges or other minor parts are excluded. Paint and surface treatments are excluded.

Table 4.1. Included life cycle stages in case studies

Eight transitional shelters	Temporary homes in Japan	Reconstruction of schools in Haiti			
■	■	■	A1	Raw material supply	**Production**
■	■	■	A2	Transport to factory	
■	■	■	A3	Manufacturing	
	■		A4	Transport to site	**Construction**
	■		A5	Construction work	
		□	B1	Use	**Use**
			B2	Maintenance	
			B3	Repair	
	■	■	B4	Replacement	
			B5	Refurbishment	
	■		B6	Energy use	
			B7	Water use	
	■		C1	Deconstruction	**End-of-Life**
	■		C2	Transport	
			C3	Waste processing	
			C4	Disposal	

Table 4.2. The included building parts

Eight transitional shelters	Temporary homes in Japan	Reconstruction of schools in Haiti		
	□		1	Ground work and excavations
■	■	■	2	Foundations and external structures
■	■	■	3	Frame and roof structures
■	■	■	4	Supplementary structures
■	■	■	5	Surface claddings
			6	Furniture, equipment and machines
			7	Mechanical service equipment
				Scaffolding or other construction period items

■ *Included fully*

□ *Included partially*

Table 4.3. Data sources and calculations used in the assessment of the included lifecycle stages.

Production	A1	Raw material supply		ICE 2011 open-source database used in all cases.
	A2	Transport to factory		
	A3	Manufacturing		
Construction	A4	Transport to site	Eight shelters	Not assessed.
			Japanese shelters	Distances estimated. Fuel consumption and emissions from Zou et al. (2008) and transportpolicy.net.
			Haiti schools	Not assessed, data not available.
	A5	Construction work	Eight shelters	Not assessed, assumed to be manual.
			Japanese shelters	Working time estimated. Machine emissions from Burgess (2013) and Haynes (2010).
			Haiti schools	Not assessed, data not available.
Use	B1	Use	Eight shelters	Not assessed.
			Japanese shelters	Not assessed.
			Haiti schools	Uptake of carbon through carbonation of concrete for 50 years calculated according to Lagerblad (2005).
	B4	Replacement	Eight shelters	Not assessed.
			Japanese shelters	The production of the required materials calculated using the ICE 2011 database. Materials are estimated; work is excluded.
			Haiti schools	
	B6	Energy use	Eight shelters	Not assessed.
			Japanese shelters	Building Energy Modelling with ArchiCAD v.18.
			Haiti schools	Not assessed.
End-of-life	C1	Deconstruction	Eight shelters	Not assessed.
			Japanese shelters	Assumed counter processes to A4 with 90% fuel consumption.
			Haiti schools	Not assessed.
	C2	Transport	Eight shelters	Not assessed.
			Japanese shelters	Assumed counter processes to A4 with 90% fuel consumption.
			Haiti schools	Not assessed.

4.2 The carbon footprint of eight transitional shelters

4.2.1 Description

The aims of the study were to assess greenhouse gas emissions and the primary energy demand of different shelter designs. Calculations were made for eight different transitional shelter models that have been used in the projects of International Federation of Red Cross and Red Crescent (IFRC). These shelters represent several material alternatives and have been used during the past 10 years. Although the structural and functional quality of the shelters differ considerably, they are intended to fulfil the same function: providing temporary housing until permanent homes can be constructed. Therefore their comparison can be justified, although ideally one should compare alternatives that have equal performance in the majority of their functional criteria.

The calculation included the carbon footprint and primary energy demand of the production of shelters. The shelters are presented in table 4.4 and figure 4.1. The building materials were sorted into the categories of foundation, primary structure, secondary structure, coverings (roofing and cladding) and fixings. The dominance of emissions from different parts of the buildings were compared.

In addition the impact of the sourcing of bio-based construction materials was evaluated by comparing the carbon footprint of sustainably or non-sustainably sourced materials. This is a vital question for two reasons: first, the ethical and sustainable sourcing of wood can sometimes be a real concern in a humanitarian context; secondly, the calculation of the carbon footprint differs for wood-based products that are sourced from sustainably or non-sustainably managed forests.

The positive impacts of stored atmospheric carbon in wood and bio-based materials have been excluded. According to EN 16485 the amount of stored carbon could be given as specific information for the use phase (module B1) of the building. However, the short service life of the temporary shelters would make speculations on the climate benefits of the temporal carbon storage less relevant.

Furthermore, the energy recovery potential from construction materials has been excluded in this study. If the recycled materials were burnt, energy could be recovered. Although this might have impacts on the GHG emissions on a country level, this scenario is uncertain. Reused building components might also be landfilled, in which case bio-based materials might decompose into methane and thus become GHG sources. To avoid speculations on the end-of-life scenarios, the issue of energy recovery and landfilling are excluded. Still, they need to be considered in the operative plans when decommissioning the transitional settlements.

4.2.2 Results

The calculations show how important material decisions may be in mitigating the GHG emissions from the production of shelters. As can be seen from figure 4.2, the emissions can be very large in steel-framed and steel-clad shelters (Haiti and Vietnam) and very small in wooden shelters (Java, Sumatra and Peru). Although the technical solutions for the compared shelters varied considerably, they all fulfil the same functional need: providing shelter as temporary accommodation after a humanitarian disaster.

A closer look at the calculations revealed that the coverings seem to have a large impact on GHG emissions and primary energy demand. Claddings are the most vulnerable part of transitional shelters as they may be damaged in the storms that occur during the use period of the shelter. For example, in Haiti thousands of

Table 4.4. Information about the studied eight shelters (IFRC, 2011).

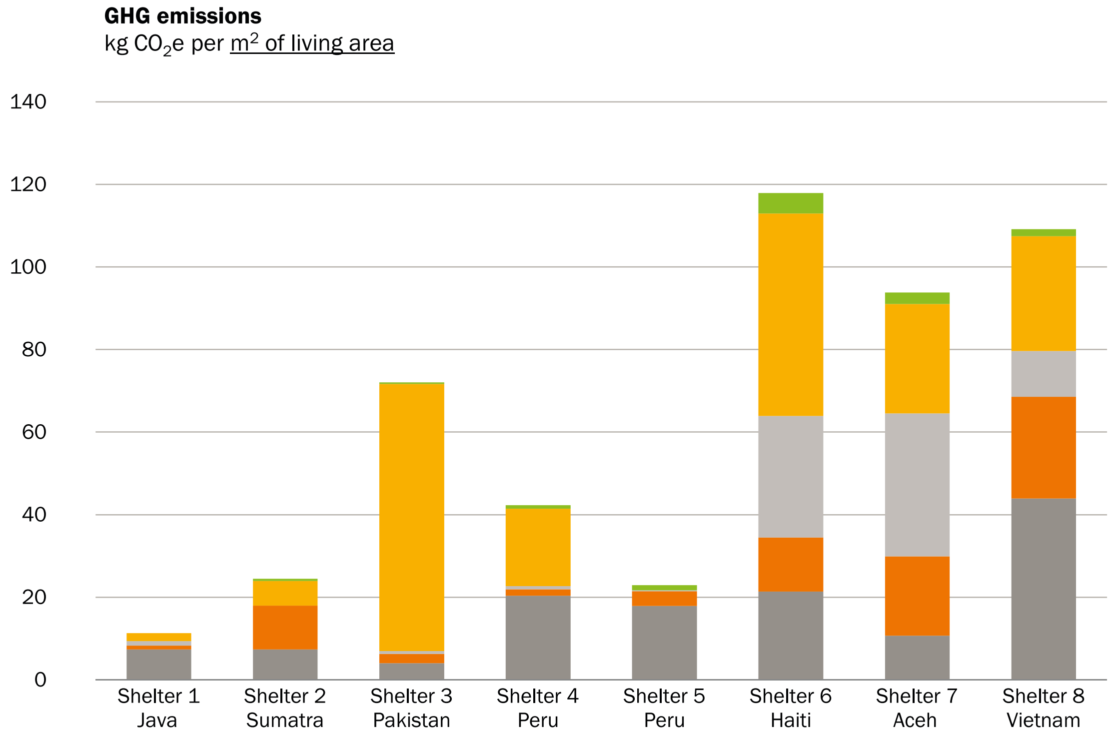
	Frame material	Units built	Building year	Living area (m^2)	Service life (yrs.)	Set-up (days)	Set-up (persons)	Material cost (USD)
Shelter 1, Indonesia, Java	Bamboo	430	2009	24	1–5	3–4	3–4	281
Shelter 2, Indonesia, Sumatra	Timber	7 000	2009	18	1	2	5	393
Shelter 3, Pakistan	Stone	10 000	2010	18	2	1	4	561
Shelter 4, Peru	Timber	2 020	2007	18	2	1	4	N/A
Shelter 5, Peru	Timber	3 000	2007	18	1	2	4	253
Shelter 6, Haiti	Steel	5 100	2010	18	2	2	N/A	1 908
Shelter 7, Indonesia, Aceh	Steel	20 000	2004	25	5	3	4	5 348
Shelter 8, Vietnam	Steel	215	2004	26	5	3	5	N/A

1	2
3	4
5	6
7	8

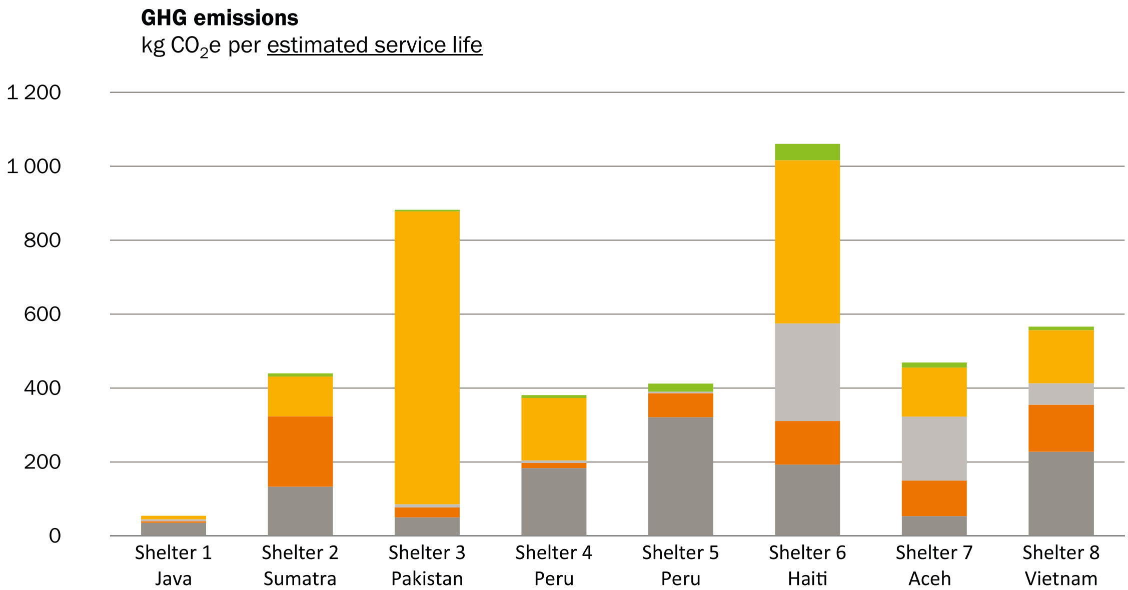
Figure 4.1. The studied shelters:

1. A bamboo shelter in Java. 2. A timber shelter in Sumatra. 3. A tent shelter in Pakistan. 4. A timber shelter in Peru. 5. A timber shelter II, Peru. 6. A steel frame shelter in Haiti. 7. A steel-frame shelter in Aceh. 8. A steel-frame shelter in Vietnam.

Photos © IFRC.



	Shelter 1 Java	Shelter 2 Sumatra	Shelter 3 Pakistan	Shelter 4 Peru	Shelter 5 Peru	Shelter 6 Haiti	Shelter 7 Aceh	Shelter 8 Vietnam
Fixings	0.00	0.48	0.37	0.86	1.23	4.96	2.76	1.69
Coverings	1.93	5.98	64.67	18.71	0.00	49.05	26.50	27.80
Secondary structure	1.14	0.00	0.72	0.80	0.23	29.38	34.61	11.12
Main structure	0.86	10.61	2.21	1.55	3.59	13.09	19.25	24.60
Foundations	7.37	7.38	4.05	20.36	17.85	21.40	10.67	43.93



	Shelter 1 Java	Shelter 2 Sumatra	Shelter 3 Pakistan	Shelter 4 Peru	Shelter 5 Peru	Shelter 6 Haiti	Shelter 7 Aceh	Shelter 8 Vietnam
Fixings	0.00	8.67	4.55	7.74	22.20	44.68	13.82	8.78
Coverings	9.27	107.63	792.49	168.38	0.00	441.46	132.49	144.11
Secondary structure	5.47	0.00	8.78	7.21	4.11	264.40	173.06	57.65
Main structure	4.15	190.95	27.08	13.92	64.65	117.84	96.25	127.53
Foundations	35.40	132.76	49.58	183.26	321.33	192.61	53.34	227.73

Figure 4.2. The carbon footprint of the production phase of the studied eight shelters per square metre of floor area (top) and per year of estimated service life (bottom).

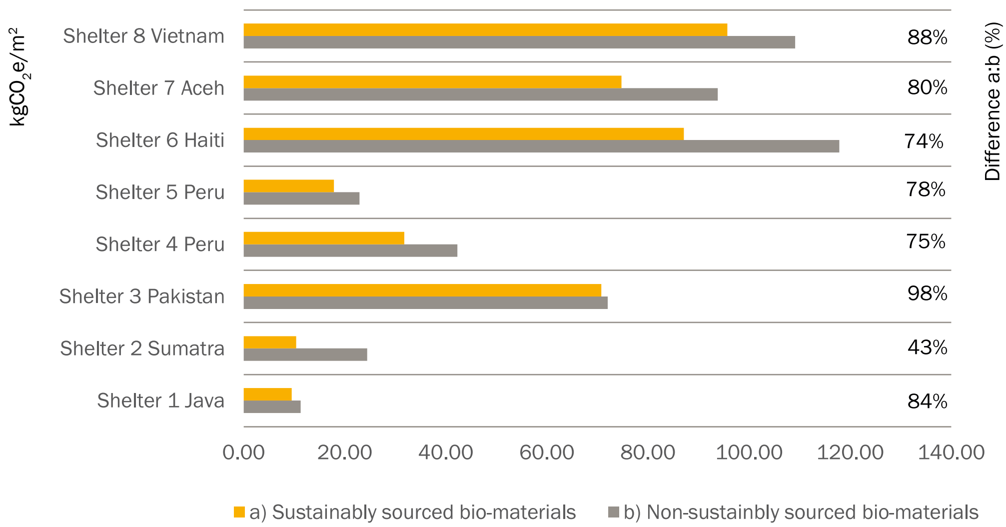


Figure 4.3. A comparison of GHG emissions from the production of sustainably and non-sustainably sourced bio-based construction materials.

shelters were destroyed or damaged in seasonal tropical storms that hit the island. If the claddings need to be replaced during the short service life of a shelter, the carbon footprint can reach high numbers. In comparison to national average figures, shelter projects may increase per capita GHG emissions dramatically, as described in chapter 5.

There is not only large variance between the carbon footprints of different shelters but also in the numbers they were built. Interestingly, those shelters that had the highest carbon footprint were also built in the greatest numbers. Thus the overall GHG emissions from these entire shelter projects were very large. With alternative materials these emissions could have been lowered considerably. Furthermore, the shelters with highest carbon footprint also had highest costs. However, there may have been logical reasons that led into the choices made.

Two alternative calculations scenarios were made for the use of bio-based materials. The first scenario was based on materials from forests that were not sustainably managed. The second scenario assumed that forests were sustainably managed. This has an impact on their carbon footprint. The carbon footprint consists of biogenic and fossil component. The former include emissions from incineration or decay of the bio-based materials. The latter are associated with the use of fossil fuels along the production process of the material, for example, fuel for chain saws or diesel for trucks. According to the standard EN 16485 (CEN, 2014), wood material from sustainably managed forests is assumed to have negative biogenic carbon content in the production phase (modules A1–3). Thus a wooden product may have a negative carbon footprint. However, this difference is balanced when the carbon returns back to the atmosphere, at the latest in the end-of-life phase (module C). If wood is sourced from non-sustainably managed forest, it enters the LCA system with positive value and thus results in a higher total carbon footprint. In addition to timber, the same principle has also been applied to bamboo and palm in this study. The outcome of the comparative scenarios can be seen in figure 4.3. The carbon footprint of the sustainably sourced shelter materials reaches between 43 to 98% of the emissions of non-sustainably sourced materials.

However, revealing the differences in the carbon footprint of shelters underlines the importance of material selection and sustainable sourcing. There are possibilities for great emission reductions, especially for NGOs who commission large numbers of a similar shelter type. Tapping into this potential can be seen as an act of environmental accountability in humanitarian construction.

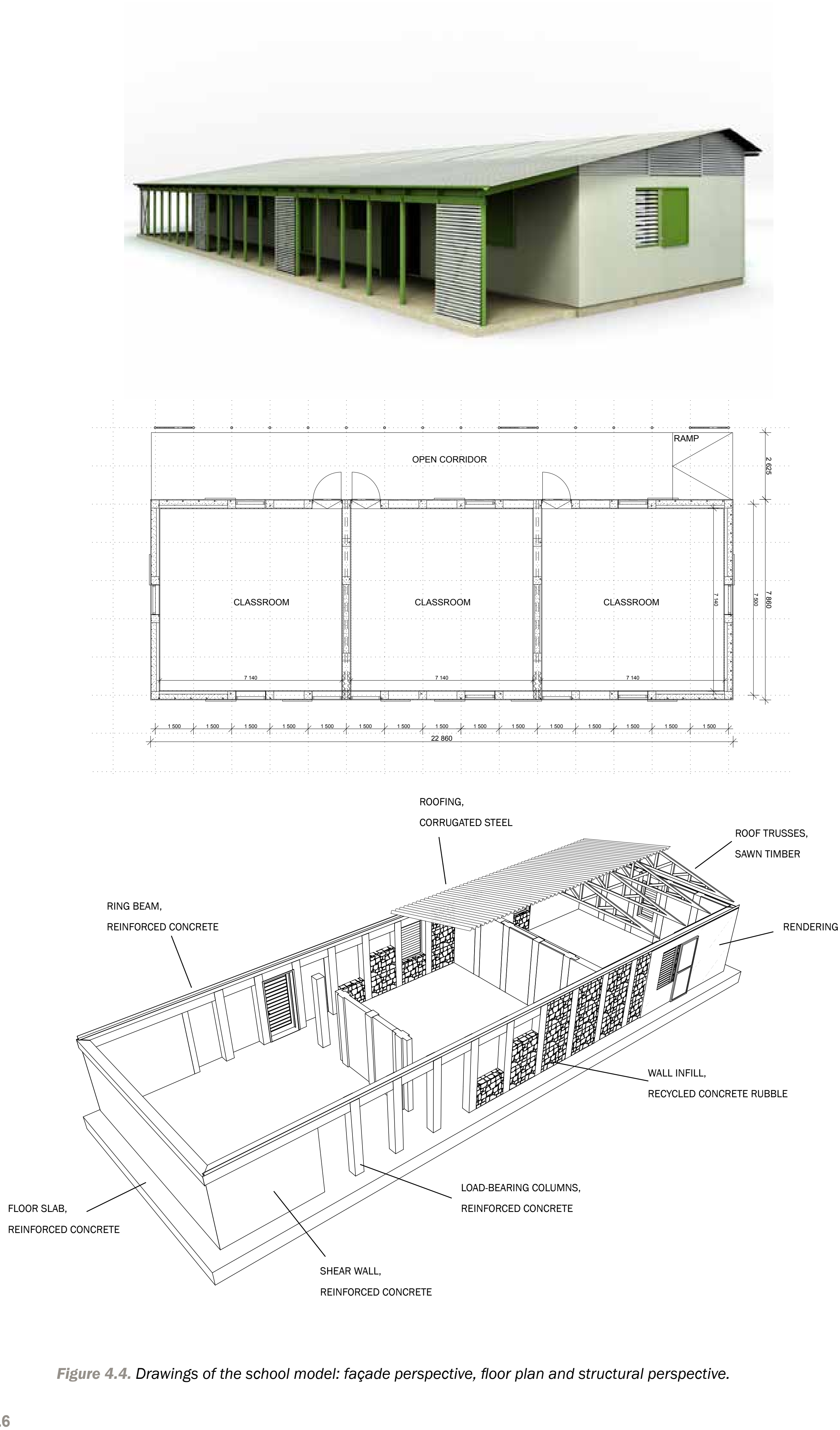


Figure 4.4. Drawings of the school model: façade perspective, floor plan and structural perspective.

4.3 Reconstruction of schools in Haiti

4.3.1 Does the use of recycled materials lower the carbon footprint?

The study from a school reconstruction project in Haiti took place after the earthquake that killed over 220 000 and injured over 300 000 people on the 12th of November 2010 (Clermont, 2011). The disaster left over one million Haitians homeless. In some areas over 70% of buildings were destroyed or damaged beyond repair.

UNDP estimated (2012) that the amount of rubble from destroyed buildings reached 10 million m^3. Because of a shortage of construction materials and the need to clear the rubble, Finn Church Aid, a member of the Action by Churches Together (ACT) Alliance, started a project in which concrete rubble was reused as construction material for the reconstruction of schools. A simple school model (figure 4.4) was designed and alternative construction systems for utilising the rubble or natural stones were developed.

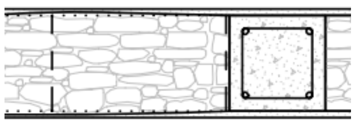
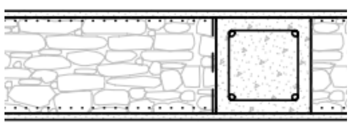
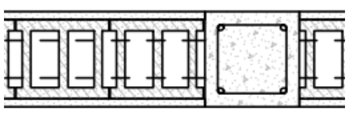
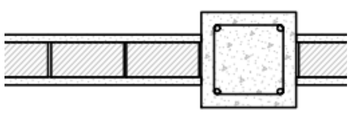
Reusing concrete rubble is not a new innovation or subject of study. The economic benefits of using recycled concrete aggregate were investigated by Noggle and Glick (2010). They concluded that new concrete made using entirely recycled concrete aggregates can be safely used in seismic regions. Furthermore they calculated a break-even point after which using the rubble would become economically feasible. Crushing concrete rubble for use as aggregate in new concrete after the earthquake of Haiti has been studied by DesRoches, Kimberly and Gresham (2011). They concluded that Haitian concrete debris, even though originally being of poor quality, could effectively be used as coarse aggregate in new concrete mix.

In the current study, however, concrete rubble was used as infill material in gabions and as masonry. Research was carried out to find out which structural combinations would cause the lowest carbon footprint. New reinforced concrete was chosen as the load-bearing material. Alternative wall structures that were made from reused concrete rubble or blocks were compared to alternatives made from virgin materials (table 4.5). In addition, the impact of cement substitutes was studied: two concrete mixes containing fly ash and two mixes containing blast furnace slag were compared to typical concrete made from ordinary Portland cement.

Concrete may sequester atmospheric carbon through carbonation, which is a counter-reaction to calcination in cement manufacturing. Carbonation is a slow process that is enhanced when concrete is crushed. Therefore the conditions in Haiti after the disaster were interesting for studying this specific aspect as well. In this case carbonation was estimated for a period of 50 years. Although carbonation also occurs in the possible concrete structures of, for example, the foundations of temporary shelters, their short service life make this positive impact very marginal.

One of the social goals of developing a new construction system was to create opportunities for local participation in the construction work, as also instructed in Clinton´s proposition

Table 4.5. Alternative structure types for wall infills between the columns.

	**Rubble gabions** - Gabion cages from galvanized steel - Loose concrete rubble filling - Rendering on both sides
	**Rubble masonry** - Concrete rubble masonry with cement mortar - Supporting galvanized steel mesh on both sides - Rendering on both sides
	**Recycled concrete blocks** - Concrete blocks with galvanized reinforcement bars - Rendering on both sides
	New concrete blocks - Concrete blocks with galvanized reinforcement bars - Rendering on both sides
	**New bricks** - Brick masonry with cement mortar between concrete columns - Rendering on both sides

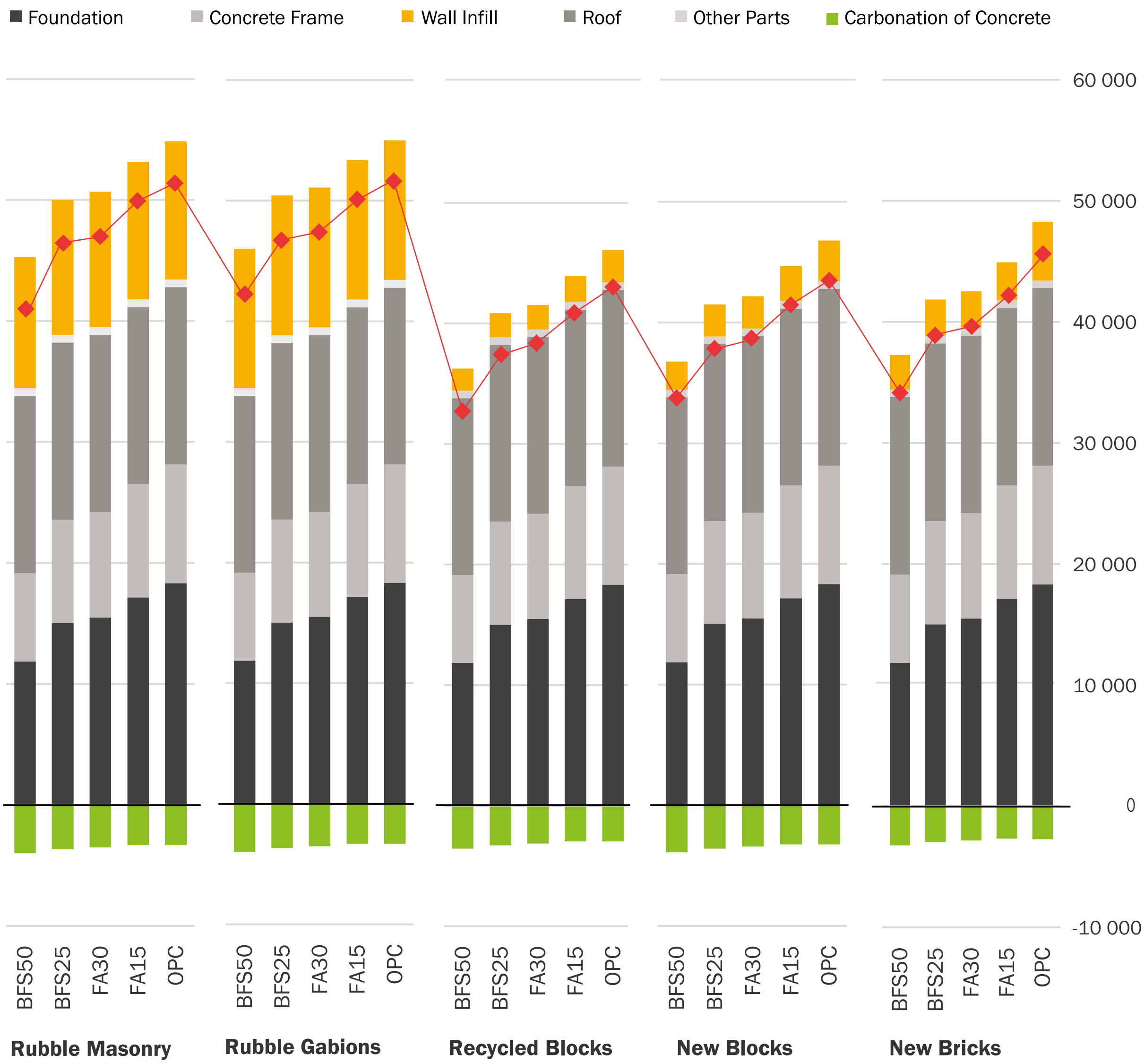


Figure 4.5. CO_2 emissions, uptake and balance (red line) for schools with different alternative wall structures and cement mixes for a 50-year study period.

8: building back better (Clinton, 2006, p. 18). Indeed, Hirano reported (2012) that turning rubble into reconstruction products could provide short-term employment for 800 people through a single construction initiative in Haiti.

4.3.2 Results

The calculations reveal which structural alternative and which cement mix give the lowest carbon footprint (figure 4.5). Looking at the structural solutions, the interesting finding is that using recycled rubble in a form of gabions or rubble masonry yields the highest carbon footprint. This is because such structures require a great amount of reinforcement steel to bring the required high degree of seismic safety. If concrete rubble can be used in non-seismic areas, it will have a lower carbon footprint because less reinforcement steel is needed for structural safety.

On the contrary, reusing concrete blocks in walls caused the smallest carbon footprint as they could be laid between the loadbearing concrete columns in a stable manner. Looking at the cement mixes one finds that large quantities of blast furnace slag considerably reduce the GHG emissions arising from the production of concrete.

The impact of carbonation was found to be of relatively high importance. If 50% blast furnace slag concrete is used in combination with new blocks, carbonation during 50 years may reach 12% of all GHG emissions arising from the production of construction materials for the school. This figure can be considered high. However, the structures of the designed schools are extremely simple. No emissions are caused from the production of thermal insulation, sheathing or building service installations. Therefore the share of carbonation appears large.

Thus the ideal combination for school with a low carbon footprint would include a concrete frame made from 50% blast furnace slag cement and wall infills of reused concrete blocks.

It can be learnt from this study that using recycled or reused materials may be the best or worst choice for lowering the carbon footprint. The method of how recycled materials are used was found to be of great importance. However, utilising demolition debris for construction has other benefits: it can help in post-disaster waste management and create livelihoods.

4.4 Temporary homes in Japan

4.4.1 Background

The Great Eastern Tohoku Earthquake shook Japan on 11 March, 2011. Together with the following tsunami wave it caused major humanitarian disaster. Over 450 000 people were housed in evacuation centres and after the emergency phase was over, some 115 000 transitional shelters were built.

In addition to human suffering, the disaster led into a remarkable change in the energy supply of the Japanese society. As the Fukushima nuclear plant was seriously damaged, the government chose to idle all Japanese nuclear power plants. To meet the resulting shortage of energy, importation of natural gas was increased.

The interest of the study was to investigate the energy efficiency and carbon footprint of temporary homes compared to existing ones. After field trips to the Miyagi prefecture and Sendai area in 2012 and 2013, three shelter models were chosen for comparison: prefabricated shelters, log shelters and sea container shelters. The study included production, construction, use and deconstruction of the shelters (see tables 4.1–4.3 for details).

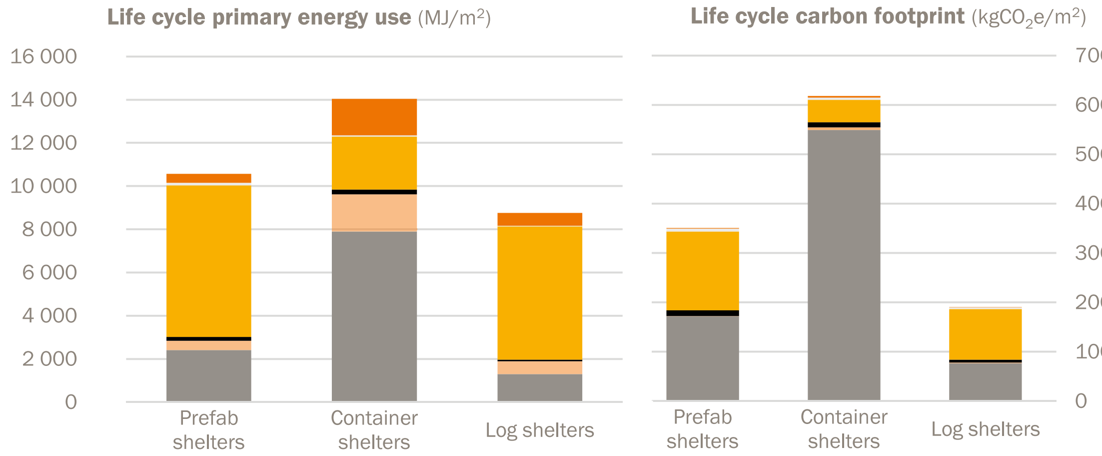
The studied use period was set to three years. Typically temporary housing in Japan is planned for two years. However, the scale of the disaster and the slow relocation process of survivors has taken more time. Therefore the study period is extended.

The reuse or recycling of the used temporary homes in Japan is hard to predict. Often temporary housing or office containers are used several times. However, the great number of containers in the after-sales markets is likely to saturate the markets fast and thus the typical reuse scenarios may not be applicable. Therefore this part of life cycle has been excluded from this study.

The prefabricated shelters seemed to be the dominant model of temporary housing. Settlements of these shelters were erected on sports fields, parks, empty sites and along the roads. Their structures consisted of tubular steel frames, mineral wool or polystyrene insulation and vinyl or steel cladding. After the first winter a number of prefabricated shelters were upgraded to better meet the cold winter conditions of the Sendai area by adding extra insulation and a second layer of glass in the windows.

Log shelters were built in areas where there was adequate supply of timber and experienced labour. The studied log shelter settlement is located in Gohyakugawa village, south of Fukushima. The structures are made of solid log walls and a wood-framed floor and roof.

Figure 4.6. Studied shelters, from top to bottom: prefabricated shelters in the city of Sendai; log shelters in Gohyakugawa; sea container shelters in Onagawa.



	Prefab shelters (MJ/m²)	Container shelters (MJ/m²)	Log shelters (MJ/m²)	Prefab shelters (kgCO₂e/m²)	Container shelters (kgCO₂e/m²)	Log shelters (kgCO₂e/m²)
Transportation from site	426.79	1 697.41	592.63	0.78	3.11	1.08
Deconstruction	118.34	61.97	39.52	6.29	4.72	3.03
Operative energy use	7 012.03	2 447.92	6 172.22	159.80	45.39	102.71
Construction on site	186.23	215.42	77.77	11.37	10.54	5.89
Transportation to site	426.79	1 727.03	592.63	0.78	5.20	1.08
Production	2 404.72	7 895.76	1 289.61	171.34	548.95	76.74

Figure 4.7. Energy use in the studied shelters (left) and the resulting carbon footprint (right).

The sea container shelters were designed by architect Shigeru Ban and are located in Onagawa village, north-east of Sendai city. They are placed on a former sports field, two or three stories high. In addition to efficient land-use, the container shelters utilise sea containers for accommodation. The containers are insulated with polyurethane, clad with plywood and gypsum board and well furnished. The architectural quality of these temporary homes is very high. Containers are manufactured specifically for this project. They could also have been refurbished old containers. In such case, their carbon footprint would have been lower.

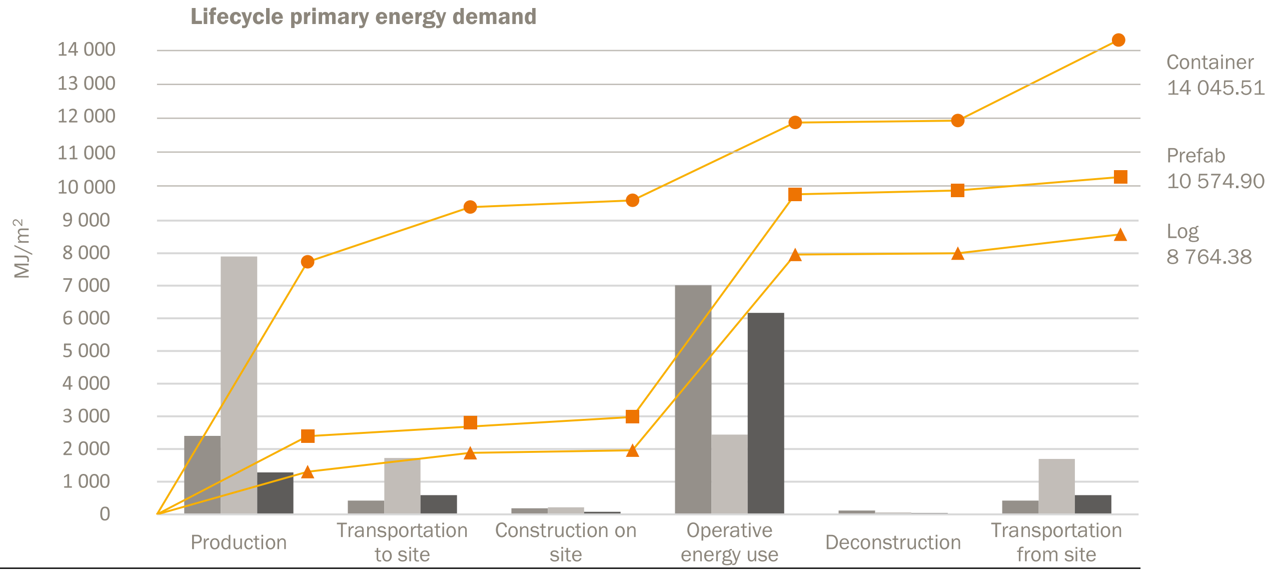
4.4.2 Results

When looking at the energy efficiency, the two- and three-story high container shelters are superior to the one-story prefabricated shelters or log shelters (figure 4.7). Energy efficiency was found to follow the economies of scale: the bigger the cluster of shelters, the better the energy efficiency. This is due to there being less building envelope that faces the outdoor air.

However, the benefits of stacking shelters on top of each other also leads to a greater demand for construction material per shelter. The loads that each story has to take are higher and there needs to be stairs and entrance decks to each floor. This increases the embodied energy and carbon footprint of manufacturing the shelters. If the shelters had been made from reused containers, their GHG emissions would have been lower. Also the transportation of more construction materials leads into higher energy use. In fact, these material-related emissions outrun the energy efficiency benefits of grouping the shelters. When the full life cycle is taken into account, the log shelters perform best and the most energy-efficient container shelters perform worst (figure 4.8).

If the shelters had longer service lives than the studied three years, the energy benefits would start to play a role. However, the container shelters would need to be used for 10 years before they would reach the same life cycle emission level as the log shelters. This is typically not favoured as shelters are intended for temporary use. Should the shelters be used for shorter period than three years, the impacts from the production, construction and end-of-life phases would become more dominant. This would lead to even more favourable results for the log shelters.

However, in the case of the container shelters, the temporary residents expressed the wish to start using them as permanent apartments (Ban, 2013). Interestingly, the container shelters were found to have better energy efficiency than the average permanent housing in the Sendai area (figure 4.9). If the use of the container shelters continued, it would have a positive effect on the societal energy efficiency and perceived living quality simultaneously.



	Production	Transportation to site	Construction on site	Operative energy use	Deconstruction	Transportation from site
Prefab shelters	2 404.72	426.79	186.23	7 012.03	118.34	426.79
Container shelters	7 895.76	1 727.03	215.42	2 447.92	61.97	1 697.41
Log shelters	1 289.61	592.63	77.77	6 172.22	39.52	592.63

Figure 4.8. Primary energy demand accumulation throughout an exemplary three year use of the shelters.

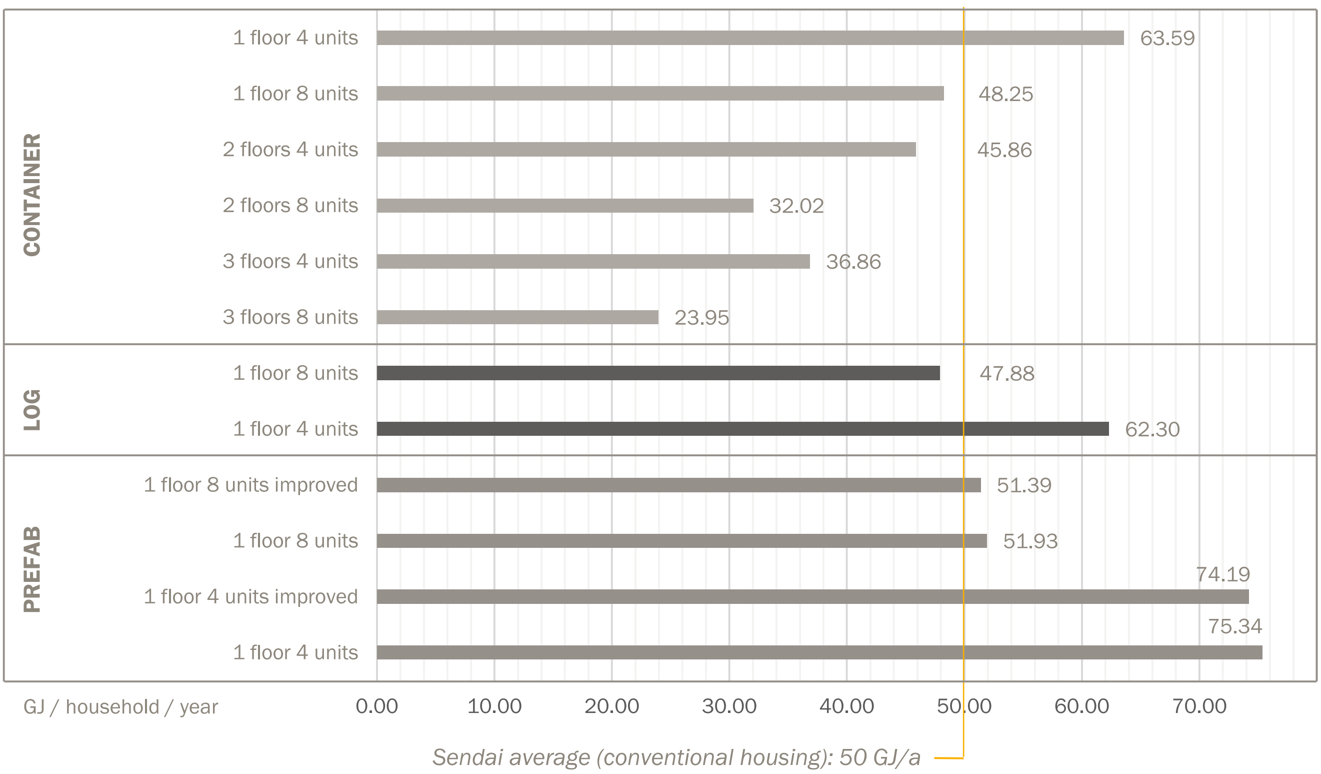


Figure 4.9. A comparison of household energy use of different shelter combinations and the normal households of the Sendai area.

4.5 Temporary or permanent – differences in the carbon footprint?

In addition to the three case studies, a comparison of the emissions of temporary and permanent building was made. In this comparison the GHG emissions from producing materials for a modular, cost-effective house were compared to the corresponding emissions of the eight shelters described in chapter 4.2. In addition to the estimation of GHG emissions, also the carbon stored in the bio-based building parts is calculated according to EN 16449 (CEN, 2014b) and the balance between production-phase emissions and biogenic carbon storage is shown.

The design for the cost-efficient modular house is based on a concept design for Haiti (figure 4.10). The building is designed from plywood and polycarbonate sheets. Its emissions have been estimated using the same methods and system boundaries as for the eight shelters.

The results of the comparison reveal that, in some cases, building a permanent home instead of a transitional shelter does not cause considerably more GHG emissions per square metre (figure 4.11). If the carbon balance is compared, the GHG balance of the permanent plywood home is even better than in some of the steel-framed shelters in Haiti (no. 6), Aceh (no. 7) and Vietnam (no. 8). Although this is a single result and cannot be generalised, it still gives environmental support to the arguments (Sanderson et al., 2014) that suggest building permanent homes directly after a disaster´s emergency response phase instead of erecting transitional shelters as an act of early recovery.

4.6 Conclusions from the case studies

4.6.1 New information and new problems

The three case studies presented in this chapter shed light on the dominance of GHG emissions along the life cycles of humanitarian construction. They also reveal knowledge gaps and the need for further research.

New findings give useful information for planning temporary shelters and reconstruction in a manner that may mitigate climate change. This information can be embedded into disaster preparedness planning and accountability protocols that humanitarian NGOs or government bodies follow.

New problems are linked to the relatively large level of uncertainty in the LCA of humanitarian construction. There is a risk of making mistaken conclusions because of incomplete background information. As humanitarian operations can be large in their coverage, these mistakes may easily be multiplied.

However, the field of environmental impact assessment and LCA is constantly developing. If we wait for perfect harmony of complete scientific understanding and a practical set of rules, we will end up doing nothing in the meantime. The big picture of carbon footprinting presented in the case studies of this research cannot be entirely false. Therefore, taking some action instead of none is an act of extended accountability and fulfilling the “do no harm” principle of humanitarian work.

4.6.2 The carbon footprint levels for transitional shelters differ depending on the region

From the case studies the average levels of the carbon footprint and primary energy demand in the production of transitional shelters can be collected. Figure 4.12 shows the variation of values.

The average of all studied shelters 117.35 kg CO_2e/m^2 is the average of a range of values from 11.31 to 548.95 kg CO_2e/m^2. The data are divided into shelters from developing countries and from Japan. Interestingly the wooden log shelter from Japan scores lower than the average carbon footprint of shelters from developing countries. The only exception in the data range is the GHG peak of container shelters. However, as described in section 4.4, it may remain permanent and thus the overall emissions will decline as a function of years of service life.

4.6.3 The importance of construction materials

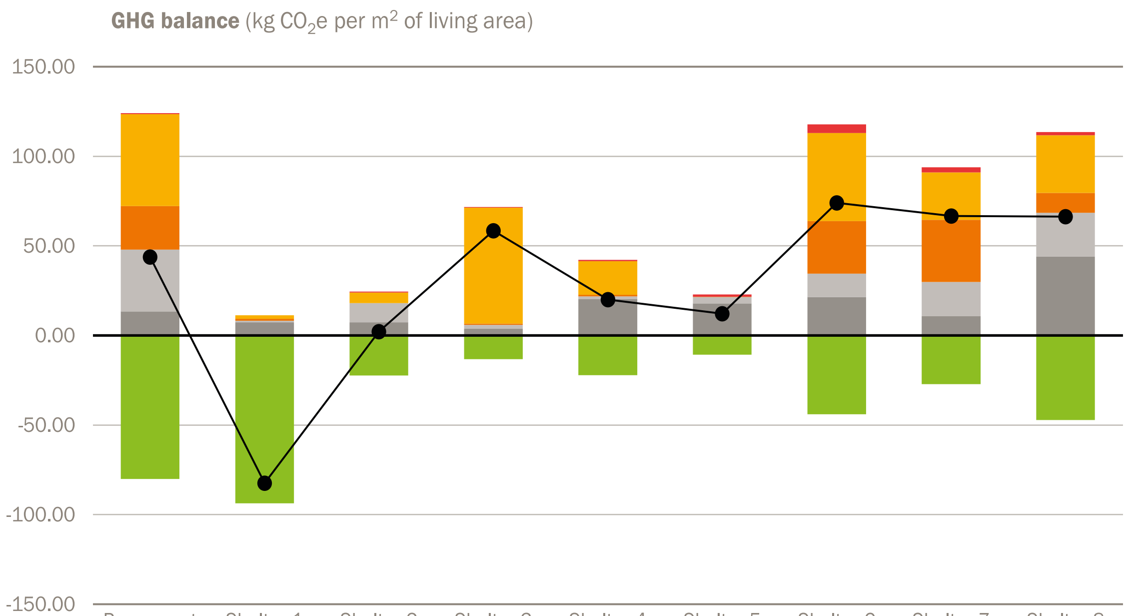
As can be concluded from the case studies, the selection of construction materials is of key importance in order to lower the carbon footprint and embodied energy of humanitarian construction. Furthermore, sustainable sourcing of bio-based materials can improve the environmental friendliness considerably.

As known from the LCAs of conventional construction, wooden structures on the average perform better than comparable alternatives made from steel, concrete or bricks (Dodoo et al., 2013; Häkkinen & Wirtanen, 2006; Pajchrowski et al., 2014; Eriksson, 2004; Lippke et al., 2004; Heeren et al., 2015; Spitzbart & Fischer, 2014; Takano et al., 2014). The same seems to apply to humanitarian use as well. Transitional shelters across the globe made from wood are superior to their alternatives in carbon footprint calculations, especially when wood products from sustainably managed forests are used.

The impact of choosing materials with low embodied carbon and energy is emphasized by the fact that the emissions from use stage of shelters are usually remarkably lower than in normal buildings. The two main reasons for this are the short use phase (desirably only 6–24 months) and low-tech or no-tech building services. As there are less than average emissions (or even no emissions) from the operative energy use of shelters, the dominance of material production grows.

However, using bio-based materials (e.g. bamboo or straw) is not always possible because of limited availability, concerns of legal sourcing or cultural suitability. Furthermore, tropical

Figure 4.10. *An alternative to a transitional shelter: a permanent plywood home for Haiti. © Kombi Architects Ltd.*



	Permanent house	Shelter 1 Indonesia	Shelter 2 Indonesia	Shelter 3 Pakistan	Shelter 4 Peru	Shelter 5 Peru	Shelter 6 Haiti	Shelter 7 Indonesia	Shelter 8 Vietnam
Biogenic carbon storage	-80.13	-93.65	-22.25	-13.27	-22.21	-10.68	-43.89	-27.12	-47.15
Fixings	0.48	0.00	0.48	0.37	0.86	1.23	4.96	2.76	1.69
Coverings	51.19	1.93	5.98	64.67	18.71	0.00	49.05	26.50	32.17
Secondary structure	24.47	1.14	0.00	0.72	0.80	0.23	29.38	34.61	11.12
Main structure	34.38	0.86	10.61	2.21	1.55	3.59	13.09	19.25	24.60
Foundations	13.46	7.37	7.38	3.77	20.36	17.85	21.40	10.67	43.93
GHG balance	43.86	-82.34	2.19	58.47	20.07	12.22	74.00	66.67	66.37

Figure 4.11. *A comparison of the GHG balance of a permanent house and eight transitional shelters.*

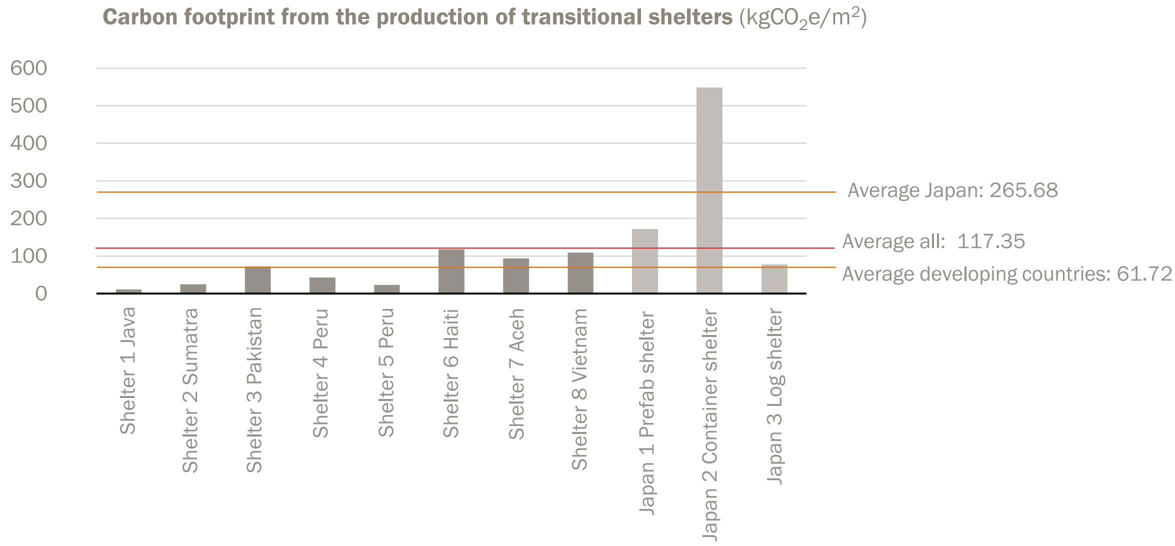


Figure 4.12. *Carbon footprint levels of transitional shelters in developing and developed countries.*

climate may increase conditions for the decay of wood and risk for termite damages. In such cases there is still plenty of possibilities for lowering the carbon footprint. The examples from the reconstruction of schools in Haiti show that within the field of concrete construction, the differences in carbon footprint may be significant.

The findings underline the use of bio-based materials from sustainably managed forests. The GHG emissions from their production was found to reach on average 81% of the corresponding emissions of non-sustainably sourced bio-based material alternatives but less than 50% of emissions can be reached in shelters that are mostly made from bio-based materials.

4.6.4 The potential of design

Although dealing with primarily humanitarian response, the quality of proper architectural and engineering design cannot be surpassed. The example from Japan shows how well-designed temporary homes may even have better energy efficiency and give higher user satisfaction than normal housing.

The design, however, can seldom be carried out during the operative process of transitional shelter projects but should be integrated into preparedness planning. For reconstruction projects the steps of design are closer to the normal design process and environmental iteration may be done along the typical stages of design.

On the other hand, a risk of "over-designing" structures to meet rigorous seismic safety standards has been identified. In the case of the reconstruction of schools in Haiti the first structural solutions that had concrete rubble inside gabions were secured with an exceptionally high amount of reinforcement steel. This led to a high price and high carbon footprint.

Humanitarian project managers are usually dependant on outsourced construction professionals and do not necessarily have in-house expertise in construction management. In these cases it may be difficult to steer the design towards the desired specific goals, for example, a low carbon footprint. The knowledge of low carbon design is not yet wide-spread among architects or engineers and especially the hectic context of humanitarian response may not offer possibilities for investigating the topic further.

It is often difficult to draw the line between safety and costs. Focusing on costs will result in a greater number of shelters, but they will most likely be of lesser quality. Maximising quality will lead to being able to help a smaller amount of survivors. A middle path would need to include analysis of local hazards, their frequency and setting a value-based choice of desired safety class. Thereafter a risk analysis can be carried out and the likelihood for the design to fail in the anticipated use conditions minimized. This is however beyond the scope of this work and a topic of further research.

4.6.5 Poor data quality is a concern in humanitarian LCA

As described in chapter 2, the data for LCA can be obtained from real sources (i.e. from the environmental records of each manufacturer that provides materials for the studied building) or from databases (i.e. the average values that describe the production impacts of typical construction materials). In the case studies of this research, the latter option has been used. From the several available databases, an open-source option, ICE

2011, was chosen as it could be widely used in humanitarian work without cost. Ideally, as pointed out by Hellweg and Milà i Canals (2014), LCA databases should be open for assessors, but this is usually not possible due to the high costs associated with their maintenance.

Using a database inevitably leads to end results that do not describe the exact environmental impacts of the studied building but merely an average of the impacts that might arise. This is a fundamental dilemma but usually accepted in LCA.

However, in the assessment of humanitarian buildings that are made from construction materials from developing countries, the suitability of any conventional database can be questioned (Kuittinen & Kaipainen, 2011). The entire industrial infrastructure that produces the construction materials may have very different inputs (of energy, materials and capital) and outputs (of products, waste and emissions) than the corresponding processes in developed countries. On the other hand, some products may be the results of mainly manual labour (e.g. mud bricks) and require considerably less energy inputs than the comparable product from a developed country because the unit costs for manual labour are low in developing countries. Thus one can conclude that the level of uncertainty of databases can be considerably higher in developing countries than in developed countries.

If the social sustainability of the construction materials were taken into account, the picture would look even more complicated. Inevitably there will be concerns of the potential use of child or forced labour. On the other hand there might be possibilities to offer livelihoods if the construction methods are more labour-intensive than in the efficiency-oriented factories of developed countries.

In addition to the concerns about material-specific environmental data, the question of service life estimation can also be raised. It seems that for most of the temporary shelters, especially in developing countries, no reliable service life estimation can be done as required in ISO 15868 standard series. This leads to unclarity regarding the correction factors that EN 15978 suggests for adopting modules B and D_B, if the required service life differs from the reference study period.

In order to bring clarity to the LCA of humanitarian construction there would thus be need for collection of data from the production of construction materials and their service lives in developing countries. Ideally this could be coupled with industrial development or livelihood programmes. The end results would not only make it possible to adjust existing datasets to the humanitarian context but also provide the developing countries with more exact information on the efficiency and sustainability of their construction sector. This, in turn, would enable developing local pathways for meeting climate mitigation targets.

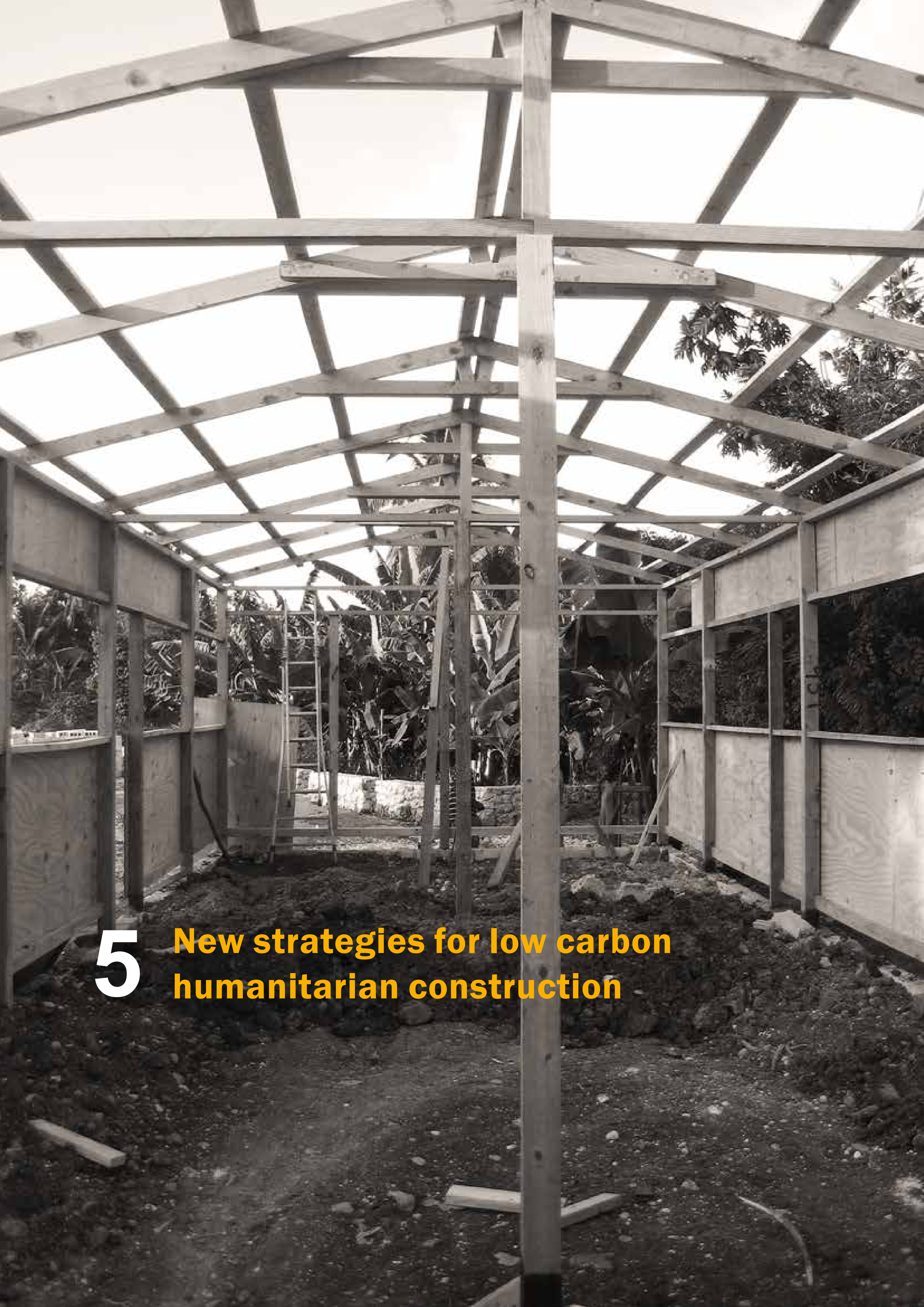
4.7 Summary

Studies reveal new information on the carbon footprint of humanitarian buildings. On average, the studied transitional shelters had a carbon footprint of 117.35 kg CO_2 e/m^2. The range of emissions is however wide. The most typical frame types include bio-based (timber or bamboo) and metal-framed alternatives. The latter yield a considerably higher carbon footprint. In addition to the frame, the coverings seem to have a significant impact on the carbon footprint. If bio-based materials are used, the emissions stay much lower than when corrugated metal or plastics are applied.

The sustainable sourcing of materials is important. If bio-based materials are acquired from sustainably managed forests, their production emissions may be over 50% lower than non-sustainably sourced bio-based material alternatives.

While new information is obtained, also new problems are encountered. Quality of background data is rather weak. Case-specific data on the production emission of materials was not found and therefore the calculations are dependent on general databases. However, no databases were found for construction materials manufactured in developing countries. This causes uncertainty of an unknown magnitude.

The calculations reveal a general trend of the carbon footprint and give enough information for decision making. However, more studies are required along regional disaster preparedness planning projects so that local pathways to low carbon construction can be recognised and utilised.



5 New strategies for low carbon humanitarian construction

5.1 Developing strategies and practices

5.1.1 Background

From the case studies it is possible to get an understanding of the scale of GHG emissions and energy demand associated to manufacturing and using transitional shelters and for reconstruction projects. However, the assessment methods applied for them are scientific and as such less agile for operative decision making (Häkkinen et al., 2015) and iteration in the design phase of humanitarian construction.

This chapter introduces new robust strategies and methods for controlling, mitigating and optimising the GHG emissions of humanitarian construction. They have been developed as a part of this research. First a strategy for setting benchmark levels for carbon footprinting in different countries is presented. Secondly new indicators of carbon efficiency and carbon economy have been developed (annex 4) for optimisation of the carbon footprint, energy efficiency and construction costs.

This chapter gives an overview of these studies and provides discussion on their applicability, especially in relation to the descriptive case studies of chapter 3. Detailed description of the used background studies is provided in annexes 4 and 5.

5.1.2 Case-sensitive adaptation of environmental assessment in humanitarian construction

As explained in chapter 2, LCA is often a too demanding process for evaluating the carbon footprint of temporary shelters in less developed countries. The same applies for the current versions of green building certification schemes. Their potential can be seized in the disaster preparedness planning, where more time and resources may be available. This indicates that humanitarian operators should prepare plans for shelter and reconstruction projects in their geographic focus areas. These plans could include environmental considerations that may use knowledge from LCAs, green certification schemes or international standards for sustainable construction that have local relevance.

Figure 5.1 illustrates how conventional environmental assessment may be implemented into humanitarian construction. In the emergency and transitional phases the most prominent stage

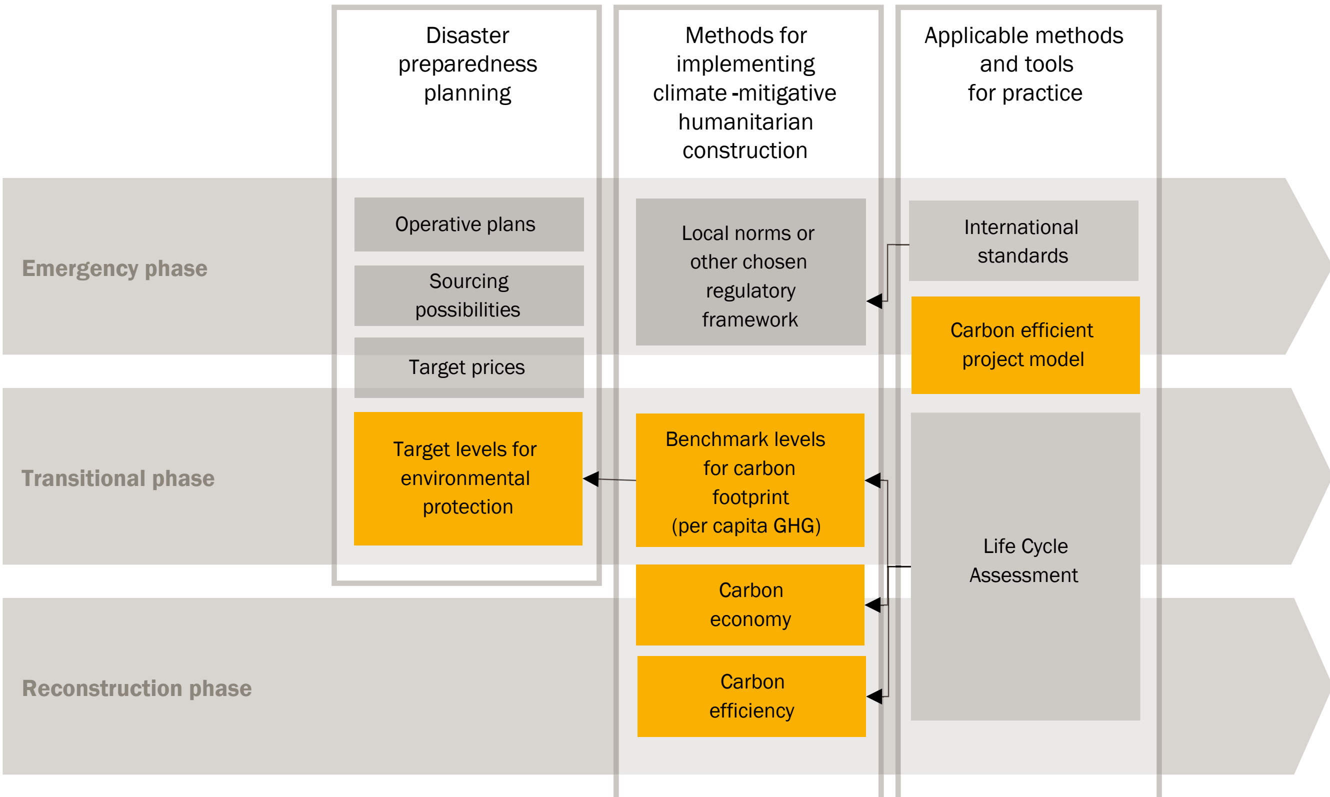


Figure 5.1. Case-sensitive adaptation of climate-mitigative humanitarian construction. New interventions are marked in yellow.

for implementing either LCA or green certification is in disaster preparedness planning, because the desired rapid response times in these operations seldom allow for environmental assessments. Preparedness planning may include operative plans for sourcing sustainable construction materials and setting target prices for public procurement. As a new intervention, desired levels for environmental protection could also be taken into disaster preparedness planning. To achieve this, both local conditions (e.g. the energy mix, sourcing, transportation alternatives, construction traditions, norms) and disaster scenarios (e.g. natural or man-made disasters) need to be evaluated and optimal solutions planned accordingly. This may also apply to reconstruction in less developed countries.

Methods for implementing construction that mitigates climate change from its share need to be built on local norms. In addition to these, benchmark levels for the carbon footprint in comparison to the national per capita levels may be set as a new intervention. Furthermore, the carbon economy and carbon efficiency of prepared activities may be set.

An example of applying a carbon-efficient project model for climate-mitigative humanitarian construction is presented in chapter 6.

Setting target levels for the carbon footprint is important and may be done with the help of "per capita carbon footprinting" (see chapter 5.2). To prevent carbon footprinting from being a horizontal silo in the project, an optimisation of the carbon footprint, energy and costs may be carried out by controlling the carbon efficiency and carbon economy (see chapter 5.3) of a carbon-efficient project model (see chapter 6), which can be used as an extension to existing humanitarian quality management processes. In addition, a set of either international environmental standards (see chapter 2) or local norms should be applied.

Note that the humanitarian construction process does not always proceed linearly from emergency to reconstruction. People from transitional shelters need to be evacuated back into emergency shelters in cases of repeated natural disasters or wars.

5.1.3 The system boundary for the carbon footprinting of humanitarian construction

Based on the presented case studies (chapter 4) a proposal for a system boundary is drafted. It is a simplification of LCA and intended for assessing the GHG emissions and primary energy demand of humanitarian construction. There are alternatives for the emergency, transitional and reconstruction phases. The recommendations, illustrated in figure 5.2, describe the minimum requirements for the LCA of humanitarian construction.

In the emergency phase the possible environmental assessment may take place during the product development of emergency shelters or other built structures. During the actual emergency response there is no time to carry out LCAs. When assessments for emergency shelters are made, the included life cycle stages should contain the production stage and parts of the end-of-life stage. This way the production and recycling emissions become known. In addition, the transportation emissions during construction stage (A4) and end-of-life stage (C2) may give important information on how transportation distances and methods affect emissions and energy use.

Transitional shelter projects should be assessed at least for the production stage. Including the construction and end-of-life phases is recommended. In areas where heating or cooling are inevitable, their impacts should be estimated as well (see the case study of Japanese shelters in chapter 4). In addition to the structures, the foundations of transitional shelters should also be assessed. Ground works may be difficult to estimate, as soil surveys may be difficult to obtain from disaster areas.

The assessment of reconstruction should be similar to the environmental assessment of conventional construction. Thus it depends on the context and applied normative framework. For humanitarian operators the recommended minimum life cycle stages in reconstruction projects include the production phase and estimation of operational energy use. These modules provide the assessor with a minimum understanding of the impacts of the project. Depending on the case, end-of-life scenarios should be included. In the context of developing countries, however, it may be difficult to make scenarios of the evolution of waste management infrastructure.

The suggestions for functional units (c) are based on annex 4. For the assessment of the actual shelter or building, a proper functional unit may be a square metre of floor area. For estimating the impacts of ground work or foundations, a recommended functional unit would be a square metre of a building´s site or refugee camp's block. This way the impacts that are caused by the selection of the site will not be mistakenly mixed with the impacts caused by the selection of building materials.

5.2 Setting benchmark levels for low carbon humanitarian construction

5.2.1 Different contexts require a different criteria setting

Each humanitarian construction project differs in terms of the reason for the response (the disaster type), geographic area, climate, season, budget, project team, project time, mandate and available resources. Thus it is not reasonable to propose setting the same, fixed carbon footprint values for every project. Instead, using flexible, country-specific carbon footprint criteria may offer a better starting point for humanitarian organisations. In terms of carbon footprinting such a reference level may be obtained from the statistics of country-specific per capita GHG emissions.

5.2.2 Per capita GHG values

Per capita GHG values describe how much emissions a country emits annually when divided by its number of residents. Regularly

a. Life cycle stages

Emergency	Transitional	Reconstruction	Code	Stage	Phase
Required	Required	Required	**A1**	Raw material supply	Production
Required	Required	Required	**A2**	Transport to factory	Production
Required	Required	Required	**A3**	Manufacturing	Production
Recommended	Recommended	Recommended	**A4**	Transport to site	Construction
	Recommended	Recommended	**A5**	Construction work	Construction
		Recommended	**B1**	Use	Use
		Recommended	**B2**	Maintenance	Use
		Recommended	**B3**	Repair	Use
		Recommended	**B4**	Replacement	Use
		Recommended	**B5**	Refurbishment	Use
	Recommended	Required	**B6**	Energy use	Use
		Recommended	**B7**	Water use	Use
	Recommended	Recommended	**C1**	Deconstruction	End-of-Life
Recommended	Recommended	Recommended	**C2**	Transport	End-of-Life
Recommended	Recommended	Recommended	**C3**	Waste processing	End-of-Life
Recommended	Recommended	Recommended	**C4**	Disposal	End-of-Life

■ *Required*

■ *Recommended*

Emergency	Transitional	Reconstruction		**b.** Building parts	**c.** Functional units
	Recommended	Required	**1**	Ground work and excavations	1m² of site
Required	Required	Required	**2**	Foundations and external structures	1m² of building
Required	Required	Required	**3**	Frame and roof structures	1m² of building
Required	Required	Required	**4**	Supplementary structures	1m² of building
Required	Required	Required	**5**	Surface claddings	1m² of building
			6	Furniture, equipment and machines	1m² of building
			7	Mechanical service equipment	1m² of building
			8	Scaffolding or other construction period items	1m² of building
				Vegetation	1m² of site

Figure 5.2. Recommendations for a minimum system boundary in the LCA of humanitarian construction.

updated statistics are available from open sources, such as the World Bank (2015), the World Resource Institute (2014) or the Shift Project (2013).

The range of per capita emissions is large, ranging from nearly zero metric tons of CO_2e per capita (Chad) to over 40 (Qatar). There may even be considerable variation in the emissions within the cities of the same country (IPCC WG III, 2014, p. 90). Figure 5.3 shows the differences in per capita emissions. As the per capita emissions are directly linked to the population, they have also a linkage to GDP. The final goal is to stabilise the per capita GHG emissions on a lower level than before the disaster.

Using per capita GHG values as a reference level for setting criteria for humanitarian operations may provide several advantages:

- It takes into account the socio-economic context.
- It supports national actions towards reduction of GHG emissions and encourages sustainable development.
- It enables the use of alternative paths for reaching the desired per capita emission levels.
- It enables sustainable building pilot projects that are tailored to local needs.

Improving any per capita indicator must be done in accordance with quality standards. It would (theoretically) be possible to improve the indicator by accommodating more people in the same shelter. This would however violate the minimum standards of humanitarian response (Sphere Project) and is therefore out of the question.

The method includes the steps described in table 5.1. The process begins with acquiring the national per capita GHG emissions from inventories of, for example, the World Bank (step 1). This sets the reference level, which should be improved after the construction project. The magnitude of improvement can be set according to national climate targets (step 2). Furthermore, the maximum GHG peak may be defined (step 3), as all construction projects inevitably lead to additional emissions. Thereafter practical recommendations for reaching the defined targets need to be given (step 4) to authorities and operative personnel. Finally, the construction project needs to be monitored and documented so that the actual realised impacts may be understood (step 5). This gives also data for further learning and improvement.

The outcomes of the per capita process are illustrated in figure 5.3, which shows how GHG emission levels should develop over time. Before a disaster the emission level (GHG-a in figure 5.3) fluctuates annually based on, for example, seasons. After the disaster, the per capita emissions are likely to drop dramatically in the beginning of the emergency phase (T_e). This is because the household emissions are reduced due to reduced energy use. The magnitude of this drop is very context dependant. In developing countries that have a warm climate, the household emissions are low and the drop may not be dramatic. In highly developed countries and cold climates the drop may be significant as nearly all household energy use collapses.

Towards the transitional phase (T_t) there is a peak in the emissions, if transitional settlements are built instead of utilising existing building stock. The magnitude of this peak has been shown in the studies of chapter 4. After the transitional construction work the GHG emissions return to the stable fluctuating pattern that reflects the energy demand per season. The reconstruction phase (T_r) causes a second peak in the emissions, because energy has to be invested into the production of construction materials, transportation and at the building site. Thereafter, however, the new annual per capita emission level (GHG-n) should be lower than before the disaster.

5.2.3 Per capita GHG in practice

The use of the per capita GHG values in humanitarian construction is exemplified in table 5.2 for four transitional shelter construction projects in Haiti (annex 1) and Japan (annex 3).

In stage A, the reference GHG-a value (see figure 5.1) is obtained from the World Bank´s public statistics. Next, the share of the construction and manufacturing sector is defined from the open-source database of the Shift Project. This figure includes a knowledge gap, as the sector data is not disaggregated to show construction-related emissions set apart from all manufacturing emissions. However, the combined value can be used based in favouring "conservative assumptions" in LCA, in other words, by using this value the end-results appear less favourable for the studied option. As more complete data become available, the accuracy of the calculations will improve.

Transitional shelters are typically planned for households. In stage B the GHG and construction sector values that are provided per capita are converted into a "per household" level. This may be done by multiplying the per capita values with the average national household size from the Demographic Yearbook of the UN Statistics Division (2013). The same multiplication also gives the household-level GHG values. Setting the level of the allowed GHG peak or overshoot is a subjective and value-based choice. It may be taken after the consultation of local authorities, environmental experts and other key stakeholders.

After the project the GHG peak from the manufacturing of the shelters can be compared to the goals in stage C of table 5.2. As the example shows, high case-dependent variance can be seen. The shelters in Haiti and Indonesia are aimed at the climate and context of a tropical developing country. Different material selection leads into dramatically different impacts on the per capita emissions. The emissions caused by the steel shelter in Haiti can be considered as a radical overshoot. For Japan, the ambition levels for reducing GHG peaks for the transitional phase is (in this example) set higher due to the country´s high disaster response capacity and top-level construction sector. Still, depending on shelter materials, large variation in relation to per capita emissions can be observed. Shelters made from renewable materials, wood or bamboo perform very well in this comparison.

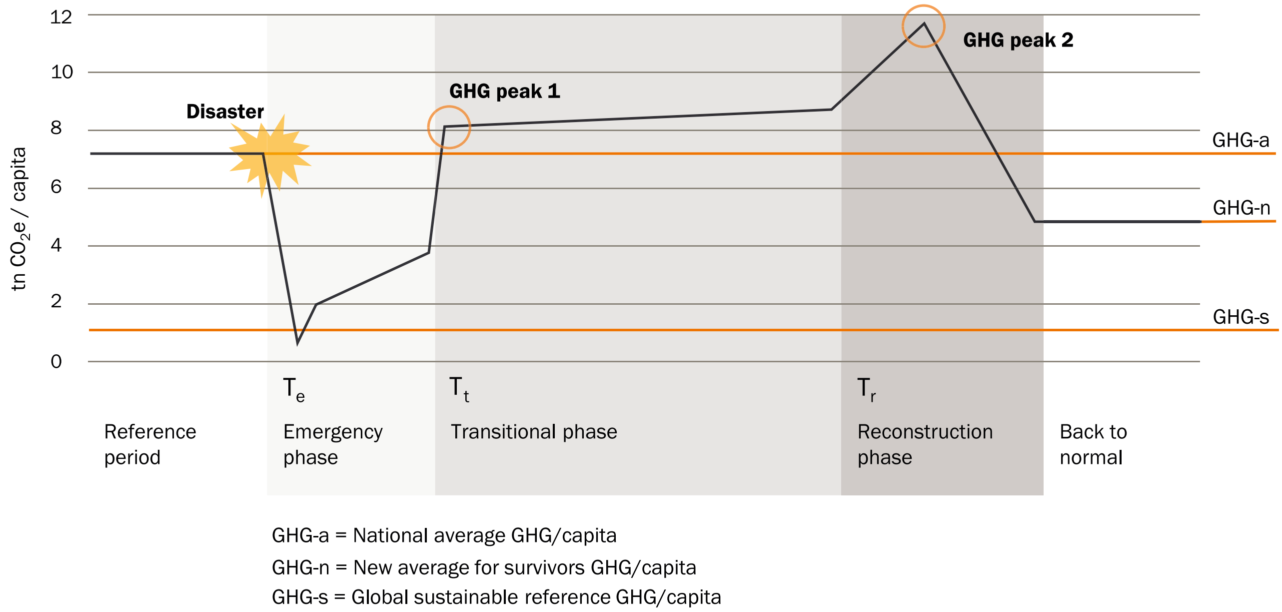


Figure 5.3. Levels of per capita GHG emissions during the stages of emergency response, transition and reconstruction.

Table 5.1. Steps for mitigating the per capita GHG emissions. Adapted from annex 5.

Step		Background	Outcome
1	Documentation of average annual per capita GHG values for construction in the chosen country.	GHG inventories of e.g. the World Bank.	Annual reference level (GHG-a).
2	Setting a goal for the desired lowered level of emissions that should be achieved after the project.	National climate mitigation targets or relevant IPCC pathways.	New emission level target (GHG-n) that is set based on emission reduction pathway towards a sustainable level of emissions (GHG-s).
3	Defining the maximum allowed GHG peak that may accumulate from the temporary shelters and construction processes.	Share of construction-related per capita GHG emissions.	Recommendations for mitigating the GHG peak.
4	Providing relevant stakeholders with practical recommendations for reaching the targets.	Carbon efficient project model (chapter 6).	Guidance and instruction notes.
5	Monitoring and providing required assistance during the construction process.	Goals set in step 1 and 2.	Evaluation report.

Table 5.2. Exemplary use of the per capita GHG value setting for various shelter projects in developing and developed countries. Further developed from annex 1.

Country		Haiti	Indonesia	Japan	Japan	Japan
Frame material		Steel	Bamboo	Steel	Wood	Steel
A. Per capita reference values						
A1	GHG benchmark[1]	0.2	2.3	9.3	9.3	9.3
A2	The share of the construction and manufacturing sector[2]	5%	13%	26%	26%	26%
A3	The GHG benchmark for construction per capita ($tnCO_2e$/capita) = A1 * A2	0.01	0.299	2.418	2.418	2.418
B. Conversion into household level						
B1	Average household size[3]	3.4	4.5	2.5	2.5	2.5
B2	GHG reference for construction per household (A3*B1)	0.034	1.346	6.045	6.045	6.045
B3	The allowed emission peak per household (% and $tnCO_2e$) = B1 * B2	50%	50%	20%	20%	20%
		0.051	2.0183	7.254	7.254	7.254
C. Comparison						
C1	The measured GHG peak of the project (tn CO_2e/household)	2.211	0.271	5.470	2.226	14.172
Comparison to goal (C1:B3)		**4 336%**	**13%**	**75%**	**31%**	**195%**

1) source: The World Bank, data from 2011

2) source: The Shift Project Data Portal (www.tsp-data-portal.org), data from 2013

3) source: Demographic Yearbook, UN Statistic Division

5.3 Introducing carbon efficiency and carbon economy

5.3.1 From a single indicator to key indicators

The per capita GHG approach presented earlier is suitable for setting national reference levels for the carbon footprint of humanitarian construction via the top-down approach. However, there are other indicators that affect the sustainability and feasibility of a humanitarian construction project: the construction and transportation costs or energy demand. In practice, single construction decisions, for example, the choice of frame material or energy system, are seldom done in isolation. They are usually done in relation to each other.

The environmental impacts of a building or construction product should not be evaluated without comparing the impacts to other factors that highly influence decision-making in building design or materials selection: costs and energy. Focusing only on ecological indicators may lead to sub-optimisation, which has been found to increase the price of sustainable construction (Becchio et al., 2014; Liu et al., 2014). However, the construction costs do not include externalities. Should they be included, the environmental impacts would be in the core of the decision-making process.

To overcome this problem, a method for cross-comparing the carbon footprint, energy demand and construction costs was developed (annex 4). It is based on a development project for building low-carbon schools and nurseries for the city of Espoo. The difference to existing green building certification schemes that apply multi-parameter comparison (e.g. DGNB and CASBEE) is that the method uses only existing data without subjective weighting.

This example is not a humanitarian construction project. It is based on a conventional construction case study because of better access to all relevant data: drawings, comprehensive bills of quantities, detailed budget calculations and energy simulations. Such were difficult to find in the humanitarian context. However, the outcomes of this example can be generalised into humanitarian use, as shown in sub-section 5.4.3 and chapter 6.

Formula 1.

Carbon efficiency = (C x E)/1000

Formula 2a.

Carbon economy of buildings = $(C \times E \times €_B)10^{-7}$

Formula 2b.

Carbon economy of building products
= $(C \times \lambda \times €_P)10^{-7}$

C = GHG emissions from the production phase ($kgCO_2e/m^2$)

E = Operative energy demand (kWh/m^2a)

$€_B$ = Construction costs of the building per m^2

λ = Thermal conductivity of the product (W/mK)

$€_P$ = Purchase cost of the product per FU,

FU= Functional unit chosen for the comparison (e.g. m^2 or unit).

E = 1 for humanitarian shelters that have no heating or cooling devices.

λ = 1 for non-insulating building parts or humanitarian structures that do not require thermal insulation.

The numbers are used unit free. Results are divided or multiplied to ease comparison.

5.3.2 Cross-comparison of carbon, energy and costs

The approach includes comparison of three key indicators, as shown in formulas 1 and 2. These multi-parameter fitness functions were developed for this study. Conventionally efficiency (r) is calculated as the ratio of desired output (P) to its inputs (C): r = P/C. However, the same efficiency only describes the ratio of outputs and inputs, not their numeric value. Utilising a fitness function therefore gives better information for comparison.

The outcomes from formula 1 and 2 include carbon efficiency and carbon economy. They are the smaller the better the performance of the building or product is.

Carbon efficiency shows how much GHG emissions are caused when a certain level of energy efficiency is aimed at. It is suitable for temporary shelters or reconstruction in cold climates (see case study from Japan in section 4.4).

Carbon economy describes the interdependence of GHG emissions, energy and construction costs. It can be calculated for buildings or building products. In humanitarian use there may be cases where, for example, transitional shelters are built in a warm climate without any building service installations. In such a case the carbon economy is calculated without the indicator of energy, as described in formula 2.

Both carbon efficiency and carbon economy offer the designer or constructor flexibility in reaching a sustainable building. If for instance the carbon footprint of construction materials is high due to reasons of, for example, the availability of only such materials that have a high carbon footprint, the carbon efficiency may be compensated for by aiming at low operative energy consumption.

The values required for the calculation can be obtained from sources presented in table 5.3.

5.3.3 Carbon economy in humanitarian use

A comparison of eight shelters commissioned by IFRC exemplifies the accumulation of carbon economy (table 5.4). Although the shelters are intended for the same end use, their carbon economy is very different. The bamboo shelters (no. 1) and wood-framed shelters (no. 5) perform best. There is significant contrast to the more expensive and GHG intensive steel shelters in Haiti (no. 6) and Aceh (no. 7).

It should be noted that it is not relevant to compare shelters from different areas and projects as the humanitarian priorities, cost structure and technical requirements may differ. Instead, by comparing the GHG emissions and price of shelters for the same project and same area it is possible to analyse which design decisions have enabled better carbon economy.

How then could the carbon economy of shelters be optimised? Sometimes costs accumulate due to logistic reasons or price peaks can be caused by the suddenly increased demand for construction materials in the area of operation. Because price fluctuations are mostly beyond the control of humanitarian operators, it is therefore easier to focus on lowering the carbon footprint of shelters. This calls for preparedness planning, as explained in chapter 5.1.

Looking at the steel-framed shelters in Haiti (no. 6) and in Aceh (no. 7), the choice of frame material may have been due to securing the structural performance in areas that have termites causing damage to bio-based construction materials. For this reason, a steel frame is a logical alternative. However, in both cases wood

Table 5.3. Sources for the values required for the calculation of carbon efficiency and carbon economy in humanitarian use.

Indicator	Source
C	The results of carbon footprint calculation that is based on a bill of quantities (for buildings) and/or calculation with the ICE V2.0 database: the dry weight of each material *x* embodied carbon value of material.
E	The results of building energy simulation or a building´s energy certificate (where applicable).
λ	The material's constant value from open-source material guides (e.g. www.engineeringtoolbox.com).
$€_B$ and $€_P$	Price from quotation.

Table 5.4. The carbon economy of eight transitional shelters by the IFRC.

	C	E	€	C x E x €
	Carbon footprint	Oper. energy use	Material costs	Carbon economy
	$kgCO_2e/m^2$	kWh/m^2a	USD/m^2	
Shelter 1	11.31	1	11.69	132.21
Shelter 2	24.45	1	21.82	533.40
Shelter 3	72.01	1	31.18	2 245.27
Shelter 4	42.28	1	N/A	-
Shelter 5	22.90	1	14.03	321.36
Shelter 6	117.89	1	106	12 496.08
Shelter 7	93.79	1	213.92	20 063.86
Shelter 8	109.14	1	N/A	-

has been used for floorings and claddings, in other words, for non-structural parts. Therefore one could argue that a wood frame with preservatives could also have been used instead of steel in the primary or secondary frame. This would have lowered the emissions considerably and resulted in the much better carbon economy of the project.

5.4 Summary

The evaluation of the carbon footprint in a humanitarian context requires a high degree of case sensitivity. Therefore it is neither relevant nor possible to set fixed values for transitional shelters or reconstruction projects. Instead, a country-specific approach is required.

The system boundary for assessing humanitarian construction should include the production phase in minimum. However, impacts associated to transportation, recycling and waste management should not be forgotten in projects where large numbers of temporary shelters are provided.

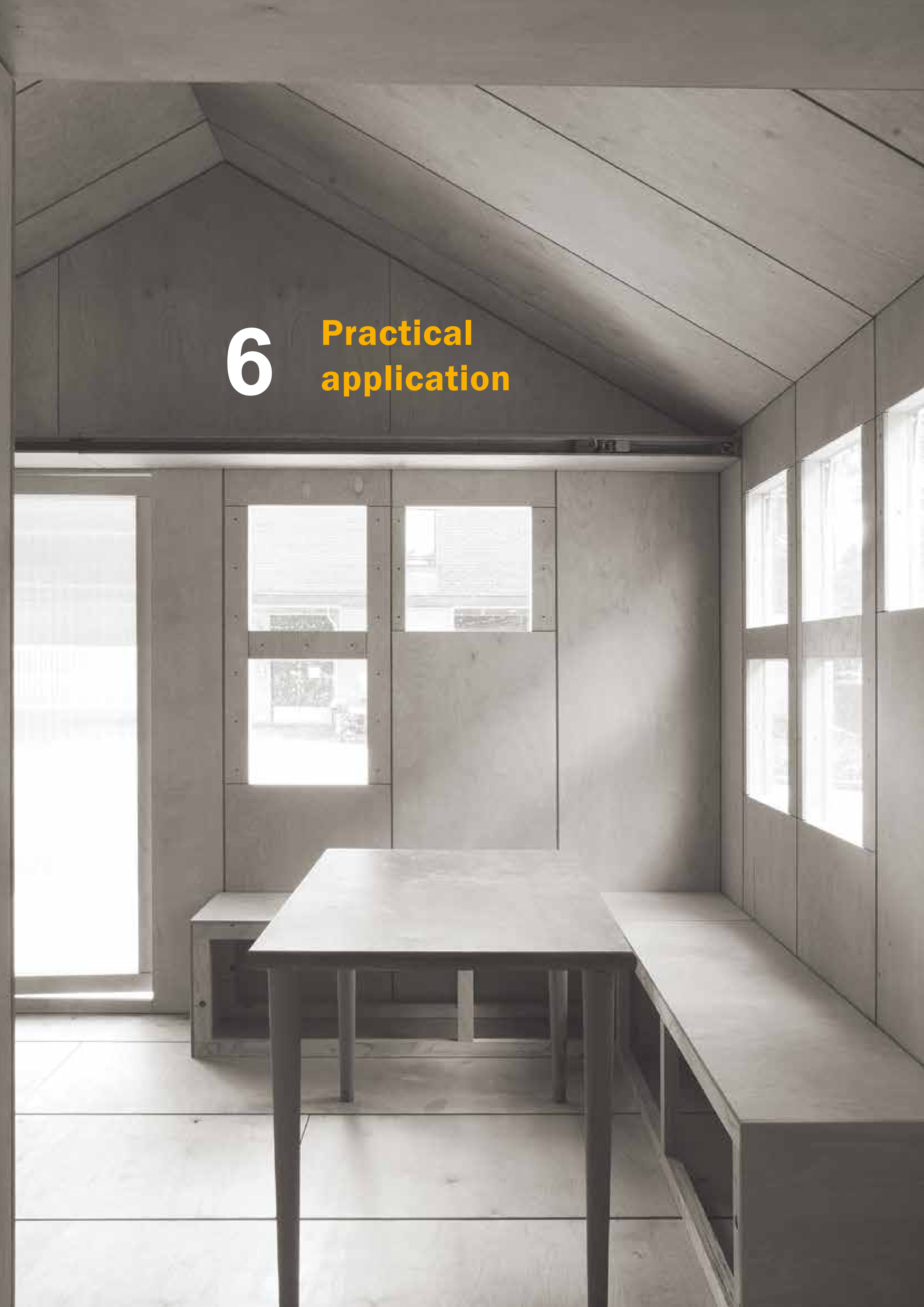
The benchmark carbon footprint values for each country can be obtained by utilizing per capita GHG emission statistics. From them the construction sector specific target values for, for example, a shelter for one household can be derived. With these values it is possible to set targets for the mitigation of the GHG emissions that arise from the humanitarian construction project. This top-down approach to reference carbon footprint levels enables the management of emissions with internationally available open-source data that is constantly updated.

However, the focus should not become too narrow. Instead of only looking at the carbon footprint, each project should be evaluated in comparison of its impacts on GHG emissions, energy and costs. This is made possible by calculation of carbon efficiency and carbon economy. By utilizing available data in a bottom-up approach, the project team can find an optimal solution for their need. This is valuable, especially in the procurement phase when the quotations are compared and awarded.

Part 2

Practice

6 Practical application



6.1 How to adopt LCA into humanitarian construction?

6.1.1 A practical project model is needed

The per capita carbon footprint method provides LCA assessors with a reference level for setting emission criteria. The carbon efficiency and carbon economy approaches offer flexible method for the optimisation of emissions, energy and costs. Still, neither of them gives practical advice or recommendations for bypassing the known complexities of building-level LCA in a humanitarian context.

Relevant application areas include strategic decision making, project planning (also funding and communications), the operative project phase (including the typical phases of a construction project according to RIBA 2013), the use phase, decommissioning, evaluation and documentation.

This chapter presents practical suggestions on how to integrate a streamlined LCA-based carbon footprinting into humanitarian construction projects. For this purpose the chapter is built around a fictional humanitarian construction project. It shows the integration of carbon footprinting into design work, setting emission targets with the per capita method and optimising performance with carbon efficiency and carbon economy. Furthermore, a role-based matrix of action for carbon-efficient humanitarian construction is presented at the end of the chapter.

Every humanitarian construction project has its own character and there is probably no project model that would perfectly match every case. However, the model presented in this chapter is general in its approach and applicable for the majority of needs.

The aim of the carbon-efficient project model is to form a clear frame of reference for those humanitarian projects in which the mitigation of GHG emissions is chosen as important. It is applicable for both transitional and reconstruction phases. The model is further developed from the previous models of the author which are aimed at defining roles and responsibilities in building sustainable humanitarian schools (Kuittinen & Kaipainen, 2013) and mitigating embodied GHG emissions in the design phase of buildings (Kuittinen & Häkkinen, 2013; Häkkinen et al., 2015). The model is illustrated in table 6.1.

6.1.2 The use of the project model exemplified with the help of hypothetic projects

To exemplify the use of the project model, two hypothetic cases are presented. They show how carbon efficiency could be taken into practice, if a transitional shelter or reconstruction project were to begin in Syria.

The first example is a transitional shelter project and the second example shows the application in reconstruction of homes. With the help of these cases, the carbon-efficient project model presented in table 6.1 is exemplified by observing how each of its milestones could be met in such projects. The milestones, corresponding tasks, background data and outcomes are presented in table 6.1.

Depending on the case, there may be recent information about the household sizes in the country statistics and reports of humanitarian organisations, such as the International Organization for Migration (IOM) or UNHCR. In such a case this data should be used instead of general statistics.

6.2 Introducing the carbon-efficient humanitarian construction project model

6.2.1 Strategic planning

The phase of strategic planning often starts with needs assessment or a base line study. After participation in the humanitarian operation has been decided and funding potential mapped, the first milestone for carbon efficiency is found in the project preparation stage (1.3). It includes defining the reference carbon footprint level for construction in the country, which is very important for setting the performance criteria further in the project. This data is retrievable from open online sources. If any areal plans are drawn, the land-use related decisions and assessments should be taken on in the strategic planning stage.

Example 1 (table 6.1) shows how the average per capita GHG emissions of Syria are calculated per household. The same figure can be used for both the transitional shelter and reconstruction phases. However, the environmental goals are likely to be more ambitious in the reconstruction work. To provide both project types with relevant goals, a project-specific GHG peak figure is assigned in milestone 2.

6.2.2 The design stage

The design stage of transitional shelters or a reconstruction project differ from each other. Still, the same steps for ensuring carbon efficiency can be taken. Milestone 2 requires the project manager and other relevant stakeholders to make a value-based decision on how much the per capita GHG emissions can be exceeded in the transitional or reconstruction phases. This goal should take into account the practical realities and the overall priorities. The proposed design interventions are an addition to the typical design process that was used in the studied humanitarian construction projects.

After the allowed GHG peak has been defined, an important task is to study how available technical alternatives meet the goal.

Table 6.1. Carbon efficient project model for transitional shelters and reconstruction.

Stages			Objectives	Deliverables	*Ensuring carbon efficiency* Milestones	Responsibility: Project manager	Building designer	Local authority	Environ. consultant	Further information
1 Strategic planning	1.1	Needs assessment	Identify construction needs	Needs assessment report	Identify the potential of carbon efficiency in the project	●		○	○	
	1.2	Project proposal	Ensure mandate, prepare budget and funding scheme	Project plan	Include carbon efficiency as quality criteria	●	○		○	
	1.3	Project preparation	Establish project team, identify partners, appeal for funding	Funding applications, MOU´s and personnel contracts	**M1:** Define reference CO_2 level for construction from national per capita GHG values	●			○	Annex 5
2 Design	2.1	Concept design	Develop alternative designs	Sketch drawings, preliminary bills of quantities	**M2:** Set the maximum allowed GHG peak for selected lifecycle stages	●		●	○	Section 5.2
	2.2	Technical design	Prepare final design that meets local norms	Building drawings, bill of quantities, construction specifications	Investigate structural and material alternatives and compare their impacts to carbon footprint		●		○	Annexes 1-3
					M3: Calculate GHG peak for the selected final design	●	○		●	Section 5.2
3 Construction	3.1	Procurement	Issue tender	Request for price	Request price specifically for the low-carbon solution chosen in stage 2.2	●	○			
			Compare quotations	Report if required	**M4:** Compare carbon economy of quotations	●	●		●	Section 5.3
			Select suppliers	Contracts	Add GHG peak and its monitoring into the contract of main constructor	●		○		
	3.2	Construction work	Constructing the building(s) as designed	Site reports	Monitor that materials are not replaced with alternatives that have higher GHG emissions	●	○	○		
	3.3	Handover	Handover to end-users	Maintenance manual (for permanent buildings)	Instruct for maintenance and repairs with carbon economic materials	●	○			
4 Use			Inspection report and impact assessment if agreed		Consultation of carbon efficiency and economy in case of repairs or renovations	○	○	○	○	
5 End-of-life	5.1	Deconstruction	Deconstruction plan	Decommissioning plan with links to next construction stages or waste management	Ensure that organic materials are not landfilled for the prevention of methane leakages; monitor that toxic or harmful materials are properly treated	●	○	○	○	
			Deconstruction work	Agreement with contractor						
	5.2	Site restauration	Prepare plans for restauration	Restoration plan	**M5:** Create carbon sinks by planting woody vegetation or using concrete for landfills	●	○			Annex 2
	5.3	Recycling	Reuse or upcycle as much of the materials as feasible	Recycling plan, contracts, required permissions	Estimate the climate benefits or drawbacks for the use of recycled materials in construction	○			○	Annex 2

● Leading role

○ Participation

	Example 1: Transitional shelters in Syria	*Example 2: Reconstruction of homes in Syria*
Strategic planning **1**	Syrian per capita GHG value for the construction sector from the World Bank: 0.27 $tnCO_2e$ /capita ↓ Average Syrian household size from UNHCR: 6.3 persons ↓ Construction-related GHG per household in Syria: 0.27 x 6.3 = 1.70 $tnCO_2e$ / household	
Design **2**	Exemplary decision: **+50%** → 1.70 $tnCO_2e$ x 1.50 = **2.55 $tnCO_2e$ /shelter** Alternative A: **xx $tnCO_2e$/shelter** Alternative B: **yy $tnCO_2e$/shelter** Alternative n: **zz $tnCO_2e$/shelter** ↓ Embodied GHG emissions: **xxx $tnCO_2e$/shelter**	Exemplary decision: **+30%** → 1.70 $tnCO_2e$ x 1.30 = **2.21 $tnCO_2e$ /home** Estimate GHG emissions for each design alternative Simulate GHG emissions from operative energy use for each design ↓ Embodied & operative GHG emissions: **yyy $tnCO_2e$/home**
Construction **3**	**Company A** (X $tnCO_2e/m^2$) x (X EUR) = $(\text{Carbon efficiency})_A$ **Company B** (Y $tnCO_2e/m^2$) x (Y EUR) = $(\text{Carbon efficiency})_B$ **Company n** (Z $tnCO_2e/m^2$) x (Z EUR) = $(\text{Carbon efficiency})_n$ ↓	**Company A** (X $tnCO_2e/m^2$) x (X EUR) = $(\text{Carbon efficiency})_A$ **Company B** (Y $tnCO_2e/m^2$) x (Y EUR) = $(\text{Carbon efficiency})_B$ **Company n** (Z $tnCO_2e/m^2$) x (Z EUR) = $(\text{Carbon efficiency})_n$ ↓

Contract: "The maximum allowed GHG peak is ..."

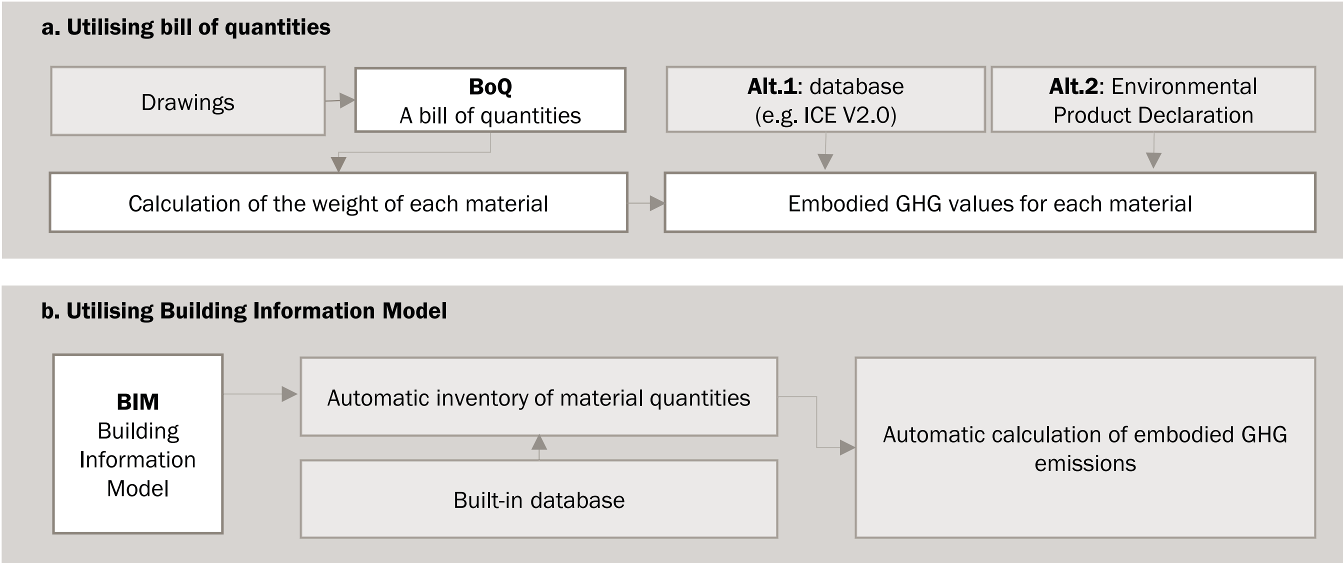


Figure 6.1. Alternative paths for estimating the embodied GHG emissions of humanitarian buildings.

This forms milestone 3 in table 6.1. The recommendations for the system boundary of this study are given in section 5.1.

For shelter projects it may be ambitious enough to estimate the GHG emissions from the production of the building materials. Manufacturers or designers should therefore provide the evaluator with bills of quantities. As shelter projects are usually not single buildings but settlements of even hundreds of shelters, this labour is not too demanding in the comparison of offered solutions. In transitional construction projects the third milestone would require the availability of EPDs or other environmental reports if entire shelter kits are purchased. If such are not available, a rough comparison of alternatives may be done based on the findings of chapter 4.

For permanent construction the ambition level in the design phase should be higher. In addition to estimating the emissions from the production of construction materials, a simple energy simulation should be carried out. This is essential for understanding the trade-offs: more building materials in the wall may lead to a larger carbon footprint in the manufacturing phase but save energy in the use phase and thus become a feasible option. In reconstruction projects the design work should ideally be done with the BIM and building energy model (BEM) that enable the designer to observe constantly how changes affect the accumulation of embodied and operative GHGs without having to master the finesses of environmental assessment. The alternative paths for this estimation are described in section 6.3.

As the projects proceed, the designer or manufacturer of shelters or buildings can reach milestone 3 by estimating the actual emissions from the finished design.

6.2.3 The construction stage

Procurement, construction work and handover are here integrated into the “construction stage”. Great potential for mitigations of GHG emissions lies in the procurement phase.

Milestone 4 includes comparison of the carbon economy of offered solutions based on the example given in subsection 5.3.3. This can be done in both transitional and reconstruction projects. However, for purchased transitional shelter kits the prerequisite is the availability of an EPD or other documentation of the environmental impacts of the shelter. Alternatively, a simplified LCA can be carried out for the chosen shelter models utilising the system boundary presented in section 5.1. In large-scale shelter projects these steps for ensuring environmental accountability should not be ignored as the environmental impacts of shelter projects may be significant.

If the project is following the EU´s procurement directive (European Parliament, 2014), its paragraph 61 may be used to justify the awarding of contracts in a manner that would not give conditions for justified legal complaints.

During the construction work the need to alter plans may arise (stage 3.2). In such a case the carbon efficiency and economy of the project should be ensured. This may be done by adding clauses to the constructor´s contract that allow changes to materials, products or processes only if they do not threaten carbon economy (e.g. a 10% overshoot may be set as maximum limit and reliable documentation requirements added) or can be compensated in other parts of the project.

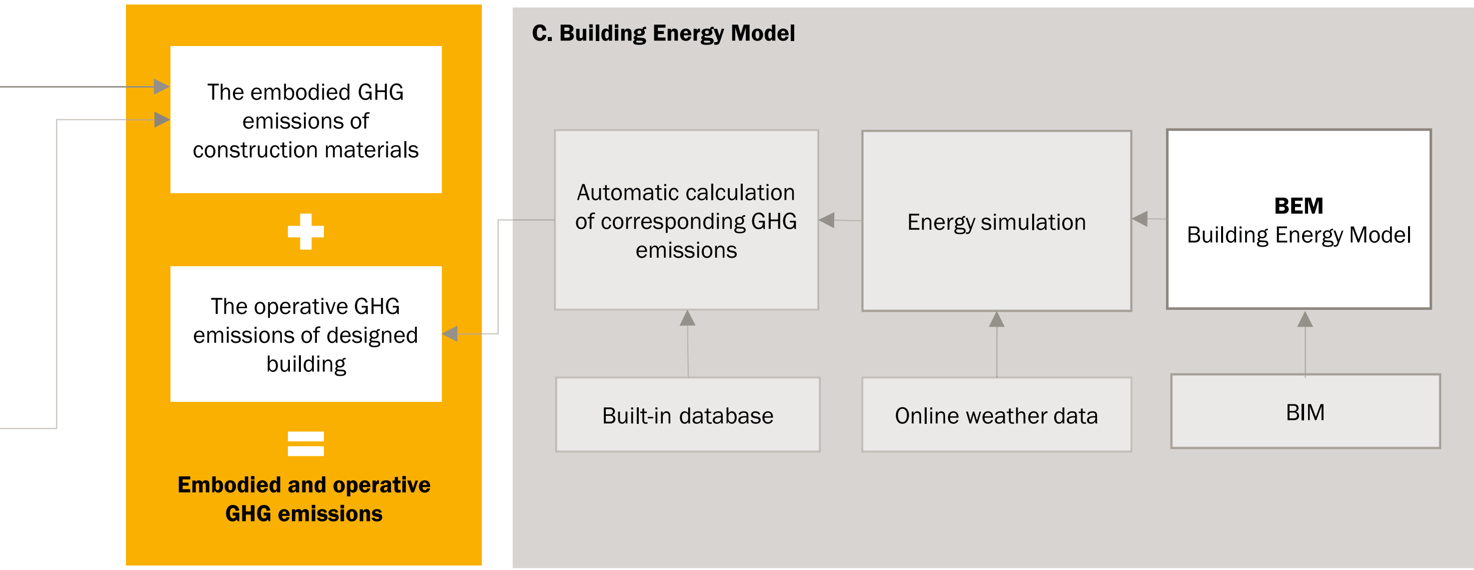
The handover of buildings (stage 3.3), especially in reconstruction projects, is important in order to ensure the operative carbon efficiency of the project. End-users should be given clear instructions (e.g. a maintenance manual) on how to operate and repair the building.

6.2.4 The use stage

Using the shelter or building does not usually require the intervention of the project team apart from agreed quality inspections. These inspections may include observing, for example, operative energy use and giving consultation if the realised GHG values appear higher than planned.

6.2.5 End-of-life

Especially for transitional shelter projects, the end-of-life phase is important as it happens usually within few years’ timeframe. In addition to the environmental care that is related



to all deconstruction and waste management work, there are possibilities in restoring the site (e.g. the refugee camp) into a carbon sink. This may be done by utilising the potential of ecosystem services for capturing atmospheric carbon in growing plants and soil (Davies, et al., 2011; Edmondson et al., 2012; Edmondson et al., 2013).

Although this fifth milestone may appear insignificant at first, in practice it offers a possibility for compensating emissions from the production of materials. Depending on the case, the impact of this compensation may be significant and reach up to 10% of the emissions of a building's life cycle (Kuittinen et al., 2016). Also, as described in section 4.3 and annex 2, concrete rubble can be used in landfills and embankments to form a carbon sink through the open-air carbonation of cement.

If materials are reused or recycled, the environmental impacts may be estimated. Section 4.3 and annex 2 give an example of the impacts of recycling concrete for reconstruction. If organic materials are not reused, they may be burnt for bioenergy to substitute more environmentally harmful energy carriers.

6.3 The design environment for carbon-efficient humanitarian buildings

Iteration of the embodied and operative GHGs during design work has until recently required considerably more time and expertise than the conventional design process. In humanitarian projects' time is usually scarce and therefore conducting over-sophisticated environmental calculations is not relevant.

The designer may choose alternative paths for evaluating the embodied GHG emissions in the design stage. The emission can be calculated with a spreadsheet tool using the material quantities from the bill of quantities and multiplying them with material-specific embodied GHG values retrieved from a database or an EPD (path A in figure 6.1). An automated path (path B in figure 6.1) is built on the BIM that automatically lists material quantities and provides constant evaluation of their embodied emissions, energy or costs according to the embedded data sets.

The automated carbon footprinting process is faster if the design is carried out with BIM software. For simple shelters this may still be unrealistic. Instead, their bills of quantities (BoQs) may be used for calculating the emissions with the spreadsheet tool.

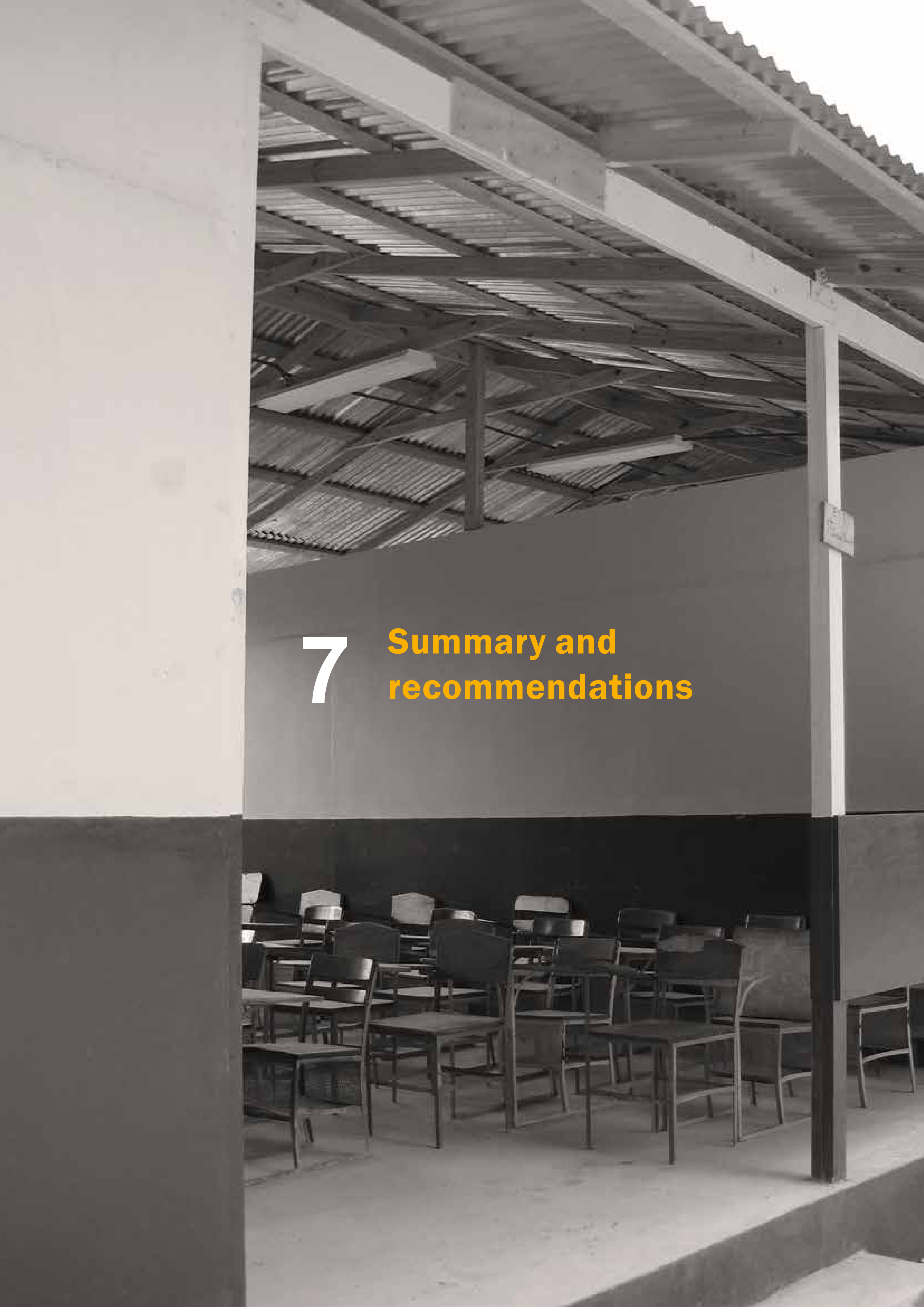
If a BIM is used, there are other advantages as well. The model can be further developed into a BEM that gives simulated information about the operative energy use and related emissions during the use of the building (path C in figure 6.1).

The BIM/BEM working environment is evolving rapidly. Already today the estimation of embodied and operative GHG emissions is included in mainstream BIM tools, such as ArchiCAD (Graphisoft, 2015). Humanitarian designers should take advantage of this development.

6.4 Summary

Carbon footprinting in humanitarian construction requires agile and simplified processes. Management of carbon efficiency and carbon economy can be carried out with the help of a carbon-efficient project model. Its key milestones include the definition of a carbon footprint reference level for the project that is based on national per capita GHG values, iterative estimation of the embodied and operative GHG emissions from alternative design solutions, evaluation of carbon economy in the procurement phase by cross-comparing quotations and the carbon footprint of the offered solutions, and finally creating carbon sinks via site restoration after the decommissioning phase of the project.

These steps do not require using the complicated methods of LCA. They can be carried out with the help of open-source data and the available, mainstream BIM tools of architectural design. Especially in reconstruction projects, carbon efficiency is more a question of attitude and less a question of capacity.



7 Summary and recommendations

7.1 Summary and recommendations

What is the role of climate change in humanitarian crises and how is its mitigation considered in humanitarian construction?

Climate change is a key driver of humanitarian crises. It has several direct and indirect impacts that cause disasters and forced migration. Changing climate especially reinforces extreme weather events. As urbanization continues, the vulnerability of human settlements increases. The main drivers of climate change are the anthropogenic GHGs. Even if emissions were cut today, their warming potential will cause the climate to continue warming for decades or centuries. *Section 1.1.*

The mitigation of climate change is almost excluded in the environmental guidelines for humanitarian construction. There are a number of guidelines and environmental hazard mapping tools or impact assessment tools. Only very few of them give guidance on the mitigation of climate change. Humanitarian scientific literature, in contrast to the academic literature of the conventional construction sector, also lacks studies on the subject. *Section 1.5.*

How can the methods developed for the carbon footprinting of conventional buildings be applied and developed for a humanitarian context?

Life cycle assessment is a comprehensive but too complicated method for assessing the carbon footprint in humanitarian construction. LCA offers well-defined science-based methodology for environmental assessment. Its labour-intensity makes it seldom used in conventional construction projects, let alone in the humanitarian sector. Reconstruction projects in developed countries are a potential exception to this conclusion. *Chapter 3.*

Life cycle assessment in the humanitarian context suffers from the poor quality of reference data. A number of databases exist for the environmental impacts of the production of construction materials in developed countries. Their applicability in humanitarian construction is very uncertain. The collection of data from industrial production in developing countries could be integrated into development programmes. *Subsection 4.6.5.*

Green public procurement is a promising scheme for ensuring the implementation of sustainability in humanitarian construction. Procurement criteria should be based on the international standards of sustainable construction. Such criteria may ease the awarding of quotations and clarify the requirements for suppliers. For European procurers the revised procurement directive gives solid support for awarding the environmentally best offer. *Subsection 1.5.5.*

Carbon footprinting in humanitarian construction should include the production phase but the considerations of transportation and waste management should not be forgotten. Based on the case studies it can be concluded that structures and coverings seem to cause most of the emissions. However, in cold climates the heating of transitional shelters should also be included in environmental assessments. For emergency and transitional shelters it is recommendable to also estimate the impacts from recycling and waste management, as the waste management infrastructure in the operative area may be damaged or less developed. *Section 5.1.*

Per capita GHG emissions are a useful point of reference for setting carbon footprint criteria. Regularly updated and monitored national GHG emission statistics enable the carbon footprint criteria setting to be adjusted to the local context. Thus it becomes possible to lower national building-related emissions in line with global commitments to the mitigation of climate change. *Section 5.2.*

The overall sustainability of humanitarian construction can be optimized by cross-comparing the carbon footprint, energy demand and costs. This comparison increases flexibility, as it is not always possible to choose the best option. The observation of carbon efficiency and carbon economy gives an understanding of which solutions meet a wider range of the targets of environmental and economic sustainability. *Section 5..*

Carbon footprint calculations can be performed with the help of Building Information Models. Both embodied and operative GHG emissions can be estimated with widely used, commercially available CAD software. All the required background information for the calculation of the carbon footprint, carbon efficiency, carbon economy or national GHG peaks for the project are available using open-source databases. *Chapter 6.*

How large are the carbon footprint and primary energy demand in the selected humanitarian construction projects?

Due to the short service life of transitional shelters, their construction materials are essential for the mitigation of GHG emissions. Bio-based materials, wood and bamboo were found to yield a considerably lower carbon footprint in their production phase. Steel frames, metal coverings and concrete foundations were found to cause large emissions. Of all the studied phases of the life cycle, the emissions from the production phase were found to dominate. Operative energy may also reach high values in cold climates. Emissions from the transportation of heavy construction materials were marginal compared to their production emissions. *Chapter 4.*

Table 7.1. Further research needs

Topic	Open questions
Life cycle inventory data for construction materials	What are the GHG emissions and primary energy demand of construction materials manufactured in developing countries? What is the share of manual work in the respective manufacturing sector?
The technical service life of structures in tropical conditions	How long will construction products endure in tropical climates? How should the seasonal storms and hurricanes be taken into account in technical service life predictions?
Energy mixes in developing countries	What are the energy mixes in developing countries? How does the energy mix change during typical humanitarian disasters, such as storms, floods, earthquakes, draughts or war?
The energy demand of a refugee camp	How much energy do the planned self-settled refugee camps consume per capita, per shelter or per m^2 in different climates? How is this energy produced? How is the energy use distributed in heating/cooling, cooking, domestic hot water use or other uses?
Recycling rates in developing countries	What are the recycling rates in developing countries for different materials or products? How much energy does the recycling require?
What are the collateral GHG emissions of humanitarian projects?	How much energy is used and what emissions are created in the needs assessment, planning, monitoring and evaluation phases of humanitarian projects? These phases may include the flights of several experts and stakeholders to the project area. What are the net emissions compared to funds used in humanitarian projects?
The role of local materials and methods	How can local construction materials and traditional methods be applied in humanitarian construction in order to mitigate emissions?
Factors for energy recovery and the recycling potential of materials	How can the specified materials and/or products be recycled in the area of construction? What may be the avoided environmental, economic and social impacts of doing so? How does this support local livelihoods?

Transitional shelter projects may cause very large emissions compared to national per capita GHG emissions. As large numbers of GHG intensive shelters are produced, their emissions may increase the national per capita GHG emissions by over 4000%. On the other hand, bio-based structural solutions do not cause any remarkable increase to the baseline level. *Section 5.2.*

Clustering shelters improves their energy efficiency considerably. If shelters are grouped into row houses or multi-storey units, their relative amount of external surfaces decreases. This gives clear advantages for energy efficiency in cold climates. Long shelter clusters have lower life cycle GHG emissions compared to multi-storey clusters. This is because additional storeys require more structural capacity and external staircases, which add to the carbon footprint of the project. *Section 4.4.*

The recycling of construction materials for reconstruction can cause larger or smaller GHG emissions in comparison to virgin materials. Reused or recycled materials offer the potential to replace virgin materials and avoid their production emissions. However, such materials, and especially reused materials, may require significant amounts of additional reinforcements if high functional requirements (e.g. structural safety) are aimed at. The environmental feasibility of recyclable material depends on the intended end use and context. *Section 4.3.*

How could the mitigation of the carbon footprint be put into practice in humanitarian construction?

Humanitarian construction projects should include clearly defined maximum GHG peaks. Setting these peaks can be done with the help of national per capita GHG emissions. The project manager should set the maximum levels in collaboration with national authorities and environmental consultants. In the future these levels should be taken into the core of the environmental accountability of humanitarian construction projects. *Sections 1.4 and 5.2.*

Encourage the use of bio-based construction materials. In addition to several studies from the conventional construction sector, the studies of this research indicate that wooden and bamboo buildings have a clearly lower carbon footprint and primary energy demand compared to those made of other materials. As long as renewable, bio-based materials are culturally suitable and sustainably sourced, they usually help to keep the GHG emissions to a minimum. In requests for prices that fall into the coverage of the EU´s procurement directive, the procurer is entitled to define freely the construction materials without the possibility for the supplier to draw a legal complaint. *Subsection 1.5.5, sections 4.2 and 4.4.*

Favour clustered shelters in cold regions. The energy efficiency of grouped shelters is better than single or semi-detached shelters. Especially if the energy infrastructure is damaged, energy-efficient winterized shelters may bring co-benefits to the mitigation of the emissions of the energy sector as well. *Section 4.4.*

Make goals for carbon efficiency and assign role-based responsibilities in the project preparation phase. The carbon-efficient project model gives humanitarian operators a frame of reference for managing the GHG impacts of humanitarian construction projects. The project model can be used in both transitional and reconstruction projects. It may be integrated into the quality assurance systems of the operators. *Chapter 6.*

Further research needs

There are several needs for further research, as concluded in this study. The main research needs and open questions are listed in table 7.1.

Sustainability belongs to all

Mankind is preparing to encounter one of its greatest eras of challenge: the mitigation of climate change while dealing with planetary boundaries, population growth, energy crises, mass migration and poverty. People all around the globe face the need to adapt to changing and extreme weather, and to the social and economic consequences of the climate change.

Changing course towards a sustainable future should begin in our homes. Their mental climate gives us the skills for communicating, collaborating and looking at our planet and its inhabitants. Their physical frame consumes much of the energy available to us and causes most of our GHG emissions. As there are more and more households, the impact of a single home cannot be neglected.

Temporary humanitarian construction is, unfortunately, stabilising its position as a permanent typology of building. The survivors of disasters – poor and vulnerable people groups in temporary homes – should also have the possibility to lead a sustainable life. It goes without saying that the basic needs have to be met first. However, when meeting these needs the beneficiaries should not be distanced from a climate-friendly life. Regarding shelter this means that while providing the survivors of humanitarian crises with shelters we should not cause further harm by accelerating climate change. This viewpoint may be adopted as a paradigm shift when shelters, slum upgrades, social housing or reconstruction projects are considered.

Sustainable living should be considered a basic human right. It should not be marginalised to the domain of the western elite in their zero energy villas nor forgotten in the romantic shadows of vernacular outdoor museums. We must start including sustainability in the increasing needs of humanitarian construction.

Photographs and illustrations

Pages 2 & 28	Pasi Aaltonen / Finn Church Aid
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Pages 46, 53 & 101	Julia Bilenko (3D renderings)
Pages 51 &117	Atsushi Takano (Onagawa shelters)
Page 68	Anne Kinnunen / Aalto University

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List of annexes

Annex 1. Kuittinen, M. and Winter, S. (2015) "Carbon footprint of transitional shelters". *International Journal of Disaster Risk Science* 6(3): 226–237.

Annex 2. Kuittinen, M. (2016) "Does the use of recycled concrete lower the carbon footprint in humanitarian construction?" *International Journal of Disaster Resilience in the Built Environment* (Forthcoming).

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Author's contribution

Annex 1

Author defined the research plan, collected data and performed calculations. The paper and its discussions were written by author with valuable input and comments from the co-author.

Annex 3

Author defined the research plan, collected data, performed site visits and carried out calculations. Valuable input from the co-author was received for Japanese translations, definition of materials and quantities and commenting the manuscript.

Annexes 2, 4 and 5

The research for these annexes was performed and the articles written by the author alone.

Annex 1

Carbon footprint of transitional shelters

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Carbon footprint of transitional shelters

Abstract

Extreme weather events, sea level rise, and political disputes linked to climate change are driving masses to leave their homes. Their transitional settlements should be produced in a manner that causes minimum greenhouse gas (GHG) emissions to prevent any further acceleration of climate change and the humanitarian crises it causes. This article presents a study of the carbon footprint and primary energy demand of the construction materials of eight different transitional shelters.

The lowest carbon footprints were found from shelter models made from bamboo or timber. The highest emissions were caused by shelters that have either a short service life or that are made from metal-intensive structures. The choice of cladding materials was surprisingly important. The findings were further compared to the overall impacts of each construction project, to national per capita GHG emissions, and to construction costs. Some shelter projects had notable total energy consumption even compared to the annual energy use of industrialized countries.

The study concludes that construction materials have an important impact on the carbon footprint of shelters. Comparisons should however be made only between similar functional units. Furthermore, benchmark values and more background data are urgently needed in order to give humanitarian nongovernmental organizations tools for lowering the carbon footprint of their construction operations.

Keywords

Carbon footprint, humanitarian construction, lifecycle assessment, primary energy.

1. Introduction

It is not common to carry out assessments of carbon footprint in the field of humanitarian construction. The following section includes viewpoints that explain the relevancy and timely importance of science-based environmental assessment in humanitarian work.

1.1 Are carbon footprint and energy efficiency relevant in humanitarian construction?

The primary objective of humanitarian aid is to save lives, alleviate suffering, and maintain human dignity. However, this noble task inevitably causes environmental impacts as a side effect. For instance, energy is needed to transport food or medicines. Greenhouse gas (GHG) emissions are caused when blankets or tents are manufactured with the help of fossil energy. These manmade GHG emissions are the main cause of ongoing climate change (IPCC, 2014). Global warming has links to loss of arctic sea ice (Stroeve et al., 2007), sea level rise (Hansen et al., 2013), changes in weather (UNISDR, 2012), and finally a growing number of refugees (Christian Aid, 2007). Extreme weather conditions seem to become more common and as many ecosystems, also human systems, are highly vulnerable to them (IPCC, 2014). Storms and cyclones cause losses of life and property. Droughts force people to find new areas for their livelihood and increase competition for scarce resources. Warming temperatures can cause diseases to spread further, as for example the habitat for mosquitoes carrying malaria is expanding. Therefore, it would be necessary to optimize the environmental impacts of humanitarian aid without jeopardizing the aid itself.

1.2 The importance of carbon footprinting

Carbon footprint (CF) can be understood as a “sum of greenhouse gas emissions and removals in a product system, expressed as CO_2 equivalent and based on life cycle assessment” (ISO, 2013, p. 1), although several definitions exist (Wiedmann and Minx, 2007). For practical reasons, the global warming potential (GWP) of various greenhouse gases (methane, nitrous oxide, hydro fluorocarbons, and so on) is usually converted into corresponding GWP of carbon dioxide and expressed as kilograms of carbon dioxide equivalents (kg CO_2e). The amount of CO_2 in the atmosphere has increased rapidly during the industrial era. The content of CO_2 in the atmosphere is now higher than ever during the existence of human kind on earth (Pagani et al., 2010). In only a couple of centuries, the atmospheric CO_2 has risen from 300 ppm to around 400 ppm (NOAA, 2014).

Mitigating the amount of CO_2 is important for several reasons: First, it is the most influential of all greenhouse gases because of its significant and increasing quantities (NOAA, 2014). Second, it stays in the atmosphere for long periods of time. Around 20% of an impulse of CO_2 emitted today would continue causing global warming even after 500 years (Hansen et al., 2013). Third, mankind still has the possibility to “turn down the heat,” by lowering GHG emissions from fossil-fuel use and land-use change, as repeatedly proposed by the World Bank (2012a, 2013).

After all, there is nobody else in this solar system to reduce GHG emissions on our behalf.

Humanitarian shelters can be made from several material combinations. A shelter made from steel, wood, bricks, straw, or plastic can fulfill the same minimum requirement that has been set for humanitarian work (The Sphere Project, 2012). But the emissions that are caused when these shelters have been manufactured may differ greatly.

1.3 Growing primary energy demand is causing more emissions

Primary energy (PE) is energy in nature that has not been transformed in any means. For example, oil, wood, sunlight, and wind are carriers of energy. When we try to take advantage of this natural primary energy, there are always losses in its efficiency. For example, production of solar electricity cannot generally yield more than 18% of the available primary solar energy (Repo et al., 2013, p. 950).

Different energy carriers enable different efficiencies of utilizing primary energy. Because of this, the energy efficiency can be expressed as primary energy efficiency. It describes how much of the available energy potential was actually utilized in the end-use.

Based on the statistics of International Energy Agency (IEA ,2012), the energy needs of our planet are largely satisfied by burning fossil fuels. In 2010, around 81% of the world's total primary energy was made using fossil fuels.

As fossil fuels are burned, they emit CO_2 into the atmosphere. Since this CO_2 originates from the Earth's crust and not from the natural circulation of carbon in forests, soil, and seas, it accelerates global warming. Thus, both primary energy use and carbon footprint are tightly linked to climate change.

Shelters can be made of materials that require very little primary energy for their production. Such materials help to mitigate the growth of the primary energy demand and the emissions that are caused along with it.

1.4 Focus on the construction sector

The construction sector is globally accountable for around 30% of GHG emissions and around 40% of primary energy use (UNEP 2009). Buildings are seen to hold the greatest estimated economic mitigation potential for reducing GHG emissions (IPCC, 2007). Only by measuring the amount of CO_2 emissions for construction products is one able to define how environmentally harmful the selected combination of materials within a building will be.

The assessment of the environmental sustainability of construction works is often based on international standards. The ISO 14040 standard suite (ISO, 2006) for lifecycle assessment (LCA) forms a basis for several further-developed standards. ISO 21930 (ISO, 2007) and EN 15804 (CEN, 2012) give guidelines for developing environmental product declarations for construction products. EN 15978 (CEN 2011) outlines rules for the sustainability assessment of construction work. Several voluntary green labeling schemes for buildings have also been developed. For example, LEED (USA, global), BREEAM (UK, global), HQE (France), DGNB (Germany), CASBEE (Japan), and GBL (China) all offer different approaches for assessing and communicating the environmental impacts of a building.

Several studies about the carbon footprint and primary energy demand of modern construction have been conducted. Gustavsson and Sathre (2011) summarized the steps essential in the lifecycle assessment of a building. Häkkinen (2012) and Häkkinen et al. (2015) developed reference values for sustainability and performance assessment of buildings. Ruuska et al. (2013) compared the environmental impacts of building materials. Guggemos and Horvath (2005) have studied the lifecycle aspects of alternative concrete and steel structures. The carbon footprint of several wood-framed buildings have been calculated and analyzed according to ISO and EN standards (Kuittinen et al., 2013). Environmental impacts on residential neighborhoods have also been analyzed in detail, by using, for example, economic input-output assessment methods (Heinonen et al., 2012).

Despite the great number of carbon footprint studies that have been performed and normative standards that have been developed, there is not adequate scientific information about the environmental impacts or GHG emissions of humanitarian construction. Therefore, this article presents the carbon footprint and primary energy demand analyses of eight transitional shelters. Needs for further methodological development and practical implementation are drawn as conclusions.

2. Methodology

The methods that were used for this study are presented in the following. Main approaches are based on lifecycle assessment, with focus on the production phase of construction materials.

2.1 Scope and goal

There were two aims for the study: (1) To assess greenhouse gas emissions and the primary energy demand of eight different shelter designs. (2) To investigate how suitable LCA-based carbon footprinting is in a humanitarian context. Humanitarian construction can be divided into three phases: emergency, transitional, and reconstruction. This study focuses on the transitional phase.

2.1.1 Covered lifecycle phases

In order to communicate which part of the buildings lifecycle is the most dominant in an environmental assessment, the lifecycle has been arranged (EN 15643-2:2011) into four main and 17 sub-modules as follows (Table 1).

Table 1. Lifecycle phases according to EN 15643 (included phases are coloured).

A	**Production**	Raw material supply	A1
		Transport to factory	A2
		Manufacturing	A3
	Construction	Transport to site	A4
		Construction work	A5
B	**Use**	Use	B1
		Maintenance	B2
		Repair	B3
		Replacement	B4
		Refurbishment	B5
		Operational energy use	B6
		Operational water use	B7
C	**End-of-life**	Deconstruction	C1
		Transport	C2
		Waste processing	C3
		Disposal	C4
D	**Additional**	Benefits and loads beyond system boundary	

The lifecycle assessment can be carried out for these entire stages — "cradle to grave"— or only for the construction materials of the building — "cradle to gate." In the latter, it is possible to include parts of other modules as well (EN 15978:2011).

The required information for calculating the environmental impacts for modules A1—A3 can usually be gathered from a bill of quantities of the designed building. All further modules require scenarios of construction methods, tools, technical service life, maintenance strategy, renovation, deconstruction methods, recycling options, and waste management with associated logistics and storing. Therefore, estimations for modules from A4 and A5 to C may be more prone to uncertainties, as it is not exactly possible to know how the building will, in practice, be maintained during its lifespan or what type of waste management options will be available thereafter. Drafting reliable scenarios for the lifecycle of the building is especially demanding in the context of humanitarian construction or developing countries. For instance, the service life of a transitional shelter is short when compared to conventional buildings, ranging from some months to some years in most cases. This causes different dominance of lifecycle modules and challenges traditional thinking of the order of their importance (Hafner et al., 2012). Furthermore, a war, tsunami, or earthquake may damage infrastructure so severely that reconstruction of waste management or energy infrastructure may take an entirely different direction than before the incident. As an example, the national energy mix in Japan changed considerably after the Great East Japan Earthquake and Tsunami, because nuclear power plants were idled and natural gas imported as a replacing source of energy (NPR, 2012). This gave the national energy mix a higher GHG intensity than before the disaster.

Drafting reliable scenarios for the lifecycle of a building requires professional LCA assessors, who are used to working with databases and setting scenarios. This article focuses only on the tasks of the humanitarian project team, and is therefore limited to module A1—A3 (cradle to gate).

Use-phase energy demand and end-of-life scenarios will be studied separately in the future. Efforts will be made to reconstruct reliable scenarios for the full lifecycle (modules A—C) and additional consequential benefits or drawbacks of selected shelters (module D).

2.1.2 Functional unit

Functional units are m^2 of living area and estimated service life. A functional unit helps to compare different objects of study. It describes the amount of emissions released per chosen unit. Otherwise, the results would not be comparable, because larger buildings would need more materials and thus cause more environmental loads. On the other hand, a building that lasts longer may, during its full lifecycle, cause less environmental impact than a building that is made from more environmentally friendly building materials but that can be used only for a shorter period of time.

2.1.3 Service life

Estimated service life was taken from the assumptions given in the case reports of the studied shelter designs. No further scenarios were developed. In reality, storms or floods may lead to shorter service lives of certain building parts. Similarly, reusing construction components in a downgraded function may give them longer service life than initially planned.

2.2 Inventory

Inventory is based on the bills of quantities provided by the International Federation of Red Cross and Red Crescent Societies (IFRC, 2011). Presumably the inventory may not be quite as accurate as required by LCA standards (ISO 14040 series), as it was not intended for making an LCA. It was not possible to assess individual shelters in detail, as that would have required travelling to locations across the globe to interview constructors.

2.3 Impact assessment

Because it was not possible to track back global warming potential and primary energy demand from the production of the particular construction materials in the studied shelters, reference values for construction materials from a database were used. The chosen database was the Inventory of Carbon and Energy (ICE 2.0) by the

University of Bath (2011). Despite its limitations — for instance, it excludes the carbon storage of wood material and does not have values for vernacular building materials (such as bamboo, coconut wood) — the ICE database is publicly available and could thus easily be accessed by the humanitarian consultants and organizations. Supplementary information for assessing the carbon footprint of bamboo was adapted from the LCA study of bamboo by Vogtländer (2011) and for the assessment of its embodied energy from Reiner et al. (2007).

The biogenic carbon storage of wood and other bio-based materials is an important topic to be included in this study. According to European standards (EN 16485:2014) (CEN, 2014), if wood originates from a sustainably managed forest, its biogenic component to global warming potential is negative. If wood is harvested from a forest for which sustainable management cannot be assumed, the products biogenic carbon balance over time is considered to be zero, but it adds to the global warming potential of the product (EN 16485:2014, 6.3.4.2) (CEN, 2014). In our study, it was not possible to investigate the origin of wood, bamboo, or coconut in the assessed shelters. Therefore, we have separately calculated both GWP scenarios for wooden and bamboo frames: sustainably sourced and non-sustainably sourced.

Carbon storage of wood and bio-based products helps to mitigate climate change. The atmospheric carbon stays locked in such material until it decays naturally or is burned for energy. However, in our study, we exclude the positive impact of carbon storage because according to standards (EN 16485:2014, 6.3.4.4.2) (CEN, 2014) the benefits of storing carbon in a product are shown in lifecycle module B1 as technical scenario information, and this module is outside the system boundary of our study.

It has to be pointed out that regardless of how norms guide us to communicate carbon storage, it is still an important phenomenon that helps to mitigate climate change and therefore should be kept in mind when considerations for the sustainability of construction materials are made.

2.4 Interpretation of results

Results were studied through comparing assessment findings.

1. The scales of total emissions of relief projects were compared to each other and to annual total energy use and carbon emissions of a cold industrialized country in northern Europe (Finland).
2. The GHG emissions of constructing transitional shelters were compared to national annual per capita GHG emissions.
3. The joint impact of GHG emissions and material costs (carbon economy) of shelters were compared.

Conventionally, LCA studies would include sensitivity analysis and normalization of results. They were not included in the scope of this article.

2.5 Uncertainties and limitations

There are a number of uncertainties in the study. Locating them was actually one of the goals of the assessment.

2.5.1 Quality of data

It seems to be very difficult, if not impossible, to get reliable environmental data about vernacular construction materials that are used in developing countries. Several bamboo species, coconut wood, and various local tree species are not typically listed in environmental databases. For this study, the following commercial or open source databases were checked: ICE 2.0, IBO, KBOB, Idemat 2010, and ecoinvent 2.2. Furthermore, consistent information about the density and dry mass calculations of these materials seems to be hard to find. Such values would be needed for the assessment of sequestered atmospheric carbon in the material.

Due to the lack of data, conservative assumptions were made. Primary energy and carbon footprint values for coconut and other local tree species were replaced with general soft wood values of ICE 2.0. Carbon storage was excluded from the study. The biogenic component to the global warming potential was calculated by using densities for wood-based materials from the ecoinvent 2.2 database.

The used database is compiled from the sources of developed countries and thus reflects the environmental impacts of production facilities and raw material acquisition in developed countries. Without a separate study, it cannot be known how great a difference there would be to the figures that would be gathered from industrial processes in developing countries. The level of manual work is supposedly higher, but the implementation of environmentally friendly manufacturing technologies is presumably lower. Therefore, in this study, it has been assumed that the positive environmental gains from manual work are offset by the emissions of less environmentally friendly industrial processes.

2.5.2 Accuracy of inventory

Due to practical reasons, it was not possible to travel and check the exact construction of each shelter type. Nor is there information about possible variation in the construction of similar shelter types. The great number of shelters built would indicate that there is likely a variance in detailing, materials, and even dimensioning of individual shelters. Thus, the inventory may not fully reflect an average shelter of each type.

The inventory and impact assessment were checked twice. Although reasonable effort has thus been made to ensure that no errors would distort the results, such may always occur in lifecycle assessment.

2.5.3 Exclusion of carbon storage, feedstock energy, and land-use change

Due to the previously explained reasons, both carbon storage and the embodied feedstock energy of wood were left out of the study. Had they been considered, the results would have been more favorable for wood and bamboo-based shelters.

On the other hand, the consequential effects of using wood from possibly non-sustainably managed forests were also left out. The consequential effects may have an impact in a wider system analysis. However, they should be taken into account regarding all materials, if a consequential LCA would be made in the future.

GHG emissions associated to direct or indirect land-use change have been left outside of this study. The required amount of data could not be gathered within this study. Furthermore, there is no commonly agreed scientific method for quantifying land-use related GHG emissions (Mattila et al., 2011).

3. Studied transitional shelters

The selected shelter models are all published by the International Federation of Red Cross and Red Crescent Societies (IFRC) in Transitional Shelters— 8 Designs (IFRC, 2011). All shelters have been built during the last 10 years in various parts of the world, many of them in great numbers. The materials of the shelters have been arranged into the following building part categories for this study:

- Foundation
- Main structure (load-bearing frame)
- Secondary structure (supporting frame for coverings)
- Coverings (external and internal claddings)
- Fixings (nails, screws, straps, etc.)

The shelter models differ from each other in many ways (Table 2). Their functional and structural design cannot be compared. However, they all fulfill the fundamental function of temporary housing. The main differences that affect the studied environmental impacts include:

- Living area
- Construction materials
- Estimated service life
- Cost of materials

GHG emissions and PE demand that are linked to the manufacturing of these building parts were estimated.

4. Results

Results from the assessment are presented in this section. We report carbon footprint calculations for two alternative material sourcing scenarios: sustainably sourced and non-sustainably sourced wood and bamboo. Also primary energy calculations are presented.

4.1 Carbon footprints differ according to chosen materials

The results are shown with two different functional units: m^2 of living area and estimated service life. In addition, two alternative scenarios are presented: base scenario without calculating the climate benefits of sustainably sourced wood and comparative scenario showing the positive impacts of sustainable forestry (SF).

Findings clearly show the dominant impact of coverings in nearly all shelters. A majority of the shelters had coverings made of steel or plastic, which both cause remarkable CO_2e emissions when compared to other assessed materials. This trend can be seen regardless of functional units (Fig. 1). Also, the negative impact of concrete foundations is shown in the results. Manufacturing of concrete generates considerable GHG emissions.

The most environmentally friendly shelter seems to be the Indonesian model Shelter no. 1. Its structures are mainly made from bamboo, which is renewable material. Although the GHG emissions of the used bamboo are based on adaptive simulations from other studies, as explained earlier, it can be assumed with reasonable certainty that the emissions are very low.

Also, timber-based shelters from Peru (Shelter no. 4 and 5) seem to perform well in GHG comparison. This is due to the low global warming potential of wood material. In their case, a majority of emissions come from concrete foundations. When considering the climate benefits of sequestered atmospheric carbon of sustainably sourced wood material, these shelters perform even better.

It has to be noted that although uncertainties can distort the results, the trend is likely to be even stronger if possible

Table 2 Information about the studied shelters

	Frame Material	Units Built	Year	Living Area (m^2)	Service Life (yrs.)	Set-up (days)	Set-up (persons)	Material cost[1] (USD)
Shelter 1, Indonesia, Java	Bamboo	430	2009	24	1–5	3–4	3–4	281
Shelter 2, Indonesia, Sumatra	Timber	7 000	2009	18	1	2	5	393
Shelter 3, Pakistan	Stone	10 000	2010	18	2	1	4	561
Shelter 4, Peru	Timber	2 020	2007	18	2	1	4	N/A
Shelter 5, Peru	Timber	3 000	2007	18	1	2	4	253
Shelter 6, Haiti	Steel	5 100	2010	18	2	2	N/A	1 908
Shelter 7, Indonesia, Aceh	Steel	20 000	2004	25	5	3	4	5 348
Shelter 8, Vietnam	Steel	215	2004	26	5	3	5	N/A

[1] *Prices have been converted from Swiss Franc (CHF) to US dollars (USD), rate 1 to 1.12237.*

replacements of coverings during the lifespan of the shelter would have been included in the study. It is likely that, especially in cyclone-prone areas, parts of the coverings would need to be replaced during the estimated service lives of the shelters.

A similar amplifying effect might also be caused, if the carbon storage capacity would have been taken into account. While trees and bamboos grow, they absorb CO_2 from the atmosphere. This biogenic carbon is stored in construction materials until it will be released back into the atmosphere in energy recovery (incineration) or natural decay. This inherent material property of wood and bamboo helps to mitigate climate change — assuming that it does not lead to deforestation due to illegal or un-sustainable forestry practices.

It is interesting to observe the impact of assuming sustainable forestry in the GWP of wooden frames. For example, the total GWP of the primary structures of Shelters 2, 4, and 5 turns negative.

4.2 Primary energy demand stays low if bio-based materials are used

The consumption of primary energy follows the same pattern as the carbon footprint. The major impact of coverings can again be clearly noticed, as well as the better performance of timber-based shelters (Fig. 2).

The best of the shelter solutions seems to be Indonesian Shelter no. 1. It has a high amount of bamboo as construction material. Primary energy demand on bamboo — although there are uncertainties — is far smaller than for steel products, which add the energy demand for shelters in Haiti (no. 6), Aceh (no. 7), and Vietnam (no. 8).

The findings would be even more dramatic if the energy potential of wood, bamboo, and plastics would be taken into account. In the end of the life span of the shelters, their bio-based and oil-based materials could be recycled into energy by burning them. If this end-of-life benefit would have been taken into account, the share of steel-cladding caused primary energy use would have been even more dominant. However, burning wood or bamboo for energy results in biogenic GHG emissions that can be assumed carbon neutral if the materials originate from sustainable sources (EN 16485:2014) (CEN, 2014). Burning oil-based plastics causes fossil GHG emissions that are an additional burden to the natural carbon cycles of our planet.

It should also be mentioned that steel used in structures can be recycled into other uses after the shelter is no longer in use. Thus, the primary energy demand for making virgin steel products would be avoided, and environmental balance would be slightly milder for the share of steel and aluminum products (University of Bath, 2011). These benefits are however outside of our system boundary.

Most likely, all of the raw materials for shelters would not be manufactured in their use areas. Manufacturing energy demand would cause impacts only in the areas of manufacturing units. Depending on the energy mix of the factories, different environmental impacts are caused. For example, production of aluminum requires plenty of energy. That can be sourced, for example, from coal plants or wind turbines. They represent practically opposite ends in the greenhouse gas emissions required for producing 1 kWh of energy.

A full lifecycle approach would be needed to conclude the operative energy demand of the given shelters. Including heating energy demand would raise the impact of shelters that are located in a cool climate. Most likely, shelters from Pakistan and Peru would show more PE demand during their operational phase.

5. How should the results be understood?

The results describe the GHG emissions and PE demand from the production phase of the construction materials of the transitional shelters. The results show the dominance of cladding and roofing materials. But are the figures good or bad? Where can they be compared to? In the following, three alternative benchmarking approaches are presented: (1) Overall impacts of a project; (2) Per capita GHG emissions; and (3) Carbon economy.

5.1 Overall impacts of each shelter project

The total climate impacts of shelter projects were compared by multiplying the GHG emissions and PE demand by the number of shelters (Table 3). It has to be noted again that there are most likely differences in the material combination of shelters in large projects. Such variations have not been simulated in the study due to high uncertainties.

The finding is interesting: Although the largest number of shelters was built in Aceh, Indonesia (no. 7), the shelters from projects in Pakistan and Haiti still reach the same or higher level of emissions. From a project-level viewpoint (top-down approach) this shows that the number of units built is not necessarily linearly related to their environmental impacts. Some construction material choices, as explained earlier, seem to cause significant emissions even in smaller projects.

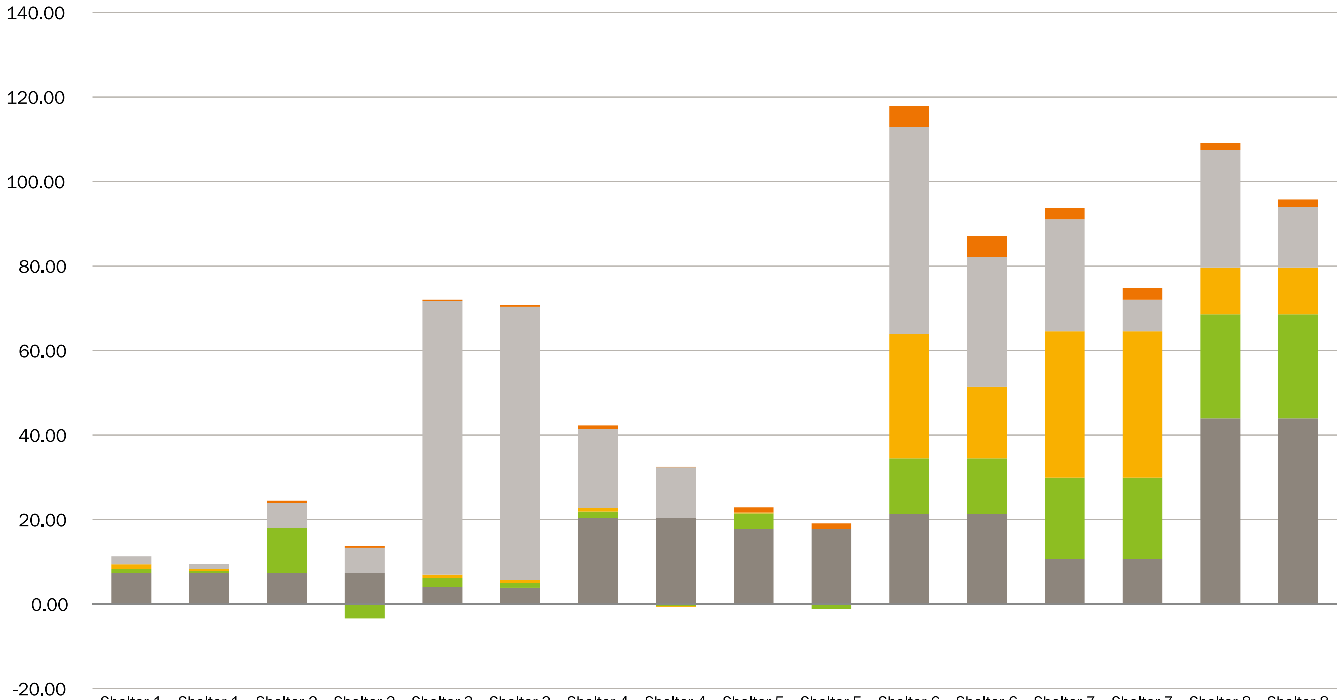
From an energy viewpoint, the findings are slightly different. Although the most environmentally harmful shelter models are the same, their order changes. This is explained by the higher amount of steel and aluminum used in Aceh and Haiti compared to the Pakistani shelters.

To understand the magnitude of GHG and PE impacts of individual projects, their total emissions and energy use were compared to corresponding annual statistic data of a European country, in this case Finland (Statistics Finland, 2013, 2014). As a result, it was found that the GHG emissions from the Pakistani shelter project (no. 3) were 0.026 % of all annual GHG emissions in Finland in 2013 (excluding emissions related to land use, land-use change, and forestry), and the PE demand for the manufacturing of the construction materials of the Aceh shelter project (no. 7) was 0.013 % of the annual energy used in Finland for the whole manufacturing sector during 2012. These can be considered as relatively high figures. The findings underline the environmental importance of choices that nongovernmental organizations (NGOs) make in humanitarian construction practices.

5.2 Per capita GHG emissions of shelters

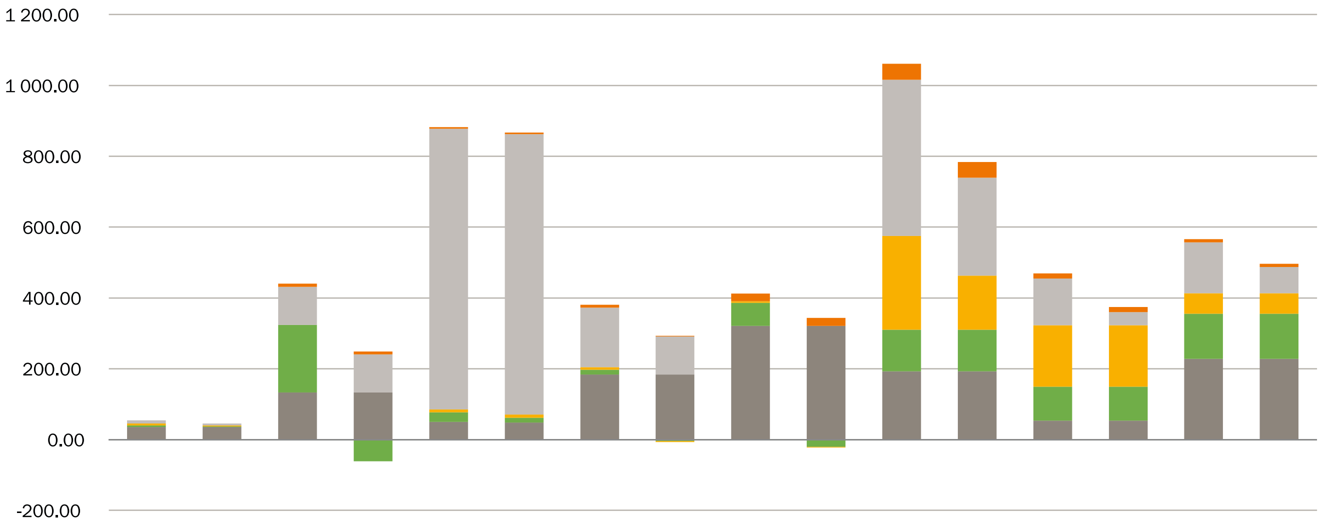
Global statistics are available on the per capita GHG emissions for each country. The World Bank (2012b), for instance, provides these statistics. Kuittinen (2015a) presented a method for setting benchmark levels for low carbon humanitarian construction: the emissions of humanitarian shelters are compared to the per capita GHG emissions of their countries. By applying this method, a context-sensitive benchmark may be found.

GHG emissions
kg CO_2e per m^2 of living area



	Shelter 1 Java	Shelter 1 SF	Shelter 2 Sumatra	Shelter 2 SF	Shelter 3 Pakistan	Shelter 3 SF	Shelter 4 Peru	Shelter 4 SF	Shelter 5 Peru	Shelter 5 SF	Shelter 6 Haiti	Shelter 6 SF	Shelter 7 Aceh	Shelter 7 SF	Shelter 8 Vietnam	Shelter 8 SF
Fixings	0.00	0.00	0.48	0.48	0.37	0.37	0.86	0.19	1.23	1.23	4.96	4.96	2.76	2.76	1.69	1.69
Coverings	1.93	1.13	5.98	5.98	64.67	64.67	18.71	11.99	0.00	0.00	49.05	30.71	26.50	7.49	27.80	14.38
Secondary structure	1.14	0.57	0.00	0.00	0.72	0.72	0.80	-0.26	0.23	-0.07	29.38	16.92	34.61	34.61	11.12	11.12
Main structure	0.86	0.43	10.61	-3.42	2.21	1.10	1.55	-0.50	3.59	-1.16	13.09	13.09	19.25	19.25	24.60	24.60
Foundations	7.37	7.37	7.38	7.38	4.05	3.91	20.36	20.36	17.85	17.85	21.40	21.40	10.67	10.67	43.93	43.93

GHG emissions
kg CO_2e per estimated service life



	Shelter 1 Java	Shelter 1 SF	Shelter 2 Sumatra	Shelter 2 SF	Shelter 3 Pakistan	Shelter 3 SF	Shelter 4 Peru	Shelter 4 SF	Shelter 5 Peru	Shelter 5 SF	Shelter 6 Haiti	Shelter 6 SF	Shelter 7 Aceh	Shelter 7 SF	Shelter 8 Vietnam	Shelter 8 SF
Fixings	0.00	0.00	8.67	8.67	4.55	4.55	7.74	1.70	22.20	22.20	44.68	44.68	13.82	13.82	8.78	8.78
Coverings	9.27	5.44	107.63	107.63	792.49	792.49	168.38	107.89	0.00	0.00	441.46	276.36	132.49	37.46	144.11	74.55
Secondary structure	5.47	2.74	0.00	0.00	8.78	8.78	7.21	-2.32	4.11	-1.32	264.40	152.26	173.06	173.06	57.65	57.65
Main structure	4.15	2.07	190.95	-61.49	27.08	13.54	13.92	-4.48	64.65	-20.82	117.84	117.84	96.25	96.25	127.53	127.53
Foundations	35.40	35.38	132.76	132.76	49.58	47.90	183.26	183.26	321.33	321.33	192.61	192.61	53.34	53.34	227.73	227.73

Figure 1. Greenhouse gas emissions of the studied shelters using two alternative functional units (m^2 and service life). Note the impact of comparative scenario (SF) that demonstrates the impact of using sustainably sourced wood material.

Table 3. Total GHG emissions and primary energy demand of selected projects

Shelter Type	Units Built	GHG Emissions (kg CO_2e)	Primary Energy Demand (MJ)
Shelter 3, Pakistan	10 000	17 649 645	227 686 209
Shelter 7, Indonesia, Aceh	20 000	12 310 813	176 777 158
Shelter 6, Haiti	5 000	11 277 850	125 300 971

The share of construction sector related emissions from the annual per capita GHG emissions was retrieved from the open-source data of the Shift Project Data Portal (2013). The resulting figure is then multiplied by the average national household size in order to get an estimation for the GHG emissions of an average family. Then, this "GHG per household" value was compared to the GHG emissions of the construction materials of the shelter. This way it was possible to see how the building of a transitional shelter added to the average annual GHG emissions of people living in each of the studied countries.

From Table 4, it can be seen that some of the shelters made a significant addition to the per capita GHG emissions. The steel-framed and steel-covered shelter in Haiti (no. 6) especially shows remarkable addition to the average annual Haitian per capita GHG emissions. On the other hand, some shelters are made of materials that hardly add to the per capita figure at all — Indonesian bamboo and timber shelters are such examples. Because per capita GHG emissions vary significantly between countries, the values in Table 4 can only be compared with values from the same country.

5.3 Carbon economy of shelters

The source publication (IFRC, 2011) of this study gives prices for materials and project of each shelter. This opens a possibility to define carbon economy or the joint impact of GHG emissions and material costs of a building (Kuittinen, 2015b). Carbon economy of a shelter model can only be compared with other shelter models from the same area. This is because material costs are different in different countries and disaster response actions.

From Table 5 we can see that there are large absolute differences between the construction costs of each shelter. However, the ratio of GHG emissions and construction costs allows one to compare shelters that are carried out in the same area or project. The values in Table 5 are higher if the material production of the shelter emitted high amounts of GHG and lower if the emissions are low.

6. Conclusions and future work

Conclusions from the study are drawn in the following section. They include summaries about environmental assessment in humanitarian construction, construction material choices, comparison of different shelters, and benchmarking of carbon footprint.

6.1 Environmental assessment in humanitarian construction is important

The results show that there are significant differences in the carbon footprint and PE demand of individual shelters and shelter projects. The comparisons to national per capita GHG emissions, construction costs, or to reference values from industrialized countries all indicate that there may be environmental gains available if action would be taken by humanitarian actors.

Therefore, the LCA-based environmental assessment processes should be further developed for the humanitarian context. Lack of relevant databases for LCA and scenarios for the full lifecycle of shelters especially casts a shadow of uncertainty over the carbon footprinting of shelters. Although results would have a higher degree of uncertainty in the beginning, there may be more benefits in adopting the LCA-based environmental assessment in humanitarian construction project planning and reporting.

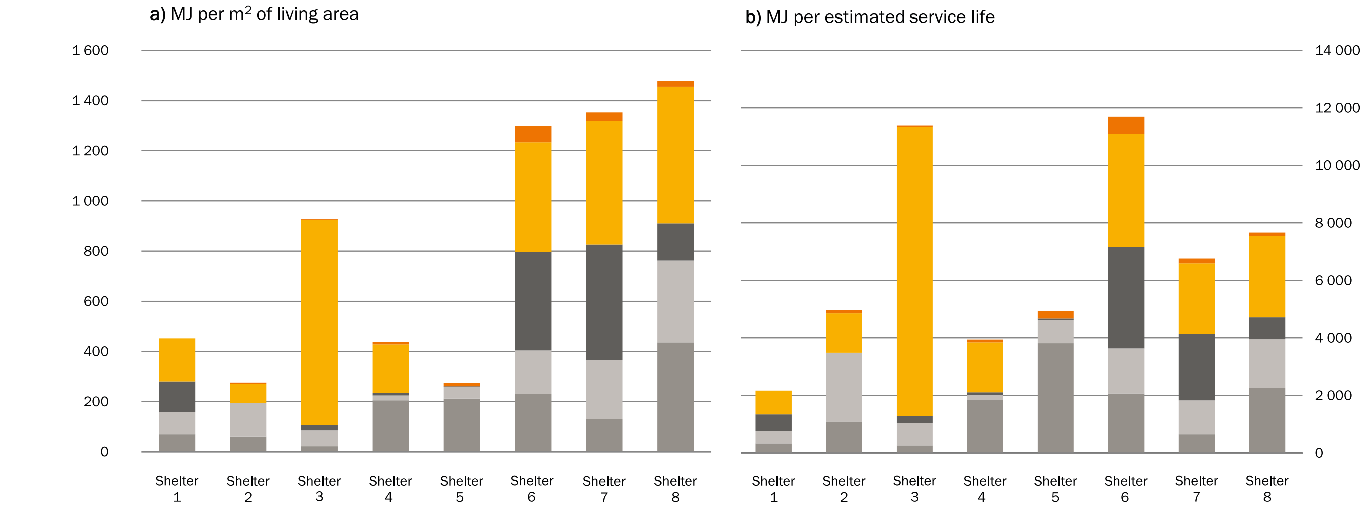
6.2 Materials make a difference

Results show that cladding materials of the studied shelters cause a significant amount of greenhouse gas emissions and primary energy demand. The only difference can be seen in wood and bamboo clad shelters. The result is not surprising, because most shelters had a significant amount of metal components and metal claddings. As known, the manufacturing of metal products is energy intensive and thus causes more greenhouse gas emissions than the production of wood- or bamboo-based claddings. Still, the environmental dominance of claddings can be seen as a new finding.

Based on this study, it can be recommended that cladding materials especially need to be carefully selected. The findings in this study should not be used for judging one construction material better than the other. A wider consequential analysis would be needed, and still the results would likely be case-specific. The same structural and building physical performance can be achieved with various material combinations. As a general rule, however, it can be said that bio-based renewable construction materials are usually more environmentally friendly, as long as they are sustainably sourced.

Construction materials for shelters need to fulfill several functions: They need to be cost-efficient and easy to transport and assemble. Their service life in the climatic conditions of the shelter has to be adequate. They have to withstand possible storms and heavy ultraviolet radiation and temperature caused by the sun. Furthermore, shelter materials need to be recyclable or bio degradable without harmful emissions to land, water, or air.

In addition, the sourcing of wood material seems to be important for lowering the carbon footprint of shelters. If wood is sourced from sustainably managed forests, it has a negative biogenic component to the global warming potential. Therefore, selecting sustainably sourced timber can be recommended for low-carbon shelters, if transportation distances do not considerably change.



a) MJ per m² of living area	Shelter 1	Shelter 2	Shelter 3	Shelter 4	Shelter 5	Shelter 6	Shelter 7	Shelter 8
Fixings	0.00	5.90	3.67	10.57	14.70	65.98	33.86	22.52
Coverings	172.03	75.93	819.84	193.77	0.00	436.76	492.36	545.18
Secondary structure	119.72	0.00	20.47	10.05	2.87	392.64	459.95	147.78
Main structure	90.72	133.06	63.14	19.40	45.05	174.00	235.79	326.93
Foundations	69.02	60.80	21.83	204.49	212.17	229.59	130.68	435.42

b) MJ per estimated service life	Shelter 1	Shelter 2	Shelter 3	Shelter 4	Shelter 5	Shelter 6	Shelter 7	Shelter 8
Fixings	0.00	106.20	45.02	95.14	264.60	593.80	169.28	116.74
Coverings	825.75	1 366.78	10 047.1	1 743.91	0.00	3 930.85	2 461.78	2 826.23
Secondary structure	574.67	0.00	250.86	90.45	51.59	3 533.73	2 299.74	766.11
Main structure	435.45	2 395.01	773.80	174.64	810.87	1 565.96	1 178.95	1 694.80
Foundations	331.30	1 094.36	267.52	1 840.37	3 819.10	2 066.27	653.40	2 257.20

Figure 2. Primary energy demand per m² and service life. The impact of coverings is significant in most cases.

Table 4. GHG emissions per capita (kg CO_2e)

	a. GHG per Capita	b. Share of Construction Sector	c. Household Size	d. GHG per Household from Construction	e. GHG of Materials	f. Ratio e:d
	(national averages from statistics)			(a*b*c)	(for each shelter)	
Shelter 1, Indonesia, Java	1 800	13 %	4.50	1 053.00	271.44	26%
Shelter 2, Indonesia, Sumatra	1 800	13 %	4.50	1 053.00	440.01	42%
Shelter 3, Pakistan	900	14 %	6.41	807.66	1 719.89	213%
Shelter 4, Peru	2 000	16 %	4.10	1 312.00	776.53	59%
Shelter 5, Peru	2 000	16 %	4.10	1 312.00	434.49	33%
Shelter 6, Haiti	200	5 %	3.40	34.00	2 211.34	6 504%
Shelter 7, Indonesia, Aceh	1 800	13 %	4.50	1 053.00	615.54	58%
Shelter 8, Vietnam	1 700	13 %	3.80	839.80	2 872.94	342%

Table 5. The carbon economy of eight transitional shelters

	a. Material Costs (USD/m²)	b. GHG from Materials (kg CO_2e/m^2)	C. Carbon Economy a*b
Shelter 1, Indonesia, Java	11.69	11.31	132.21
Shelter 2, Indonesia, Sumatra	21.82	24.45	533.40
Shelter 3, Pakistan	31.18	72.01	2 245.27
Shelter 4, Peru	Not available	42.28	-
Shelter 5, Peru	14.03	22.90	321.36
Shelter 6, Haiti	106.00	117.89	12 496.08
Shelter 7, Indonesia, Aceh	213.92	93.79	20 063.86
Shelter 8, Vietnam	Not available	109.14	-

6.3 Comparisons should be made between functionally similar shelters

To get exactly comparable results, shelters should fulfill the same functional, technical, and economical requirements. The shelters in this study do not seem to be comparable in these aspects. However, a previous study of alternative construction materials for reconstruction of schools in Haiti showed the advantage of recycled construction materials in humanitarian construction.

As the development of shelter models continues, it would be recommendable to compare shelter models that fulfill the same technical requirements with different construction material combinations and choose the optimal solution. Cost estimation could be carried out in the same process.

6.4 Benchmarking is required

When the per capita GHG values or carbon economy of different shelters are evaluated, they can be placed in context. It would be advisable to compare either of these factors in larger humanitarian aid projects. Such comparisons may be especially suitable for the reconstruction phase and development projects where there are less time constraints.

Environmental impacts of construction materials for shelters need to be weighted in relation to their other benefits and drawbacks. However, given the high importance of climate change mitigation, the reduction of greenhouse gas emissions and primary energy demand should be taken into consideration in coming shelter projects — especially if the number of shelters is high.

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Annex 2

Does the use of recycled concrete lower the carbon footprint in humanitarian construction?

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Does the use of recycled concrete lower the carbon footprint in humanitarian construction?

Abstract

Are recycled construction materials more environmental than virgin materials? To estimate which alternative construction solution has the smallest carbon footprint, a survey was made for the school model used for the reconstruction programme in Haiti after the 2010 earthquake.

The carbon footprint was calculated using LCA methodology for five different concrete structure alternatives and five different cement mixes for the same design of a school building. In addition, the uptake of CO_2 through the carbonation of concrete during 50 years was calculated.

The carbon footprint of recycled materials can be either the best or worst option, depending on how the materials are used. The difference to using virgin materials is not big. This is mainly due to the lower structural performance of recycled materials, which needs to be compensated for by using additional reinforcements. Using cement mixes that have high amounts of substitutes for cement seems to lower the carbon footprint of structures considerably. The uptake of CO_2 in carbonation has potential but requires an optimal design and environment.

The findings give information for humanitarian project managers and designers on lowering the carbon footprint of their construction projects.

Keywords

Carbon footprint, recycling, concrete, cement, carbonation, earthquake, Haiti, reconstruction.

1. Introduction

1.1 Needs for reconstruction after the 2010 earthquake in Haiti

This study investigates the carbon footprint of the alternative structure types and materials used for the reconstruction of schools in Haiti.

The earthquake in Haiti on November 12th 2010 killed over 220 000, injured over 300 000 and left over one million Haitians homeless (Clermont, 2011). In addition, around 300 000 buildings were destroyed beyond repair (UNDP, 2012). In some areas, especially west of the capital Port-au-Prince, over 70% of buildings were damaged (UNITAR, 2010). In addition to earthquakes, Haiti is vulnerable to hurricanes. Its ability to recover from them is weaker than in neighbouring Cuba and the Dominican Republic because of a lower institutional capacity and educational level (Pichler and Striessnig, 2013).

The need for construction materials for emergency shelters was high immediately after the earthquake, whereas the need for permanent reconstruction materials developed gradually. The local construction industry was partly paralyzed because of losses in personnel, facilities, transport services and networks of subcontractors. Also, the ability to import construction materials was limited. The main airport was damaged and the remaining capacity was taken by high-priority humanitarian logistics. This turned attention to the use of unconventional and recycled construction materials.

1.2 Why should we recycle concrete?

In a humanitarian context, recyclable concrete is usually the result of buildings and structures that have been destroyed in either natural or man-made disasters. After mechanical destruction – for example, by an earthquake or an explosion – there are typically large amounts of broken concrete and less dismantled building elements that could be reused. UNDP estimated (2012) that after the disaster there was approximately 10 million cubic metres of concrete and brick rubble in Haiti. In the reconstruction work some of this material could be recycled for construction purposes.

The use of recycled materials in construction may have positive or negative environmental impacts. For example, the BRE presented (2007) a summary of life cycle assessment (LCA) studies for the use of recycled construction materials. They concluded that the use of recycled insulation, flooring or roofing materials may reduce the carbon footprint of the building, but the use of recycled content, for example in concrete paving blocks or dense concrete blocks, leads in some cases to higher emissions compared to using virgin materials because more cement may be needed. Braunschweig, Kytzia and Bischof (2011) discovered that the difference between the environmental impacts of using recycled or virgin concrete is small and that it depends on the end-use application. They found out that recycled concrete used for lower quality end-uses does not need additional cement to compensate for its lower quality and thus is environmentally sound, especially if compared to disposing of the concrete instead of recycling it.

There are several ways of either reusing or recycling concrete: reusing dismantled concrete building elements such as concrete blocks or entire floor slabs (Huuhka et al., 2015; Hradil et al., 2014), reusing concrete rubble in gabions or masonry for embankments for example (World Business Council for Sustainable Development, 2009) and reusing recycled crushed concrete as coarse or fine aggregate in new concrete (Etxeberria, Mari and Vázquez, 2007; World Business Council for Sustainable Development, 2009). Recycling concrete rubble into coarse aggregate for post-disaster reconstruction has also been studied with positive findings (Noggle and Glick, 2010; DesRoches, Kurtis and Gresham, 2011).

1.3 Emissions and uptake of CO_2 over the life cycle of concrete structures

Concrete is the second most used product on Earth (Low, 2005). Estimations of its share of global annual greenhouse gas (GHG) emissions vary from 4.5% (Boden, Marland and Andres, 2010) to 7% (Malhotra, 2010). Around half of these emissions come from chemical reactions in the production of clinker, a component of cement, and the other half from the energy use of the whole manufacturing process. The exact ratio of emissions from chemical reactions and energy use depends on the country and the manufacturer (Worrell et al., 2001).

Clinker is manufactured in high temperatures in a limestone calcination process. During calcination limestone ($CaCO_3$) is converted into lime (CaO) and CO_2, a harmful GHG, is emitted into the atmosphere. In addition to the production of clinker, the energy that is required for the whole production chain of cement leads to GHG emissions. The amount of emissions depends on the used fuel type. Typically the production of one tonne of the burned cement clinker of limestone and clay results in the release of 0.65–0.7 tonnes of carbon dioxide (Gibbs, Soyka and Conneely, 2000).

Concrete structures bind atmospheric CO_2 slowly over decades through the carbonation effect if concrete is exposed to air. It is a counter-process to the calcination that occurs during the manufacturing of cement. In carbonation the atmospheric CO_2 molecules react with moisture in the micro cavities of concrete converting lime back into limestone (Engelsen et al., 2005). Carbonation may pose a significant structural risk to reinforced concrete structures, because the steel reinforcement bars may corrode and lose their structural capacity (Heckroodt, 2002; Andersson et al., 2013).

However, the uptake of CO_2 in carbonation has direct climate benefits. Andersson et al. (2013) found that approximately 17% of the CO_2 emitted in the manufacturing process of concrete – including emissions from both calcination and the use of fossil fuels – may be taken back into concrete through carbonation on a country level. Kjellesen, Guimaraes and Nilsson estimated (2005) that if only calcination is studied, up to 57% of the CO_2 emissions from the process may be reabsorbed over 100 years. Collins (2010) concluded that if carbonation is excluded from calculations, the GHG emissions maybe overestimated by 13–48%, depending on the cement binder type and the use of recycled concrete aggregates during the secondary service life.

According to Engelsen et al. (2005), carbonation depends on several factors: the strength class of the concrete, the size and shape of concrete structure or pieces, exposure to weather, the relative humidity of air (optimal for carbonation: relative humidity [RH] 50–60), temperature and exposure time. An ideal situation for binding CO_2 back into concrete would occur when low-strength concrete is crushed and then exposed to air in dry and warm conditions. This was the case in Haiti for several months after the earthquake: crushed concrete rubble lay exposed to air in warm temperatures. In addition, the average RH in Haiti is 60.6% (NNDC, 2015), which is very close to being in the optimal range for carbonation of RH 50–60% (Engelsen et al., 2005).

1.4 Concrete type makes a difference

Concrete mixes have different environmental impacts depending on the amount and type of materials in the mix. Cement is typically the most energy-intensive material in the manufacturing process and its production also significantly releases CO_2: For example, Jiménez et al. (2015) have shown that cement has the largest contribution to the environmental impacts of concrete in several impact categories, even when different cement types are analysed.

Cement can be substituted by material alternatives that have a lower carbon footprint. Usual materials for substituting cement include fly ash (FA) and blast furnace slag (BFS) (Nielsen, 2008). FA is generated in combustion of, for example, coal or wood. It typically contains silicon dioxide (SiO_2) and calcium oxide (CaO) but the exact components depend on the burnt materials. BFS is a residue of iron manufacturing. It is made from molten iron slag that is left in the blast furnace and then powdered for further use. The exact composition of BFS differs depending on the initial iron production process. In addition to FA and BFS, more rare industrial pozzolans – such as metakaolin, burnt oil shale, container glass, paper mill sludge ash or incinerated sewage sludge ash – may also offer significant potential for lowering the carbon footprint of concrete (Tyrer et al., 2010).

In addition, the carbon footprint of the production phase and also the rate of carbonation change according to cement types. When comparing the carbonation of OPC (CEM I) to Portland-slag cements containing up to 20% of blast-granulated furnace slag (CEM II/A-S) or between 35–95% of slag (CEM III) the carbonation capacity changes respectively (Andersson et al., 2013; Gruyaert et al., 2013). The reasons for this are that the gas permeability increases along with the content of slag in cement, but the CO_2 content of the air and the temperature (Gruyaert et al., 2013), especially in cities (Ruixia 2010), also have an impact.

1.5 Why is this relevant in humanitarian construction?

Environmental performance criteria can be seen as relevant in humanitarian construction as well as in conventional construction (Kuittinen, 2015b). Using recycled construction materials may save virgin raw materials, energy for the manufacturing process and emissions from transportation (BRE, 2007). However, it has not been known if using recycled concrete rubble for reconstruction would be an environmentally better or worse option compared to using new construction materials in the context of Haiti. The Haitian structures and buildings are very simple and therefore environmental impacts may differ from the above-mentioned comparative studies. Without knowing how beneficial or harmful the use of recycled concrete is in humanitarian construction, project managers or designers have little possibility to "build back better" with the environment in mind.

2. Methods and materials

2.1 Methodology and goals

The applied methodology follows a descriptive qualitative case study. The case is a reconstructed school in Haiti. This single case includes several embedded units of analysis within the same context: five alternative concrete structure types and five alternative cement mixes for each structure type. A process-based, streamlined life cycle assessment, as presented by Crawford (2011, p. 42), has been used as tool. System boundaries, functional units and data sources are chosen to serve the scope and goal.

The main goal of this study was to find out if using recycled concrete rubble would bring reductions to the carbon footprint of the manufacturing phase of reconstructed schools in Haiti. Specific goals include comparing innovative new recycled concrete rubble structures to new concrete structures or reusing concrete blocks. Furthermore, the impacts of different cement mixes have been studied and compared. Finally, the potential carbon uptake by the carbonation of concretes made from different cement mixes was calculated.

2.2 The case study building

The building that has been used for comparison in this study is a three-classroom school in Haiti. It was designed as part of the reconstruction project of schools after the earthquake in 2010 by the author. Since then, 14 school centres have been built with the same school concept in Haiti and 10 projects are planned for 2015–16. The design of the building is presented in Figure 1. Although the built school centres differ from each other depending on the site and need for classrooms, the basic geometry and design of an individual school building is the same. The building studied is the part of the first project in the village of St. Matthieu, near the city of Leogane.

The floors of the built schools are massive reinforced concrete slabs that are cast to the ground on site. The roofs of the already-built schools are made of wooden roof trusses (though in some cases steel roof trusses have also been used). In this study the original wooden truss design is used. The roof is made from corrugated metal sheeting with a plywood ceiling and reinforcements. The floors and roofs in the built schools have no thermal insulation.

2.3 Alternative structures and concrete mixes

The walls have load-bearing concrete columns and shear walls. The infills between load-bearing concrete columns were originally designed to be made from recycled rubble, either in gabions or as masonry. For comparison, this study also includes alternative solutions: recycled concrete blocks, new concrete blocks and new clay bricks, as illustrated in Figure 2. The schools that have already been built in Haiti include the structural variations of rubble gabions and rubble masonry. In addition, schools with cement fibre board walls instead of stone structures have been built, but they are not covered in this study.

The compared concrete mixes are of the strength class 25 MPa. Alternative mixes include ordinary Portland Cement (OPC), 15% FA cement (FA15), 30% FA cement (FA30), 25% BFS cement (BFS25) and 50% BFS cement (BFS50).

2.4 Carbonation

The calculation of carbonation in this study is based on the method presented by Lagerblad (2005). Carbonation slows down as a function of time and most of the carbonation occurs during first 50 years of the structure. This has been used as a reference calculation period. The uptake of CO_2 is calculated for all cement-based building parts. They are first divided into exposure classes (indoor, outdoor sheltered, outdoor, in the ground). Correction factors for surface treatments are used. The carbonation of different cement mixes is based on binder correction factors that differ according to the strength class and percentage and type of cement substitutes. For concrete rubble it was assumed that 10% of its cement has already been carbonated during its first service life before the earthquake and during the intermediate phase after the earthquake as the rubble was lying in the ground. Lagerblad's method is developed for Nordic climate conditions, and the carbonation would in reality be faster in Haiti's climate conditions (with higher RH and temperature), as explained in subsection 1.3. Thus the results likely show a smaller climate benefit for carbonation, but this has been accepted as it distorts the results towards a more conservative direction.

2.5 The covered life cycle phases

The modules of buildings' life cycles have been defined in European norm EN 15978 (2011). This study covers the production phase (modules A1–3). In addition the replacement phase (B4) is taken into account. The life cycle of the building was assumed to be 50 years.

The reason for excluding other parts of the life cycle are because schools in Haiti are very low tech in their approach. For instance, no ventilation, cooling or heating is installed. Thus the relevance of including operative energy use was deemed marginal. In addition, these parameters would not vary depending on the chosen construction materials. The carbon footprint of the construction work and transportation (modules A4–5) was excluded as it was impossible to gather accurate field data about transportation emissions, fuel use and construction work. The exclusion of the end-of-life phase (Phase C) is based on the very high degree of

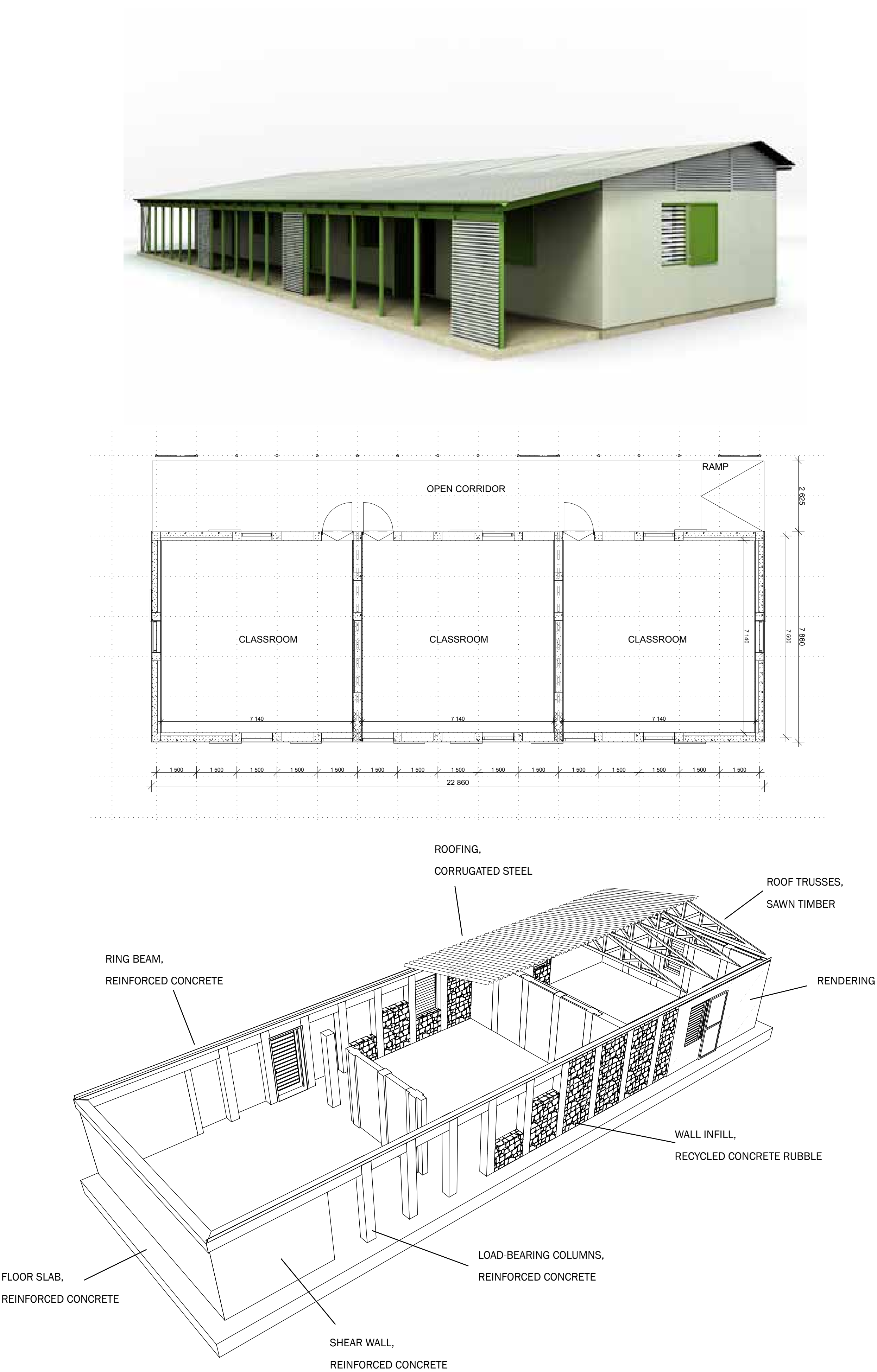
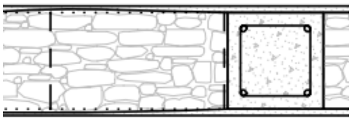
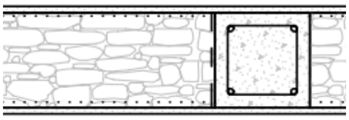


Figure 1. Drawings of the school model: a façade perspective, the floor plan and a structural perspective.

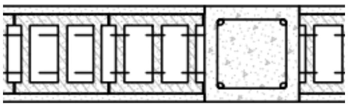
Figure 2. Alternative structure types for wall infills between the columns.



Rubble gabions
- Gabion cages from galvanized steel
- Loose concrete rubble filling
- Rendering on both sides

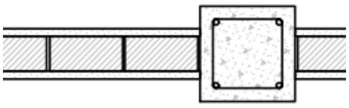


Rubble masonry
- Concrete rubble masonry with cement mortar
- Supporting galvanized steel mesh on both sides
- Rendering on both sides



Recycled concrete blocks
- Concrete blocks with galvanized reinforcement bars
- Rendering on both sides

New concrete blocks
- Concrete blocks with galvanized reinforcement bars
- Rendering on both sides



New bricks
- Brick masonry with cement mortar between concrete columns
- Rendering on both sides

Table 1. System boundary and life cycle scenarios

Life cycle phase		*Consideration*	*Scenarios used*
A1–3	Production stage	Included.	
A4–5	Construction stage	Not included.	
B	Use stage	Use in building (B1) partially included.	The carbonation of concrete during a 50-year service life (SL)
		Replacement (B4) included.	Roofing and hurricane shutters: SL 10 years
			Roof trusses, rendering, doors and windows: SL 25 years
			Wall infills: SL 50 years
			Concrete frame and foundation: SL 100 years
		Other sub-modules not included.	
C	End-of-life stage	Not included.	
D	Additional information	Not included.	

uncertainty involved in the development of waste management infrastructure in Haiti.

2.6 Functional units and technical service life

Functional units are required for comparing different alternatives. In this study the functional units are one square metre of the school building area and a service life of 50 years.

The technical service life (Table 1) describes how long the building will maintain its technical performance within the assumed use patterns, weather conditions and other relevant factors. The reason for the short technical service lives of the roofs, doors and windows is because hurricanes are an annual phenomenon in Haiti and buildings need repairing after the hurricane season. The roofing of the building may often be the most vulnerable part in hurricanes (Li and Ellingwood, 2006). Furthermore, the humid tropical climate and termites may shorten the technical service life of wooden building parts (Arango et al., 2004). This assumption is made on the basis that if scenarios for certain parts of service life cannot be accurately known, a conservative assumption should be chosen. In reality the technical service life may be longer.

The long service life that has been estimated for the load-bearing frame is based on its significantly strong structural design. Although Haiti is in a seismically active area, and earthquakes are likely to occur within 100 years from the construction of the schools, the designed frame should withstand earthquakes.

2.7 Inventory, data sources and the interpretation of results

The amount of parts has been calculated from technical drawings of the schools. The weight of each building part is based on its volume and average density. The environmental impacts for each construction material may be obtained from product- and manufacturer-specific environmental product declarations or from general databases. In this study a database has been used. The selected database is the Inventory of Carbon and Energy (ICE) version 2.0 (Hammond and Jones, 2011). The reasons for choosing this database are that it is open-source and thus could be utilised by humanitarian consultants in the future as well. However, there are several uncertainties and reservations that are described in subchapter 2.8.

2.8 Uncertainties and limitations

The intention has been to conduct the study as well as possible with the available data. The biggest uncertainties are related to the used database and gaps in data collection.

The selected open source ICE 2.0 database is a summary of the environmental loads of the typical construction products of developed countries. There is no similar database for developing countries. This may distort the results. To bypass this problem the environmental loads of the manufacturing of construction products in Haiti should be studied. Such a task would require exhaustive field work and still might have proven impossible to finish because presumably energy metering at production facilities may not exist and because the actual energy mix of Haiti may vary considerably depending on power shortages and the use of temporary energy sources during these periods of time.

Another uncertainty is linked to the actual type of construction material (e.g. concrete or steel) that would be used. Despite that the designs including strength classes and types for materials, the availability of materials is the defining factor in Haiti. For example, if a certain strength class were not available, an alternative would be favoured instead of letting the whole construction project idle.

The results of the study only apply to the studied school model, its structural alternatives and cement mixes. They cannot be used for interpreting the environmental loads or benefits in other cases.

3. Results

3.1 The dominance of building parts

The calculated results are presented in Table 2, which shows combinations of different wall structures and different cement mixes. When the carbon footprint of the structures is studied, the important role of the roof and foundations becomes apparent.

The foundations of the school buildings seem to have the largest impact. The mass of the foundation is high and the emissions correlate to the amount of used materials. The foundations were designed to be very strong in the Haitian context, so that the building would perform well in the case of an earthquake or mudslide. This results in a large amount of both concrete and steel reinforcement bars. The production of both materials results in high energy consumption and GHG emissions.

The roof has the second largest carbon footprint of the building parts and its emissions are close to the emissions of the foundation. The reasons for this are twofold: primarily, the steel that is used for the corrugated sheets has a rather high primary energy demand in its production phase and thus – even if world average production figures and energy mixes are used – has a high carbon footprint as well; secondly, the service life for the roof is short in the studied context. The scenario is based on the service life scenario that includes annual tropical storms and hurricanes that are strong enough to damage the roof structures. The need to replace the roof structures twice during the service life of the school accumulates the carbon footprint. A stronger roof (e.g. a massive reinforced concrete slab) would have less need for hurricane-related repairs. However, in the discussions with local authorities and end-users of the buildings, a concrete slab roof was not accepted. The main reason for this seemed to be historical: in the 2010 earthquake a significant amount of casualties were caused by collapsing concrete roofs and people were genuinely afraid of massive concrete roofs. Even though the concrete roofs that collapsed seemed to have been inadequately constructed, the concrete roof still had a strong stigma that made it an unpopular design alternative.

3.2 Structural alternatives

The estimation shows that the lowest carbon footprint is associated to the wall structure type in which recycled concrete blocks are used between concrete columns and concrete shear walls. The difference to new concrete blocks is however marginal and may fall within the uncertainty range of the calculation. The largest emissions are linked to the alternatives in which recycled rubble has been used in either gabions or masonry.

The explanation for this result can be found in detail when only the wall infill is studied. The alternatives that utilise recycled concrete or brick rubble need additional reinforcement (steel mesh and ties) in order to meet the strict seismic performance criteria set for the design of the schools. The carbon footprint of making steel is high, even if a significant percentage of recycled materials were used. The rubble masonry wall structure option included a steel mesh on both sides of the masonry wall. In addition, the amount of masonry mortar needed in this alternative is quite high, because the pieces of rubble are uneven in their shape and may need more mortar than uniform concrete blocks. Although there is no carbon footprint or primary energy consumption allocated to the manufacturing of the reclaimed rubble infill, the additional reinforcements and materials offset the environmental gains of using recycled frame infill materials.

3.3 Cement mixes

The estimation of the carbon footprint of different concrete mixes shows that the mix that has 50% BFS content has the smallest carbon footprint. The highest carbon footprint is associated to the OPC mix. If separate building parts are studied, the total carbon footprint reduction potential in the foundations of the school reaches 35% (Figure 3). In comparison to other parts of the school building, the emission saving potential through the selection of concrete mix is more than the emissions from wall infills made of new blocks or bricks. Concrete mixes also affect the carbonation potential.

Table 2. GHG emissions, uptake and balance in kg of CO_2e for schools with alternative wall structures and cement mixes during a 50-year study period.

		OPC	FA15	FA30	BFS25	BFS50
Rubble Masonry	Foundation	18 316.63	17 140.95	15 495.00	15 024.72	11 850.39
	Concrete frame	9 813.94	9 354.76	8 711.91	8 528.24	7 288.45
	Roof	14 659.24	14 659.24	14 659.24	14 659.24	14 659.24
	Other parts	638.80	638.80	638.80	638.80	638.80
	Wall infill	11 427.71	11 354.17	11 180.18	11 144.11	10 848.74
	Carbonation	-3 335.31	-3 335.31	-3 515.21	-3 674.99	-3 994.55
	Total	**51 521.00**	**49 812.60**	**47 169.90**	**46 320,11**	**41 291.06**
Rubble Gabions	Foundation	18 316.63	17 140.95	15 495.00	15 024.72	11 850.39
	Concrete frame	9 813.94	9 354.76	8 711.91	8 528.24	7 288.45
	Roof	14 659.24	14 659.24	14 659.24	14 659.24	14 659.24
	Other parts	638.80	638.80	638.80	638.80	638.80
	Wall infill	11 582.97	11 582.97	11 582.97	11 582.97	11 582.97
	Carbonation	-3 335.31	-3 335.31	-3 515.21	-3 674.99	-3 994.55
	Total	**51 676.26**	**50 041.40**	**47 572.70**	**46 758.97**	**42 025.29**
Recycled Blocks	Foundation	18 316.63	17 140.95	15 495.00	15 024.72	11 850.39
	Concrete frame	9 813.94	9 354.76	8 711.91	8 528.24	7 288.45
	Roof	14 659.24	14 659.24	14 659.24	14 659.24	14 659.24
	Other parts	638.80	638.80	638.80	638.80	638.80
	Wall infill	2 677.70	2 121.83	2 024.88	1 999.60	1 836.77
	Carbonation	-2 983.04	-2 983.04	-3 146.16	-3 289.17	-3 575.18
	Total	**43 123.26**	**40 932.53**	**38 383.66**	**37 561.43**	**32 698.46**
New Blocks	Foundation	18 316.63	17 140.95	15 495.00	15 024.72	11 850.39
	Concrete frame	9 813.94	9 354.76	8 711.91	8 528.24	7 288.45
	Roof	14 659.24	14 659.24	14 659.24	14 659.24	14 659.24
	Other parts	638.80	638.80	638.80	638.80	638.80
	Wall infill	3 365.81	2 870.90	2 683.72	2 647.79	2 315.39
	Carbonation	-3 264.86	-3 264.86	-3 441.40	-3 597.82	-3 910.68
	Total	**43 529.56**	**41 399.78**	**38 747.26**	**37 900.96**	**32 841.58**
New Bricks	Foundation	18 316.63	17 140.95	15 495.00	15 024.72	11 850.39
	Concrete frame	9 813.94	9 354.76	8 711.91	8 528.24	7 288.45
	Roof	14 659.24	14 659.24	14 659.24	14 659.24	14 659.24
	Other parts	638.80	638.80	638.80	638.80	638.80
	Wall infill	4 835.77	3 121.11	3 023.53	3 004.01	2 838.13
	Carbonation	-2 718.83	-2 681.12	-2 829.83	-2 958.46	-3 215.72
	Total	**45 545.54**	**42 233.73**	**39 698.63**	**38 896.54**	**34 059.28**

Table 3. The percentage of CO_2 uptake during 50 years including the emissions of the production and replacement phases.

	OPC	FA15	FA30	BFS25	BFS50
Rubble Masonry	6.47%	6.70%	7.45%	7.93%	9.67%
Rubble Gabions	6.45%	6.67%	7.39%	7.86%	9.51%
Recycled Blocks	6.92%	7.29%	8.20%	8.76%	10.93%
New Blocks	7.50%	7.89%	8.88%	9.49%	11.91%
New Bricks	5.97%	6.35%	7.13%	7.61%	9.44%

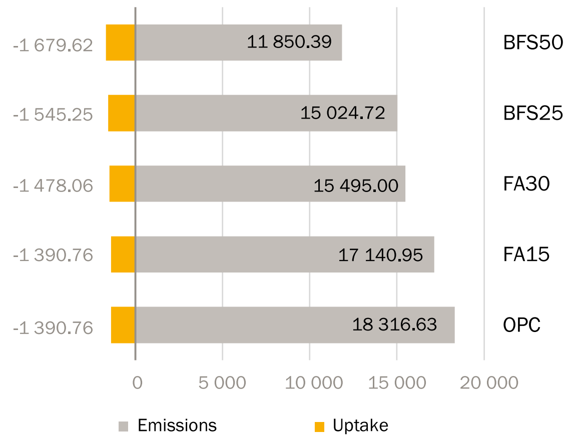


Figure 3. The impact of the cement mix on the CO_2 emissions and uptake of the foundation. BSF50 has 35% lower emissions compared to OPC. The CO_2 uptake increases only marginally as carbonation is slow in structures that are in contact with the ground.

3.4 Carbonation

The carbonation calculations were performed separately for all cement-based building parts and all cement mixes. The results show that largest amount of CO_2 uptake happens with the BFS50 cement mix (Table 3). The maximum amount of CO_2 uptake is found in a combination of the BFS50 cement mix and rubble masonry structures. It totals 3 994.55 kgCO_2 during 50 years.

The maximum depth of carbonation during 50 years is 31.2 mm in the indoor concrete surfaces. In walls this means that there is no practical difference in the carbonated amount of cement in alternative rubble structures, because the rubble is covered with 30 mm of rendering. Thus only the rendering layer may carbonate during the study period. In outdoor surfaces the rendering is supposed to be replaced during the service life, in other words, the carbonation will start again from the surface.

The share of carbonation to CO_2 emissions from the production and replacement phases depends on the concrete mix (Table 3). BSF50 concrete applied to recycled blocks or new blocks results in a calculative CO_2 uptake of over 10%. The maximum amount of CO_2 uptake (11.91%) with the combination of BFS50 and new concrete blocks can be considered significant.

4. Discussion

4.1 The environmental friendliness of recycled structure types varies considerably

As the results reveal, using recycled concrete materials may be the best or worst option, depending on the case. If recycled concrete blocks are used, the lowest carbon footprint of all calculated structures can be achieved. However, if the concrete is recycled in gabion structures, it causes the largest carbon footprint. Both new concrete blocks and new bricks seem to perform better than recycled rubble. The difference between the lowest and highest carbon footprints varies from 17% to 22%, depending on which cement type is used. In other words, the method of how recycled material is used seems to be of vital importance in controlling the GHG emissions of the structure. This is a new finding that was not previously known in the studied context. However, it cannot be applied directly to other cases without case-specific consideration.

If concrete rubble is reused in a seismically safe area, it might be an environmentally more competent option. In such a context the walls would not have to have so high strength criteria and there would be less shear walls. Thus the role of the wall infill materials would start to have larger impact. Suitable application areas may be found, for example in the reconstruction of Syrian towns after the ongoing war is over. Although the differences in building product comparison may not be dramatic, the consequences of recycling rubble into construction instead of disposing it may bring additional environmental benefits.

4.2 The right concrete mix can significantly lower emissions

The choice of concrete mix is of significance if a low carbon footprint for the manufacturing phase of the building is aimed at. For instance, by changing the concrete mix there is a possibility to reduce 35% of emissions from the manufacturing of the floor slab (Figure 3). This advantage is significant. In addition, there is potential for increasing the CO_2 uptake through carbonation by choosing an appropriate concrete mix: BFS-based mixes showed the highest carbonation potential. Interestingly, the CO_2 emissions and uptake of the studied concrete mixes follow each other. BFS-based concrete mixes also have the lowest CO_2 emissions. These findings are in line with previous studies of Ruixia (2010) and Gruyaert et al. (2013). However, the implications of the strength of the concrete and the technical service life of the building in the seismic areas would require further study.

4.3 Carbonation has potential but its utilisation requires optimal applications

The CO_2 uptake through carbonation can be considered noteworthy. Because reconstructed schools are of very simple design, the relative positive impact of carbonation is greater than in more complex buildings that may include several magnitudes of greater GHG emissions from insulation materials, building services, foundations etc.

Concrete rubble is an ideal material for maximising carbonation. However, using the most robust construction method of filling gabions with rubble without any mortar was found to cause considerable collateral GHG emissions. Therefore the end-use of rubble should be reconsidered. As carbonation requires direct contact between concrete and air, the concrete rubble should not be covered with rendering but used as stand-alone walls that would only be tied together mechanically. Such structures would be more suitable for gabion constructions along riverbanks or roads (wherein they serve to mitigate flooding or landslides) – provided that the physiological conditions for carbonation exist. Based on the findings of this study, the use of concrete rubble in buildings while aiming at maximising its carbonation effect does not seem feasible in seismic areas. However, if rubble was used for wall infills in areas less prone to earthquakes, the use of loose infills of concrete rubble could be more justified from a climate benefit viewpoint. Even then, the design should overcome issues of pests or insects dwelling in the cavities of rubble walls to avoid potential harm to residents or their belongings.

5. Conclusions

Based on the study, the following can be concluded:

- There are major differences between the CO_2 emissions of recycled concrete structures. In seismic areas, recycling concrete rubble into gabions does not reduce CO_2 emissions. It proved to be the worst option of the studied alternatives. On the contrary, the use of recycled concrete blocks has the lowest CO_2 emissions, although the difference to using new concrete blocks is marginal.
- The selection of the concrete mix is essential. By choosing BFS concrete the CO_2 emissions may be substantially lowered and CO_2 uptake increased. In some structures this may lead into emission savings of tens of percentages.
- The potential of CO_2 uptake through carbonation depends on the concrete mix and exposure class. To utilise this environmental benefit into maximum, BFS concrete mixes should be favoured. Protecting the walls of the building from rain and leaving internal concrete surfaces unpainted and uncovered increases the rate of carbonation.
- If structural safety is a high priority, recycled materials may be difficult to prove feasible. This does not mean, however, that they would not be safe. It is just much more difficult to estimate the safety of reused building parts or rubble-filled walls.
- If there are needs for landfilling, embankment or similar end-uses, recycled concrete rubble might be better suited to such end-uses than to building construction. Especially if rubble can be exposed to the air, the carbonation effect would turn the concrete rubble into a carbon sink.

As our planet struggles to meet the material needs of the growing number of people, it is inevitable that we also apply considerably greater resource efficiency in humanitarian work. Reusing and recycling construction materials is nothing new. Numerous examples from history show how building parts have been reused several times (Brenk, 1987; Huuhka et al., 2015). For achieving greater material efficiency together with optimal environmental and economic performance we need agile design and assessment methods in which the uncertainties for the performance of recycled materials are taken into account. Humanitarian operators should also support the concept of recycling in the field of construction. The famous “do no harm” principles (Anderson, 1999) of humanitarian response should therefore be understood as an extended responsibility over the environmental impacts of construction materials and methods.

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Annex 3

The energy efficiency and carbon footprint of temporary homes: A case study from Japan

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The energy efficiency and carbon footprint of temporary homes: A case study from Japan

Abstract

Purpose: This study investigates the energy efficiency and life cycle carbon footprint of temporary homes in Japan after the Great Eastern Tohoku Earthquake in 2011.

Methodology: An energy simulation and life cycle assessment have been done for three alternative shelter models: prefabricated shelters, wooden log shelters and sea container shelters.

Findings: Shelter materials have a very high share of life cycle emissions because the use period of temporary homes is short. Wooden shelters perform best in the comparison. The clustering of shelters into longer buildings or on top of each other increases their energy efficiency considerably. Sea containers piled on top of each other have superb energy performance compared to other models and they consume even less energy per household than the national average. However, there are several gaps of knowledge in the environmental assessment of temporary homes and field data from refugee camps should be collected as part of camp management.

Originality/value: The findings exemplify the impacts of the proper design of temporary homes for mitigating their energy demand and GHG emissions.

Keywords

Shelter, Japan, energy, carbon footprint, climate change, life cycle assessment, Great Eastern Tohoku Earthquake

1. Introduction

1.1 The energy efficiency and carbon footprint of humanitarian construction

The level of energy efficiency and the carbon footprint of humanitarian construction are not as well-known as their impact in "conventional" construction. The priority has been on humanitarian aid and other aspects have understandably had lesser importance. However, the global quest for dramatic reductions of greenhouse gas (GHG) emissions is putting pressure on the environmental improvement of humanitarian work as well. And to know where it can be improved and how much it should be improved, we must know the status quo first.

Most natural disasters today are climate-related (UNHCR, 2009) and extreme weather events are becoming more frequent. It has been argued (Hansen et al., 2013) that climate change is the biggest single threat that mankind faces today. The man-made addition to the delicate balance of climate forcings is mostly a result of GHG emissions from multiple sources. Today cities and urban areas are accountable for 71–76% of all GHG emissions and 67–76% of all primary energy demand (IPCC, 2014). Buildings themselves can account for approximately 40% of energy use and 30% of GHG emissions globally (UNEP, 2009). Although a global consensus to keep the warming to under two degrees Celsius was reached in the Paris agreement (UNFCCC, 2015), even this much warming may cause significant risks of polar ice melting, rising sea levels and leading to "superstorms", as concluded by Hansen et al. (2016). Therefore mitigating the emissions in the built environment is highly important.

Typically buildings cause most of their emissions during their use phase. A comparison of 73 buildings in 13 countries (Ramesh, Prakash and Shukla, 2010) revealed that operative energy use is dominant (80–90%) and embodied energy use – that is to say the energy required for the production of building materials, construction work, repairs, demolition and waste management – accounts for the rest. However, this trend seems to change as we move towards more energy-efficient buildings. Recently it has been discovered that in houses that have a very good level of energy efficiency, being at the "passive house" level, the emissions from the embodied energy and the emissions from the production of construction materials may become more important than the emissions from operative energy use (Dodoo et al., 2013; Kuittinen, 2013; Takano, 2014; Takano, Winter and Hughes, 2014). However, the construction of dense and energy-efficient areas results in a peak in GHG emissions and energy demand. This peak may be large and it may take several decades before it is amortized (Heinonen et al., 2012).

In Japan, the estimations for the residential sector's share of final energy consumption vary from 14.2% (Nakamura, 2013) to 14.8% (Murakami, 2006). The main focus of Japanese energy-efficiency measures is on residential and commercial sectors, because their share of final energy consumption has grown 1.33 fold between 1990 and 2011 (Ito, 2013). Energy consumption is expected to decrease by 16% in households, especially because of more energy-efficient lighting and electrical appliances (Sugiura, Miwa and Uno, 2013).

As shown in the examples shown, we have a relatively good understanding of the energy and GHG impacts of conventional housing. But how do humanitarian constructions – emergency shelters, temporary homes and reconstructions – perform when compared to normal building stock? The impact is larger the greater the need for temporary housing and the more the infrastructure of the community is damaged.

1.2 The need for temporary housing after the Great Eastern Tohoku Earthquake

The Great Eastern Tohoku Earthquake on March 11, 2011, and the following tsunami wave caused a shocking amount of human loss and material damage. After the disaster, more than 450 000 people were accommodated in evacuation centres (Shiozaki et al., 2012). Around 115 000 transitional shelters were built and some 136 000 existing buildings were allocated for temporary housing purposes. The planned period of stay is normally two years (Okuyama, 2015). One year after the earthquake, the Japanese Ministry of Health, Labour and Welfare already allowed an extension for the dwelling periods in temporary homes (JiJi Press, 2012). The main reason for this was the longer-than-expected process of building permanent houses. Normally post-disaster dwelling in temporary homes has only been allowed for two years but the schedule for all of the internally displaced people having a permanent home is unclear.

There were multiple alternatives for temporary housing. According to Shiozaki et al. (2012) the palette of options included private rental apartments (48%), public housing (6%), government-owned accommodation (7%) and temporary homes (39%) (which are mostly prefabricated and are discussed in this study). One of the key challenges for building temporary housing was a shortage of flat land that could be built upon as debris from the tsunami was scattered across large areas and clearing it away was time-consuming.

The transitional shelters were not ideal during the winter months (Chu and Mochida, 2014). Thermal comfort was poor and during cold nights the water pipes froze in some shelters (Ishii, 2013). To keep the water running, people left taps running overnight. This in turn caused condensation on windows and doors, which occasionally froze to the extent that elderly people could not open their doors from the inside.

Because temporary buildings are not usually aimed at having the same energy performance as permanent ones, they may be less energy efficient. This may lead into greater GHG emissions per capita from transitional shelters compared to permanent ones. In addition to the energy efficiency of the buildings, the available energy source also has an impact on the emissions of temporary housing. But how big is this impact?

1.3 Fossil energy replaced nuclear power

A sudden and unexpected disaster disrupts the activities of a society. This also applies to the sector of energy production. After the earthquake seriously damaged the nuclear power plant in Fukushima, strong public concern about the safety of nuclear energy was raised. The Japanese government decided to temporarily idle all 54 nuclear power plants in the country after April 2012 (Yamaguchi, 2012). In order to replace the energy demand, the natural gas import was especially increased. According to Kihara (2013) approximately 29% of the country´s electricity was generated by nuclear power before the disaster (2010) and it sank to 2% by 2012. Imported liquefied natural gas was used to compensate for the gap: its share in electricity generation rose from 29% (2010) to 48% (2012). The climate consequences of this change in energy mix are negative. While the generation of electricity in a nuclear power plant is considered to be climate neutral, the use of natural gas and other fossil energy carriers results in GHG emissions.

As a consequence, the energy for heating and cooling temporary homes and providing them with household electricity has been generated by using an increased share of fossil fuels. This average change has added to household GHG emissions. In addition, the energy efficiency of temporary homes can be weaker than that of permanent housing. This may be the result of regulation that makes it possible to build temporary homes that have a maximum service life of five years without complying with the same energy efficiency standards as permanent homes.

A change in the energy mix also affects the embodied energy and carbon footprint of temporary homes. The industrial production of construction components has been fuelled by using a larger share of fossil fuels than before the earthquake. This has presumably increased the average GHG emissions from production that has taken place after the earthquake.

Together these two factors – the change in the Japanese energy mix and the possibly weaker energy efficiency of temporary homes – may amplify each other into an environmentally problematic direction. However, this assumption remains theoretical without closer studying real cases. Should the impacts of a seismic disaster be taken into account in energy and housing preparedness planning?

1.4 Filling the gaps of environmental knowledge in humanitarian construction

As the conventional construction sector has been moving towards greater environmental accountability for years, the same ambition should finally be taken into the humanitarian construction sector as well. Literature and research on the environmental impacts of humanitarian construction are very thin, and only a handful of studies can be found.

Abrahams (2014) investigated what barriers exist to environmental sustainability in shelter projects. He studied the procurement

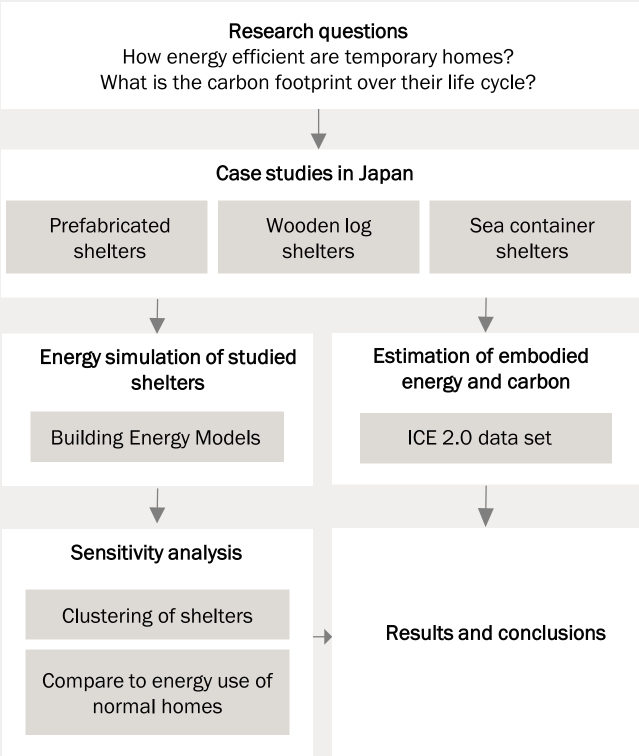


Figure 1. *Structure of the research.*

phases of transitional shelters in Haiti after the 2010 earthquake and concluded that sustainability is not generally included in procurement criteria. The main reasons for this seem to be concerns that environmental management would slow down the humanitarian response.

Zea Escamilla and Habert (2015) compared the sustainability of local and imported construction materials for twenty transitional shelters. Their findings show that generally local materials may have lower carbon footprint than imported construction materials.

Kuittinen and Winter (2015) studied the carbon footprint of eight transitional shelters by the International Federation of Red Cross and Red Crescent Societies (IFRC) and compared the emissions to their construction costs. They concluded that construction materials can make a remarkable difference to the carbon footprint during the production phase of the shelters. In addition they found out that some shelter projects could increase the annual per capita GHG emissions by even 70 times compared to normal.

However, these few pioneering studies have not compared both the energy efficiency and carbon footprint of humanitarian construction. These indicators often go hand in hand in cold climates, where warming and domestic hot water have to be provided for temporary homes as well. Such a context is very different from warm climates and the dominance of energy use and GHG emissions over the life cycle of the shelter requires special study.

2. The studied shelters

2.1 Filling knowledge gaps

To find answers to the energy efficiency and carbon footprint of transitional shelters, we carried out a case study in the Sendai area after the disaster. The structure of the study is shown in figure 1.

Our goal was to investigate the energy efficiency of temporary homes and estimate their carbon footprint over the life cycle (from cradle to grave). We chose three alternative types of temporary shelter for closer analysis: prefabricated shelters, wooden log shelters and a shelter settlement made from sea containers.

The shelters were visited and evaluated with the help of the available technical drawings and documentation. Energy simulation and the estimation of embodied energy and carbon footprint were carried out and complemented by a sensitivity analyses. The results and conclusions were then summarised as recommendations for the preparedness planning of energy-efficient temporary homes.

2.2 Prefabricated shelters

The prefabricated temporary homes (“prefab shelters”) seem to be one of the most typical temporary homes in the city of Sendai and across the Miyagi prefecture. These homes cover around 90% of all homes provided by the prefecture (Ishii, 2013). These shelters were built in large quantities at several sites in the Sendai area. Settlements of this type of shelter have been built in parks, empty sites, industrial areas and on riverbanks. Housing areas seem to follow the same geometry in which houses are arranged in straight rows.

Typically there are several apartment layouts: one, two and three-room options for different needs. We studied an exemplary prefab shelter that consisted of four homes.

The typical structural solution includes a steel-tube frame, 50 mm mineral wool insulation and sheathing on the inner and outer surfaces. This basic solution was later upgraded for better energy efficiency, which is required in the climate of Sendai. Thermal improvements include 100 mm of mineral wool and extra glass to double-glaze the windows. Some of the shelters were clad with imitation-tile sheathing that seemed to blend them better into their environment and decreased the temporary appearance.

2.3 Log shelters

Wooden temporary houses are an alternative to prefabricated steel shelters. In certain areas there were the available raw material for wood construction – for instance forests damaged by a tsunami wave – or experienced carpenters who had lost their livelihood in the disaster. An important aspect when choosing wood is its “soft” feeling. It has been observed that elderly people living in wooden transitional care homes suffered less anxiety than elderly people living in steel container care homes (Ishii, 2013).

The studied example of a four-apartment log shelter is from the village of Gohyakugawa. The settlement is located in a former park in Emukai. The buildings are arranged in straight rows. There is one communal building and a temporary elderly home in the settlement.

The walls of the log shelters are made from solid sawn logs without additional thermal insulation. The floor structure is made from wooden beams and soft thermal insulation. The roof has load-bearing wood beams, insulation and steel roofing. The architectural appearance of the log shelters is pleasant and calming. The shelters do not have the character of a temporary building, as most of the prefab shelters do.

2.4 Container shelters

A group of 189 temporary homes in Onagawa are made from shipping containers that are stacked in a checkerboard-pattern of two or three floors on top of each other, located in a former sports field. The containers were manufactured in China and shipped to the construction site. The thermal and acoustic properties of the containers are improved with polyurethane insulation and layers of sheathing in the walls, floors and roof. The stairs, corridors and balconies are all made from steel frame. They are partly clad with Finnish composite planks that include recycled plastic. Built-in furniture was specifically designed to help to store household items in temporary conditions. Novel material combinations, including cardboard tubes, were used. Much of the on-site installation work was carried out by the Voluntary Architects Network.

The project is a result of trying to increase the efficiency of land use for temporary housing by making multi-story shelters from shipping containers. The container shelters have been designed by the world-famous architect Shigeru Ban and have been widely published in the media. The design of these transitional shelters is of exceptionally high architectural quality, both inside and outside. The goal was to reach a quality category of four stars, the highest rank for transitional homes in Japan (Hirano, 2012). The ambition to offer the survivors good quality temporary accommodation seems to be well met. According to Ban (MakMax Taiyo Kogyo Corporation, 2013), many of the occupants would prefer to continue staying at the container shelters, even if they would need to pay rent. In his opinion the role of an architect is to add the quality aspect into a building, even in an emergency response, without challenging the economic feasibility.

Figure 2. The studied shelters, from top to bottom: prefabricated shelters in the city of Sendai; log shelters in Gohyakugawa; sea container shelters in Onagawa.

3. Methodology and materials

3.1 The life cycle approach

The environmental impacts in this study are assessed along the life cycle of a building. The life cycle is divided into four main phases according to standard EN 15643-2 (CEN, 2011): the production stage, the construction stage, the use stage and the end-of-life stage. Each of these contains several sub-stages. Dividing the environmental impacts along the life cycle illustrates the relative dominance of each phase and enables improvement of the environmental performance.

For the production stage, all of its sub-stages have been included in the study: raw material supply (A1), transport to the factory (A2) and the manufacturing process (A3). Regarding the construction stage, all sub-stages are included: transport to the construction site (A4) and construction work (A5).

For the use stage we have included the sub-stages that are supposed to have the main impact: refurbishment (B5) and operational energy use (B6). Other sub-stages of the use stage are not supposed to occur or to have significant impact: maintenance (B2), repair (B3) and replacement (B4). Operational water use (B7) has not been taken into account, as water footprinting is not in the focus of this study.

From the end-of-life stage we have included deconstruction work (C1) and transport to the waste processing site (C2). The actual waste processing (C3) and disposal (C4) are excluded due to high uncertainties in the scenarios.

3.2 The assessment process

The assessment of energy efficiency and GHG emissions included both energy simulation for operative energy use (B6) and life cycle assessment (LCA) for the other life cycle stages included.

Building Energy Models (BEMs) were constructed with ArchiCAD® software for all studied shelters. The simulation used real weather data from Sendai. Building service systems and energy usage patterns were kept similar for all of the studied shelters.

For LCA we carefully calculated the quantities of all building materials from technical drawings of the shelters. The carbon footprint and primary energy demand for the production of all construction materials were calculated by using the open source ICE 2.0 database (Hammond& Jones, 2011).

For the transport stage (A4) the weight of each material was calculated. We used same hypothetical transport distance for all shelter projects, assuming 200 km to the site and 200 km to return. The hypothetical vehicle was a diesel-powered truck with a maximum capacity of 28 tons. Fuel consumption was based on the fuel efficiency of heavy-duty trucks in Japan (transportpolicy.net, 2015). The GHG intensity of the used diesel fuel was assumed to be 0.414 kg CO_2/km, assuming that the trucks would meet the 2002 Japanese regulation level. For the sea freight of the Chinese shipping containers used in the Onagawa project we assumed them to be shipped from Shanghai to Sendai and we utilised energy and emission factors for a short sea shipping from Zou, Smirti and Hansen (2008).

Construction work (A5) was supposed to be carried out in different processes for each studied shelter type. For the Sendai and Onagawa models it was assumed that the assembly was done with lifts. GHG emission values for modular construction from Burgess, Buckett and Page (2013, p. 80) and energy use from Haynes (2010, p. 13) were used for on-site assembly and for the preceding assembly work at the prefabrication mill. For the log shelters we assumed there to be manual labour on site, helped with electric hand tools. We estimated the working hours for using a screwdrivers, nail guns and hydraulic lifts and calculated the corresponding emissions by using the unit values for each tool.

The refurbishment work (B5) was only calculated for the Sendai model. It was assumed that 50% of the shelters were equipped with additional thermal insulation that consisted of a wooden stud frame and mineral wool insulation clad with thin metal sheets. Refurbishment is reported in the production stage.

For the end-of-life stage the process of deconstruction (C1) was assumed to be a counter process to the construction work (A5) that would only require 80% of its energy due to less care and accuracy supposed to be required. Transportation distances were assumed to be 90% of the corresponding distances of module A4, as some of the material could be taken into centralised waste management facilities.

Finally the energy efficiency and GHG emissions of the transitional shelters are compared to the performance of conventional Japanese homes in the Tohoku area. Murakami et al. (2006) reported that the average energy consumption was 46.3 GJ/household in a year but that significant regional differences occur. The value for the Tohoku area, where the studied shelters are located, is approximately 50 GJ/household, slightly above the average. According to Murakami et al., space heating and cooling account for 25–30% of energy consumption, the hot water supply for 35–40% and lighting and appliances for 35–40%. The annual CO_2 emissions from construction, renovation and operation of buildings were estimated to be 470 million tons.

3.3 Uncertainties and limitations

It was not possible to study all the details of the shelter projects. Some of the information was not available. Therefore assumptions have been made, as is common in LCA.

The used database represents the average values of the manufacturing processes of construction materials and does not therefore directly represent the environmental impacts of the particular products of this study. The shift in the energy mix of Japan to the use of a greater share of fossil fuels due to the idling of nuclear power plants after the earthquake is taken into account in the operative energy use only and not considered for the production of materials. It was not known how much of the construction material was actually taken from stock and how much was produced after the disaster. Transport distances are assumptions on the justification that shelters are located in several places and that the chosen distances represent hypothetical averages.

The change of living habits because of temporary housing has not been fully included. For example, traditional bathing customs in Japanese homes account for a large share (29.5%) of water heating when compared to other countries (Murakami et al., 2009; Wilhite et al., 1996). We have reduced the consumption of domestic hot water to 100 litres/person/day, but this is purely an assumption and real use may be different.

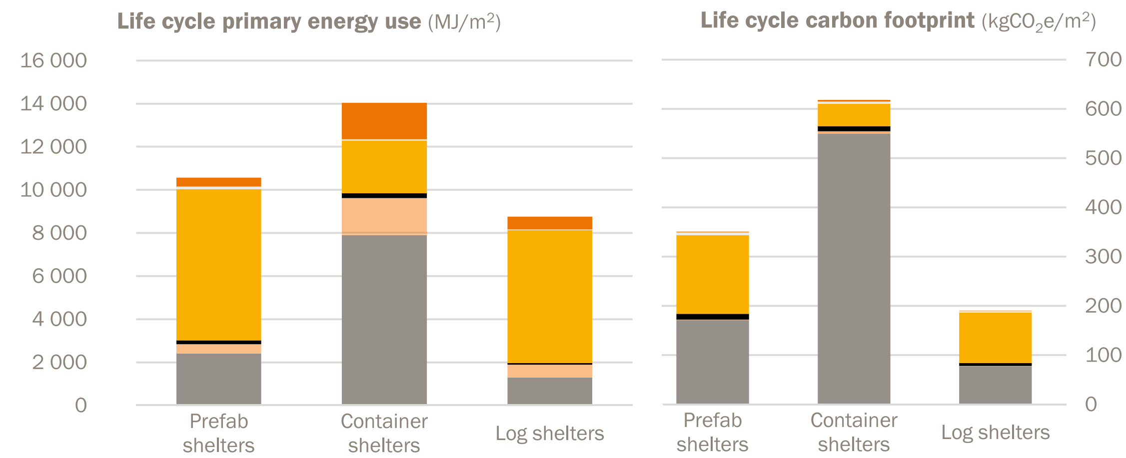
4. Results

4.1 The energy efficiency of shelters

Which of the shelters consume the least energy for heating, cooling, ventilation, hot water and electricity? Figure 3 shows the results of the energy simulation. The container shelters were found to be the most energy efficient. The annual energy consumption of the three-floor container shelters is 51% less than that of the log shelters and 65% less than that of the prefab shelters. The same trend applies for the carbon footprint of operative energy use.

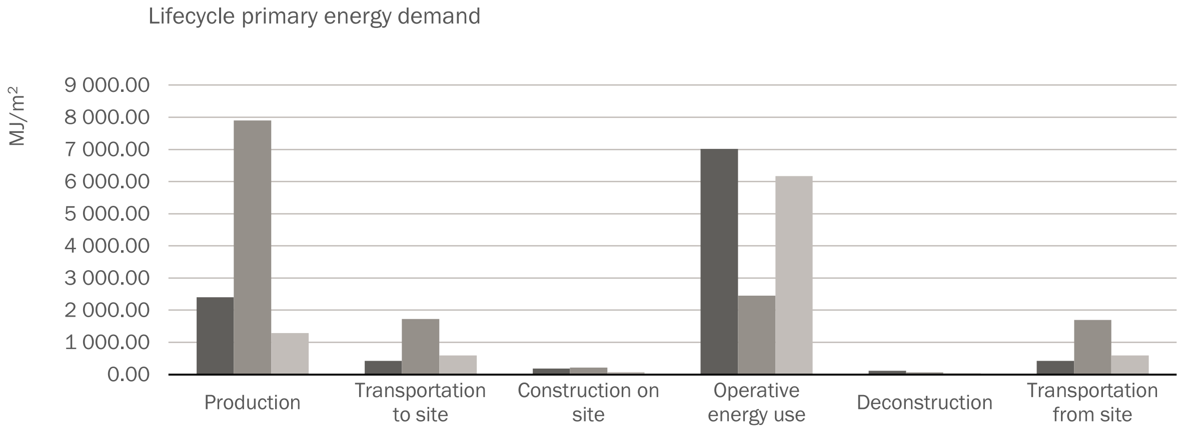
4.2 Life cycle energy use and the carbon footprint

However, the picture changes when the embodied energy and emissions are taken into account. Figure 4 shows the how each



	Prefab shelters (MJ/m²)	Container shelters (MJ/m²)	Log shelters (MJ/m²)	Prefab shelters (kgCO₂e/m²)	Container shelters (kgCO₂e/m²)	Log shelters (kgCO₂e/m²)
Transportation from site	426.79	1 697.41	592.63	0.78	3.11	1.08
Deconstruction	118.34	61.97	39.52	6.29	4.72	3.03
Operative energy use	7 012.03	2 447.92	6 172.22	159.80	45.39	102.71
Construction on site	186.23	215.42	77.77	11.37	10.54	5.89
Transportation to site	426.79	1 727.03	592.63	0.78	5.20	1.08
Production	2 404.72	7 895.76	1 289.61	171.34	548.95	76.74

Figure 3. Energy use in the studied shelters (left) and the resulting carbon footprint (right). Prefab and log shelters are close to each other in their performance, but the container shelter has considerably smaller impacts.



	Production	Transportation to site	Construction on site	Operative energy use	Deconstruction	Transportation from site
Prefab shelters	2 404.72	426.79	186.23	7 012.03	118.34	426.79
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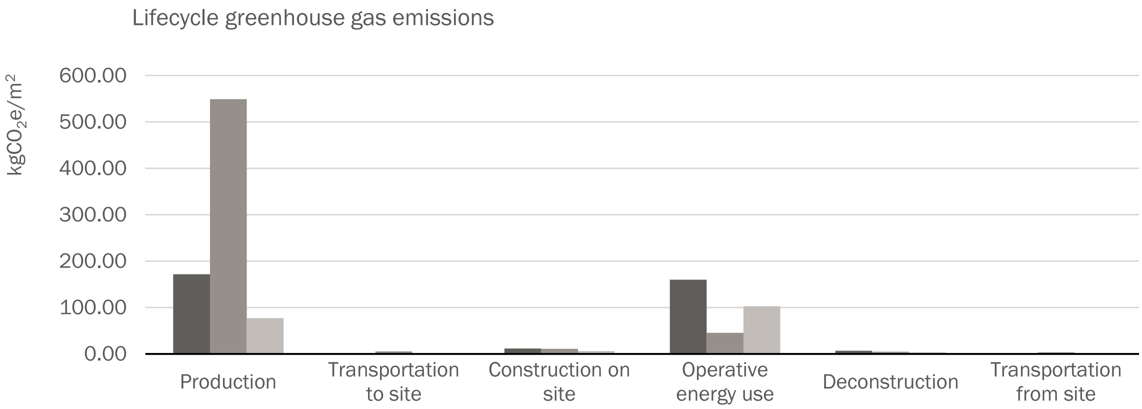


	Production	Transportation to site	Construction on site	Operative energy use	Deconstruction	Transportation from site
Prefab shelters	171.34	0.78	11.37	159.80	6.29	0.78
Container shelters	548.95	5.20	10.54	45.39	4.72	3.11
Log shelters	76.74	1.08	5.89	102.71	3.03	1.08

Figure 4. The primary energy demand (top) and GHG emissions (bottom) of shelters. The columns show the amount of energy and carbon footprint in each studied stage of the shelters´ life cycle. The production stage and operative energy use stage are dominant.

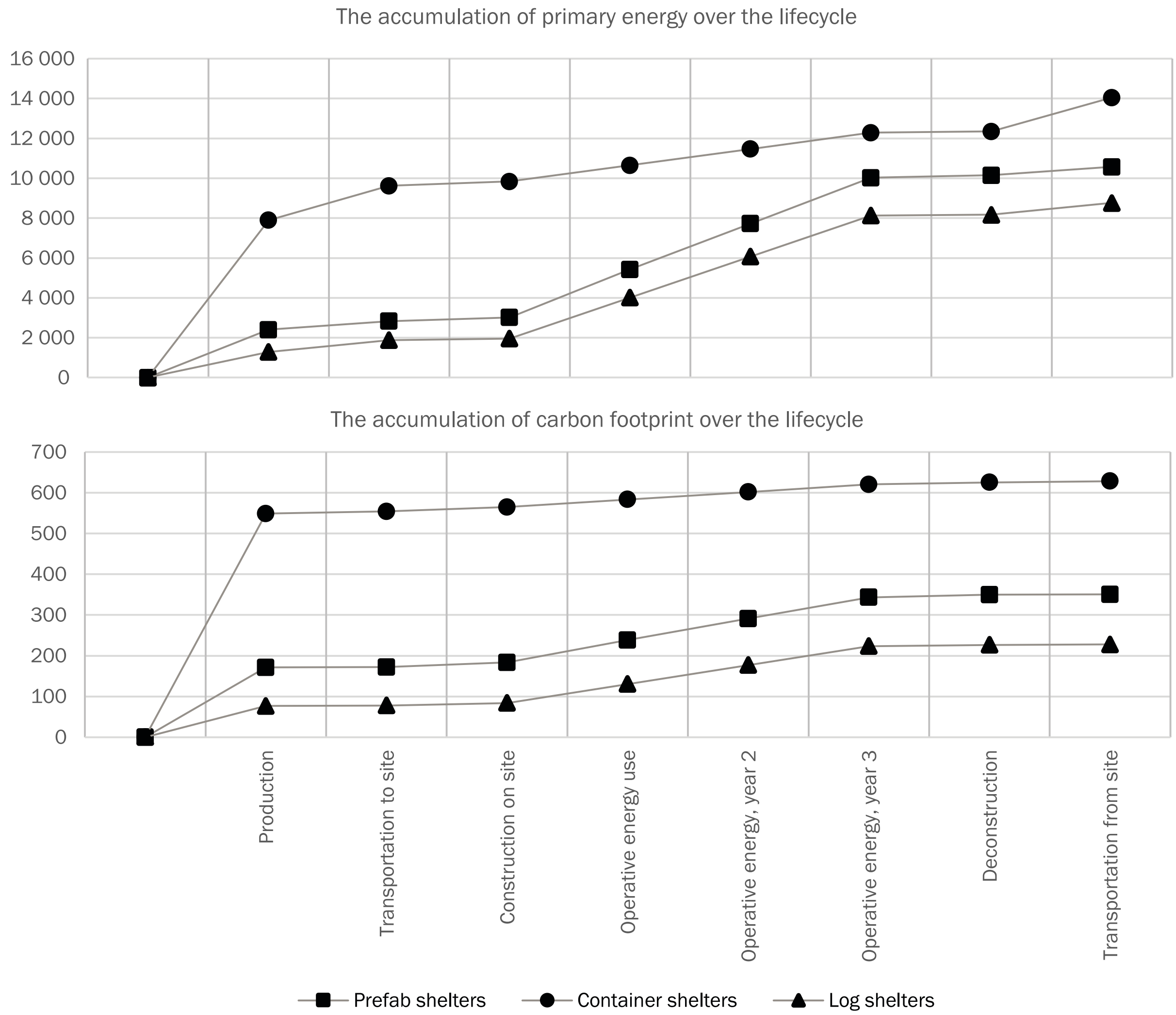


Figure 5. Primary energy demand (top) and GHG emissions (bottom) accumulation throughout an exemplary 3-year use of the shelters. The material selection sets the course and even a good level of energy efficiency is not enough to even out the differences during the short observation period.

stage affects the overall primary energy demand and carbon footprint of the shelters.

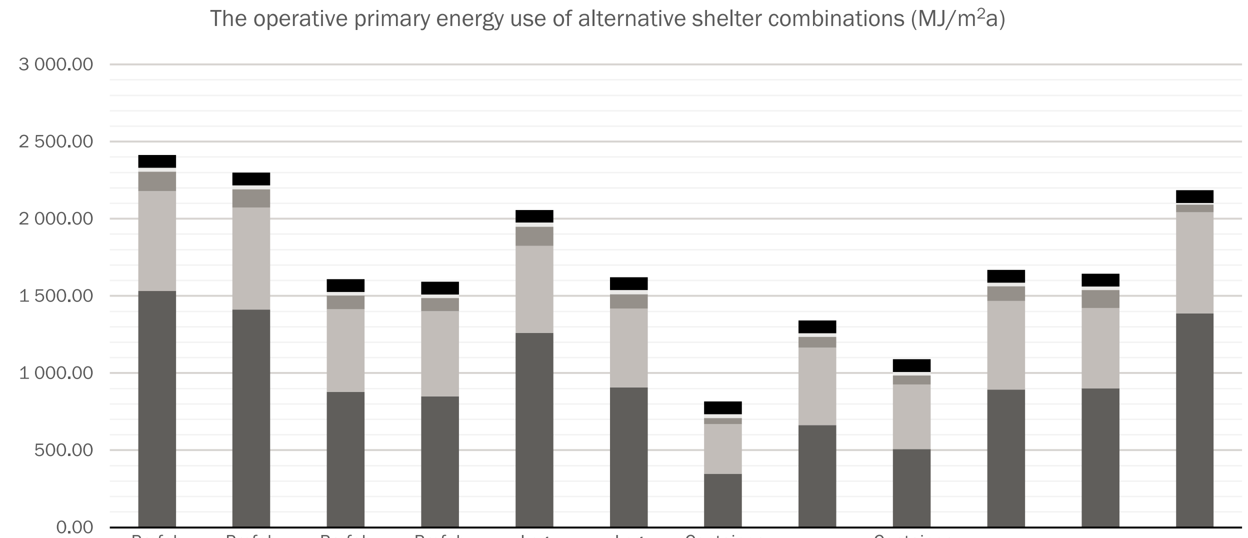
In the prefab and log shelters the operative energy use is dominant, representing 62% and 64% of the life cycle energy balance respectively. The container shelter shows a very different energy balance. Most of the energy (59%) is consumed in the production phase and less (14%) is required for the operation of the shelter. In all shelters the role of construction and deconstruction was marginal, ranging from 1–2%. Likewise transportation requires marginal energy in the case of prefab and log shelters but somewhat more for container shelters, which are heavier and partly transported from outside of Japan.

If we look at the absolute energy consumption per square metre of shelters´ floor area, the container shelters have the highest primary consumption over its life cycle. Log shelters consume the least primary energy. Although the container shelters are more energy efficient than the others, the short service life (three years) does not change their order.

The calculations and simulations show that the container shelters cause the largest carbon footprint over their life cycle. It is 187% higher than log shelters and 142% higher than prefab shelters. Most of the emissions of the container shelters are caused from the production stage (89%) whereas the operative energy use causes only 7% of its emissions. The balance is the opposite in prefab and log shelters: in their case most of the carbon footprint is caused by operative energy use (62% and 64%) and the production phase is clearly smaller (25% and 18%).

4.3 How do the impacts accumulate during the use of the shelters?

Figure 5 illustrates how each stage of the life cycle adds to the overall impacts of the shelters. The calculations reveal that although the container shelters are the most energy efficient during their use, this benefit is not enough to bridge the gap in impacts that are caused in their production stage. If the life cycle was longer than the studied three years, the prefab shelter would meet the primary energy consumption of the container shelters in five years and the log shelters would reach the level of container shelters after 10 years.



	Prefab shelter - original 1 floor x 4 units	Prefab shelter - improved 1 floor x 4 units	Prefab shelter - extended 1 floor x 8 units	Prefab shelter - improved 1 floor x 8 units	Log shelter - original 1 floor x 4 units	Log shelter - extended 1 floor x 8 units	Container shelter original 3 floors x 8 units	Container shelter - 3 floors x 4 units	Container shelter - original 2 floors x 8 units	Container shelter - 2 floors x 4 units	Container shelter - 1 floor x 8 units	Container shelter - 1 floor x 4 units
Equipment	82.76	82.76	82.77	82.77	82.77	82.78	82.78	82.77	82.78	82.77	82.77	82.75
Ventilation	24.79	24.57	24.69	24.69	26.81	26.80	24.81	24.80	23.85	23.87	23.61	11.86
Cooling	126.77	119.75	87.74	84.50	124.47	92.96	38.63	70.01	57.38	94.04	114.53	49.49
Hot water	646.90	660.95	536.65	551.40	562.30	510.34	323.07	502.44	419.54	575.04	521.50	654.84
Heating	1 531.92	1 411.41	877.44	849.26	1 261.06	908.21	346.68	661.79	507.21	893.50	901.19	1 386.99

Figure 6. Sensitivity analysis: studying the operative energy use of alternative shelter combinations. Simulations show that long shelter clusters have the highest relative energy efficiency.

5. Discussion and further comparisons

5.1 Does the amount of shelters have an effect on energy efficiency and emissions?

To investigate the effect of clustering shelters into rows or on top of each other we performed a sensitivity analysis. From the initial energy simulations (figure 3) it can be seen that the Onagawa container shelters clearly have better energy efficiency compared to the other shelters. This is partly due to the thermal properties of the structures. The structure of the container shelters includes polyurethane insulation, which has better thermal resistance than the mineral wool used in the prefab shelters or the bare log walls used in log shelters.

The main difference is that the container shelters are built in large units and consist of two or three floors in long rows. Previous studies (Takano et al., 2014) show that larger and multi-storey buildings have better energy efficiency than smaller buildings on average. This is because the area-to-volume ratio is more efficient in larger buildings. When apartments only have two external walls and share partition walls, floors and roofs with their neighbours, the heat losses are smaller. This is emphasized as the structures of the shelters are of moderate thermal conductivity. When such units are piled on top of each other, the relative savings in energy losses can be significant.

However, the shelters in different settlements have been arranged in a variety of combinations. The prefab and log shelters are arranged into terraced houses that typically consist of four to eight individual home units but are only one floor high. The container shelters differ from this setup being two and three floors high. To investigate if the grouping improved shelters' operative energy use and emissions, a simulation was made with different options. For the one-floor high log and prefab shelters we used a terraced house model either four or eight home units long. For the container shelters we simulated the energy efficiency of one-, two- and three-floor high groups that were either four or eight home units long. Figure 6 shows the results.

This analysis reveals that grouping the shelters in longer rows seems to be an effective way to improve their energy efficiency. The eight-unit long log and prefab shelters are better in their relative energy efficiency than shorter units. The same applies to the container shelters. If we compare a group of 16 shelters, a variation that has two floors by eight units is more energy efficient than a unit of three floors by four units. The main reason for this lies in the weaker insulation of the roofs of the shelters. Thus the energy efficiency of shelters seems to follow the economy of scale.

5.2 How does the energy consumption of temporary shelters compare to normal housing?

One could ask whether the assessment of energy efficiency and GHG emissions is at all relevant in the field of humanitarian construction. One way to look at the issue is to compare how much more or less the energy consumption changes per household in temporary shelters. By using the average household energy consumption from Murakami et al. (2006) we can simulate the differences. Figure 7 shows the comparison of energy use in different shelter clusters.

The chart reveals that in some shelters the annual energy consumption may be considerably lower than in average homes

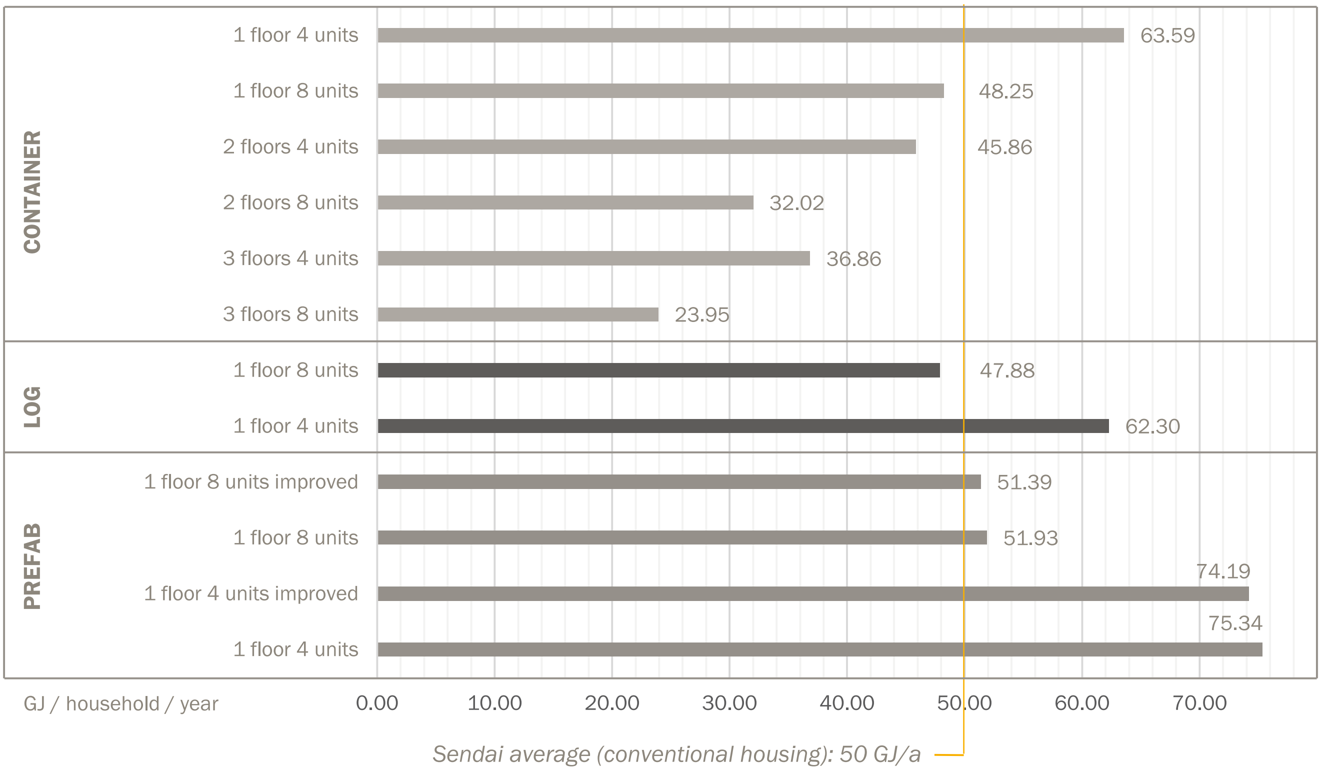


Figure 7. A comparison of household energy use in different shelter combinations and the normal households of the Sendai area.

in the Sendai area. The container shelters perform especially well in the simulation.

There are two main reasons for this. First of all, the shelters are very small. Their floor space varies from 27.47 to 32.27 m^2. Thus the shelters only have 29 to 34% of the average Japanese floor area in apartments, which is 94.85 m^2 (Ministry of Internal Affairs and Communications, 2013). The smaller the home, the bigger the housing density becomes on average. As a smaller volume of air is heated in the winter and cooled in the summer per household, the energy consumption from this can be less in shelters compared to normal housing. In temporary housing people live in smaller apartments than they normally would. Increased housing density lowers energy consumption and the related emissions.

The other reason is that in addition to energy consumption, the quality of life should therefore also be taken into account. In exceptional circumstances, living patterns adapt accordingly. The Spartan conditions of temporary living were assumed to change living habits, for example using less hot water.

It is noteworthy that the studied combinations of the prefab shelter show higher household energy consumption than the regional average. The prefab shelters are the most common type of temporary homes (Shiozaki et al., 2012) in the region. Therefore, although the log shelters and container shelters were simulated to be more energy efficient than average homes, the majority of the shelters were constructed in a manner that increased the household energy consumption without producing any improvements in the living conditions. From the calculations we can conclude that the overall societal impact of shelters has mostly increased the use of energy. An increased use of energy and a change in the Japanese energy mix towards more carbon intensive energy sources have led to increased residential GHG emissions from the temporary homes. However, there is always a difference between the measured and simulated energy consumption and drawing exact conclusions would require having access to the measured energy use data of the temporary homes.

5.3 Materials make a difference

The construction materials of the shelters seem to play an even more important role in the life cycle impacts of shelters than in conventional buildings that have much longer planned service lives. Several studies have already pointed out that using sustainably-sourced wood in construction makes the production of the frame of the building less GHG intensive when compared to concrete or steel for example.

In temporary shelters the same trend can be seen. The log shelters have the smallest embodied energy and GHG emissions values of all the compared design alternatives. Simple wooden structures do not require many processing stages compared to the manufacturing of steel and plastics. In addition to having lower embodied energy, the wood may also be burnt for bioenergy at the end of its service life.

5.4 The quality of temporary homes cannot be surpassed on environmental causes

The quality of temporary housing is an important issue. The psychological and physiological trauma of the survivors may in some cases be better healed with the proper design of the living environment.

The container shelters in Onagawa are an example of an exceptionally high architectural quality, which is rare in a humanitarian context. How much does that help the residents to heal from their traumas? It is difficult to compare the psychological or restorative aspects of a building into its technical and environmental features. The intention of the container shelters was to improve the living quality of the survivors and judging by the visited sample shelter it may have done just that. However, this is an exceptional case and may prove difficult to mainstream. Still it should serve as a key benchmark for the further development of an optimal quality of humanitarian housing. In the case of ordinary prefab shelters, improving their energy performance may significantly improve the living quality as well, especially considering the primary function of thermal comfort.

6. Conclusions and recommendations

This study has shown which factors have the main importance in the energy efficiency and carbon footprint of temporary homes. We conclude that:

- The construction materials of temporary homes play a key part in optimising their carbon footprint. Because the use period of shelters should be short, the energy used for the production of building materials and the related carbon footprint is of dominant importance. In this aspect the studied temporary homes seem to differ from most conventional buildings. Wooden shelters were found to be superior in this aspect.
- Clustering the shelters in larger units clearly improves their energy efficiency. Clustering into rows seems to be better than piling shelters on top of each other as in the latter option the need for additional structures and ensuring fire safety and accessibility increase material-related embodied energy and emissions. Clustering also improves the efficiency of land use.
- After a disaster the climate impacts of energy use may be affected either by the energy efficiency of temporary homes or by changes in the national or regional energy mix. In the studied case both scenarios happened simultaneously: there was a shift from nuclear power towards more carbon intensive fossil fuels and the average household energy consumption increased.
- In some cases the temporary homes may be better in their environmental and architectural quality than the previous permanent homes. This finding calls for the optimisation of temporary construction investments compared to reconstruction investments. Further analysis for disaster preparedness planning is required.

For increasing the accuracy in coming preparedness planning the following should be further investigated:

- The actual energy use of temporary homes: Adding meters for each settlement can easily be carried out. This information is crucial in setting proper energy use profiles for the energy simulations of temporary homes in each context. Humanitarian operators could start collecting and sharing information on the energy use of shelters and refugee camps.
- The construction and transportation of shelters for refugee camps: Documentation of the construction work for each proposed shelter type could be done by the companies offering shelter solutions. By gathering knowledge and comparing best practices the humanitarian community would have the facts for optimising the environmental impacts and speed of delivery in the set-up phase of transitional settlements.
- The end-of-life scenarios for different materials in an emergency context: Technical consultants in the humanitarian field should develop scenarios for the decommissioning stage of transitional shelters as a part of preparedness planning. These scenarios should include consideration for using the materials of the shelters for reconstruction or for easily recycling them into secondary products or into energy. This should be done together with the scenario setting for managing debris.

Finally, we recommend that a platform for collecting environmental data from emergency shelters, transitional settlements and reconstruction is established. An open data repository with annual analysis of new projects would empower humanitarian operators and governments to respond to urgent housing needs in a sustainable manner without compromising the humanitarian priorities.

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Annex 4

Setting the carbon footprint criteria for public construction projects

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Setting the carbon footprint criteria for public construction projects

Abstract

This paper describes a method for controlling the growth of the carbon footprint of buildings during the preparation, design and procurement stages of construction projects. The process utilizes prevailing cost estimation techniques. As an outcome, new indicators for carbon efficiency and carbon economy of buildings are proposed. They have been developed together with the city of Espoo in a research project that included carbon footprinting of existing buildings and arranging an architectural competition for a low-carbon public building. Both carbon efficiency and economy seem to offer flexible opportunities for an integrated comparison of the environmental and economic sustainability of buildings.

Keywords

Carbon footprint, carbon efficiency, carbon economy, public buildings, design, procurement, cost estimation.

1. Introduction

1.1 The relevance of carbon footprinting of public buildings

The Nordic Built Charter (2012) – signed by more than 120 cities, companies and organizations – states ten principles for the future built environment. Among these is "zero carbon emissions over the full lifecycle" of a building. Indeed, drastic reductions in anthropogenic greenhouse gas (GHG) emissions are required if we wish to avoid the severe risks (Hansen et al., 2013) that may follow anthropogenic climate change.

As we move towards nearly zero energy buildings, nZEBs (European Parliament, 2010), we need to widen our perspective from the emissions of operational energy use. After all, new buildings will reach nZEB class by 2020; the dominance of emissions seems to change. The relative dominance of the use phase – lifecycle module B6 according to standard EN15643-2 (CEN, 2011) – of the building seems to decrease and the impact from the material production phase (lifecycle modules A1-3) seems to increase (Hafner, Ott and Winter, 2013). This trend is reinforced by the decreasing carbon intensity of energy (IPCC, 2014), although some studies have found that the decarbonization of energy may slow down in the future (IEA, 2014).

Material selection may change the carbon footprint of energy efficient buildings considerably (Kuittinen, 2013). It has also been found that alternative construction materials may lead into greatly differing weights of building parts thus influencing the emissions of the complete building (Pasanen, Korteniemi and Sipari, 2011). Thus there is a growing need for developing methods for estimating and managing the accumulation of carbon footprint throughout the full lifecycle of the building.

1.2 New approaches needed

In design work, there will likely be needs for estimating the dominance of emissions associated with the lifecycle stages of a building, especially in the production and operation phases. The design process of a building today can benefit from energy simulation tools that allow the architect to simulate how iterative changes affect the energy performance of a building. A similarly practical and widespread method is not, however, used for tracking the carbon footprint of construction products. Several BIM-based (VTT, 2013; Liukka, 2014) and standalone (VTT, 2013; Finnish Environment Institute, 2013; Bionova 2014) estimation tools have been developed, but they have failed to gaining wider use. This is partly due to the legal need to calculate the energy certificate for buildings (Ministry of the Environment, 2013) while no requirement for calculating the carbon footprint exists.

Yet, environmental assessment interventions may have considerable impact on the carbon footprint of a building. For instance, the design of the new office for WWF in Woking, UK, included environmental assessment for minimizing the GHG emissions. Lowenstein (2014) found that during and after the design phases the carbon footprint of the building could be reduced from 16 510 to 10 920 t CO_2e. This improvement was the result of comprehensive lifecycle assessment and iterative comparison of alternative technical solutions.

From an economic perspective there exists the need for optimizing the payback times of investments that are needed for nZEB´s both in terms of money and GHG emissions. For example, Becchio et al. (2014) found out that the global cost of nZEB solutions is still (in 2014) from 212 to 313 €/m^2 more expensive than standard solutions. Liu, Gao and Hu (2014) discovered that if only incremental economic benefits of energy efficiency applications are observed, sustainable buildings seem to have poor potential for market investments. However, it will be considerably more expensive to postpone the mitigation of climate change than to take action now (World Bank, 2012).

1.3 Green public procurement yet to reach its potential

The revision of the EU´s procurement directive (European Parliament, 2014) aims at "facilitating a better integration of environmental considerations in procurement procedures" (European Commission, 2014). Based on the revision of the directive, public purchasers can now decide to choose the product or service based solely on its environmental performance. Therefore the public procurement of construction products requires reliable and transparent practices for rewarding the least harmful environmental impact of the purchased product or service.

However, difficulties have been reported in the recent implementation of green public procurement (GPP) criteria. For example, Alhola (2012) discovered that Finnish public procurers have not known how stringent environmental criteria can be demanded and therefore the criteria have been set low. Sporrong and Bröchner (2009) found out that only 30% of Swedish municipalities used environmental awarding criteria when purchasing design services. Of them, almost 40% reported difficulties in the awarding of the environmental criteria of design services. To unleash the potential of the revised directive, procurers need practical instruction for setting the GPP criteria of building products and design services.

Life cycle assessment (LCA) has been proposed as the most comprehensive means for environmental awarding of different products in GPP (European Commission, 2014b). However, this may, in many cases, require an external LCA consultant and thus make the procurement process longer. Today, the calculation of the carbon footprint of buildings is still a specialty. It is not commonly carried out in public or private building projects, apart from pioneering building projects or architectural competitions.

2. Materials and methods

2.1 Collaboration with the city of Espoo

Because of steady population growth in Espoo, the second largest city in Finland, there is constant demand for new kindergartens and schools. The city aimed at implementing its climate action plan (Espoo, 2011) while developing a concept for new kindergartens. The project was carried out with Aalto University, which is located in the same city, and aimed at development of a simplified carbon footprint management method for the city's building department. Intermediate goals included arranging tutored design competition for a new low-carbon kindergarten project, calculating the carbon footprint of the city's existing public buildings and assessing the m^2-based carbon footprint of typical structure types that are used in public buildings.

2.2 Calculation of the carbon footprint of existing public buildings in Espoo

Three recently built kindergartens and one school were carefully analyzed. The carbon footprint from the production phase of their construction materials was calculated according to standards EN 15978 (CEN, 2011b) and EN15804 (CEN, 2014) using ICE 2011 dataset (University of Bath, 2011). In addition to the emissions, also biogenic carbon storage of wood-based construction materials was calculated according to standards EN 16449 (CEN, 2014b) and EN 16485 (CEN, 2014c). Inventory was based on the exhaustive bills of the quantities from the procurement phase of each project. Structural details were checked within construction drawings and by interviewing structural designers and project managers. The exclusion of other lifecycle phases than A1-3 was made based on the hypothesis that lifecycle modules B6 (operative energy use) and A1-3 (production) have been found to be the dominant for the accumulation of GHG emissions, as described in chapter 1. Building service components were excluded, as they are not listed in the structural cost estimation documentation and there is generally no information for their environmental impact in data sets. In future studies it would also be important to include their GHG emissions, as they may in some cases be significant (Lowenstein, 2014).

2.3 Workshops for promoting carbon footprinting through an architectural design competition

The aim of the competition was to design the concept of low-carbon an energy-efficient kindergarten for the city of Espoo. The assignment included the design of buildings, their energy concept, parks and playgrounds as well as the immediate infrastructure of the development. Five teams were selected for the competition, each consisting of architects, landscape architects, structural engineers, energy consultants and infrastructure planners. To ensure that each team would have the same starting level for designing low-carbon buildings, a series of lectures and workshops was arranged by Aalto University. The workshops were followed by the actual design competition. After the competition entries were handed in, carbon footprint estimations were done for the buildings and for the park, including the carbon sequestration of urban trees. Calculation results were given to the jury.

3. Results

3.1 Current level of carbon footprint in public buildings

Calculation results are divided into GHG emissions (Figure 1) and biogenic carbon storage (Figure 2). Results are broken down into building parts according to the classification commonly used in cost estimates.

The results reveal the importance of using a proper functional unit for the assessment. For ground works, foundation and exterior structures (building part categories 1 and 2 in Figure 1) a relevant functional unit seems to be $1m^2$ of site area. The amount and type of ground work is directly related to the area and soil condition of the site. Likewise, the foundation type is dependent on the soil type, although the selected structural system has an influence as well. However, from the viewpoint of allocating emissions, it can be argued that foundation-related emissions are more subject to the particular site in question.

For structural parts that are directly related to the building (categories 3–5 of Fig. 1), $1m^2$ of buildings´ gross area seems to be the relevant unit. If gross-m^2-based functional unit would be used for e.g. ground works, the results would not describe the amount of emissions that are caused by different sizes of the sites. Similarly, if the site area-based functional unit would be used for describing emissions caused by structures of the building, the results would be distorted as the area of the site and of the building have no influence on each other in terms of GHG emissions.

The carbon footprint calculations also reveal that in some cases the biogenic carbon storage of wooden building parts in the frame and roof may lead to significant emission savings during the production phase of the building (Figure 2). It has to be noted, however, that the same savings are to be amortized over the full lifecycle of wood-based construction products following the corresponding flows of biogenic carbon (see EN 16485, chapter 6.3.4.2). Still, as wood-framed buildings are lighter per m^2 than the corresponding concrete-framed buildings, lower average emissions may be achieved.

3.2 Tutored carbon footprinting can improve the results of an architectural competition

The experience from the tutored design competition of a kindergarten in Espoo proved that with a moderate intervention – workshops and lectures – it seems to be possible to influence low carbon design. Some entries included novel ideas for minimizing the carbon footprint of the buildings. One of the entries demonstrated the potential of optimal landscape architecture: the carbon uptake of planted park trees during 50 years was equal to the emissions from the production of construction materials of the buildings on the same site. The experience proved that universities and research institutes can help cities to implement their climate strategies into public building projects.

The selected kindergarten concept did not perform best in terms of carbon footprint or energy efficiency. However, they were not the only criteria. The integration of carbon footprinting into the multi-criteria awarding process can be considered as a new viewpoint to the decision makers. Therefore it has potential for infiltrating gradually into forthcoming building projects.

3.3 Development of a simplified assessment method for the city of Espoo

The observations from the tutored design competition and the findings from the carbon footprinting of existing buildings were used for developing a method for managing the carbon footprint of buildings during their design stage. The method consists of development of design reference values in the form of a catalogue of typical structure types including their m^2-based carbon footprint and costs. These reference structures can be used in the preliminary planning phase of a building.

Below-ground construction materials and external materials (for, e.g., fencing, parking lots and playground structures) vary greatly depending on the size of the site and its soil conditions (see Figure 1). Therefore, especially in the preliminary planning phase, it is more relevant to tackle the emissions that can be altered rather than taking the burden of estimating the carbon footprint of building parts that are closely related to the given site. However, it would be very important to tackle the climate impacts of the latter as well, when it comes to city planning and site selection.

4. Conclusions: Introducing carbon efficiency and carbon economy

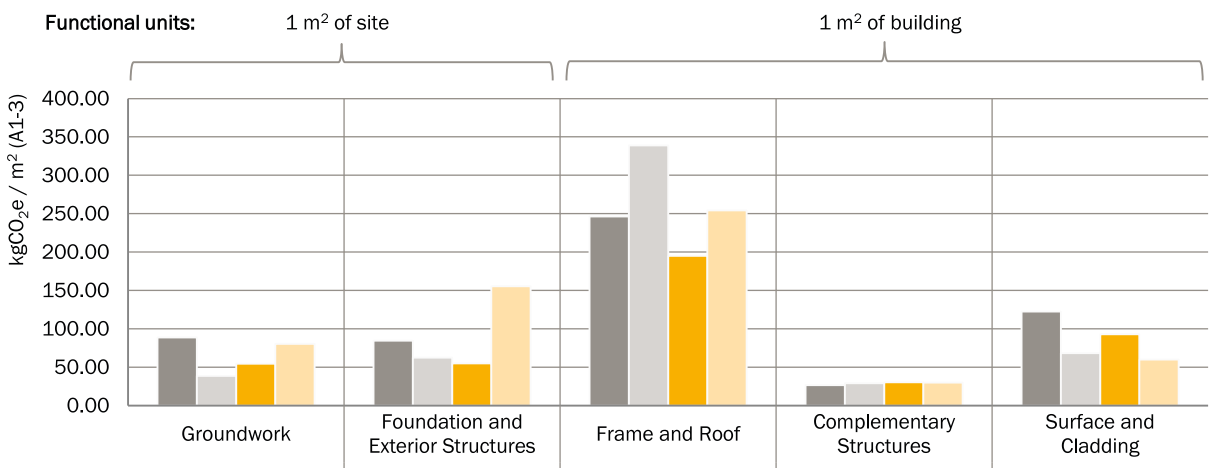
4.1 Carbon efficiency is the ratio of embodied GHG emissions and operative energy use

The main finding is in the cross-comparison of GHG emissions, energy demand and construction costs of the case study buildings. The ratio of these indicators may be more important than observing any of them separately. Instead, a flexible method for optimizing the “carbon efficiency” of the building could be used. It can be defined by utilizing the information from existing documents that are usually required in the building permit application.

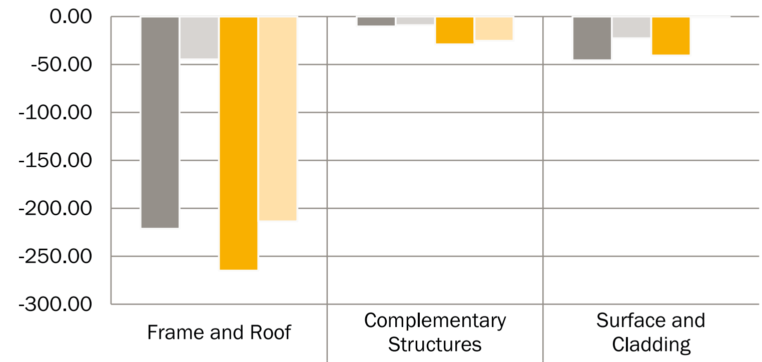
Carbon efficiency is derived from the output of GHG emissions from the production phase of the building and operative energy demand (E-value). Carbon stored in wooden parts is not included in the equation, as it will be released back into the atmosphere in the end-of-life stage.

Traditionally, efficiency (r) is understood to be the ratio of desired output (P) to inputs (C): $r=P/C$. The greater the number, the greater the efficiency. In our case we have chosen to aim at low figures by multiplying the factors instead of dividing them, as shown in formula 1. This way the outcome is understandable in comparison to other

Figure 1. Greenhouse gas emissions from the production phase of the studied buildings.



	Groundwork	Foundation and Exterior Structures	Frame and Roof	Complementary Structures	Surface and Cladding
Building 1	88.88	84.51	246.39	26.52	122.41
Building 2	38.64	62.34	338.90	28.99	68.40
Building 3	54.43	55.03	195.23	30.21	92.89
Building 4	80.34	155.45	254.10	29.94	60.09



	Frame and Roof	Complementary Structures	Surface and Cladding
Building 1	-221.40	-10.40	-45.80
Building 2	-44.70	-9.17	-22.90
Building 3	-264.91	-29.11	-40.87
Building 4	-213.70	-25.50	-1.10

Figure 2. Biogenic carbon storage of the wooden parts during the production phase of the case study buildings.

Formula 1. The carbon efficiency of buildings.

Carbon efficiency= (C x E)/1000

Carbon economy of buildings = (C x E x €$_B$)10^{-7}

C = GHG emissions from the production phase (kgCO_2e/m^2)

E = Operative energy demand (kWh/m^{2}a)

€$_B$ = Construction costs of the building per m^2

Table 1. Exemplary calculations of the carbon efficiency of case study buildings. Lower values indicate better performance. Building 4 has the second lowest carbon footprint but clearly the best energy efficiency, being a passive house. Therefore it has the best overall carbon efficiency and carbon economy. Building 3 has the lowest carbon footprint, but the weakest energy efficiency, thus not scoring well.

	Building 1	*Building 2*	*Building 3*	*Building 4*
Gross building area (m^2)	1 288.00	10 546.00	498.50	1 475.00
Carbon footprint (above ground, A1-3) $kgCO_2e/m^2$	395.32	436.29	317.37	348.79
Operative energy use $kWh/m^2/a$	168.00	119.00	242.00	94.00
Construction cost EUR/m^2	3 504.84	2 996.21	3 011.38	4 152.08
Carbon efficiency	**66.41**	**51.92**	**76.80**	**32.79**
Carbon economy	**23.28**	**15.56**	**23.13**	**13.61**

environmental performance factors – such as energy efficiency and carbon footprint – which are lower the better the performance gets. For ease of use, the digits have also been modified.

Carbon efficiency enables case-specific flexibility for the design and operation of the building. Efficiency is improved if carbon footprint of the construction products is lowered. Alternatively, efficiency can be improved by lowering the energy demand of the building. This enables designers and project managers to find out the most feasible way of reaching climate-conscious solutions.

Public building projects are different from each other. For example, soil conditions may lead to extensive stabilization or piling. This will give the building frame a large carbon footprint regardless of above-ground material choices. Available energy mix, on the other hand, may be carbon-intensive or it may not be possible to utilize on-site energy. In such case the operative energy use GHG emissions will grow and burden the buildings' lifecycle carbon footprint.

Furthermore, by including carbon efficiency into sustainability assessment, the lifecycle coverage is broadened. Ideally, the full lifecycle should be studied. However, in typical public building projects, such a comprehensive analysis may often be too demanding. Therefore carbon efficiency is a realistic step towards full lifecycle assessment.

4.2 Carbon economy and other cost-related indicators

In addition to optimizing carbon efficiency as described above, the relation of construction costs and lifecycle carbon footprint can be optimized for better "carbon economy" of public buildings. This is done by simply multiplying the m^2–based GHG emissions and operative energy use with construction costs.

In addition to carbon economy there are several other cost-related indicators that may be worth studying. For instance, the ratio of carbon efficiency and lifecycle costs of the building gives information about the economic and environmental performance of the life cycle of the studied building. The ratio of operative energy demand to construction costs informs decision makers how soon the investments that are made for the improvement of energy efficiency can be amortized via savings of operative energy use, given that the price trend of energy can be reliably defined. Together with the optimization of buildings life cycle costs, carbon economy may improve the environmental comprehensiveness of economic decision making in public building projects.

4.3 Setting the system boundaries for carbon footprinting in public building projects

Defining clear and understandable criteria for GPP awarding has proved to be challenging (see chapter 1.3). EN standards have been proposed in the GPP guidebooks for criteria setting. Standard EN15978 states that the system boundary for environmental assessment of buildings shall include the entire building and site, including temporary structures and scaffolding. Based on the findings of this study it can be argued, however, that the system boundary for GPP criteria setting should be limited to only frame and roofing, complementary structures and claddings (categories 3-5 of Figure 1).

Using such boundary would make it considerably easier to compare which of the offered structural solutions has the least GHG emissions on the given site. Furthermore, this practical system boundary would also enable construction companies to use environmental product declarations for their building products or buildings without having to assess the environmental burdens associated with construction conditions on each site. However, environmental impacts for groundwork, landscaping and external structures should be assessed separately.

By making a division on the carbon footprinting of building and site, it would be possible to propose that the busy building permission authorities and project managers could take the essential step into the world of carbon footprinting in public building projects.

5. Summary

This study has shown how existing documentation methods can be utilized for defining the carbon footprint of construction materials in different phases of a design and construction project. The existing processes of cost estimation provide valuable data for this definition.

The proposed new indicators, carbon efficiency and carbon economy, are steps forward in the evolution of climate-conscious buildings. First, they introduce the carbon footprint of construction materials as an elemental part of a building's sustainability assessment. Secondly, they enable flexible strategies to reach good carbon efficiency and are thus suitable to different contexts. Thirdly, they help to describe the economic dimension of sustainable construction.

To reach these indicators, it is important to set the functional units of comparison right. As described in this study, the area of the site can be used as functional units for the carbon footprinting of groundwork and foundations, whereas the area of the building is the appropriate functional unit for carbon footprinting of structural parts of the building.

Furthermore, it could be observed that modest interventions to design work of public buildings help to mitigate GHG emissions. Especially in architectural competitions, focused seminars and tutoring can improve the environmental quality of design.

Finally, widening the sustainability assessment of public buildings by introducing carbon efficiency does not require major changes in design processes. It only requires cross-comparison of data that is already being documented. Optimization of carbon efficiency may significantly deepen the understanding of the interdependence of energy and material use in buildings. This enables designers and authorities to improve the environmental and economic sustainability of our built environment.

In order to reach ambitious climate goals – such as described in the Nordic Built Charter – more than incremental changes are needed. Carbon efficiency and carbon economy should be tested in the public construction sector so that their potential in mitigating the GHG emissions of the construction sector can be quantified and taken into practice.

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Annex 5

Strategies for low carbon humanitarian construction

Matti Kuittinen, 2015

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Strategies for low carbon humanitarian construction

Abstract

Due to climate change, the number of refugees is estimated to reach 1 billion by 2050. Building temporary shelters and reconstructing homes even for a fraction of the future refugees would give rise to significant greenhouse gas emissions (GHG) to further accelerate the man-made climate change. Due to high degree of context-related differences in each humanitarian construction project, it would be extremely challenging to fix the maximum values for GHG emissions linked to reconstruction work or operative energy use. Instead, setting the target GHG levels based on per capita emissions in the specific country would give humanitarian aid organisations and funders a static point of reference in a path towards a sustainable built environment. This paper presents a model for robust strategic evaluation of GHG emissions associated with humanitarian construction activities.

Introduction and background

The number of refugees is likely to exceed 1 billion by 2050 (Baird et al., 2007, p.7). This is partly due to climate change (UNISDR, 2012; Brown, 2008). Extreme weather events, sea-level rise (Hansen et al., 2013, p.6) and conflicts based on these are forcing great numbers of people to leave their homes. When the number of refugees increases, also the environmental impact of emergency aid increases – unless current emergency response practices can be improved.

In developed countries, it is estimated that the construction sector and the built environment sector generally are the dominating sources of greenhouse gas emissions. According to UN, the construction sector is globally accountable for around 30% of anthropogenic greenhouse gas emissions and around 40% of primary energy use (UNEP, 2009, p.3).

Nearly all developed countries have regulations for sustainable construction and environmental impact assessment. Several of these are linked to the ISO 14040 standard suite for life cycle assessment and ISO 21930 Sustainability in building construction (ISO, 2009). European norms have also been actively developed so that the environmental assessment of buildings and construction products would be standardised and comparable (CEN, 2012). In addition, voluntary certification schemes, such as LEED, BREEAM, HQE and DGNB, are actively used in the construction and real-estate markets.

There are only a handful of instruments for environmental assessment of humanitarian construction. Pioneering contributions, such as Checklist-Based Guide to Identifying Critical Environmental Considerations in Emergency Shelter Site Selection, Construction, Management and Decommissioning (Kelly, 2005) or WWF Tsunami Green reconstruction guidelines (WWF, 2005) were useful, but rather general in their approach. Especially their coverage of issues related to climate change was limited.

Mitigating climate change needs rapid action. It can be considered as a key environmental social and economic challenge for humanity. Therefore, this paper focuses on mitigation of climate change. Furthermore, greenhouse gas emissions are chosen as the central environmental indicator, because they are of main importance in the man-made climate change (Hansen et al., 2013, p.1).

Wealthy and developed countries are main donors for humanitarian aid (Global Humanitarian Assistance, 2014). If they would apply their existing environmental goals and regulations into humanitarian aid, then the assessment of environmental impacts should be internationally standardised and promoted in chosen fields of humanitarian assistance. However, it is not known how the environmental norms prepared in the developed countries fit into the very complex humanitarian aid processes, construction of emergency shelters or temporary homes, for instance. Furthermore, the use of environmental norms may not be required in countries that receive humanitarian assistance or they may not have capacity to control that environmental standards are met directly after a catastrophe.

Therefore, a strategy is needed to guide the environmental assessment of humanitarian construction. This paper presents a draft method for setting the target levels for greenhouse gas emissions through the phases of humanitarian construction.

Material and methods

This study was made by comparing the results from my field assessments (Haiti 2010–2011 and Japan 2013), greenhouse gas calculations of transitional shelters (Kuittinen and Winter, 2015) built by the International Federation of Red Cross and Red Crescent Societies (IFRC, 2011) and energy simulations of temporary homes in Japan (Kuittinen and Takano, 2016). The results of these background studies were used as research material in this paper and are summarised below.

Background study 1: Carbon footprint of transitional shelters by IFRC

The carbon footprint assessment of eight transitional shelters was based on technical drawings and bills of quantities provided by the IFRC. Standard EN 15978 was followed in the calculation of greenhouse gas emissions. The system boundary included the production of construction materials, as other data was not available. Database ICE 2.0 from University of Bath was used for calculation of environmental impacts. The study revealed that the greenhouse gas emissions from the construction materials of the transitional shelters range from 28% to 6 504% of annual average per capita greenhouse gas emissions of each corresponding country. Such a large deviation results mainly from highly differing shelter designs. It could be concluded that façade and roofing materials, especially, played important role in the carbon footprint of the studied shelters.

Background study 2: Life-cycle energy efficiency of temporary homes in Japan

The intention of this field study was to investigate the balance of operative and embodied energy and GHG emissions of refugee camps in the Sendai area, Japan. Calculations were done for the most typical transitional shelter model built by the local prefecture. Furthermore, energy simulations for these shelters were carried out by modelling the buildings in building information modelling software (ArchiCAD) and thereafter running an energy simulation with a simulation software (EcoDesigner). The building services of typical temporary homes were used in the simulation of energy supplied and emitted per month. It was concluded that the operative energy demand exceeds the embodied energy of construction materials already during a 3.5–year lifespan of the shelters. In terms of carbon footprint, the tipping point comes later, around 4.5 years after the construction. However, when the basic shelter model was compared to alternative designs based on wood or re-used steel containers, there was much more deviation. Especially wooden shelters seem to perform well in terms of carbon footprint.

Phases of humanitarian construction

Humanitarian construction work is typically divided into three phases: emergency phase, transitional (or temporary) phase and reconstruction phase. Construction activities in the emergency phase usually consist of delivery of emergency shelters, if a centralised facility for emergency accommodation is not available. Emergency shelters, typically, are prefabricated tents, but in some cases only tarpaulins may be provided. The emergency phase may last from a couple of weeks to half a year. Thereafter, the emergency accommodation is ideally replaced with transitional shelters. They are made in more durable and may be used from 6 months to several years, depending on the case. There are international guidelines for the minimum requirements for shelters in emergency and transitional phases (Sphere Project, 2013), but they cannot always be met. After the transitional phase, the reconstruction phase follows. It includes rebuilding the homes and municipal infrastructure of the displaced population. Disaster risk reduction (DRR) strategies should be integrated into the reconstruction projects.

Results

The difficulty of setting fixed carbon footprint values for humanitarian construction

When examining the results previously referred to, it became obvious that it is not possible to recommend fixed values for the greenhouse gas emissions of humanitarian construction. There is simply too much case-specific deviation, and there are too many points of uncertainty in the assessment. Emissions associated with the production of construction products (e.g. a brick) differ in accordance with the energy that the producer used and the exact material combination of the product. Furthermore, operational energy demand may be satisfied with various sources of energy that all come with differing greenhouse gas emissions. These differing emission values depend on the efficiency of energy production and on national energy mix. Life cycle assessment (LCA) may not be feasible in humanitarian projects. A conventional, process-based LCA would suffer from large degree of uncertainty because of the lack of accurate specific or general data. Economic input-output LCA would be hard to perform as well, as the required national statistics may not be available for developing countries and may not be applicable for a developed country that has suffered a major disaster. Therefore, an alternative robust approach has been developed.

Per capita emissions as reference value

Taking the greenhouse gas emissions (GHG) per capita as a reference for comparing the global warming potential of humanitarian construction activities would provide humanitarian actors and consultants with a robust mitigation method that is context-related and therefore takes into account the variable circumstances of individual countries.

In brief, the process for mitigating per capita GHG emissions can be built with the following steps:

1. Documentation of normal annual per capita GHG values for construction in a specific country.
2. Setting a goal for the desired lowered per capita GHG emissions after the reconstruction phase.
3. Setting the maximum allowed per capita GHG peak accumulation values arising from the construction process.
4. Providing the relevant stakeholders with practical recommendations for reaching the targets.
5. Monitoring and providing required assistance during the construction process.

Steps 2–4 need to be carried out with all relevant stakeholders. Especially participatory planning practices should be utilised so that end-users would be actively engaged in the process of lowering household GHG emissions.

Ideally, the reconstructed homes should operate with GHG emissions that are lower than before the disaster. This would mean rebuilding better and with the climate in focus. Per capita GHG emissions give a static point of reference for the outcome of the reconstruction. However, the GHG peak due to reconstruction work should be kept moderate. Because of the timely importance of avoiding GHG emissions, the "payback time" of any single ton of CO_2 emitted into the atmosphere should be minimised. This means that the GHG emissions from the reconstruction should soon become amortised by clearly lowered GHG emissions from the operation of the building, e.g. energy demand for heating and cooling.

The described steps can be explained with the help of Figure 1. It is arranged along the phases of a generic humanitarian construction project, but may be adapted into a differing process as well.

Per capita GHG emissions of a reference year

The starting point in the proposed approach is formed by the annual per capita greenhouse gas emissions of the country ("GHG-a" in Fig.1). If it is not known how much of the national GHG emissions are caused by the built environment, the average value of 30% by UNEP (UNEP SBCI, 2009) can provide a rough starting point for the evaluation.

The concept of "per capita" emissions and emission rights is being debated. There are alternative methods for documenting, calculating and allocating emissions (IPCC, 2007). In addition, the share of building-related GHG emissions from total per capita emissions may not be known with sufficient accuracy. Still, the existing dataset of the World Bank (The World Bank, 2012) gives a stable point for estimation.

There is seasonal fluctuation in the GHG emissions of each country. Fluctuation in household energy demand is typically caused by increased heating demand during cold periods or increased cooling demands during hot periods. The intensity of

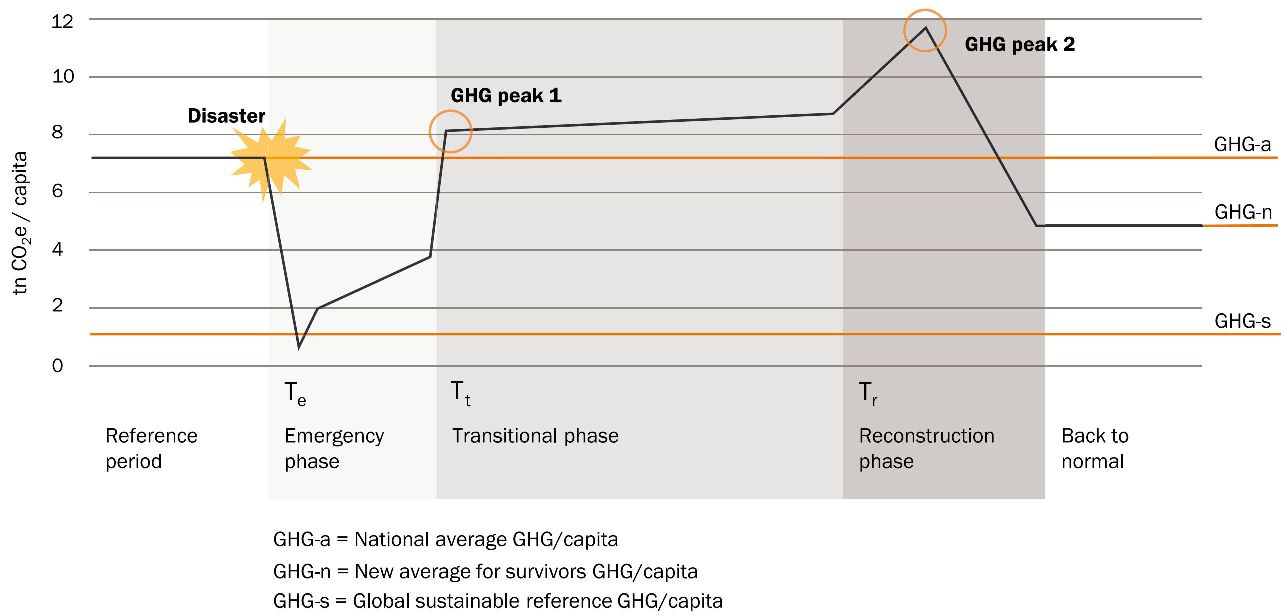

Figure 1. GHG emissions and phases of humanitarian construction.

the fluctuation of household energy use depends greatly on the climate zones.

When a disaster occurs and people are displaced from their homes into emergency shelters, the GHG emissions from housing presumably sink first. This is linked to significant reductions in the availability of energy for heating, cooling, cooking or other household activities. There may be case-specific differences, however.

Reconstruction with lower GHG

References for the new, lowered per capita GHG emissions ("GHG-n" in Fig.1) from construction work and operational household energy use may be obtained from national climate goals, guidelines and aspirations of the funders of humanitarian construction operations (e.g. the World Bank), or be based on recommendations for sustainable level of per capita emissions. The level of "sustainable per capita emissions" ("GHG-s" in Fig.1) is dependent on the global goal. A candidate value could be 0.3 t. of carbon per capita, if a 450 ppmv reduction target is aimed at (IPCC, 2001). This target value, however, is very ambitious.

GHG accumulation between the disaster and reconstruction

GHG peaks ("GHG peak" in Fig.1) will arise whenever new material or energy input is required for repairing shelters or when emergency shelters are replaced with transitional shelters. These peaks may be unavoidable, as the provision of adequate living conditions should not be risked. However, the magnitude of the peaks may be controlled by controlling the embodied energy and embodied GHGs of construction materials, transportation distances, machinery required on the construction site and, finally, by controlling the energy efficiency of shelters and the GHG emissions associated to the production of energy.

In addition to the GHG peaks, there are operational GHG emissions during the emergency and transitional phases. Operational GHG emissions are volatile because they are caused by the changes on the demand side, such as energy and material input, to meet e.g. seasonal weather changes. However, certain supply side changes may cause differences to operational emissions as well. For instance, changes in national energy mix are an example of the latter. After the Great Eastern Tohoku Earthquake (2011) in Japan, majority of nuclear power plants were made idle for safety reasons. The resulting shortage of energy was met with much more GHG-intensive sources of energy, such as imported natural gas.

According to calculations, GHG emissions from the construction of transitional shelters and from their energy use may be clearly higher than during reference years (Kuittinen and Winter, 2015). There may be large unrecognised potential for lowering the GHG emissions of this phase by selecting construction materials and energy supply based on their GHG intensity.

Discussion and conclusions

Advantages of the proposed method

Choosing per capita GHG emissions is likely to give the following advantages:

- Suitable to the humanitarian context. It is not possible to dictate the amount of global average GHG emissions allowed for displaced people after the disaster. In addition to different climate zones, differing cultural backgrounds and consumption patterns set the stage for reference GHG values.
- Promotes transition towards a sustainable society. The emission reduction plan along the reconstruction process gives the society an example of rebuilding with smaller climate impacts.
- Alternative paths to reduction of emissions. By focusing on actual per capita emissions, it is possible to choose which of their sources can be reduced in a feasible and practical way in the given context. This gives flexibility for various humanitarian organisations or other stakeholders who participate in the construction activities. For example, if it is not possible to lower the energy consumption of transitional shelters, it might still be possible to lower the embodied energy and GHG emissions of construction materials, and vice versa.

Needs for development in the environmental assessment of humanitarian construction

The life cycle assessment of humanitarian construction operations may have significant shortcomings in the quality of data for life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases. This is mostly due to the fact that documentation of the environmental impacts of a specific humanitarian construction operation cannot be obtained before the operation is completed. Even then it is highly unlikely that any specific data (e.g. energy metering from construction site or environmental product declarations of locally available construction products) would be available. Thus it is necessary to use average values for the environmental impacts of construction products. These can be obtained from various data bases. Due to its generic nature, the data from databases may have large uncertainties (Takano, 2014). This is quite likely, especially if the humanitarian operation includes the use of products or services from developing countries. Therefore, it would be important to develop databases that would take into account the context of humanitarian operations.

Next steps

A proposal for a robust method for mitigating greenhouse gas emissions of humanitarian construction has been presented in this paper. Next the proposal would need to be tested with new case studies. A potential avenue for this purpose would be to engage selected humanitarian organisations so that they could prepare documentation of suitable humanitarian construction projects in the near future. Data from the field would be very valuable in testing the proposed model. In addition to field testing, also the methodology of calculating and allocating per capita GHG emissions would need to be studied in depth and tested with case studies in order to identify the most suitable per capita emission calculation methods and existing datasets. In addition, linking the emission reduction agenda into humanitarian accountability approaches is a field to develop.

Finally, it has to be said, to avoid any misunderstanding, that controlling GHG emissions should never challenge the fundamental aims of humanitarian aid. Saving lives, alleviating suffering and maintaining human dignity must be of primary importance. They should, however, be pursued with the environment in mind.

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**If we do not change direction,
we are likely to end up
where we are headed.**

— Chinese proverb

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