Quantifying the attributional and consequential impacts of Kenya's future timber construction developments: Ndarugu Student City

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ALCA – Attributional Life Cycle Assessment

CLCA – Consequential Life Cycle Assessment

CLT – Cross-laminated Timber

CO_2 – Carbon Dioxide

CO_2e – Carbon Dioxide Equivalent

GWP – Global Warming Potential

IPCC – Intergovernmental Panel on Climate Change

LCC – Life Cycle Cost

NDC – Nationally Determined Contribution

PA - Paris Agreement

SSA – sub-Saharan Africa

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1 Introduction

1.1 Timber Architecture and its Contribution to Climate Action in Africa

Following the 2015 Paris Agreement (PA), all nations have committed to ensuring global temperatures remain far below 2 degrees Celsius, with parties developing nationally determined contributions (NDC's), aiming to peak global emissions before 2050 (United Nations and United Nations Framework Convention on Climate Change, 2015). Africa has been highlighted by the Intergovernmental Panel on Climate Change (IPCC) as one of the most vulnerable regions to both the physical and socio-economic impacts of climate change, placing it at the forefront of the battle, with the need to immediately apply mitigation and adaption (Intergovernmental Panel on Climate Change, 2015; Serdeczny *et al.*, 2017).

By 2050, the population of sub-Saharan Africa (SSA) is projected to double to 2.1 billion before further tripling to 3 billion by 2100, eventually contributing up to 35% of the global population (United Nations, 2019b; Ezeh, Kissling and Singer, 2020). With an estimated 68% of this population increase moving into urban areas, the predicted future global population will be based in Africa, and its cities are anticipated to undergo extreme growth, resulting in the development of mega cities over the next decades (United Nations, 2019a). To accommodate the population increase, an extraordinary rise in infrastructure including housing and energy is needed. However, Africa currently has an estimated annual infrastructure investment shortfall of 52-65% or US$ 130 to 170 billion (African Development Bank Group, 2018). Countries within SSA, such as Kenya, now have the daunting challenge of catching up to this infrastructure deficit through the mobilisation of local and international private capital ensuring economic and social development without compromising their NDC's.

The built environment is responsible for 39% of total direct and indirect carbon dioxide (CO_2) emissions globally and plays a key role in decarbonising the planet (World Green Building Council, 2019). Over the last three years building emissions have continued to rise and by 2050, if carbon-intensive materials such as concrete and steel are not addressed, emissions from new buildings have the potential to claim between 35-60% of the remaining carbon budget (International Energy Agency, 2019a; Churkina *et al.*, 2020). Since 2007, the Kenyan Government has been following its “Vision 2030” plan, the country’s development blueprint to realising its potential as a “middle-income country” (The Ministry of Planning and Devolution, 2007). Within this blueprint, the government targets the construction of 200,000 homes per year, however, with the lifespans of buildings stretching up to 60 years, Kenya and other SSA countries must immediately assess its current application and standards for new buildings to avoid the risk of locking in inefficient and carbon-intensive practices (Ürge-Vorsatz *et al.*, 2014).

Hailed as a “carbon neutral” product due to its natural ability to sequester carbon, timber is resurfacing as a viable building material (Skullestad, Bohne and Lohne, 2016). During its manufacturing process, one tonne of timber locks in up to 4 times the amount of carbon emitted, displacing the high carbon footprint of existing carbon-intensive building materials such as concrete (Pierobon *et al.*, 2019; Churkina *et al.*, 2020). With modern technology now able to engineer and guarantee the required level of fire-resistance within the product, increased demand for timber can incentivise sustainable forest management, providing economic benefits such as mass employment as well as other physical environmental benefits (Balasbaneh, Marsono and Khaleghi, 2018). Carried out in partnership with the International Institute for Environment and Development and Swedish climate developers Arvet, this paper will assess the economic and environmental opportunities within Kenya to address the predicted environmental impact of its required infrastructure through the substitution of concrete with cross-laminated timber (CLT). Using the proposed Ndarugu Student City (NSC) shown in figure 1, this paper will carry out a comparative attributional and consequential life cycle assessment (LCA) and an attributional life cycle costing (LCC) to assess the environmental impacts of concrete against CLT, aiming to provide policy recommendations on the potential role timber could play to mitigate climate change within the SSA region.

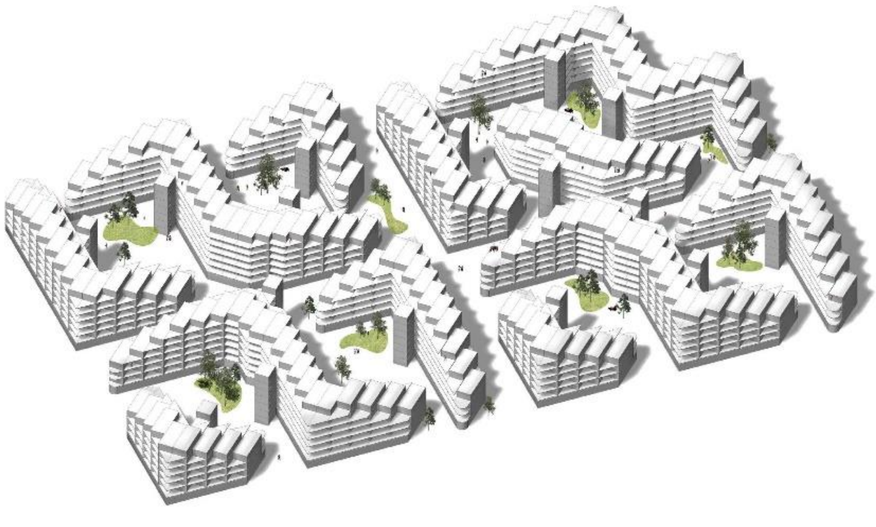

Figure 1 Ndarugu Student City Design

1.2 Climatic Impacts of Current Buildings

The manufacturing and construction of buildings are currently responsible for 11% of global CO_2 emissions, and with the prediction of 2.3 billion urban settlers by 2050, if not addressed appropriately, this figure will rise exponentially (United Nations Environment Programme, 2017). The building industry is currently dominated by energy-intensive building materials such as concrete and steel (Hart, D'Amico and Pomponi, 2021). The carbon intensity of these emissions can be reduced through energy efficiency and new technologies. However, they will never be net-zero due to the emissions from associated chemical reactions (Churkina *et al.*, 2020).

Currently, the largest environmental impact of buildings is the energy consumed during their occupation. It is estimated that after 3 to 4 years of a buildings use phase, the energy consumed exceeds the total energy used for the construction of the building (Allan and Phillips, 2021). In 2018, the use phase of buildings accounted for 36% of final energy use globally (International Energy Agency, 2019a). Through the development of low-energy and nearly zero energy buildings, it is estimated that the embodied carbon (emissions from producing a material) of a building will play a larger role than its use phase, potentially becoming responsible for around 50% of the buildings entire carbon footprint (World Green Building Council, 2019).

1.3 Requirement for Carbon Dioxide Removal

Despite the PA's commitment to limiting the rise in global temperatures, it is well accepted that current policies and commitments are far from ambitious enough to prevent the maximum increase of a 2 degrees Celsius rise, with most models suggesting that the current course will result in a 3 degrees Celsius rise (Climate Action Tracker, 2018). To address this lack of ambition, the IPCC has repeatedly stated the importance of CO_2 removal methods, including through more appropriate forest management such as afforestation, reforestation, and avoided forest conversion (Intergovernmental Panel on Climate Change, 2015). As part of Kenya's 2020 updated NDC, a significant emphasis has been put on the scaling up of nature-based solutions, emphasising their aim to achieve a tree cover of 10% nationally as well as enhancing their REDD+ activities (Ministry of Environment and Forestry, 2020).

The use of timber as a building material has the potential to increase carbon sequestration rates globally. By storing carbon within the material for the duration of its lifespan, there is the opportunity to replant the used trees and increase the carbon stock. This extra demand also solves a current issue with forests, where carbon absorption rates decrease as a tree matures (Bond *et al.*, 2019). It is important to note that the potential increase in the carbon stock from sustainably sourced wood is only positive if the lifespan of the use of timber is longer than the growth period of the planted trees, otherwise, there will be an increase in the amount of carbon emitted before the store has been replenished resulting in carbon debt. If well regulated, a high-value product such as timber for buildings can lead to farmers growing trees that are well managed, with the potential to improve forest quality and provide an extra source of income.

Forests have a number of significant risks that have to be managed actively such as fires, diseases, droughts, and insects, all of which can have extremely damaging environmental and climatic impacts (Food and Agriculture Organisation of the United Nations, 2020a). Between 2001 and 2018, more than two-thirds of wildfires globally were in Africa. These fires can largely be attributed to only 25% of forests being actively managed, further enhancing the possibility of these risks arising (Food and Agriculture Organisation of the United Nations, 2020a).

1.4 State of Kenya's Forests

At present, unregulated and low in value, demand for timber products like firewood is leading to deforestation as environmental regulations are being avoided in 'hard-to-police' natural forests (Lukumbuzya and Sianga, 2017). Regardless of a national timber logging ban that has been in place since 1999, between 2001 and 2020, Kenya is still estimated to have lost 11% of its tree cover, resulting in forests currently covering around 5.7% of the total land area (Global Forest Watch, 2021). Many of these forests are culturally and environmentally irreplaceable indigenous forests supported from 5 water towers, storing an estimated 2.91Gt of Carbon, shown in figure 2 (The World Bank, 2007). With over 80% of households in Kenya reliant on biomass, the deficit of sustainable supply against demand is estimated to be around 60%, acting as the main contributor to deforestation and land degradation (Kiplagat, Wang and Li, 2011; Welfle, Chingaira and Kassenov, 2020).

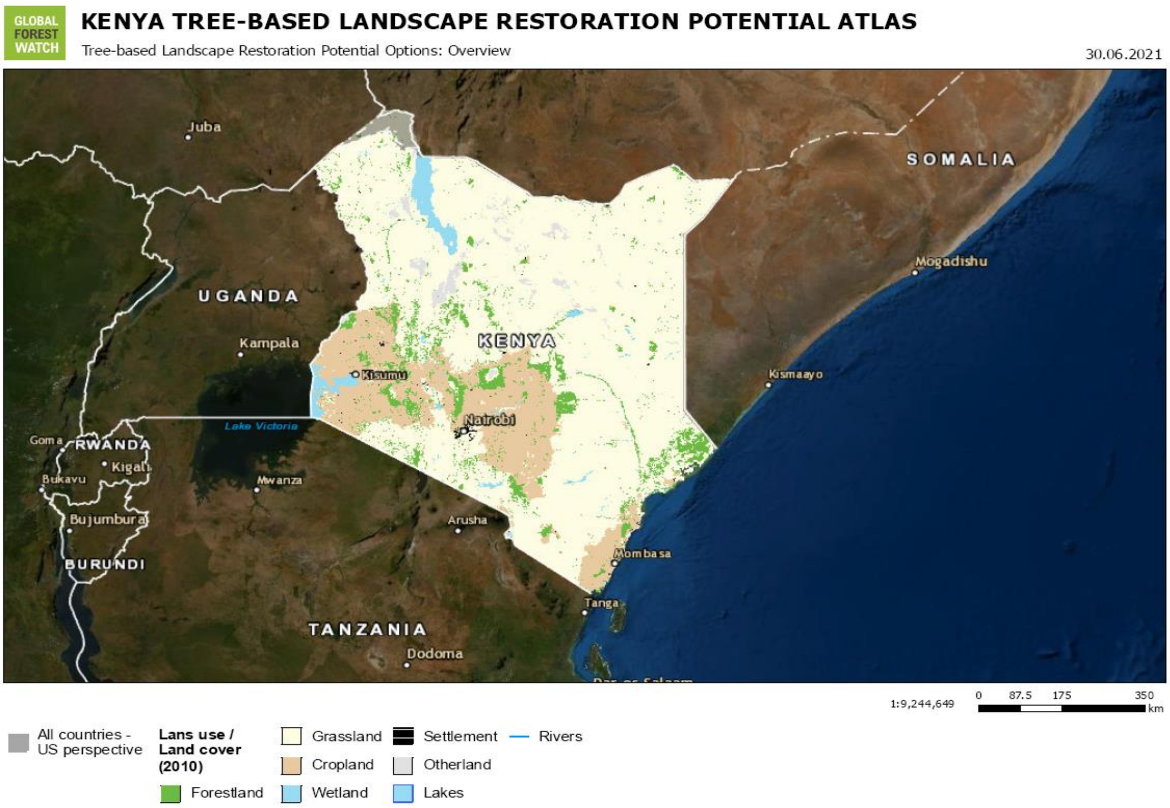

Figure 2 Kenya 2010 Land Use / Cover (Kenya Forest Service, 2021)

Regardless of its current troubles, SSA, including Kenya, remains a potential hotspot for afforestation and reforestation due to the rapid growth potential of trees in its climate (Doelman *et al.*, 2020). To help guide Kenya's reforestation efforts, a study by the Ministry of Environment and Natural Resources for Kenya (2016) estimated that there is a significant potential for landscape restoration, as shown in figure 3. With a current area of 13.9 million hectares of forest and agroforestry, there is a potential for this to double with an additional 13.8 million hectares. If a quarter of that potential area is used, it could sequester more than 320 $MtCO_2e$ by 2063 (Ministry of Environment and Natural Resources, 2016). Kenya however has a long way to go if they want to achieve this potential, starting by developing appropriate policies to protect indigenous trees and better control illegal logging (Kagombe *et al.*, 2020).

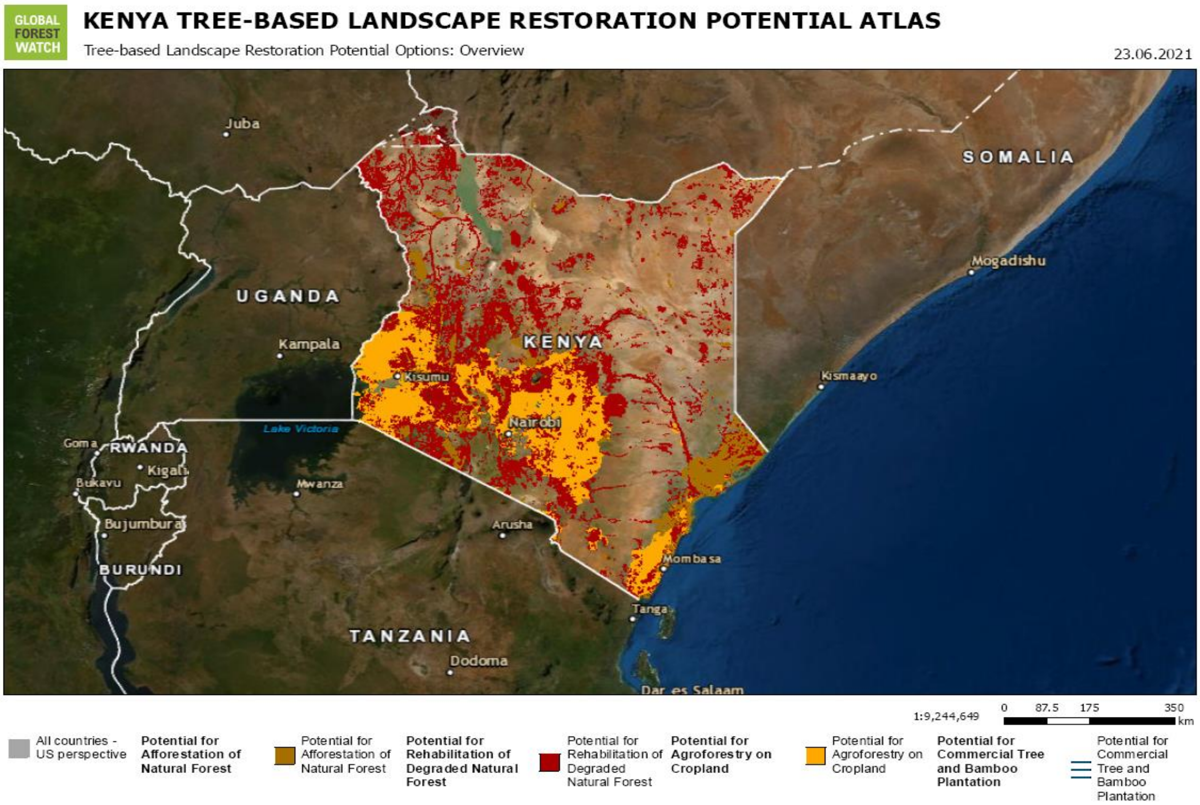

Figure 3 Kenya Landscape Restoration Potential (Kenya Forest Service, 2021)

Since 2010, Kenya has been attempting to take strides towards taking control over its forests by becoming a REDD+ country partner and through establishing requirements of a minimum of 10% national tree cover set out in the 2010 National Constitution (Government of the Republic of Kenya, 2010). Alongside this, Kenya's 2012 Agriculture bill contributes to these requirements by stating that agricultural landowners and occupiers must also establish and maintain a minimum of 10% tree cover to improve sustainable production of wood, carbon sequestration and other environmental services (Government of the Republic of Kenya, 2012). In 2016, Kenya also committed to the African Forest Landscape Restoration Initiative (AFR100), in an effort to bring an extra 100 million hectares of forest to Africa by 2030. However, as of 2021, none of the official 5.1 million hectares determined for Kenya has officially been carried out (Bonn Challenge, 2021).

With a total trade deficit of over US$ 20.4 billion between 2011 and 2020 and imports of around US$ 4 billion, the African Development Bank (2021) has identified the production and processing of timber as a large economic opportunity for growth within the continent. With more companies globally looking to reduce their emissions, the demand for carbon-neutral timber products is already seeing an increase (Food and Agriculture Organisation of the United Nations, 2019). African forests have the potential to outperform European and North American timber production.

In the UK, the most common commercial tree is the Sitka Spruce, which takes around 40 years to grow before it is harvested (University of Oxford, 2017). Within SSA, and more specifically Kenya, both Cypress and Pine trees require 25 years to reach maturity and the Eucalyptus requires only 14 years, resulting in 4 completed tree rotations over a 60-year lifespan of a building (Nyakundi, Mulwa and Kabubo-Mariara, 2018). This guarantees that the total carbon storage is increased as well as providing space for younger trees with higher sequestration, maintaining a consistent CO_2 removal system (Himes and Busby, 2020).

1.5 Cross-Laminated Timber as a Potential Climate Change Solution

Introduced as an engineered building material in the 1990s, CLT has become one of the most dominant and viable timber products within the European construction industry (Brandner *et al.*, 2016). CLT is a quasi-rigid composite, consisting of several layers of timber lamination stacked crosswise at a 90-degree angle to the row above as shown in figure 4. Currently, the tallest CLT building globally is the residential Dalston Lane project based in London, consisting of 10 storeys, 121-units, and resides at 33.8 meters (Ravenscroft, 2017).

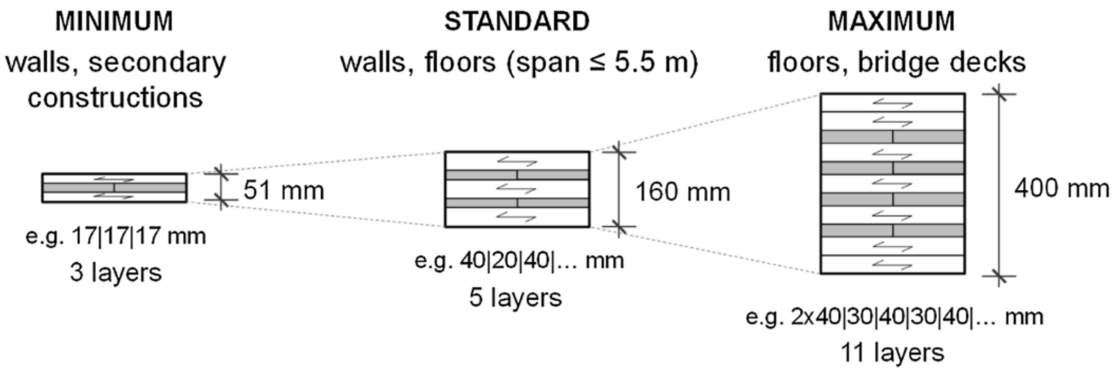

Figure 4 CLT Structural Configuration (Brandner et al., *2016)*

While developing nations have struggled to properly implement afforestation and reforestation plans, creating a new market for timber would provide an incentive to achieve this (Brandner *et al.*, 2016). Unlike other timber products such as glulam and laminated veneer lumber, small-diameter trees, which are perceived to have low or no commercial value, can be used for the manufacturing of CLT (Chen, Pierobon and Ganguly, 2019). This could broaden the supply chain involved in the process, providing local benefits to farmers and landowners as an extra source of revenue.

As well as the sustainable benefits of CLT previously discussed, the engineered material also has a significant number of economic and environmental benefits for the construction industry. As the material is engineered, it is generally pre-fabricated, resulting in faster erection times, reduced workforce, and reduced requirement for heavy on-site machinery (Espinoza *et al.*, 2015; Chen, Pierobon and Ganguly, 2019). The lightweight material also boasts a high in-plane and out-plane strength, resulting in its ability to carry heavy loads, reducing the materials needed in the foundations, as well as possessing high dimension stability (Lan *et al.*, 2019). CLT also has a high thermal, acoustic and fire-resistant performance, allowing for the material to be used across the construction industry. These benefits highlight how CLT has the potential to break into construction markets globally, however, policy and experience are required to further encourage the shift (Lan *et al.*, 2019; Jayalath *et al.*, 2020).

There are also some barriers to the deployment of CLT which must be addressed. Arguably the largest barrier is due to the historically negative perceptions surrounding the use of timber. This firstly limits the number of architects and engineers who are aware and open to CLT use, as well as some fire science engineers in Europe that do not accept wood as a construction material (Quesada, Smith and Berger, 2018). As a product looking to break into the global market, a lack of technical information is available. This has led to a serious problem with its compatibility with existing building codes, which were designed for traditional timber construction options, and now limit the application of CLT within the industry (D'Amico, Pomponi and Hart, 2021).

In Africa, one of the main barriers to the deployment of CLT is the largely significant amount of wood needed to produce it (Santos *et al.*, 2021). Currently, CLT is extensively available in mostly German-speaking parts of Europe and Scandinavia. It was introduced into the market of these countries around 30 years ago and they have had time to build up the required timber supply and technical understanding of the material (Brandt *et al.*, 2019). In wood deficit countries such as Kenya however, this further exacerbates the final issue facing the CLT market which is the higher cost compared to more traditional building materials such as concrete (Santos *et al.*, 2021).

1.6 Attributional v Consequential Life Cycle Assessment

1.6.1 Attributional LCA

To determine the environmental impact of a project, the most common and established method currently is the attributional life cycle assessment (ALCA), which aims to describe all the direct environmentally relevant anthropogenic flows within a chosen temporal window and boundary for a product or system (Brander, Burritt and Christ, 2019). ALCAs develop a profile for a product or system which then allow for the identification of hotspots, or in the case of buildings, provide information towards carbon value engineering (Fauzi *et al.*, 2021; Robati *et al.*, 2021). ALCAs generally provide accurate results, with small deviations around the mean. However, they are static studies, which largely restricts the dynamic temporal complexities of emissions (Lan *et al.*, 2019). Not taking into consideration these temporal complexities, LCA's generally also ignore short-run impacts as well as long-term transitions. These limit the temporal understanding of emissions and the suitability of decisions made as a result (Brander, 2016). Due to ALCA's only measuring the direct impacts of products pr systems, many studies have stressed the restricted information ALCA's provide towards making appropriate mitigation decisions (Dodoo, Gustavsson and Sathre, 2014; Brander, 2017; Brander, Burritt and Christ, 2019; Buyle *et al.*, 2019).

1.6.2 Consequential LCA

While a product or policy may promise a more sustainable or environmentally friendly product, the unintended and consequential impact may result in higher overall emissions (Buyle *et al.*, 2019). A consequential life cycle assessment (CLCA) attempts to estimate the marginal changes to the environment as a result of different potential decisions, creating a conceptual categorisation of different models (Fauzi *et al.*, 2021). Due to the expanded system boundary of a CLCA, which unlike the ALCA assesses the displacement of product systems and the avoidance of others, it is generally agreed that CLCAs are better for making decisions on potentially mitigating actions unless the uncertainties in the modelling outweigh the insights gained (Weidema, 2003; Brander, 2017).

1.6.3 Environmental Life Cycle Costing

Usually spurred by necessity, the construction and use of buildings are largely governed by the associated costs (Roh, Tae and Kim, 2018). With environmental and social aspects disproportionally monitored at present, environmental life cycle costing (LCC) has recently been highlighted as a potential solution to mitigate this gap. Through coupling an ALCA with an LCC, more information on the entire sustainable performance of a product or system is achieved, better informing the decision-makers (Robati *et al.*, 2021).

1.7 Case Study

Designed by architecture firm Arkemi, the proposed Ndarugu Student City (NSC) shown in blue in figure 5, is the residential portion of the larger Ndarugu Metropolis, a 575-acre business hub 35 km North of Nairobi, Kenya. The 160-acre NSC proposal consists of 15 blocks of 8 7-storey buildings containing 54 3-bedroom units each, totalling 6,480 prefabricated apartments, with a predicted capacity for 19,440 students. Each apartment, shown in figure 6, has a gross floor area of 77 m^2 (49 excl. Balcony) and all 54 units, including the ground floor, have a total gross floor area of 584,823 m^2. Alongside the NSC, the Metropolis plans to contain a wholesale market and a special economic zone providing an income for the students to pay for their accommodation during their studies. The project aims to provide sustainable, low-cost housing, protecting the students against external conditions and other harmful factors such as weather conditions.

Figure 5 Ndarugu Metropolis Design (Arkemi, 2019)

Figure 6 Ndarugu Apartment Floor Plan (Arkemi, 2019)

1.8 Research Questions

With the earth getting closer to experiencing temperature increases beyond the PA targets, the interest for CLT to be used as a carbon removal method is increasing. As such, more consequential studies are needed to assess the wider implications of its use so that the full marginal impact can be better understood. To create the most complete picture, this study will build on the recommendations of Brander et al (Brander, Burritt and Christ, 2019) and follow the example of Fauci et al (2021), Buyle (2018) and Skullestad, Bohne and Lohne et al (2016) to couple both the attributional and consequential LCA alongside an LCC. This will allow for the assessment of both the marginal and direct impact of timber buildings, allowing for suitable value engineering decisions and macro-economic policy decisions. This study will look to determine the most sustainable option for the NSC, looking at the environmental impacts of a CLT building versus a “sustainable” (30% fly ash) concrete building.

This study will look to understand the following questions:

1. What are the attributional and consequential environmental impacts of a CLT and concrete building in Kenya, and how do the two-building options compare?
2. What are the life cycle costs of a CLT and concrete building in Kenya, and how do the two-building options compare?
3. How do the results of these studies of attributional and consequential LCA differ?

By assessing the environmental impacts of locally sourced mass-timber buildings, this study will look to provide policy and subsidy recommendations to further develop the forestry sector and a sustainable timber market with Kenya and SSA.

2 Literature Review

This section provides an analysis of existing literature looking at assessing the environmental impact of timber buildings globally. Research papers were discovered using Google Scholar and Scopus by searching the keywords "Attributional", "Consequential", "Lifecycle", "Timber", "Building", "Lifecycle Cost", "CLT" and "Cross-Laminated Timber". The titles and abstracts were then screened for relevancy. A snowballing process using the "Cited by" function was further used to find all relevant articles. The entire process was limited to papers accessible through the University of Edinburgh's database.

2.1 Africa

Between 2000 and 2020, a meta-analysis by Karkous et al., (2021) found that only 199 papers existed relating to life cycle assessments for the continent of Africa, compared to over 400 for Germany alone. Out of these 199, only one paper is related to the use of timber as a building material. Crafford, Blumentritt and Wessels (2017) carried out a cradle to grave analysis on different roof truss materials in South Africa, in particular wood versus steel on a 42m^2 house and 168m^2 house. Including biogenic emissions, wood performed far better than steel for both sized houses, with local pine having a GWP of 85 kgCO_2e / m^2 compared to 1038 kgCO_2e / m^2 for the smaller house. At the time of the study, however, there was no life cycle inventory data for South Africa, limiting the accuracy. Due to the lack of continent and regionally-specific LCA's relating to timber, the literature used in this paper the scope of research has been expanded to a global system boundary.

In terms of building standards, in 2018, Kenya adopted the GreenMark Standard, a building guideline and Kenya specific benchmark for assessing the competence of new and existing buildings concerning the issues surrounding climate change and environmental degradation (Green Africa Foundation, 2018). GreenMark however, is only a voluntary assessment, with no minimum requirement for new buildings which most likely limits its implementation and use.

2.2 Attributional Life Cycle Assessments of Timber Buildings

By carrying out comparative ALCAs on the use of CLT versus more traditional building materials such as steel and concrete, recent literature has almost uniformly highlighted its environmental benefits (Allan and Phillips, 2021). A meta-analysis carried out by Saade, Guest and Amor (2020) analysing the results of comparative ALCAs ranging in system boundaries and building designs summarised that out of the 11 papers comparing timber frames to either concrete and steel buildings, timber performed the best in terms of its global warming potential (GWP) in ten of the eleven areas, with the outlier being a steel-frame made from a high percentage of recycled material. While this mostly confirms the direct carbon benefits of timber, due to a large number of variabilities and assumptions within a life cycle study there remains a challenging issue of comparability, which has limited the availability of a suitable and expansive literature benchmark (Minunno *et al.*, 2021).

2.2.1 System Boundaries

In an attempt to highlight the environmental benefits of timber as a building product, a significant number of studies have focused their LCAs on the production and construction phase of timber buildings (Monahan and Powell, 2011; Skullestad, Bohne and Lohne, 2016; Achenbach, Wenker and Rüter, 2018; Pierobon *et al.*, 2019; Pittau *et al.*, 2019; Liang *et al.*, 2020; Nakano *et al.*, 2020). A meta-analysis carried out by Himes and Busby (2020), which collated research papers solely on the production and construction phase, showed that all studies resulted in carbon savings when selecting timber buildings over concrete or steel alternatives, with an overall average savings of around 69%. However as discussed, the end-of-life portion for timber buildings play a significant role in balancing out the carbon sequestration and savings from creating a significant risk of understating the true impacts of building systems.

A meta-analysis carried out by Minunno et al., (2021) looking at the embodied carbon of timber buildings, highlighted the significant lack of end-of-life research within the field, and more specifically a lack of quantitative integration between end-of-life practices and the savings of the environmental impacts of buildings. Minunno concluded that between recycling timber or repurposing it into a fuel source the potential reductions in embodied carbon ranged between 15% and 200% (Minunno *et al.*, 2021). A study by Santos et al., (2021) focused on a cradle to grave LCA of CLT panels for the six ends of life scenarios shown in figure 7. The analysis showed that incineration with energy recovery had a GWP of 48 kgCO_2e while landfill with total rot resulted in a GWP of 251 kgCO_2e. This extensive range further reinforces the importance of the end-of-life portion of an LCA.

- Incineration,
- Incineration with energy recovery,
- Landfill assuming partial rot of wood,
- Landfill assuming partial rot of wood and energy recovery,
- Landfill assuming total rot of wood,
- Landfill assuming total rot of wood and energy recovery.

Figure 7 CLT End-of-Life Options (Santos et al., 2021)

2.2.2 Consistency of Data

Most LCAs follow ISO 14040/14044 (2006, 2018) and EN 15804/EN 15978 (2011, 2013) standards, which splits the LCA process into the sections shown in figure 8. Current academic literature however contains comparability issues where studies can pick and mix different phases to include and exclude. A study by Hafner and Schafer (2017) attempting to calculate the substitution factor of a mass timber against a traditional building explicitly stated their system boundary to be cradle to grave. While this was true, the study omitted the inclusion of 10 of the 17 phases detailed within figure 8 (A4-5, B1, B3, B5-7, C1-2, and D) due to a lack of data availability, significantly understating the overall results. Hart, D'Amico and Pomponi (2021) carried out a cradle to grave comparison of 127 different timber frames against the equivalent steel and concrete alternatives. On average, 36% of the timber frames GWP came from the Use Stage and End-of-Life Stage, however, the study did not include B2-7 and D limiting how the results can be interpreted and used.

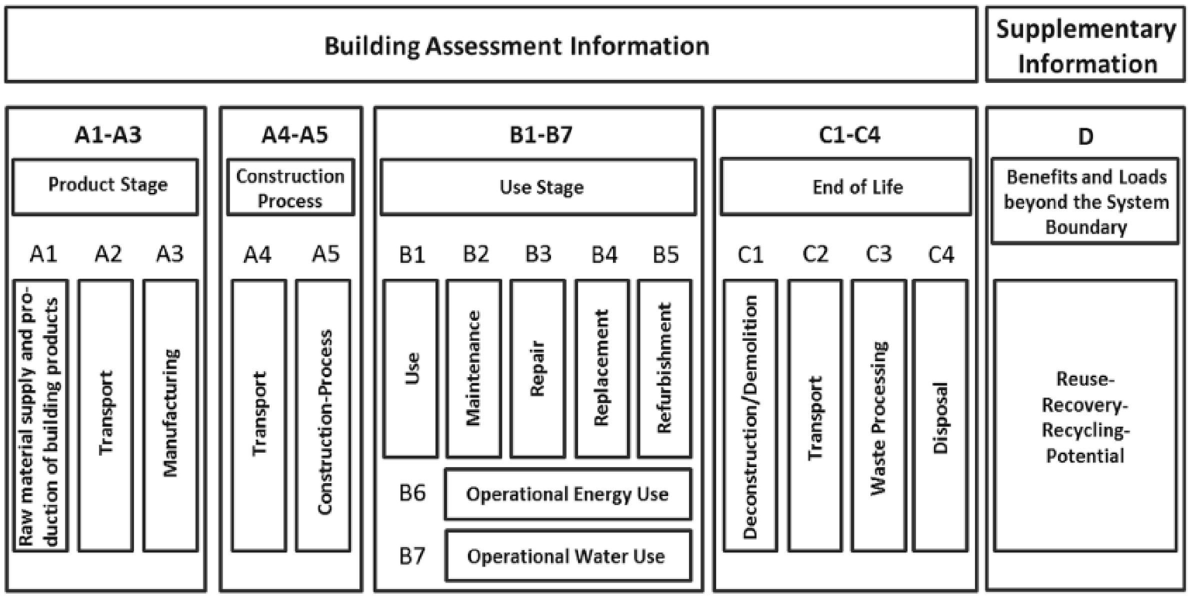

Figure 8 System Boundaries according to EN 15804/EN 15978 (British Standards Institution, 2011, 2013)

2.2.3 Biogenic Emissions

Biogenic carbon is not currently included in the international standards for the assessment of buildings EN 15978 (British Standards Institution, 2011), ISO 14044 (British Standards Institution, 2006) nor the 2019 refined IPCC GHG inventory guidelines (Intergovernmental Panel on Climate Change, 2019) which recommends disclosing the information separately. This however is a strongly debated topic where it hasn't been included due to the assumption that the uptake equals the emissions over its lifetime. The opposite argument looks at the potential positive carbon impact that sourcing wood from a sustainably managed forest could have, however, in the short run, this is beyond the scope of current LCA methods (Buyle *et al.*, 2019; Satola *et al.*, 2021).

Chen et al., (2020) carried out an ALCA for a mass timber building against a reinforced concrete alternative alongside carrying out biogenic emissions. The study concluded that when considering only phases A-C, the mass timber structure resulted in a reduced embodied carbon of 21% compared to the reinforced concrete, yet when including the biogenic emissions (Phase D), the disparity between the buildings rose to 69.5%. Allan and Phillips (2021) carried out a comparative LCA analysis of a 5-story and 12-story timber structure against a steel alternative. When including the biogenic emissions, the GWP from the timber 5-story and 12-story structures went from a total of 1,000,000 kgCO_2e and 3,150,000 kgCO_2e respectively to -141,000 kgCO_2e and -84,000 kgCO_2e. Both studies emphasise the significance that carbon sequestration can play during the life cycle of timber.

Peñaloza, Erlandsson and Falk (2016) attempt to address the issue of biogenic emissions through the application of a dynamic LCA for a Swedish timber building. The total results highlight that including forest growth in the LCA reduced the CLT GWP from 280 kgCO_2e/m^2 down to only 5 kgCO_2e/m^2. The study highlighted the significant temporal variation with the GWP rising to around 100 kgCO_2e/m^2 within the first 50 years but dropping to almost -200 kgCO_2e/m^2 after 75 years.

2.2.4 Functional Units

To date, the functional units of studies are more often expressed in kg mass rather than m^2 of building space (Himes and Busby, 2020). The misuse of the appropriate functional unit can create misleading results due to timber having a far lower mass compared to steel and concrete, creating the potential for timber to have a seemingly greater GWP than concrete (Himes and Busby, 2020). To address this issue, Minunno et al., (2021) study aimed to develop a more appropriate functional unit to assess the embodied carbon of materials, developing a benchmark for LCA practitioners. The approach uses the structural strength and strength at failure as the functional unit kgCO_2e/(kN m). The difference in the results for timber was 95.7 kgCO_2e/m^2 compared to 2.3 CO_2e/(kN m) for the structural strength.

2.2.5 Impact of Transportation

The meta-analysis by Minunno et al., (2021), analysing the embodied energy and carbon of buildings, highlighted that transportation of materials from production facilities to site could impact the entire life cycle between only 0.1% to 4%. While this is a small percentage in respect to the total life cycle when incorporating more mitigating methods such as nearly zero energy buildings, addressing the transportation will play a larger and consistent role to reduce a buildings life cycle impact. A social LCA by Balasbaneh, Marsono and Khaleghi (2018) highlighted that during the construction of a timber building in Malaysia, a 55% increase in social improvement was realised as a result of the project. Through the creation of local jobs in the acquisition, production, transportation, construction and maintenance phases of the project, the social impact on local communities from the timber building outperformed in comparison to concrete and steel projects. This ties together the importance of local supply for both lower emissions and social benefits.

2.2.6 Climatic Variations

A study by Dong et al., (2020), focused on assessing the appropriateness of mass timber in different climatic regions (mainly cold) across China versus concrete buildings. The study determined that over the building's lifetime, every timber building has improved energy and carbon savings. The concrete buildings required less cooling compared to timber, resulting in a higher GWP for this portion of the LCA in every climate but required less heating in the winter. Regardless of this, the significant savings from the construction and end-of-life phase made the timber buildings far more carbon and energy effective over their lifetime.

Satola et al., (2021) carried out a systematic review and analysis of papers carrying out LCAs for buildings in humid and subtropical/tropical climates. The study highlighted that maximising the use of timber could reduce lifetime GHG emissions by almost 50% and reducing embodied carbon by almost 80%. This was largely due to timber having a lower thermal conductivity compared to steel, concrete, or brick.

2.3 Consequential Life Cycle Assessments of Timber Buildings

In the last couple of years, the application of CLCAs has begun to rise. With no official international standard for CLCAs, there is currently a large discrepancy in methods applied to identify marginal technologies, determined by individual authors and often accompanied by a lack of transparency in achieving their results. The most used method has been built on and adapted around the five-factor model framework created by Weidema (2003) designed to predict the overall market demand instead of demand and supply.

Fauzi et al., (2021) couples both ALCA and CLCA to assess the cradle to grave environmental impacts of a timber building. Adjusting Weidemas' framework, Fauzi shows the benefits and importance of both methods. The ALCA GWP of the building was 17,400,000 $kgCO_2e$, while for CLCA, it was 38,300,000e $kgCO_2e$. For the ALCA the product phase contributed to 86% of the total while in the CLCA, the use phase contributed to 68%. Coupled together, both methods highlighted different areas of carbon intensity. The ALCA highlighted the intensity of importing steel from China, but the CLCA highlighted that the extra demand for energy made the state vulnerable to achieving its carbon reductions. While the study provides a good comparison between the ALCA and CLCA, it fails to provide the results against its functional unit, limiting its ability for comparison against literature benchmarks and academic papers. The study also fails to provide detailed figures for the CLCA method, leaving gaps and questions regarding the quantification. This is similar to Buyle (2018) who carries out a comparative ALCA and CLCA for a timber building in Belgium, however, this time the results are shown as part of the ReCiPe index, again limiting comparison against academic benchmarks. The main difference in the results of these two studies was the end-of-life phase, in which the CLCA resulted in a GWP 266% less than the ALCA due to its recycling benefits.

Skullestad, Bohne and Lohne (2016) compared the embodied carbon results of an ALCA and CLCA for varying heights of various buildings, ranging from 3-storeys, 7-storeys, 12-storeys and 21-storeys. In all scenario's CLT had a lower GWP than the concrete alternative. The ALCA GWP increased with the number of storeys, from 25 $kgCO_2e/m^2$ up to 110 $kgCO_2e/m^2$, and the CLCA had the opposite effect, resulting in a reduction alongside the increase of storeys, ranging from -140 $kgCO_2e/m^2$ to -235 $kgCO_2e/m^2$. The main variation that caused this can be attributed to the re-use and recycling benefits from timber during its beyond life phase. The study, however, limits the inclusion of biogenic emissions only in the CLCA and not the ALCA and again fails to provide a coherent determination of the CLCA method.

All of the above methods have a limited description of the intermediary processes which lead to their CLCA results, but also have the suggestion that the main difference they determine between the CLCA and ALCA is through the inclusion of end-of-life processes. Another common failure is that due to the inherent assumptions within the CLCA approach, it is recommended that different scenarios for modelling the different marginal systems affected by the decisions should be incorporated to assess all options (Brander, Burritt and Christ, 2019). None of the studies aforementioned contains multiple scenarios, raising more questions about the determination of the marginal impact and how they were quantified. All CLCA studies suggest different methodologies and inputs. This suggests that until a standardised method is created, consequential LCA's will continue to be difficult to compare and verify, depending on the author's interpretation of its purpose and inputs.

2.4 Timber building Life Cycle Costing

The most significant recent development towards LCC came from a paper published in 2008, which developed the concept and classified LCC models as either conventional, environmental or societal depending on the scope of assessment and cost category (Hunkeler, Rebitzer and Lichtenvort, 2008). The study defined the purpose of an LCC as a tool to evaluate the economic performance of a product or service, assessing both private costs directly related to a product or service whilst also adding in external costs related to the direct environmental impact.

The majority of LCC studies are based on ALCA studies for timber buildings. Balasbaneh, Marsono and Khaleghi (2018) and Robati et al., (2021) carried out a cradle to grave LCC for timber. Balasbaneh, Marsono and Khaleghi (2018) looked at different timber products to form walls in Malaysia while Robati et al., (2021) conducted a case study focused on a single CLT design in Australia. Both studies showed that construction and production were the most expensive portions of the entire lifecycle, making up 79% and 82% respectively (45% construction). Balasbaneh, Marsono and Khaleghi (2018) determined that concrete was the most expensive portion of each structure due to the large number of materials, heavy machinery, maintenance, and demolition, while timber and steel produced an extra source of revenue once they reached their end-of-life. Jayalath et al., (2020) also based in Australia, compared a CLT against a concrete alternative in three of the largest cities. While the CLT produced GHG savings of 34% to 29%, cost savings were also found in all three cities, ranging from 1.3% to 0.9%.

Fauzi et al,. (2021) provide a detailed methodology for carrying out timber ALCC, looking to determine the costs associated with a timber hybrid building. The results of the study determined that the ALCC for the project was $26 million, however without its functional unit, the study can't be compared. This figure was largely dominated by material production where increasing market prices of steel made it the highest price. Liang and Bilek (2019) study solely focus on the LCC comparing a CLT building to a concrete alternative in the USA. The study highlighted that regardless of the study period and discount rate, CLT was the cheaper option, mainly again down to the end-of-life savings by reselling the wood, while concrete is limited to landfilling and low-quality aggregate.

2.5 Research Gap

In line with everything discussed in the literature review, this study will look to address the following gaps in the research:

1. A lack of life cycle assessments for timber buildings in Africa
2. A lack of consequential life cycle assessments for timber buildings globally

3 Method

3.1 Goal and Scope of LCA

The goal of this study is to compare the environmental impacts of a CLT dominated building (CLT NSC) versus a “sustainable” (30% Fly Ash) concrete dominated building (Concrete NSC). The ground floor of the NSC will be used for communal purposes, however, as the rest of the NSC is residential, this will be assumed as the main function of the building. In line with literature, the estimated lifespan of the NSC is 60-years. To focus on the environmental impact of CLT or concrete in Kenya, the product system is limited to the structure and envelope of the building as shown in table 1. The functional unit that will be used for both material studies is 584,823 m^2.

Table 1 CLT NSC Constituent Parts (Concrete NSC is the same with the CLT replaced with concrete shown in brackets)

Building Parts	Building Component	Constituent part for each building component
Foundation	Slabs on ground	Concrete 150 mm Aggregate 200 mm
First Floor	Supporting Exterior Wall	Concrete 200 mm Concrete 80 mm
	Supporting Interior Wall	Concrete 200 mm
	Floor Structure Above Floor	Concrete 250 mm
Floors 2 – 7	Floor / Ceiling	CLT 140x2 mm (Concrete) Gypsum Board Mineral wool cavity insulation 50 mm Plasterboard 2x10 mm
	Wall	Fermacell 2x12.5 mm CLT 90x2 mm (Concrete)
	Balcony	Steel Beam Clamps CLT (Concrete)

The following study will carry out an attributional and consequential LCA, along with an attributional life cycle cost. The structure and methodology will be discussed in detail within this section.

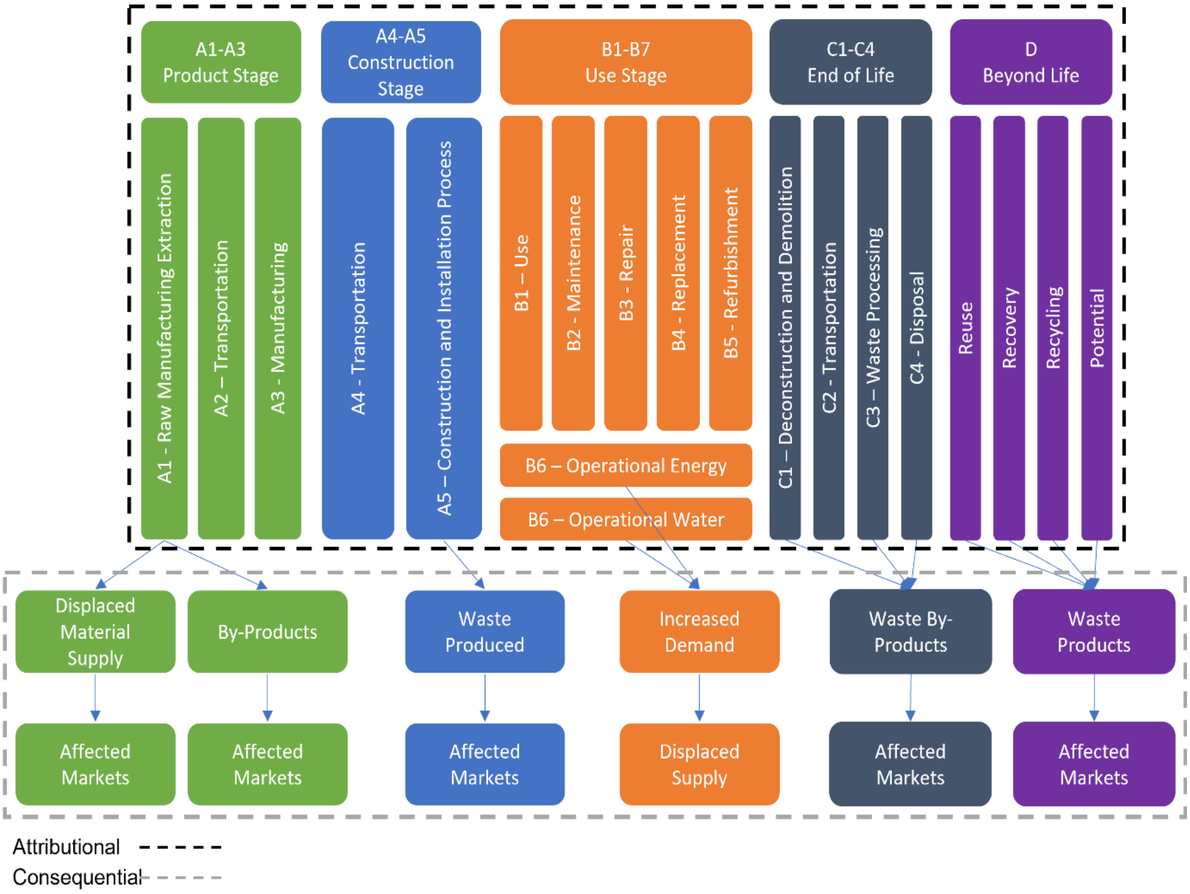

Figure 9 Attributional System Boundary from BS EN 15978:2011 (British Standards Institution, 2011). The Consequential system boundary is a vague illustrative determination to help understand the different scopes of the studies.

3.2 ALCA

The attributional portion of the study aims to determine the direct environmental impact of building either with CLT or concrete in Kenya. As seen in figure 9, the system boundary of the ALCA is a cradle to grave study, including the beyond life phase. A cut-off approach is used so that the end-of-life phase is allocated to the life cycle that uses the recovered materials. To ensure a minimum standard and maintain consistency with existing studies, the ALCA will be carried out according to BS EN 15978:2011 (British Standards Institution, 2011). As shown in figure 10, the ALCA is broken down into four distinctive steps: (1) the goal and scope definition, (2) the inventory analysis, (3) the impact assessment, and (4) the interpretation.

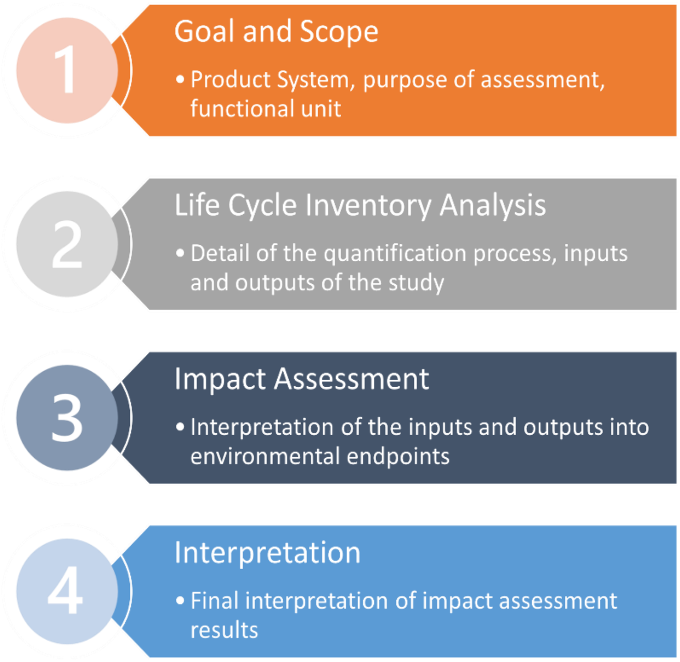

Figure 10 Attributional Life Cycle Assessment Model (British Standards Institution, 2011).

3.2.1 CLCA

As previously discussed, there is no international standardised method for carrying out a consequential LCA (Brander, Burritt and Christ, 2019). Due to its simplicity and to provide comparability with previous literature, we used the adopted model by Fauzi et al., (2021) originally based on the five-step procedure by Weidema (2003), summarised in figure 11. This will assess the system-wide emissions from introducing either a CLT NSC or Concrete NSC.

This study assumes that the impact of a single building will be similar to the result of multiple buildings. Figure 9 attempts to visually illustrate the system boundary for the CLCA, where the inputs are the marginal impacts of the NSC, which vary depending on the predicted demand either in the short term or long term. The following sections will describe the method used to identify the marginal impacts shown in figure 11.

Figure 11 Consequential Life Cycle Assessment Framework (Fauzi et al., 2021)

3.2.1.1 Time Horizon

To remain consistent with existing literature a time horizon of 60 years has been selected.

3.2.1.2 Market Delimitation

Market delimitation aims to determine the system boundary shown in figure 9, by identifying all the processes and markets affected by the project. This was achieved through a causal chain map that can be seen in figure 12 with the components summarised in table 2. Table 2 summarises all the identified components of the project and lists out the markets that it influences. The impact of the intervention assessed on the affected markets identified will be analysed in detail.

Table 2 Affected processes and by-products

Marginal Components	Affected Processes and markets	By-products
Aggregate	Mining	None
Cement	Mining - Limestone, Fly Ash	Becomes Concrete
Water	The timber industry, Water and Wastewater companies	None
Concrete	Cement, Water	End-of-life is broken into aggregate (included in ALCA)
Electricity	Geothermal, Biomass Energy, Oil	None
Cooking Fuel	Wood Demand, LPG demand, Kerosene Demand	None
Construction Machinery	Import	None
Insulation	Mining, recycled aggregate	Recycled for further insulation
Steel	Imported materials	Slag for cement and concrete
CLT	Cooking Fuel, Deforestation	Smaller biomass
Land use	Agriculture, Water	None

Figure 12 Causal Chain Map

3.2.1.3 Market Trend

The market trend looks to assess whether the affected processes and markets will increase or decrease over the long term. The results of this analysis can be found in table 3.

Table 3 Baseline Scenario Assumed Market Trend

Affected Markets	Affected Long-Term Supplier	Market Trend
Concrete	Local Concrete Suppliers	Increase
CLT	Regional Timber and CLT Suppliers	Increase
Aggregate	Local Aggregate Suppliers	Increase
Steel	International Steel Material Suppliers	Increase
Biomass for Cooking	Local timber use for cooking fuel	Decrease
Electricity Demand	Local electricity producers	Increase
Mining	Local mining suppliers	Increase
Water	Water and wastewater manufacturers	Increase
Agriculture/ Land Use	Local Farmers	Increase

Kenya's construction and manufacturing industry, which includes concrete, aggregate, mining and steel, is currently experiencing a compound annual growth rate of around 6%, (Kenya Association of Manufacturers, 2019). Steel is currently reliant on the importation of raw materials from China which makes up 14% of the manufacturing industry. However, it is still predicted to increase along with the rest of the sector (The Ministry of Planning and Devolution, 2007). With a current supply of almost 12,000 GWh of electricity, the IEA predicts a healthy raise in electricity generation to almost 45,000 GWh by 2040 in line with the population increase (International Energy Agency, 2019c).

The biggest questions raised through this analysis are the market trends associated with the use of biomass for cooking, water supply and land use. While Kenya has set out plans to achieve universal access to modern energy methods for cooking by 2028, improved water and sanitation accessible to all by 2030, and an increased agricultural area under irrigation to 1.2 million hectares by 2030 (Government of the Republic of Kenya, 2013), there are no guarantees whether these plans will materialise. Kenya has however increased its water and irrigation budget in absolute terms from $64 million in 2003/4 to $379 million in 2009/10 (USAID, 2017). For the purpose of this study, we will assume that the market will decrease regarding biomass for cooking and increase for water availability.

As discussed, Kenya has established plans to reach its 10% forest land use target, however, the country is still currently experiencing a loss of 5,000 hectares of forest per year (SouthSouthNorth, 2020). Through increased action into the biggest causes of deforestation, such as expenditure into the clean cooking fuel sector and improved water infrastructure, over the 60-year lifespan, the timber market in Kenya is expected to improve. The overall figures for these assumptions can be found in Appendix A.

3.2.1.4 Product Constraint

Product constraints aim to analyse the affected markets, to identify any potential production constraints. As this is a dynamic impact, the timeline of constraints will be considered. The results of this can be seen in table 4.

Table 4 Summary of Baseline Scenario Product Constraints

Affected Markets	Production Constraint
Cement	No Constraint
Mining (Limestone, Aggregate, Sand)	No Constraint
Steel	No Constraint
Electricity	No Constraint
Wood	Constraint
Nairobi Water	Constraint
Land Use/Agriculture	No Constraint

As mentioned previously, all aspects associated with construction are expected to be unconstrained. Although cement production currently exceeds demand in the country, there are two new facilities expected to be built over the next year (Kenya Association of Manufacturers, 2019). Mining in Kenya currently has 4 times the supply than the demand, and whilst steel is imported from China, there is no supply constraint for the country (Knoema, 2017).

In 2013 a study by the Kenyan Forestry Service (Ministry of Environment, 2013) estimated that Kenya had a wood supply deficit of 10.3 million m^3. Firewood and charcoal made up over 50% of the wood demand but used up 85% of the supply, the remaining fuel market is then made up of

Liquefied Petroleum Gas (LPG) (13.4%) and kerosene (14%) (SouthSouthNorth, 2020). Were future wood demand from CLT production to take a significant amount of this supply, the firewood and charcoal are anticipated to be the largest marginalised market. This has the potential to either roll out more sustainable options such as LPG or continue with firewood and charcoal, leading to further land degradation. For this study, we will follow the IEA's (2019c) estimation that LPG is the most scalable solution and so assume a scenario where LPG replaces the displaced timber. In another scenario, firewood is still used increasing the supply deficit. The end-of-life use of timber has the potential to displace raw wood and timber material, reducing the demand for the product and increasing the amount of carbon to be sequestered.

With less than 1,000 m^3/capital/year of freshwater, Kenya is classified as a water-scarce country (Mulwa, Li and Fangninou, 2021). Between the production of timber for CLT, the required water for concrete, and the demand during the use phase, a significant quantity of water will be required for the NSC. While water supply coverage in Kenya currently reaches 82% of urban populations, it only reaches 57% in rural areas, with an estimated deficit of 2.7 billion m^3 of water between consumption and total renewable water resources (USAID, 2017; Mulwa, Li and Fangninou, 2021). The assumed method to address the water deficit is through increased investment into both water supply and infrastructure.

While the NSC is proposed to be built over unused land, a significant amount is furthermore required to produce the timber needed for the project. This isn't expected to be a constraint as the Kenyan Ministry of Environment and Natural Resources identified an area of almost 40 million hectares of restoration potential without displacing existing agricultural land (Ministry of Environment and Natural Resources, 2016). The total sources for these assumptions can be found in Appendix B.

3.2.1.5 Most Flexible Technology

The assessment of flexibility of associated technologies within the markets aims to identify which processes are the most flexible to a change in demand or are more competitive than others. CLT has broken into markets globally and shows the most potential for growth due to its engineering strength compared to other wood products as well as the carbon benefits and so is expected to continue its uptake globally, becoming a viable and financially competitive option (Bond *et al.*, 2019).

3.2.1.6 Scenarios

From the results of all the previous steps, scenarios are then determined to assess different possibilities of marginal systems affected. 5 scenarios were determined for the NSC, with 9 sub-scenarios detailing the different impacts that can come as a result of the NSC. These are broken down between best-case scenarios (0.1's) and worst-case scenarios (0.2's). Scenario 5 is the only assumed option available for both material studies. This is summarised in table 5. A summary of the inputs into the CLCA can be seen in Appendix C.

3.3 Life Cycle Analysis Inventory and Data Sources

All the materials are predicted to be sourced locally apart from steel which is anticipated to be imported from China. Timber is assumed to be sourced from Eucalyptus trees grown locally in Kenya. While the timber industry in Kenya is far from developed, by assuming a local production, this paper aims to provide useful insight towards a future industry. The building material quantities included in the study can be found in Table 6.

These figures were extracted from floor plans and engineering designs from the industrial partner Arvet. The LCA data was sourced through One Click LCA, which source their data through Ecoinvent, environmental product declarations (EPD) and an internal source where they adapt data for regionality. The quantities shown in table 6 were input into the software and linked with regional data where available. For CLT, there was neither any regionally specific nor eucalyptus tree specific EPD's. Due to its similar properties in terms of biogenic emissions stored and density, Stora Enso's EPD (2020) was selected. A detailed list of the CLCA methods and inputs can be seen in Appendix A, B and C, where the additional trends, market data and constraint information were sourced from a range of official reports and company information.

Table 5 Consequential Scenarios

Scenario	Scenario Description	Sub-Scenario	Sub-Scenario Description
1. Regional CLT Production and Manufacture	Increased demand for timber and CLT is met through local supply	1.1 Sustainable Forest Management	The harvested Forest is replanted
		1.2 Unsustainable Forest Management	The harvested Forest is not replanted
2. Cooking Fuel	Increased demand for timber limits the amount of firewood and charcoal available as cooking fuel	2.1 Replaced by LPG	The displaced biomass for cooking fuel is replaced by LPG
		2.2 Increased Firewood	The displaced biomass isn't replaced, and timber is still used
3. End-of-Life	CLT and Concrete waste displaces new material that would have been used for other purposes such as bioenergy or firewood, leading to the biomass not being harvested and less aggregate mined	3.1 CLT/Concrete waste replaces virgin material	End-of-Life CLT/Concrete displaces fresh timber and aggregate
		3.2 CLT/Concrete waste is landfilled/incinerated	End-of-life CLT/Concrete is landfilled/incinerated, not displacing virgin material
4. Timber By-Products	Timber by-products from the manufacturing process displace the use of fresh biomass, leading to	4.1 Timber by-products displace fresh biomass	By-products from the CLT manufacturing process, make up some of the supply for biomass production

Table 6 Activity Data of NSC building materials for ALCA and CLCA

Material	Source	Unit	CLT NSC	Concrete NSC
Foundation				
Ready Mix Concrete	One Click LCA - Kenya	m^3	12,718.94	12,718.94
Aggregate	One Click LCA - Kenya	kg	4,724,179	4,724,179
Vertical Structure				
Ready Mix Concrete Ground Floor	NEPD-1717-700-SE (Skanska Industrial Solutions AB, 2019)	m^3	6,237.32	6,237.32
Plasterboard	One Click LCA - Kenya	m^2	721,716.48	721,716.48
Ready Mix Concrete Upper Floors	NEPD-1717-700-SE (Skanska Industrial Solutions AB, 2019)	m^3	0.00	64,954.48
CLT	S-P-02033 (Stora Enso, 2020)	m^3	64,954.48	0.00
Mineral wool insulation 25mm	One Click LCA - Kenya	m^2	721,716.48	721,716.48
Plasterboard	One Click LCA - Kenya	m^2	721,716.48	721,716.48
Horizontal Structure				
Ready Mix Concrete Ground Floor	One Click LCA - Kenya	m^3	12,718.94	12,718.94
Ready Mix Concrete Upper Floors	One Click LCA - Kenya	m^3	0.00	81,045.10
Mineral wool insulation 50mm	One Click LCA - Kenya	m^2	312,126.05	312,126.05
Fermacell	EPD-FER-20160218-CAD1-EN (Fermacell GmbH, 2016)	m^2	312,126.05	312,126.05
Fermacell	EPD-FER-20160218-CAD1-EN (Fermacell GmbH, 2016)	m^2	312,126.05	312,126.05
CLT	S-P-02033 (Stora Enso, 2020)	m^3	81,045.10	0.00
Steel Beam	One Click LCA - Kenya	kg	11,126,017	11,126,017
CLT Balcony	S-P-02033 (Stora Enso, 2020)	m^3	26,481.17	26,481.17

3.4 Goal and Scope of LCC

The LCC used in this study is the Environmental LCA described by Hunkeler, Rebitzer and Lichtenvort (2008) measuring the entire cost of all the attributes born directly from the actors within the products life cycle. As well as the ALCA, the LCC will be calculated through One Click LCA and carried out according to BS EN 15686/16627 (British Standards Institution, 2015, 2017). The LCCs goal is to build on the results of the ALCA to determine the economic costs associated with the physical components and management of the NSC over its lifecycle for the cost bearer.

This study will carry out an ALCC due to its clear and transparent methodology which is better suited to this study as it focuses on the direct environmental impact of CLT. Similarly to CLCA's, there is a lack of standardised methodology within CLCC's, which would lead to unclear and unreliable results from the study.

3.5 Life Cycle Cost Inventory and Data Sources

While the ALCC was also carried out through One Click LCA, unlike the ALCA where the internal emission factors were used, there was not any formal data available for Kenya, which is why it had to be extracted individually from several sources, shown in Appendix D. The costs are based on the functional unit of the product/action and then multiplied for the quantity. The LCC results calculated for the discounted cost which is the price at present as well as the nominal cost which takes into consideration the current inflation rate of 5.87% (Statista, 2021).

3.6 Assumptions

Due to the project being in the vicinity of Nairobi that houses a large number of manufacturers, 60 km was selected as the average distance for a majority of products. 600 km was selected for CLT due to the assumed varied suppliers sourced from around the country, as well as accounting for the transportation of the timber to the manufacturing plant and then finally to the site. The steel was assumed to be imported from Tianjin Harbour, China, to Kilindi Harbour, Kenya, before being transported to the site, creating a total transport distance of around 11,500 km. All materials had a service life of at least the building's life span apart from the gypsum plasterboard which had a lifespan of only 40 years. The detailed outline of the inputs can be found in Appendix E.

The study makes assumptions that the electricity required will be sourced through the national grid of Kenya and that the water consumption will be supplied through a piped connection.

3.7 Limitations

The first limitation of this study is that the building is yet to go through its detailed design phase, limiting the accuracy of the quantities of materials. Nonetheless, the study still provides a key indicator of the impacts that can be expected. Another key limitation of the study is the lack of regionally specific data for Kenya; this limits the consequential study where market data is far less detailed and accessible.

There is also no CLT EPD available for eucalyptus trees and although the tree species is spruce and pine, Stora Enso's (2020) EPD was selected due to its similar density and anticipated biogenic emissions. There is also no detailed construction data available for the study and so the only included portions were the excavation works in m^3 as well as the One Click LCA option of "Average Site Impacts" for the gross floor area affected, which assumes 5 kg/m^2 of construction waste as well as 20 kWh/m^2 of electricity usage. This understates the results but also limits the comparison as the concrete was expected to have a far higher construction phase emission (Allan and Phillips, 2021). There was also a lack of data available for the repair and refurbishment of the building, as only the frame for the structure was examined. Whilst data in previous studies is often coupled with and extracted from existing studies, given there are no detailed LCA's for timber used in Africa, this is not an option. This limits what could have been learnt from and compared against regionally specific studies.

4 Results

This section will assess the results of the three different methodologies, ALCA, CLCA, and LCC, and compare the results between the CLT NSC proposal and the Concrete NSC proposal. The results will focus on the GWP against the functional unit outlined in the previous chapter.

4.1 Attributional Life Cycle Assessment Results

4.1.1 Normalised Results

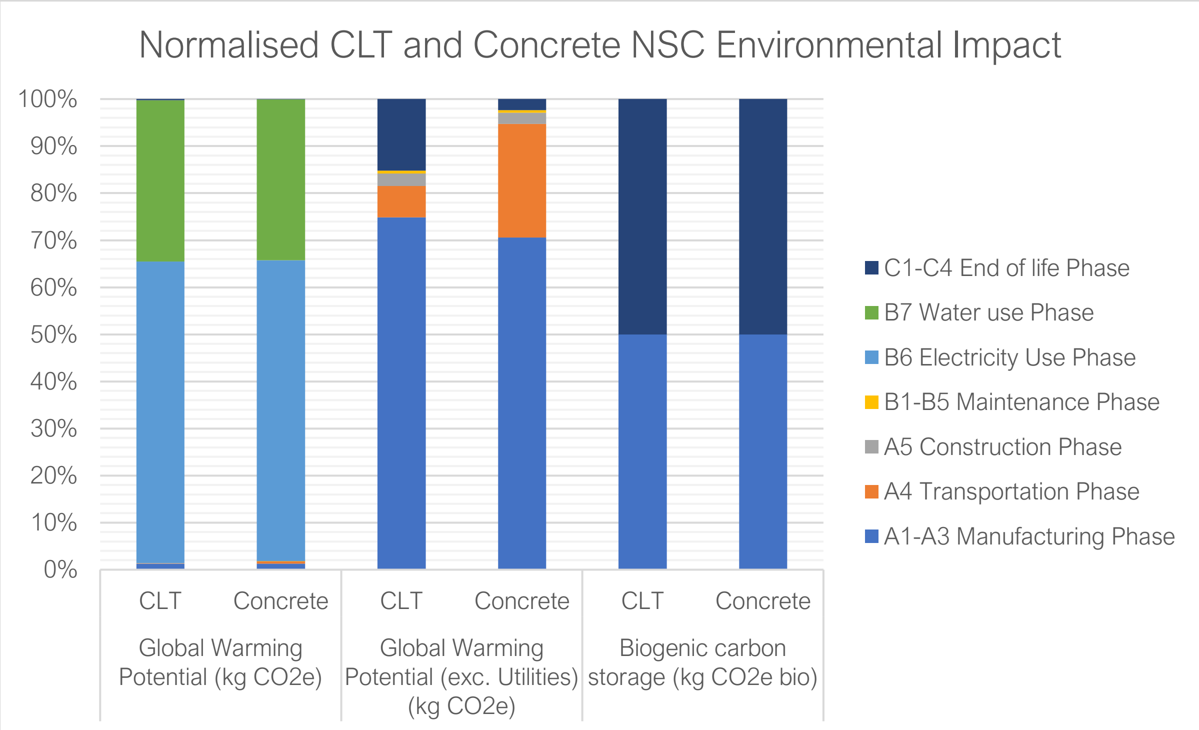

Figure 13 Normalised Environmental Impact of CLT and Concrete NSC

The result of the ALCA analysis produced a GWP of 7,098 $kgCO_2e/m^2$ for the CLT NSC compared to 7,110 $kgCO_2e/m^2$ for the Concrete NSC. As shown in figure 13, operational energy and water were the dominant contributors making up 64% and 34% respectively contributing to almost 98% of the GWP. While it was anticipated that due to the long lifespan of buildings the utilities would dominate the overall contribution to the GWP, the final results of this analysis are far higher than expected. The results also exceed Allan and Phillips (2021) estimation of utilities surpassing the material and construction phase after either 3 or 4 years. The results for the CLT NSC exceeded their estimation after just the first year of operation, and the Concrete NSC exceeded their estimation after the second year. This suggests an overestimation of the electricity and water required for the project.

Kenya and the UK had the same electricity carbon intensity in 2020 (Department for Business Energy & Industrial Strategy, 2020). Kenya has an estimated water usage of 29.37 m^3/year, 11 m^3 less than the UK average (Energy Saving Trust, 2013). The carbon intensity for water in Kenya is double that of the UK, providing an explanation for the higher results of the ALCA compared to relevant literature. When excluding utilities, manufacturing becomes the dominant phase, making up 70% and 75% for the Concrete NSC and CLT NSC GWP respectively. The CLT NSC is slightly lower than anticipated when compared to studies by Allan and Phillips (Allan and Phillips, 2021) who experienced CLT manufacturing to make up 83% of their GWP. The full results can be seen in Appendix F.

4.1.2 Total Life Cycle Phase Results

The breakdown of the LCA in figure 14, aims to provide further detail on the impacts beyond the dominant utilities by removing them from the results and to also allow for comparison to numerous studies that assessed timber buildings as either cradle to gate studies or by excluding utilities altogether.

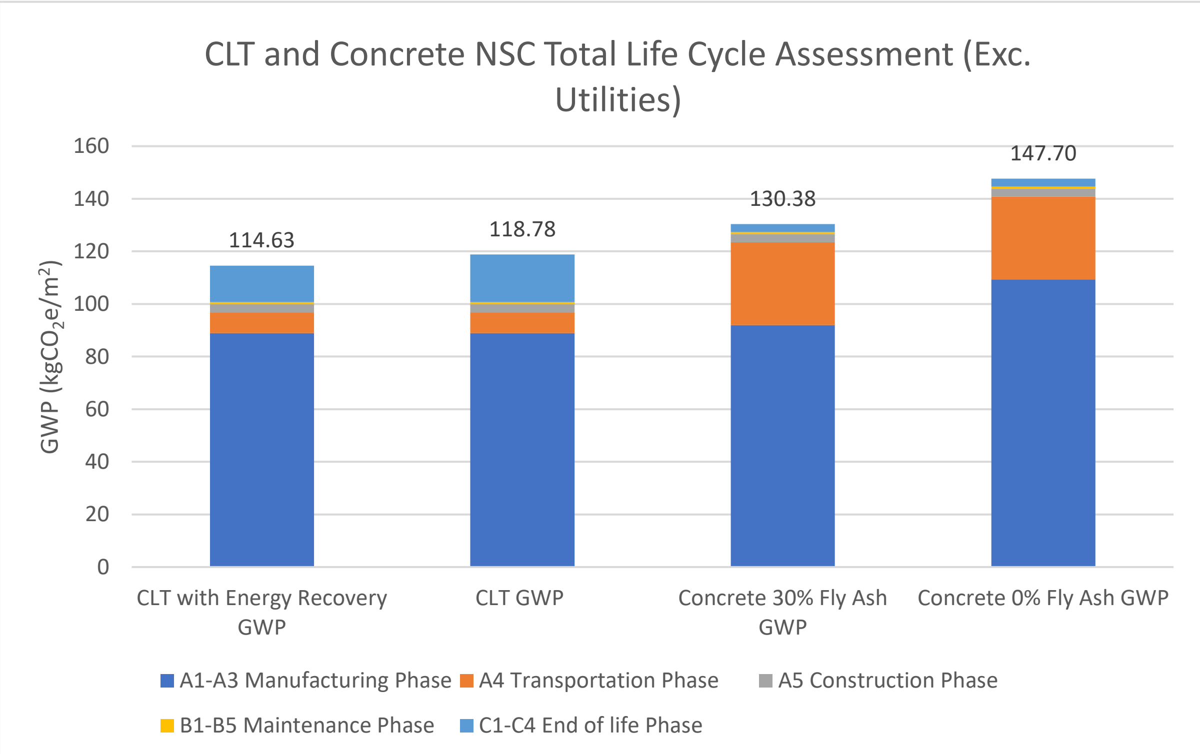

Figure 14 Life Cycle Phase Contribution to GWP per m^2 (excluding utilities)

The total GWP per functional unit is seen to be in line with other studies in academia. Where the CLT NSC total of 119 $kgCO_2e/m^2$ is in line with Dodoo, Gustavsson and Sathre's (2014) result of 120 $kgCO_2e/m^2$ as well as 104 $kgCO_2e/m^2$ from Skullestad, Bohne and Lohne (2016). For the Concrete NSC building, the GWP was lower than expected and lower than the current literature benchmark, where a study by Liang et al., (2020) resulted in a GWP of 237 $kgCO_2e/m^2$. However, their CLT results were also higher than this study at 193 $kgCO_2e/m^2$. As expected, and in line with current literature, the highest contribution to both buildings excluding utilities is the manufacturing phase making up 75% and 74% for the CLT NSC and Concrete NSC respectively. These results however differ from Hart, D'Amico and Pomponi (2021) where manufacturing made up 61% of the concrete building and only 46% of the timber one. The results are more in line with Chen et al., (2020) where both CLT and concrete buildings accounted for 88-98% of emissions.

The transportation phase produced the largest difference between the two buildings, where the Concrete NSC had associated emissions four times higher than the CLT NSC. This is largely due to the substantially higher mass of concrete, which can be seen in table 7. The results estimated that an amount of almost 19,000 journeys were required for the CLT NSC and the Concrete NSC required over 25,000 trips from a concrete mixer truck; a more carbon-intensive vehicle compared to a heavy goods freight used for CLT transportation. As anticipated, the construction/installation process is expectantly low for both NSC's as regionally specific data was not available resulting in a lack of estimated detail. The process would have been expected to be in line with Himes and Busby (2020) who determined a 69% increase in construction phase emissions from CLT to concrete. This would be expected within this study, due to the prefabrication of lightweight CLT units requiring far less heavy-duty machinery than concrete installation.

Table 7 Material Composition of NSC and Concrete NSC

Building Components	Volume (m^3)		Mass (kg)	
	CLT NSC	Concrete NSC	CLT NSC	Concrete NSC
Aggregate	18,170	18,170	4,724,179	4,724,179
Ready Mix Concrete Foundation	12,719	12,719	30,182,054	30,182,054
Ready Mix Concrete	18,956	191,437	45,495,043	459,448,848
CLT	172,481	0	75,891,531	0
Mineral Wool Insulation	33,649	33,649	841,230	841,230
Gypsum Plasterboard	18,043	18,043	15,481,360	15,481,360

Fermacell	6,243	6,243	7,366,175	7,366,175
Steel	1,417	1,417	11,126,017	11,126,017
Total	281,678	281,678	191,107,590	529,169,864

The end-of-life phase produced the second-largest difference between the two products. The CLT end-of-life was assumed to be incinerated, making up 15% of the total GWP, far higher than studies such as Dara, Hachem-Vermette and Assefa (2019) who's end-of-life contribution was less than 1% of the total. It is important that while the CLT was assumed to be incinerated, the assessment doesn't take into consideration whether the incineration would be part of energy recovery. Santos et al., (2021) determined that through the inclusion of energy recovery when incinerating cross insulated panels, emissions were reduced by 23% which is reflected in figure 14. The Concrete NSC assumed the end-of-life phase consisted of breaking the material down to be used again as aggregate. This is still a far less carbon-intensive process and so only contributed to 2% of its total, however, the CLT end-of-life still proved to be a far more beneficial product. A detailed breakdown of the results can be found in Appendix F.

4.1.3 Beyond life phase emissions

As shown in figure 15, the largest beyond life benefits from either building comes from CLT, which when assuming incineration provides emission savings of 98 $kgCO_2e/m^2$ which is assumed to be due to the displacement of biomass to supply incineration processes. The extra concrete quantity for Concrete NSC results in beyond life phase savings 4.6 times higher than for the CLT NSC but still only a fraction compared to the benefits from CLT. Almost all of the steel quantity has the potential to be recycled and reused, which provides a high beyond life phase benefit for the quantity consumed in the model.

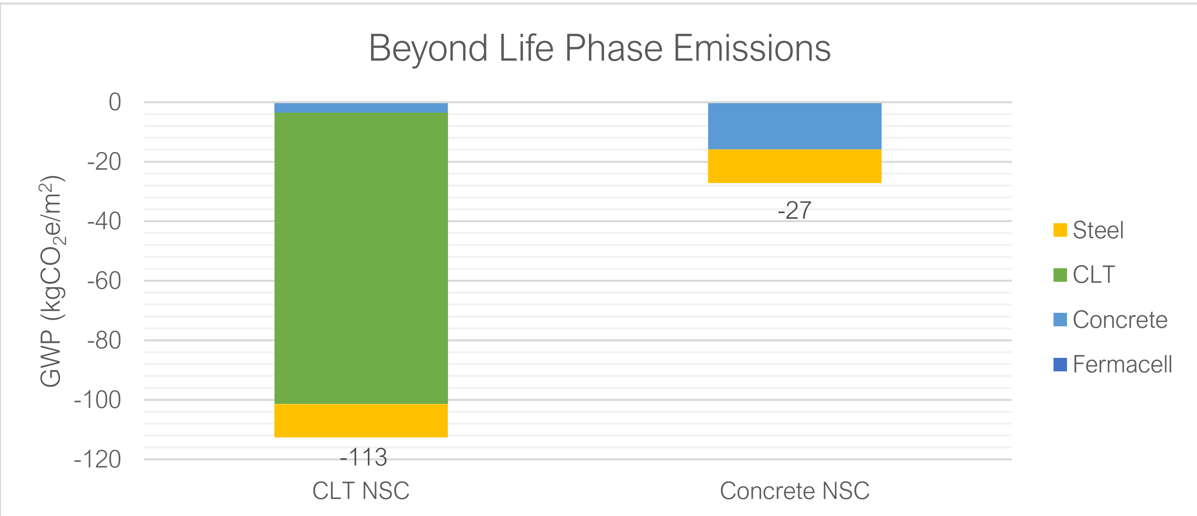

Figure 15 Beyond Life Phase Emissions

4.1.4 Biogenic Emission Results

Biogenic emissions associated with wood is one of the key selling points for the use of CLT as a climate change mitigation option and this is in line with the results that can be seen in figure 16. The CLT NSC dropped from 119 $kgCO_2e/m^2$ to a GWP of -111 $kgCO_2e/m^2$ when including biogenic emissions remaining in line with academic benchmarks where Dodoo, Gustavsson and Sathre (2014) had a result of -93 $kgCO_2e/m^2$. As can be seen in figure 15, the biogenic emission stored in the CLT sequesters enough carbon to account for every phase of the building, and while this will all be released again along with the end-of-life phase, it provides 60 years to replenish this quantity.

The Concrete NSC on the other hand only dropped from 130.3 $kgCO_2e/m^2$ to 129.9 $kgCO_2e/m^2$ due to the concrete carbonation. With an estimated amount of 1.77 $kgCO_2e$ captured per kg a total of 211 $kgCO_2e/m^2$, compared to only 0.44 $kgCO_2e/m^2$ for the total CLA for Concrete NSC, the CLT NSC including biogenic emissions returned a difference of 241 $kgCO_2e/m^2$. The full results can be found in Appendix F.

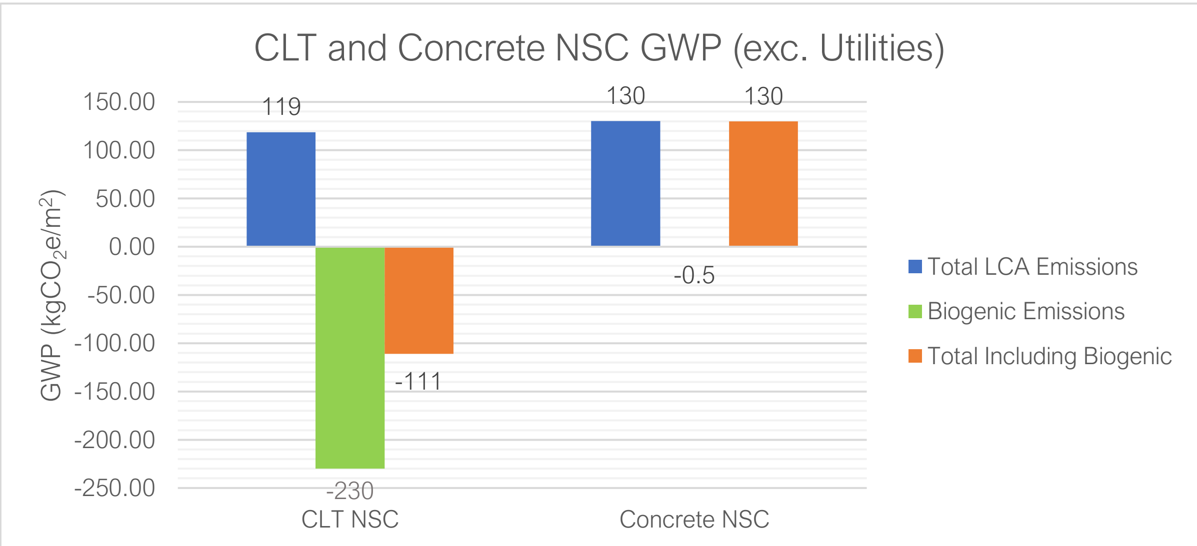

Figure 16 CLT and Concrete NSC GWP including Biogenic Emissions

4.1.5 Embodied Carbon Results

While operational energy and water contribute to the largest proportion of emissions for both buildings, it can be predicted that with the increasing development of nearly zero and low energy buildings, operational energy can be reduced to as low as 14% of the total emissions in the future (Lolli, Fufa and Kjendseth Wiik, 2019).

The embodied carbon for the CLT NSC was as anticipated at 89 CO_2e/m^2 and while studies such as Zeitz, Griffin and Dusicka, (2019) determined that the worst-case scenario for CLT was 67 $kgCO_2e/m^2$ other studies such as Dodoo, Gustavsson and Sathre, (2014) had a result of 114 $kgCO_2e/m^2$. The Concrete NSC had a result of 92 $kgCO_2e/m^2$, far lower than expected and surprisingly similar to the CLT NSC result. It is worth noting that had the study selected 0% recycled binders, it would have increased the embodied carbon of the Concrete NSC to around 1.3 times, raising the embodied carbon to 111 $kgCO_2e/m^2$ and contributing 52%.

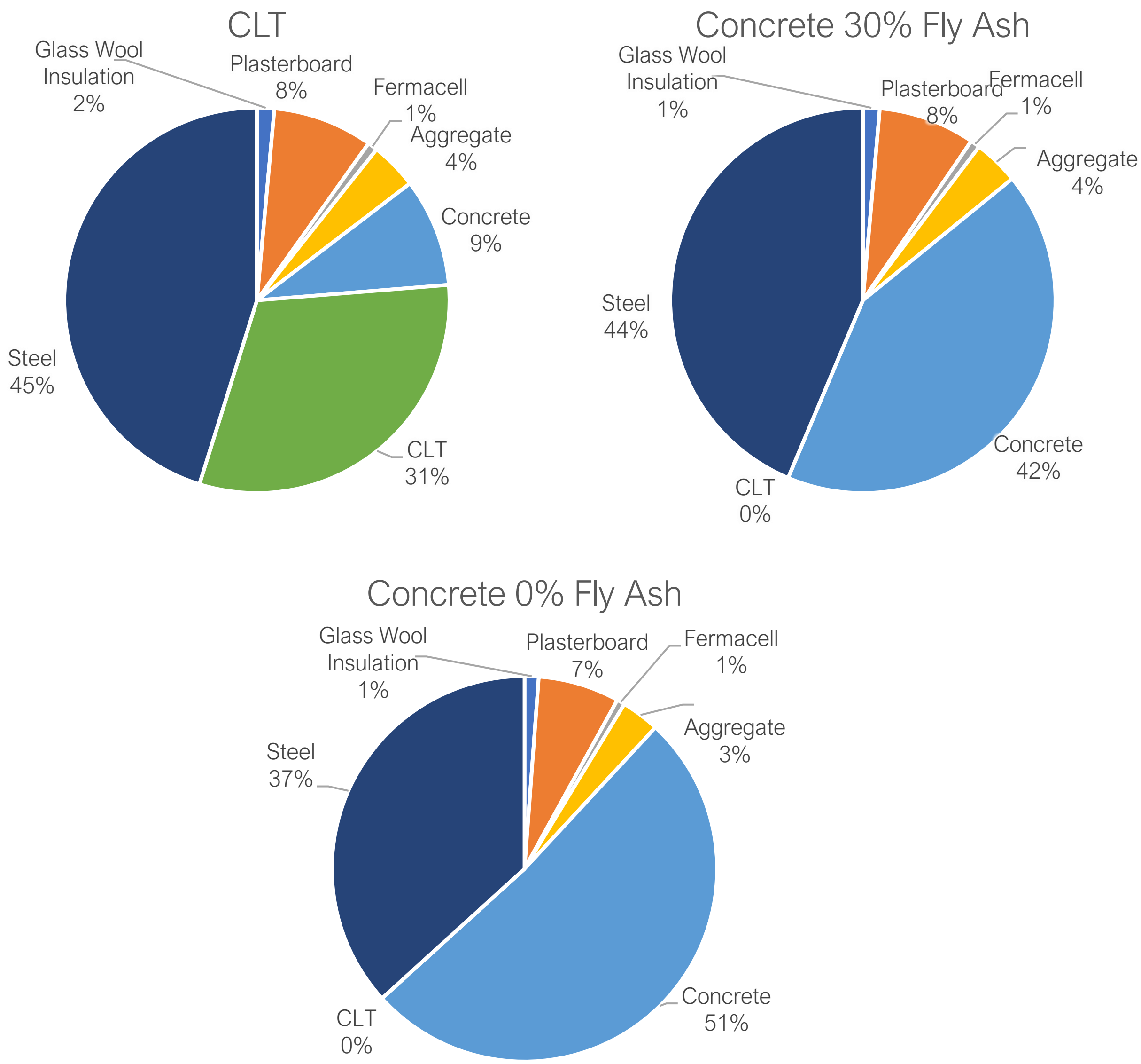

Figure 17 CLT and Concrete NSC Embodied Carbon

As seen in figure 17, for both NSC's, steel was a consistently large contributor. This was surprisingly high as the selected steel contained 60% recycled content, as well as only making up 6% of the CLT NSC mass and 2% of the Concrete NSC mass. The remainder of the embodied carbon was consistent between the two models due to the same inputs, with the full results available in Appendix G.

4.1.6 Life Cycle Cost

4.1.6.1 Normalised LCC

The analysis resulted in the CLT NSC costing a total of \$4.4 billion over its 60-year life span compared to a total of \$4.3 billion for the Concrete NSC. These figures raised to \$34 and \$33.9 billion when considering inflation. Figure 18 shows the normalised results of the LCC of the NSC options. As with the ALCA, it is dominated by the utilities, making up 96% of the CLT NSC and 97% of the Concrete NSC's discounted results. In nominal terms, it was 99% for both. Within all models, manufacturing was the next largest contributor, making up 3% of the discounted CLT NSC and only 2% of the Concrete NSC. The full results can be seen in Appendix H.

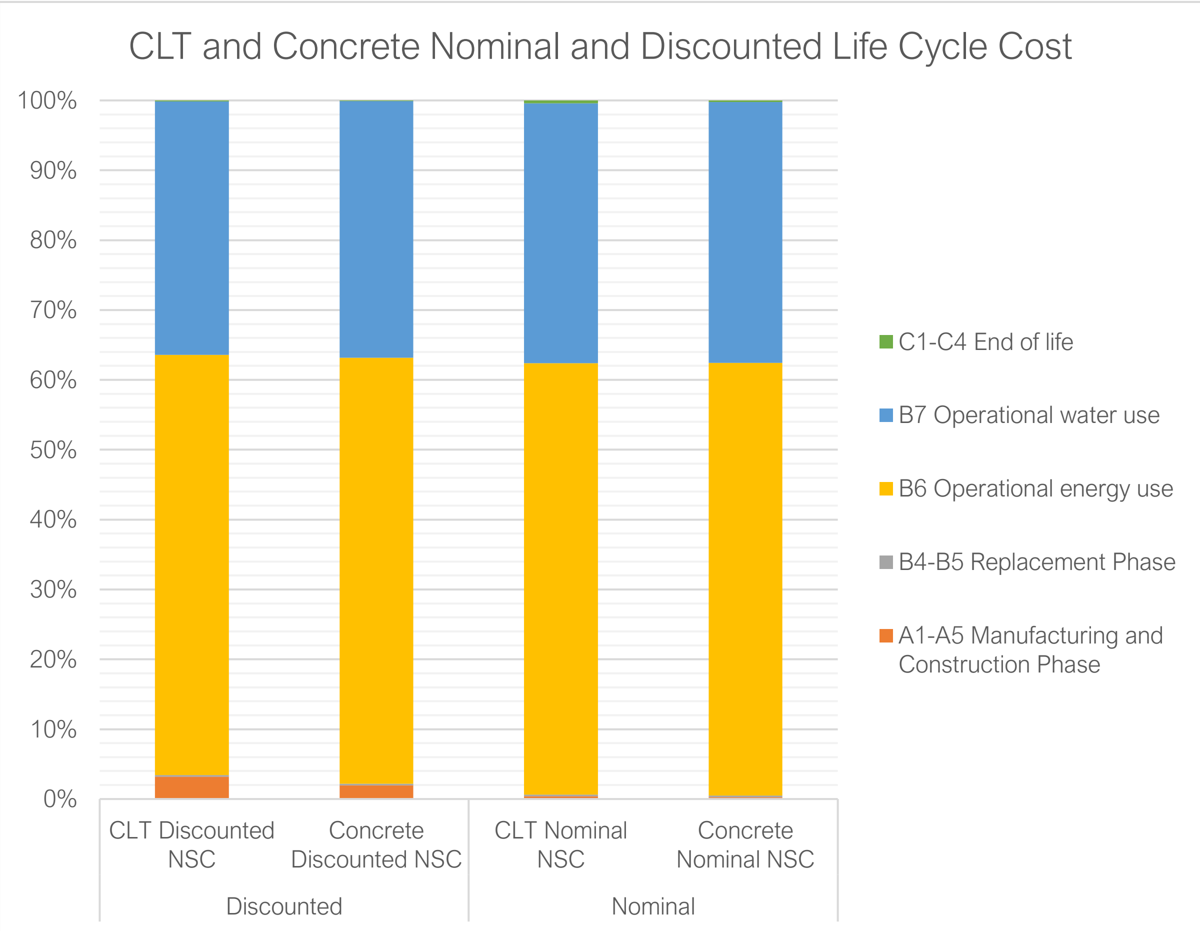

Figure 18 CLT and Concrete NSC Nominal and Discounted Life Cycle Cost

4.1.6.2 Total LCC

When excluding utilities for the discounted model, the results of the LCC highlighted the overall higher cost of the CLT NSC both in the initial CAPEX but also its end-of-life phase. The

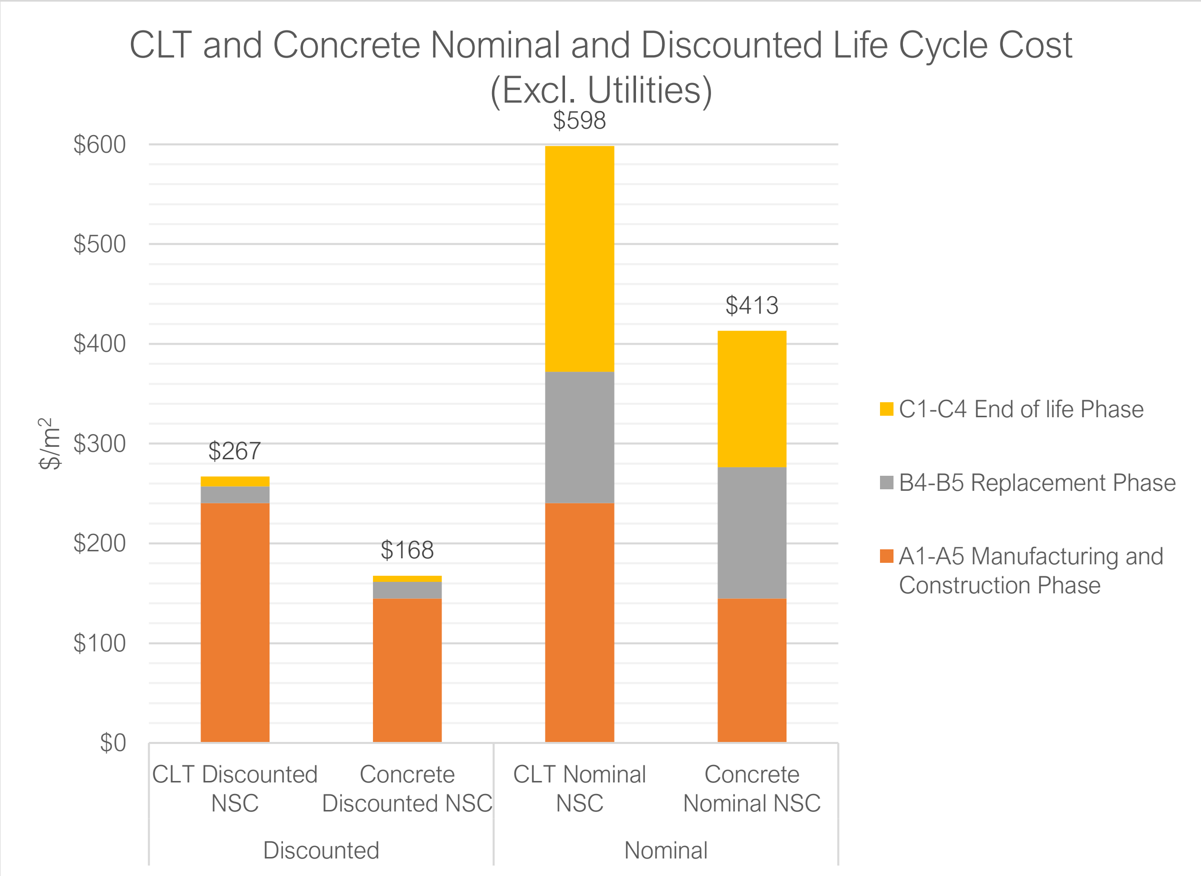

*Figure 19 CLT and Concrete NSC Discounted and Nominal LCC *exc. Utilities)*

manufacturing and construction phase of the CLT NSC came to $267 per m^2 while the Concrete NSC provided savings of $99 per m^2 with a cost of only $168 per m^2, 90% and 86% of the totals respectively. The CLT NSC also had a higher end-of-life phase, however, this was only 1.7 times higher than the concrete alternative.

As expected, the end-of-life has the largest increase from the discounted to nominal LCC. Despite an increase of 22 times for the end-of-life, the manufacturing phase still makes up a majority in the nominal model, 40% for the CLT NSC and 35% for Concrete NSC, followed by end-of-life making up 38% and 33% for the CLT and Concrete NSC respectively. Replacement and refurbishment contribute to the remaining percentage, rising significantly from a discounted price of $17 per m^2 to a nominal cost of $132 per m^2.

As highlighted in the beyond phase of the ALCA, there are significant benefits and uses for both the concrete and CLT beyond its life, but more are anticipated for the CLT, with a large displacement potential for making it into new products compared to the aggregate produced from concrete waste. It should also be noted that the construction phase for concrete is expected to have been higher than for CLT, due to the heavy machinery required and extremely extensive mass which is anticipated to balance out the results slightly more.

4.1.6.3 Embodied LCC

To further understand the material composition and implications, figure 20 looks at just the embodied discounted cost associated per functional unit. As the embodied carbon is the initial cost associated with the building, the inflation rate is not factored in yet and both results are the same. As can be seen, the Concrete NSC contains far larger savings than the CLT NSC. CLT is by far the largest contributor between NSC's making up 61% of the embodied LCC while concrete only contributes 40% in its NSC. This is largely due to the more specialised and complex manufacturing process to prepare CLT compared to concrete, which is a well accessible and common method. Even though the embodied carbon is lower for the Concrete NSC at this stage, it is important to note that the CLT NSC construction phase will have been mostly completed by this point due to its prefabricated nature requiring minimal further work, when compared to the Concrete NSC which would still require an intensive installation process.

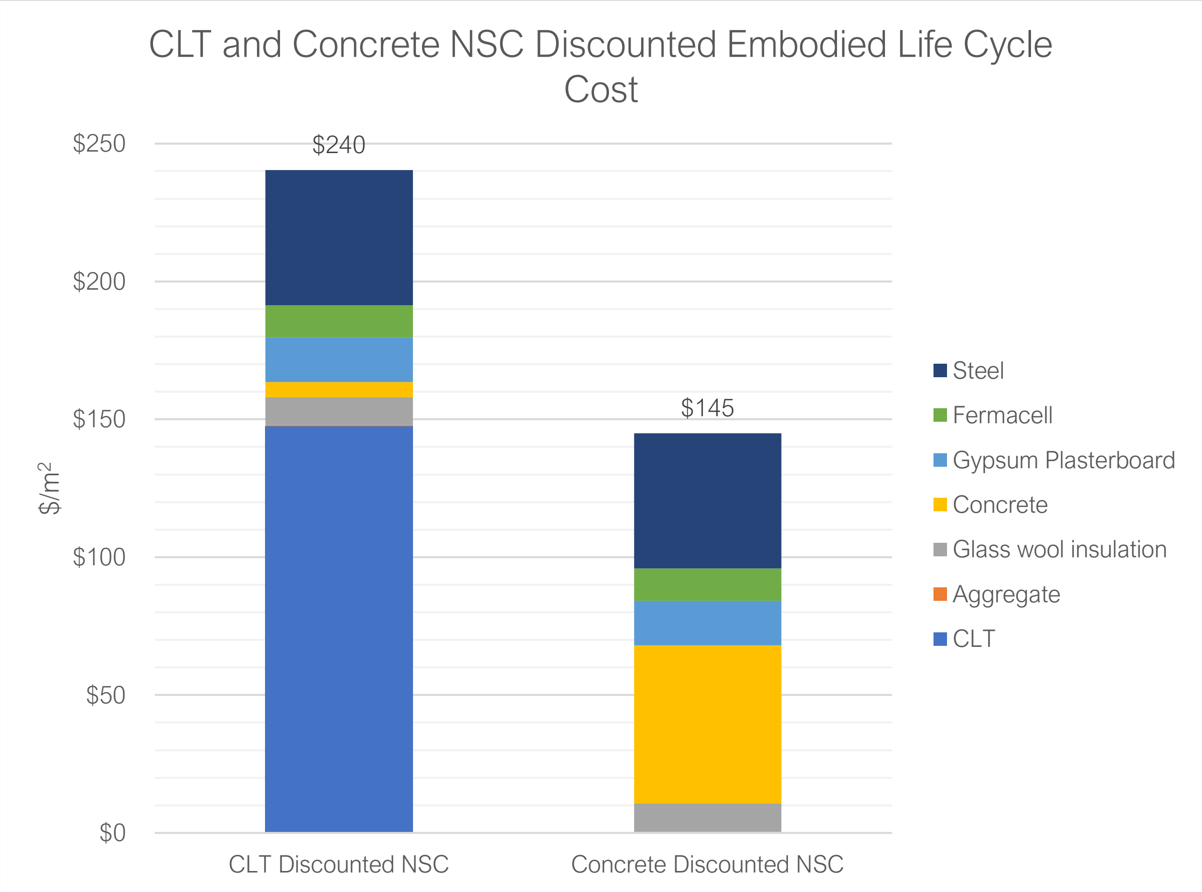

Figure 20 CLT and NSC Discounted Embodied Life Cycle Cost

The LCC of steel seems to match its mass shown in table 6 far more than the ALCA did. These suggestions that the price associated with steel is not in line with the carbon associated with the product. The insulation, plasterboard and Fermacell all play similar roles within the embodied LCC. It is worth mentioning that Fermacell is the only product that needs to be replaced within the building lifespan, doubling its price due to inflation. The total results are shown in Appendix I.

4.2 Consequential

4.2.1 Total Results

Before going into the detail from the CLCA, it is important to note that the actual result from building the NSC will not be solely either the best case or worst-case scenarios exclusively, but instead, more likely a mix of all scenarios and so interpreting the result should be used as an indicator rather than an expectation.

Table 8 CLT and Concrete NSC Consequential LCA Total Results

Scenario	CLT NSC Net Emissions ($kgCO_2e$)	Concrete NSC Net Emissions ($kgCO_2e$)
1.1 Sustainable Forest Management	-575,861,342	N/A
1.2 Unsustainable Forest Management	575,861,342	N/A
2.1 Cooking fuel - Replaced by LPG	5,764,410	N/A
2.2 Cooking fuel - Increased firewood	149,449,477	N/A
3.1 CLT/Concrete waste replace virgin materials	-137,741,052	-23,369,343
3.2 CLT/Concrete waste is landfilled/incinerated	137,741,052	23,369,343
4.1 Timber by-products displace virgin biomass	-60,447,604	N/A
4.2 Timber by-products are landfilled	60,447,604	N/A
5 Water demand met through infrastructure investment	137,969,083	82,309,737
Best Case Scenario (0.1)	-630,316,505	58,939,511
Worst Case Scenario (0.2)	1,061,468,557	105,678,197

The results of the scenarios can be seen in table 8. The consequential impact from both the CLT NSC and Concrete NSC has huge potential to widely impact the emissions as a response to its implementation. As discussed in the methodology, the estimated marginal systems affected by both designs is due to the timber use and water use, which is reflected in the results with larger marginal impacts from the CLT NSC.

Forest management is the largest consequence of carrying out the CLT NSC. A 14-year rotation period for eucalyptus trees in Kenya (Nyakundi, Mulwa and Kabubo-Mariara, 2018), over the 60-year life span of the building would result in 4.3 tree rotations over the building life-cycle. This is the equivalent of approximately 851,844 trees that could be replanted with huge sequestration savings of around 576 million kgCO_2e. This has the potential to reduce the total project's emissions by 23% when included in the biogenic emissions of the CLT NSC.

As a water-scarce country, it is assumed that due to the extremely large increase in water demand it can only be met through investment into national/local water infrastructure. While both designs have an estimated water demand of 34 billion litres over their lifetime the marginal impact from the CLT NSC still more than doubles that of the Concrete NSC due to an estimated amount of 23 billion litres of water to irrigate the tree supply. For the Concrete NSC, around 36 million litres of water are predicted to be required for the construction phase to supply the concrete.

With almost 199 thousand trees needed to supply the CLT NSC, this has a huge displacement impact on the supply of firewood as cooking fuel. In the worst-case scenario, which increases deforestation through the increased demand, emissions associated with burning firewood and the lost biogenic emissions that are equivalent to almost 150 million kgCO_2e, could be produced. Were this displaced timber to be replaced by LPG, the equivalent amount of firewood is estimated to be around 760,000 kg's of LPG, resulting in total emissions of almost 6 million kgCO_2e (Federal Ministry for Economic Cooperation and Development, 2014).

CLT production only uses an average of 55% of the tree, leaving the remaining 45% of the tree to serve as by-products (James Jones, 2021). These by-products such as sawdust and wood chips still have a high value and were this waste to be used to supply, for example, either biogas or bioenergy, it would prevent the cutting of new trees which would have been needed for those products. This is the same process when CLT comes to its end-of-life, it has the potential to further prevent the removal of the equivalent amount of biomass. Both of these methods reduce the demand for fresh timber feeding towards the circular economy.

5 Discussion

This section will interpret the results of the ALCA, CLCA and LCC, to assess the implications of using either a CLT NSC or a Concrete NSC in Kenya, and how these materials could potentially benefit the continent.

5.1 The Environmental Impacts of a CLT NSC versus Concrete NSC

5.1.1 ALCA

As anticipated and in line with literature benchmarks, the CLT NSC performed better than the Concrete NSC, however, there were only slight savings of 12 $kgCO_2e/m^2$ between the two. With CLT's label as a "carbon neutral" product, this is a very minor saving compared to the fly ash concrete, raising the question of why the final results were so similar between the two NSC's.

When excluding utilities, the manufacturing phase was the largest contributor for both NSC's. The results were surprisingly similar, with the CLT NSC only producing savings of 3 $kgCO_2e/m^2$ compared to the Concrete NSC. As shown in figure 21, CLT contains a fairly complex process to engineer wood into a suitable product, with every step further raising the embodied carbon. Excluding transportation, the lumbering process itself makes up around 38% of the total footprint, while the remainder comes from the CLT processing (Chen, Pierobon and Ganguly, 2019). Within the processing, despite only making up 1% of the total mass, the resin required for the finger jointing and face bonding contributed a vast 30%. All this combined, along with a mixture of utilities and machinery results in a carbon factor of 171.6 $kgCO_2e/m^3$ compared to 215.8 $kgCO_2e/m^2$ for concrete (Stora Enso, 2020). It is however important to bear in mind that as CLT arrives at site as a prefabricated unit, the LCA results are slightly distorted due to a large portion of the construction process already having been carried out. This further reduces emissions within the construction phase where the pre-fabricated products are quickly assembled with minimal machinery (Brandt *et al.*, 2019). This also highlights the potentially misleading labelling of wood as a "carbon neutral" product, where while the biogenic emissions and tree replanting can make this true, there are significant short-run emissions from using it as a product that cannot be overlooked.

As alluded to, the results within this study may also be more similar than anticipated due to the lack of information surrounding the construction phase. This phase of the LCA was limited due to the unavailability of data, resulting in using the One Click LCA estimates for quantities of fuel, electricity and waste, based on the “Average on-site impacts”. The excavation area was included which was the same for both. However, a study by Himes and Busby (2020) determined that timber on average resulted in a 69% reduction in construction emissions compared to conventional materials. This is a substantial variation that without consideration would have further raised the emissions for the Concrete NSC and reduced the current disparity which disproportionately affects the prefabricated CLT NSC.

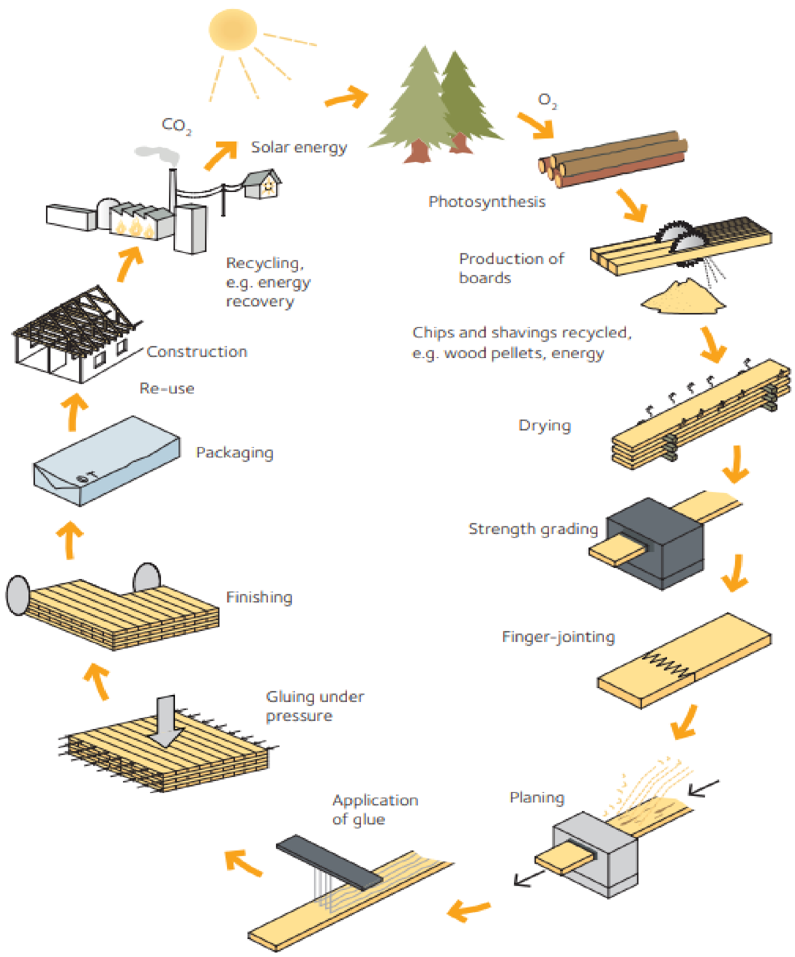

Figure 21 CLT Manufacturing Process (Swedish Wood, 2019)

A further potential cause for similarity in results is the high end-of-life emissions associated with the CLT NSC, which makes up 15% of its LCA compared to only 2% for the Concrete NSC (excluding utilities). This is limited due to the software assuming incineration as the end-of-life for CLT, however, as shown by Santos et al., (2021), there is a 23% reduction between incineration and incineration with energy recovery. If applying this, the CLT NSC GWP is reduced by 4 $kgCO_2e/m^2$ and increasing the gap to 16 $kgCO_2e/m^2$, a minor impact, however as shown in the CLCA and beyond life phase, this has significant emission savings through displacement.

The benefits of the beyond life phase with CLT alone provides GWP reductions of 98 $kgCO_2e/m^2$ compared to only 16 $kgCO_2e/m^2$. Incorporating this into the final results reduces the CLT GWP to 6 $kgCO_2e/m^2$ (excluding utilities and previous discussion), while the Concrete NSC remains high at 103 $kgCO_2e/m^2$, heavily in favour of the CLT NSC. There are also further benefits that can be experienced with the CLT which address the largest associated emissions of the project: the energy use. CLT possesses improved thermal conductivity and vapour permeability, reducing the amount of cooling and energy used for the project. This substitution from concrete to CLT is estimated to reduce the total energy use by 25%, creating a difference of 1,136 $kgCO_2e/m^2$ (Puettmann, Sinha and Ganguly, 2019). Putting all these variations together creates a final result of 3,524 $kgCO_2e/m^2$ for the CLT NSC and 4,678 $kgCO_2e/m^2$ for the Concrete NSC, a substantial benefit for the CLT NSC.

5.1.2 CLCA

For the CLCA, as anticipated, the CLT NSC contained far more potential for emissions savings, potentially reducing system-wide emissions by up to 630 million $kgCO_2e$, while in its best case, the Concrete NSC still emitted 59 million $kgCO_2e$. Regardless of this, it can be argued that the CLT NSC contains the most potential for risks in terms of achieving environmental benefits. The worst-case system-wide changes contribute an extra 1 billion $kgCO_2e$, compared to only 106 million $kgCO_2e$ for the worst-case scenario in the Concrete NSC. To achieve a more accurate understanding of the consequential impacts, a better appreciation is needed of the probability of the different scenarios coming to fruition.

Achieving the best results for the CLT NSC through the end-of-life scenarios and timber by-products scenarios are fairly probable. This is not only a result of the high timber demand within Kenya but also as the decision to achieve these scenarios is held by the practising company resulting in fewer implementational barriers. The infrastructure portion of the water use scenario also has fewer barriers, as it was determined to be the only suitable option available for Kenya to meet its 2030 goals, along with the recently increased investment (Government of the Republic of Kenya, 2013). The NSC is also located close to two of Kenya's water towers, making the site more easily accessible for the required piping. The other portion of the system-wide water impact is the required water supply for the trees. As shown in the restoration potential report (2016), while there is plenty of potential for tree growth in Kenya, this doesn't necessarily coincide with the water availability, and with a limited supply at a distance from the five water towers in the country, this has the potential to have substantial impacts.

Unfortunately for the CLT NSC, the two most potentially emitting worst-case scenarios are also the most complicated scenarios to achieve correct implementation and contain the most barriers to being achieved. While LPG taking the place of cooking fuel is the most reasonable alternative, there is still no guarantee of its wider uptake, with availability, cost and policy all playing a role in its implementation (Africa Clean Cooking Energy Solutions Initiative, 2014). As mentioned previously, fuelwood and charcoal are currently well established and unregulated markets within Kenya and so provide a low-cost option for many households which will require substantial work to displace (Bond *et al.*, 2019). This is the same for sustainable forest management, whereas mentioned, there is the desire and potential to begin establishing a sustainable forestry sector, however, policy, public understanding, and sector maturity are required to see it be achieved.

The Concrete NSC, on the other hand, does not require any timber and so the only main system-wide water impact is the water required for the piping and concrete. Similar to the scenario for the formal piping which has already been discussed, the required water for concrete will similarly be easier to supply due to its proximity to Nairobi which contains a more mature infrastructure network compared to other parts of the country, but also the five water towers (USAID, 2017). The only other consequential scenario is the by-products of concrete displacing virgin aggregate. This is a fairly likely scenario as again it has far fewer barriers to being achieved, where the cheap recycled product only requires the decision of the owner to ensure it happens.

5.1.3 LCC

In terms of the costing of the LCC, the Concrete NSC achieved costs savings of $99 per m^2 compared to the CLT NSC (excluding utilities), a far more substantial difference than the carbon savings from the ALCA, when not considering the beyond life and biogenic emissions. The large cost associated with the CLT NSC is due to the extension machinery and space required to manufacture CLT. Brandt et al., (2019) estimated that the machinery requirements alone for a small scale CLT facility would require at least $13.5 million of investment. However as mentioned, this is partially balanced out during the concrete construction phase that takes longer, requires heavier machinery and transportation of material.

What the LCC fails to address, but what is touched upon by the ALCA, is significant beyond life savings from the products, where at its end-of-life, CLT is far more beneficial and profitable. The financial implications associated with this, basing a cost estimation from the price of wood chips in the UK sold at £109.96 per tonne (Forest Research, 2021), reduces the total deficit from $99 per m^2 down to $14.27 per m^2.

5.2 Opportunities for reducing the GWP of the NSC's

Making up the majority of the direct emissions associated with both NSC designs, the electricity and water use must be addressed. As mentioned, Kenya's electricity supply currently exceeds its demand. Nonetheless, it still only reaches an estimated 75% of the population (International Energy Agency, 2019c). While this is estimated to be 100% by 2022, and alongside the predicted growth in population, the demand is expected to increase rapidly and so there is still potential for constraint if the infrastructure does not develop parallel to this (International Energy Agency, 2019c).

Kenya has one of the cleanest energy mixes in Africa, with the current mix dominated by geothermal and hydropower, making up 44% and 34% respectively (International Energy Agency, 2019c). While there is a total national supply of almost 12 thousand GWh, Kenya currently has the second-largest average electricity loss at 21%, far above the developing country average of 9%, resulting in frequent power outages that mean many businesses and homes rely on backup generators (International Energy Agency, 2019b). Providing electricity for almost 20,000 students, the NSC has an estimated electricity demand of almost 3.2 million kWh/year; a hefty strain on the local grid. With a total roof area of almost 91 thousand m^2, a method to reduce this strain and reduce the GWP of the NSC is through a hybrid solar-panel system, maintaining a connection to the grid but primarily sourcing its power through natural energy resources.

Kenya currently has a healthy solar PV market, producing around 1.5 MW per year, a small figure but high in the potential for growth (Amankwah-Amoah, 2015). With almost 700 m^2 of roof area per building, and 120 buildings in total, there is scope to install 46 solar panels at 310-watt capacity per building. This would produce an estimated 2,400 kWh per year, enough electricity to cover the demand for each building (Solar Reviews, 2021). In total, 5,520 panels would be required at the initial cost of $6,000,000 resulting in a payback period of 11 years. With a 25-year warranty, the investment would reduce the emissions from 2.7 billion kgCO$_2$e to 0 kgCO$_2$e for electricity and provide cost benefits for at least 15 years. As a new build, there is potential to save costs further by installing the solar PV using existing machinery during the construction itself. It is worth noting that these prices are for the USA and so will most likely be less in Kenya. Were this to be put in place, with the requirement to be replaced after 30 years, it would reduce the utilities GWP from 4.1 billion $kgCO_2e$ to 1.5 billion $kgCO_2e$, as well as providing cost savings of $44 million per year.

Water on the other hand may not have as simple a solution. Kenya is one of the most water-scarce countries globally, with a per capita availability of 1,000 m^3 annually, compared to countries like the UK who have a per capita availability of almost 4,000 m^3 (Lallana and Marcuello, 2004; Mulwa, Li and Fangninou, 2021). At present, 32% of the Kenyan population use unimproved drinking water sources and only half the rural population have access to suitable water infrastructure (Mulwa, Li and Fangninou, 2021). This is largely due to the five "water towers" covering only 2% of the total land area, and as can be seen in figure 22, are localised to the East of the country. With a total estimated consumption of 571,000 m^3 of water per year for the entire NSC, an integrated water system and access to appropriate piping and infrastructure, coupled with a rainwater harvesting and storage system, may be able to ease the strain on the increased demand. According to UNESCO's Rain Water Calculator (2018) there is potential to capture almost 501 thousand litres of water per building in the NSC per year, which provides the potential to reduce the total demand by 60 million litres and save around 45,000 $kgCO_2e$ per year and 2.5 million $kgCO_2e$ over the building lifetime.

If both of these methods were to be installed, assuming the solar PV has a lifetime of 30 years before needing to be replaced, it would reduce the total emissions of the CLT NSC project from 7,094 $kgCO_2e/m^2$ to 2,281 $kgCO_2e/m^2$, and the Concrete NSC from 7,112 $kgCO_2e/m^2$ to 2,298 $kgCO_2e/m^2$, reducing energy emissions to 0 but still only reducing water emission by 11%.

A large portion of both NSC's is the steel quantity, making up 45% and 44% of the CLT and Concrete NSC embodied carbon respectively. As its purpose is only to support the balcony network, it would be worth assessing the potential to remove or replace this with a more sustainable option. Steel currently has an embodied GWP of 40.16 $kgCO_2e/m^2$, however, the same quantity for either CLT or Concrete would be reduced to 0.52 $kgCO_2e/m^2$ or 0.42 $kgCO_2e/m^2$ respectively.

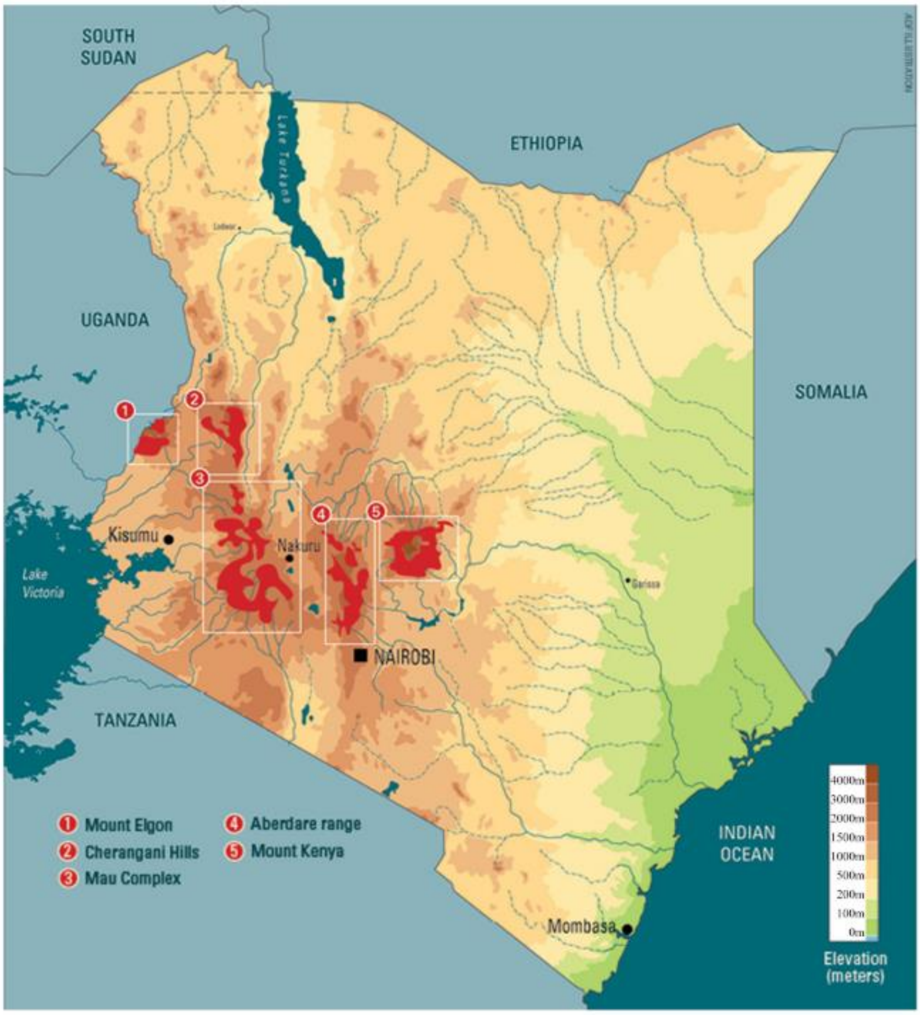

Figure 22 Kenya's Water Towers (Mulwa, Li and Fangninou, 2021)

5.3 Key success factors for CLT NSC implementation to consider

The results of the ALCA and CLCA show that in its best-case scenario, the CLT NSC has quite extreme carbon benefits compared to the Concrete NSC, particularly when including biogenic emissions and beyond life phase emissions. To achieve this potential, however, several barriers need to be addressed, to further promote CLT but also ensure the large potential for system-wide emissions doesn't take place.

The first and arguably most important barrier to be addressed is the supply of timber. The CLT NSC would require the supply of 24,000 trees annually, impacting around 411 hectares of land over the 7-year construction period. This has the potential to result in a negative carbon impact of over 650 million kgCO_2e if this land isn't replanted. As such, CLT use should only be approved with the guarantee of the wood being sourced from sustainably managed forests. Reports by the Ministry of Environment and Natural Resources (2016) that identified the total of 38.8 million hectares of potential forest in Kenya show that this is possible, but at present Kenya still has a wood deficit of 10 million m^3 per year, creating doubt over how soon the local forest management policies can change to supply the CLT NSC sustainably, without further displacing the demand needed elsewhere (Ministry of Environment, 2013). At present 70% of the supply of wood in Kenya is sourced from farms of varying sizes, however, due to limited income-generating options and low investment periods, trees are being overexploited and cut prematurely to supply charcoal and firewood (Ministry of Environment, 2013). CLT has the ability to catalyse a more efficient timber market within the region. As a product that's price is more stable than firewood and charcoal, and also more formal, with clear market forecasts for farmers and timber producers, there can be less risk for them to harvest within the correct timeframes, with less urgency and risk to leading to further degradation.

Another barrier to the deployment of CLT is the higher initial CAPEX compared to concrete. At an estimated cost of \$500/m^3 compared to \$118/m^3, the initial CAPEX for the CLT NSC was estimated to be almost double that of the Concrete NSC at \$141 million compared to only \$85 million respectively. To promote the use of CLT, action must be taken to make it a more financially competitive option. One option to help achieve this is through the application of a subsidy on either the final CLT panels or on the supply of lumber itself which Brandt et al (2019) determined to be the largest capital expenditure of the manufacturing process. This would either incentivise sustainable wood harvesting or CLT manufacturing, which would not only make the price of the product more competitive but further de-risk timber, providing system-wide economic benefits for the wider associated markets and supply chain. To make the price of CLT and concrete equal, a subsidy of \$382.5 per m^3 would be required, reducing the CLT NSC CAPEX to \$75 million. This would result in the LCC for the CLT NSC being \$10 million less than the Concrete NSC but would cost the government \$66 million for the project alone. Were the government to supply a subsidy of \$250 per m^3 (half the estimated cost), this would reduce the CAPEX to \$97 million, only \$12 million more than the Concrete NSC and cost the government \$43 million. To ensure local benefit, it would be recommended that the subsidy would be tied to the condition that the timber would be sourced locally, and sustainably, to promote local employment, building up the supply chains eventually making it more competitive.

As a first of its kind project in Kenya, there is potential for the CLT NSC to act as a market mover, establishing a precedent and replicable standard for similar CLT projects going forward. This innovation would be anticipated to have significant economic benefits, with the potential to not only de-risk future CLT projects but begin to establish previously wavering timber and cooking fuel markets associated with its supply chain (Nordin *et al.*, 2010). This would further be estimated to spur investment in local CLT manufacturing by companies identifying opportunities.

The first sector and most crucial area which would need to react to the increased demand is the forestry sector. In 2019, the forestry and logging sector in Kenya contributed 1.3% of the country's gross domestic product with an estimated output of $785 million, however, due to a 2018 hold on the logging ban, there has been an estimated 85% employment loss, with turnover reduced to a third in a year at $87 million (Kagombe *et al.*, 2020). With CLT being able to use trees of various sizes, the new market has the potential to create a stable and formal system to sell wood, reducing deforestation from short investment and over-harvesting. Eucalyptus is estimated to have a management cost of $291 per acre producing around 1,037 cubic meters over 14 years to the maturity of the trees, equivalent to $0.26 management cost per tree to produce 0.94 m^3 (Nyakundi, Mulwa and Kabubo-Mariara, 2018). At a price of around $41 per m^3, there is potential to make a profit of $42,226 in total or $0.94 per tree. This provides a suitable opportunity for small scale farmers who would have access to irrigation required.

A study for Uganda determined that a small sawmill is estimated to be able to process around 165,000 m^3 of wood per year. To get this up and running, an estimated CAPEX of $560,000 is needed (Food and Agriculture Organisation of the United Nations, 2020b). While this provides numerous financial benefits to the farmers, both plantations and farmers need to be developed and appropriately managed through well-enforced regulation to reduce the current supply gap faced in Kenya. This policy must be implemented to ensure appropriate management of and result in healthy forests. As mentioned earlier, there are a significant number of risks for forest management in Africa, which if aren't carefully managed could further lead to an increase in emissions and loss of employment. Kenya is currently lacking the required forest management policies to reduce the current supply deficit and eventually realise a flourishing sustainable timber market.

Following along the supply chain, the next market which will need to react is the deployment of CLT manufacturing factories. The presence of innovation creates the need but also an opportunity for existing companies within the supply chain to either reposition themselves or expand (Nordin *et al.*, 2010). Here there is an opportunity for wood manufacturers but also paper manufacturers to follow in the footsteps of companies like Stora Enso and diversify their products to expand to CLT manufacturing as well to the point where Stora Enso is now the biggest CLT manufacturer globally (Espinoza *et al.*, 2015). A study by Brandt *et al.*, (2019) carrying out a techno-economic analysis of CLT factories in North America estimated that a small facility producing 52,000 m^3/year would require a total capital investment of \$64.6 million with yearly operating costs of \$26.2 million. The study estimated that the minimum selling price of CLT would be \$652/m^3. While this is far above our estimate of \$500 per cubic meter, the lumber prices are anticipated to be far lower than in the US.

5.4 Policy Recommendations

It is important to keep in mind, that this study has focused on two “sustainable” building options, and as such, the 30% fly ash is the best-case scenario for concrete use currently. The first responsibility of the government is to establish ambitious and up to date building regulations and standards, to prevent locking in inefficient building practices and further encouraging more carbon-friendly materials. The CLT NSC provides the opportunity for the Kenyan government to create a CLT/timber friendly policy, highlighting the potential micro- and macro-economic benefits, as well as social benefits.

Following this, the priority must look towards establishing strong and well-regulated forest management policies. This would need to begin with clearly defined property rights of the forests, either as national, private or even communally owned forests (Torres-Rojo, Moreno-Sánchez and Mendoza-Briseño, 2016). This provides the capacity for local communities to manage their natural resources and benefit from the local socio-economic benefits, while also protecting indigenous forests and developing areas identified as potential growth (The World Bank, 2007). This can further be encouraged through a subsidy on the price of lumber, encouraging formality and sustainability.

The government must then look towards formalising the timber sector further, to develop the encouraging farm and private production while prohibiting the harvesting of indigenous sources. These policies will then need to be well-enforced with effective planning and management, to protect indigenous forests, while encouraging sustainable harvesting. Further encouraging the use of sustainable forests can also lead to an increased supply towards bioenergy plants, providing an end-of-life benefit to CLT, as well as electricity to the local communities.

A method of helping reduce the current demand and source of illegal harvesting is by addressing the largest demand, which is firewood and charcoal, demanding 75% of the supply annually in Kenya (Ministry of Environment, 2013). To assist with the supply problems more sustainable methods for energy and cooking fuel need to be established (SouthSouthNorth, 2020). LPG is currently in the best position to make up this demand and needs to be promoted further the loss of productive time mostly for women, as well as around 500,000 premature deaths per year caused by current cooking fuel practices (International Energy Agency, 2019c). Reducing firewood and charcoal demand would firstly limit the strain on forests as well as local communities, while also providing further supply for CLT manufacturing.

5.5 Attributional versus Consequential

This study suitably displays the benefit of carrying out both an ALCA and CLCA parallel to each other. The ALCA supports the deployment of a CLT NSC, highlighting the substantial emissions from the utilities and the steel as well as savings within the beyond life and the biogenic portion of the LCA. The CLCA on the other hand highlights the substantial system-wide risks associated with the CLT NSC, where it has the most potential benefits, but also the most negative impacts if not properly managed, highlighting the need for sustainable timber supply. This firstly shows that the ALCA shouldn't be used independently for decision making, while the hotspots in the ALCA must be addressed, the potential emissions caused from CLCA outweigh the biogenic and beyond life phase emissions and highlights many issues which must be addressed before wide-scale implementation of CLT can sustainably be carried out.

6 Conclusion

The ALCA highlighted utilities as the largest contributor to the GWP within both NSC's, making up around 98% of ALCA. This can be addressed through the incorporation of solar panels which has the potential to supply enough electricity to the entire NSC at an additional cost of $12 million over the lifecycle. Water on the other hand can be mitigated through rainwater harvesting but is far from enough to supply the entire NSC. Beyond utilities, the ALCA leaned in favour of the CLT NSC, with savings of 12 $kgCO_2e/m^2$. This was far less than expected due to several parameters being omitted which would have highlighted some of the benefits of CLT, such as the construction phase, a lack of detailed study on the energy use, and the assumption on incineration as the end-of-life phase. When incorporating the biogenic emissions and beyond life phase emissions, the CLT NSC GWP performs far better compared to the Concrete NSC.

Overall, CLT under the correct circumstances has a huge potential for climate mitigation. However, without these circumstances, CLT has the potential to cause significant system-wide emissions, 10-times higher than the Concrete NSC's worst-case scenario. The Concrete NSC provided a safe return in the CLCA, a mild worst-case scenario compared to the ALCA result. It is worth noting that while the concrete supply chain is well established, the CLT NSC has the potential to provide numerous benefits in the long term, incentivising sustainable forest management and providing mass employment among other micro- and macro-economic benefits

The ALCC was strongly in favour of the Concrete NSC, with savings of $99 per m^2. However, this can be reduced when considering the end-of-life benefits of CLT as it remains a valuable product. Through the application of a government-provided subsidy, CLT would require a huge subsidy of $382.5 per m^3 to bring the price in line with concrete, or $66 million in total. This would take the total cost of the CLT NSC to $10 million less than the Concrete NSC, before the inclusion of the end-of-life financial benefits.

In conclusion, there are large risks associated with the CLT NSC, which if not addressed beforehand, should prevent its adoption. Were these barriers to be overcome, CLT can play an immense role in helping Kenya, and more widely SSA, to achieve its development targets such as employment and infrastructure, all while achieving its NDCs. Through the help of development organisations, the Kenyan government have the potential to develop an appropriate and manageable strategy to incentivise timber products, further encouraging sustainable forest management. This has the potential to lay the foundations for other countries across SSA to follow suit, further reducing the wood deficit across the region, reducing emissions associated within the construction sector, and providing a new fast-replenishing wood supply globally.

This study lends itself towards further research, firstly by carrying out a social life cycle assessment for the CLT NSC and the Concrete NSC. This would then cover every pillar of sustainability to allow for the most rounded decision on the selection of the NSC to be made. This has the potential to also include a consequential life cycle cost, providing financial information of the externalities of the project itself. As the study highlights the extraordinary results of the influence of the utilities on both projects, there is the need to carry out a more detailed analysis on the heat, cooling, thermal conductivity and specific energy performances of CLT and concrete, to understand how they vary in the Kenyan climate.

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Appendix

Appendix A – Consequential LCA Market Trends

Table 9 Market Trend Data Sources

Affected Markets	Affected Long-Term Supplier	Market Trend	Compound Annual Growth Rate 2019-2027	Reference
Concrete	Local Concrete Suppliers	Increase	6%	(Kenya Association of Manufacturers, 2019)
CLT	Regional Timber and CLT Suppliers	Increase	6%	(Kenya Association of Manufacturers, 2019)
Aggregate	Local Aggregate Suppliers	Increase	6%	(Kenya Association of Manufacturers, 2019)
Steel	International Raw Steel Material Suppliers	Increase	6%	(Kenya Association of Manufacturers, 2019)
Biomass for Cooking	Local timber use for cooking fuel	Decrease	Estimate	(Africa Clean Cooking Energy Solutions Initiative, 2014)
Electricity Demand	Local electricity producers	Increase	Prediction	(International Energy Agency, 2019c)

Mining	Local mining suppliers	Increase	10%	(Kenya Association of Manufacturers, 2019)
Water	Water suppliers and Wastewater recyclers	Increase		(Government of the Republic of Kenya, 2013; USAID, 2017)
Agriculture/ Land Use	Local Farmers	Increase		(Ministry of Environment and Natural Resources, 2016)

Appendix B – CLCA Market Constraints

Table 10 CLCA Market Constraints

Affected Markets	Production Constraints	Local Supply	Demand	Notes	Reference
Cement (Tonnes)	No Constraint	5,967,200	5,933,300	Two more facilities are expected to open to increase production further.	(Kenya Association of Manufacturers, 2019)
Mining (Limestone, Aggregate, Sand) (tonnes)	No Constraint	84,000,000	21,000,000	Capacity v current operation, demand is met through Chinese importations.	(Kenya Association of Manufacturers, 2019)
Steel (kg)	No Constraint	20,000	2,229,000	Internationally supplied by EU	(Knoema, 2017)
Electricity (GWh)	No Constraint	11,769	9,300	Supply exceeds demand and is predicted to further grow.	(International Energy Agency, 2019c)

Wood (m^3)	Constraint	31,372,530	41,700,664	75% of supply goes to firewood and charcoal.	(Ministry of Environment, 2013)
Nairobi Water	Constraint	33,000,000,000	30,700,000,000	61% have access to improved drinking, 30% improved sanitation	(Government of the Republic of Kenya, 2013; USAID, 2017)
Land Use (ha)	No Constraint	5,200,000	-	The study highlighted a significant amount of area which can be used without displacing agricultural land	(Ministry of Environment and Natural Resources, 2016)

Appendix C – CLCA Inputs and Calculations

Table 11 Forest Assumptions

Detail	Unit	Quantity	Comment
Trees per acre	tree/acre	1,100.00	(Oballa *et al.*, 2010)
Trees per Hectare	tree/ha	484.00	Assuming 3x3 in line with Ugandan forestry companies (Busoga Forest Company, 2021)
Tree yield per year	m^3/ha/yr.	30.00	(Ence, 2009)
Tree yield per tree over tree lifetime	m^3/tree/14yr	0.87	
CLT per entire city	m^3	172,480.75	

CLT just for balcony area	m^3	26,481.17	
Number of trees needed	number	198,763.53	
Number of hectares needed	number	410.67	
Number of trees needed just for the balcony area	number	30,516.39	
Water requirements	litres of water / kg	306.00	(Ence, 2009)
Eucalyptus Tree Tonne Carbon Sequestration per year	$kgCO_2$/yr./tree	140.00	(Ence, 2009)
Eucalyptus Tree kg Carbon Sequestration over 20 years	kg CO_2e/20 yr./tree	570.00	(Ence, 2020)
Eucalyptus Tree kg Carbon Sequestration single year	$kgCO_2$e/yr./tree	28.50	
Eucalyptus Tree Rotation	years	14.00	
Building Life Span	years	60.00	
Forest Rotations per building life span	number	4.29	
Carbon sequestered per rotation	$kgCO_2$e	134,090,123.92	
Balcony carbon sequestered per rotation	$kgCO_2$e	277,522.47	
Carbon sequestered during lifetime	$kgCO_2$e/building lifetime	574,671,959.66	
Carbon sequestered for balcony over lifetime	$kgCO_2$e/building lifetime	1,189,382.01	

Table 12 Cooking Fuel Inputs

Forest demand and supply	Quantity	Unit	Source
Trees displaced by the project	198,763.53	Number of Trees	
Biogenic emissions lost if deforestation from displaced trees	134,090,123.92	$kgCO_2e$	
kg of firewood per tree	25.00	kg	(Food and Agriculture Organisation of the United Nations, 1983)
kg of firewood displaced	4,969,088.33	kg	
kg of firewood consumed per family per year	2000.00	kg/yr.	(WLPGA, 2018)
kg of firewood per family overbuilding lifetime	120,000.00	kg/building lifetime	
Wood Log Carbon Emission Factor	3.09	$kgCO_2e$/kg	(Department for Business Energy & Industrial Stratagy, 2021)
Wood Log Carbon Emission Factor for displaced wood	15,359,352.65	$kgCO_2e$/building lifetime	
Firewood and lost biogenic carbon over building lifetime	149,449,476.57	kg CO_2e/building lifetime	
Improved Woodstove kg equivalent to 1 kg of LPG	6.50	Kg LPG/per kg of wood	(Federal Ministry for Economic Cooperation and Development, 2014)

LPG required	764,475.13	kg	
LPG carbon Emission Factor	7.54	$kgCO_2e/kg$	(Department for Business Energy & Industrial Stratagy, 2021)
Total LPG Emissions	5,764,410	$kgCO_2e$	
Total concrete	484,750,629.51	kg	
% Recycled	0.97		
Amount of aggregate produced	470,208,110.62	kg	
Displaced amount of virgin aggregate	470,208,110.62	kg	
GWP	0.0497	$kgCO_2e/kg$	
GWP avoided	23,369,343.10	$kgCO_2e$	

Table 13 CLCA End-of-Life Emissions

Displaced End-of-Life Biomass	Quantity	Unit	Source
Quantity of CLT	172,480.75	m^3	
Displaced wood biogenic emissions	134,328,008	$kgCO_2e$	
Percentage of a tree which becomes a by-product	45%	%	(James Jones, 2021)
Displace biogenic emissions through by products	60,447,603.65	$kgCO_2e$	

Table 14 Water Infrastructure

Displaced End-of-Life Biomass	Quantity	Unit	Source
Water required per kg of timber	306	Litres/kg	(Ence, 2009)
Total amount of timber	75,891,531	kg	
The total amount of water required for timber	23,222,808,449	Litres	
Water content in kg of Foundation Concrete	204	litres/kg	One Click LCA
The total quantity of C28/C35 concrete		Litres	
The total amount of water required for C28/C35	5,333,447	Litres	
Total water use phase	34,258,975,920	Litres	
Total water required for project	57,487,117,816	Litres	
Total water required for the project in cubic meters	57,487,118	m^3	
Carbon emissions for integrated urban water infrastructure	2	$kgCO_2e/m^3$	(Byrne *et al.*, 2017)
GWP	137,969,083	$kgCO_2e$	

Appendix D – ALCA Carbon Coefficients

Table 15 Full List of Carbon Coefficients Used

Variable	Unit	Quantity	Reference
Trailer combination, 40-ton capacity, 100% fill rate	$kgCO_2e/tkm$	0.04	One Click LCA - Kenya
Concrete mixer truck, appr. 8 m^3, 100% fill rate	$kgCO_2e/tkm$	0.13	One Click LCA - Kenya

Ready-mix concrete, C28/35, XC 1, CEM II/A-V 52,5 N, Grön väggbetong (Skanska, Stockholm area)	$kgCO_2e/m^3$	118	(Skanska Industrial Solutions AB, 2019)
Lightweight expanded clay aggregate (LECA), generic, loose bulk density: 260 kg/m^3 (16.2 lbs/ft^3)	$kgCO_2e/kg$	0.45	One Click LCA - Kenya
Ready-mix concrete, normal strength, generic, C28/35 (4000/5000 PSI) with CEM II/B-V, 30% fly ash content (300 kg/m^3; 18.7 lbs/ft^3 total cement)	$kgCO_2e/m^3$	215.81	One Click LCA - Kenya
Biogenic Ready-mix concrete, normal strength, generic, C28/35 (4000/5000 PSI) with CEM II/B-V, 30% fly ash content (300 kg/m^3; 18.7 lbs/ft^3 total cement)	$kgCO_2e/m^3$	2.09	One Click LCA - Kenya
Glass wool insulation panels, unfaced, generic, L = 0.031 W/mK, R = 3.23 m^2K/W (18 $ft^2{}^\circ Fh/BTU$), 25 kg/m^3 (1.56 lbs/ft^3), (applicable for densities: 0-25 kg/m^3 (0-1.56 lbs/ft^3)), Lambda=0.031 W/(m.K)	$kgCO_2e/m^3$	2.82	One Click LCA - Kenya
Gypsum plasterboard, with cellulose fiber, 12.5 mm, 14.75 kg/m^2, 1180 kg/m^3, Gipsfaser 12.5 mm (Fermacell)	$kgCO_2e/m^2$	1.14	(Fermacell GmbH, 2016)
Structural steel profiles, generic, 60% recycled content, I, H, U, L, and T sections, S235, S275 and S355	$kgCO_2e/kg$	2.12	One Click LCA - Kenya
Ready-mix concrete, normal strength, generic, C28/35 (4000/5000 PSI) with CEM I, 0% recycled binders (300 kg/m^3; 18.7 lbs/ft^3 total cement)	$kgCO_2e/m^3$	292.13	One Click LCA - Kenya
CLT	$kgCO_2e/m^3$	171.6	(Stora Enso, 2020)
CLT	$kgCO_2e/kg$	1.77	(Stora Enso, 2020)
Electricity	$kgCO_2e/kWh$	0.23	One Click LCA - Kenya
Water	$kgCO_2e/m^3$	0.69	One Click LCA - Kenya
Average Site Impacts	$kgCO_2e/m^2$	19.98	One Click LCA - Kenya

Excavation Works	$kgCO_2e/m^3$	1.39	One Click LCA - Kenya
Average Deconstruction and Demolition	$kgCO_2e/m^2$	3.40	One Click LCA - Kenya
General Construction Waste	$kgCO_2e/kg$	0.0027	One Click LCA - Kenya
Left In place end-of-life	$kgCO_2e/kg$	0.00	One Click LCA - Kenya
Disposal of Inert Material	$kgCO_2e/kg$	0.01	One Click LCA - Kenya
Incineration	$kgCO_2e/kg$	0.13	One Click LCA - Kenya
Steel Waste	$kgCO_2e/kg$	0.01	One Click LCA - Kenya
Construction Waste to Landfill	$kgCO_2e/kg$	0.04	One Click LCA - Kenya

Appendix E – Building Material General Assumptions

Table 16 Building Material Assumptions

Assumptions and Estimates	Travel Distance (km)	Travel Method	Service Life
Foundation			
Ready Mix Concrete Foundation	60	Concrete Mixer Truck	As Building
Aggregate	60	Trailer Combination 40-tonne capacity, 100% fill	As Building
Vertical Structure			
Ready Mix Concrete Ground Floor	60	Concrete Mixer Truck	As Building
Plasterboard	60	Trailer Combination 40-tonne capacity, 100% fill	As Building
CLT	600	Trailer Combination 40-tonne capacity, 100% fill	As Building

Wool insulation	60	Trailer Combination 40-tonne capacity, 100% fill	As Building
Plasterboard	60	Trailer Combination 40-tonne capacity, 100% fill	As Building
Horizontal Structure			
Ready Mix Concrete Upper Floors	60	Concrete Mixer Truck	As Building
Insulation	60	Trailer Combination 40-tonne capacity, 100% fill	As Building
Fermacell	60	Trailer Combination 40-tonne capacity, 100% fill	As Building
Fermacell	60	Trailer Combination 40-tonne capacity, 100% fill	As Building
CLT	600	Trailer Combination 40 tonne capacity, 100% fill	As Building
Steel Beam	6500	Trailer Combination 40 tonne capacity, 100% fill	As Building
CLT	600	Trailer Combination 40 tonne capacity, 100% fill	As Building

Appendix F - LCC Cost Per Unit

Table 17 Full List of Life Cycle Cost Units

Material Production Cost	Unit	Quantity USD per unit	Comments	Reference
Site clearance	USD/m^2	$0.64	Material and Labour Cost	(Integrum, 2020)
150 mm Excavation Cost	USD/m^2	$0.83	Material and Labour Cost	(Integrum, 2020)
Aggregate	USD/m^3	$14.72	Material and Labour Cost	(Integrum, 2020)
Ready Mix Concrete Foundation (mix ratio 1:4:8)	USD/m^3	$76.03	Material and Labour Cost	(Integrum, 2020)
CLT	USD/m^3	$500	Material and Labour Cost	Arvet

Ready Mix Concrete Upper Structure (mix ratio 1:2:4)	USD/m^3	\$117.50	Material and Labour Cost	(Integrum, 2020)
Steel	USD/kg	\$2.58	Material and Labour Cost	(Integrum, 2020)
Mineral Wool Insulation 50mm	USD/m^2	\$7.11	Material	(Gypsum Ceiling Supplies, 2021b)
Mineral Wool Insulation 25mm	USD/m^2	\$5.16	Material	(Soundproofing Kenya, 2021)
Fermacell	USD/m^2	\$10.96	Material	(Insulation Shop, 2021)
Plasterboard	USD/m^2	\$6.54	Material	(Gypsum Ceiling Supplies, 2021a)
Kenya Water and sewage cost	\$/M^3	\$0.59	Water	(Nairobi City Water and Sewage Company, 2021)
Kenya Electricity	\$/kWh	\$0.18	Electricity	(Global Petrol Prices, 2020)

Appendix D – ALCA Summary Results

Table 18 Summary CLT LCA Results per m^2

Result category	Global warming ($kgCO_2e$)	Biogenic carbon storage ($kgCO_2e$)	Acidification ($kgSO_2e$)	Eutrophication ($kgPO_4e$)	Ozone depletion potential (kgCFC11e)	Formation of ozone of lower atmosphere (kgEthenee)	Total use of primary energy ex. raw materials (MJ)
A1-A3 Construction Materials	88.91	229.76	0.39	0.06	0.00	0.10	2,951.88
A4 Transportation to site	7.94	0.00	0.08	0.01	0.00	0.00	209.70

A5 Construction/installation process	3.15	0.00	0.01	0.01	0.00	0.00	56.65
B1-B5 Maintenance and material replacement	0.74	0.00	0.00	0.00	0.00	0.00	20.15
B6 Energy use	4,545.57	0.00	32.25	1.70	0.00	1.40	98,387.59
B7 Water use	2,433.58	0.00	17.03	48.76	0.00	0.71	43,912.25
C1-C4 End-of-Life	18.04	0.00	0.03	0.01	0.00	0.00	80.15
D External impacts	-129.42	0.00	-0.18	-0.04	0.00	-0.02	-2,161.63
A5-Benefit Construction site - material wastage - benefit	-16.80	0.00	-0.02	0.00	0.00	0.00	-292.63
D Installed Materials - benefit	-112.63	0.00	-0.16	-0.04	0.00	-0.02	-1,869.00
Total Excluding D	7,097.93	229.76	49.79	50.54	0.00	2.22	145,618.37

Table 19 Concrete NSC LCA Summary Results per m²

Result category	Global warming ($kgCO_2e$)	Biogenic carbon storage ($kgCO_2e$)	Acidification ($kgSO_2e$)	Eutrophication ($kgPO_4e$)	Ozone depletion potential (kgCFC11 e)	Formation of ozone of lower atmosphere (kgEthenee)	Total use of primary energy ex. raw materials (MJ)
A1-A3 Construction Materials	92.82	0.48	0.29	0.09	0.00	0.03	931.39

A4 Transportation to site	31.46	0.00	0.11	0.02	0.00	0.01	540.29
A5 Construction/installation process	3.15	0.00	0.01	0.01	0.00	0.00	56.65
B1-B5 Maintenance and material replacement	0.74	0.00	0.00	0.00	0.00	0.00	20.15
B6 Energy use	4,545.57	0.00	32.25	1.70	0.00	1.40	98,387.59
B7 Water use	2,433.58	0.00	17.03	48.76	0.00	0.71	43,912.25
C1-C4 End-of-Life	3.03	0.00	0.02	0.00	0.00	0.00	47.96
D External impacts	-28.39	0.00	-0.08	-0.03	0.00	-0.01	-217.02
A5-Benefit Construction site - material wastage - benefit	-1.28	0.00	0.00	0.00	0.00	0.00	-8.95
D Installed Materials - benefit	-27.10	0.00	-0.08	-0.03	0.00	-0.01	-208.07
Total Excluding D	7,110.34	0.48	49.71	50.57	0.00	2.15	143,896.27

Appendix G – ALCA Embodied Carbon Results

Table 20 ALCA Embodied Carbon per m²

Material	CLT ($kgCO_2e$)	Concrete ($kgCO_2e$)
Glass Wool Insulation	1.29	1.29
Plasterboard	7.46	7.46

Fermacell	0.74	0.74
Aggregate	3.52	3.52
Concrete	8.08	39.66
CLT	27.67	-
Steel	40.16	40.16
Total	88.91	92.82

Appendix H – LCC Summary Results

Table 21 LCC Summary Result Per m²

Result category	Discounted		Nominal	
	CLT Discounted NSC	Concrete Discounted NSC	CLT Nominal NSC	Concrete Nominal NSC
A1-A5 Manufacturing and Construction Phase	$240.39	$144.90	$240.39	$144.90
B4-B5 Replacement/refurbishment	$16.59	$16.59	$131.53	$131.53
B6 Operational energy use	$4,543.82	$4,543.82	$35,856.41	$35,856.41
B7 Operational water use	$2,738.16	$2,738.16	$21,607.48	$21,607.48
C1-C4 End-of-Life	$10.15	$10.15	$226.56	$226.56
Total	$7,549.12	$7,453.63	$58,062.37	$57,966.88

Appendix I – Embodied LCC Summary

Table 22 Embodied Carbon Cost per m²

Material	CLT Discounted NSC	Concrete Discounted NSC
CLT	$147	$0
Aggregate	$0.46	$0.46
Glass wool insulation	$10	$10
Concrete	$5	$57
Gypsum Plasterboard	$16	$16
Fermacell	$12	$12
Steel	$49	$49
Total	$240	$145