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Comparative life cycle assessment of four buildings in Greenland

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ABSTRACT

Assessment of environmental impacts across the life-cycle of buildings are lacking for Arctic areas, such as Greenland. Indeed, life-cycle assessments of buildings mainly focus on European or North American conditions which are very different from Arctic conditions. Hence, there is a need for assessing the life-cycle impacts pertaining to different building types to support environmentally sound decisions on the type of buildings to be constructed and used in Arctic areas such as Greenland. We conducted a life-cycle assessment on four buildings in Greenland, i.e. concrete building, CLT building, a timber frame building and a renovation of an existing concrete building. We evaluated the environmental impacts at midpoint indicator and overall damages to human health, ecosystem quality, and resources, to identify the building type with the lowest environmental impacts. Results show that renovation of existing buildings has the lowest environmental impact across all impact categories. The difference in environmental impacts among the new building types is generally small. Across all impact categories, the average difference between largest and smallest impact score for the new buildings was a factor 3.6. Still, the CLT and timber frame building appears to have the best environmental performance. The findings of this study go against current building practice in Greenland, which is dominated by construction of new concrete buildings while renovation is uncommon. Thus, a larger use of assessment methods, such as life-cycle assessment, and a reconsideration of the current building practice is recommended to support a more environmentally sustainable building practice in Greenland.

1. Introduction

It is becoming clear that the increasing pressure on the environment, as a result of human activities, are starting to cause unacceptable impacts on the environment [1–4]. For instance, the increase in climate change [5] and loss of biodiversity [6]. Creating the societal changes needed for making humanity environmentally sustainable is a global challenge and require contribution from all regions, including the Arctic, which is among the regions most impacted by global warming. In this regard, construction and use of buildings are traditionally a large contributor to environmental impacts because of the energy used during building operation and because of the materials and energy that is needed for construction of the building and the disposal of these after the building is demolished. Indeed, buildings account for about 39% of global energy related CO_2 emissions [7].

Today's choice of building materials in Greenland is largely influenced by the Danish traditions and lack of timber, meaning that most multi story buildings are constructed using concrete as the primary material. This is a concern because previous assessments have shown that concrete has a considerable environmental footprint, mainly due to the production of cement [8]. Moreover, due to the colder climate in Greenland, the need for insulation and/or energy for heating is large. This means that the environmental impacts associated with buildings in Greenland are expected to be larger than e.g. European buildings. Furthermore, Greenland have very few natural resources that can be used for building materials and very little production of building materials. Consequently, most building materials must be transported to Greenland with water, sand and gravel for concrete production as exceptions. Hence, there is a need for investigating the environmental impact related to buildings in Greenland and where these occur in the buildings' life-cycle. Previous LCAs have compared different building types and identified the materials, processes, and life-cycle stages that contribute most to environmental impact (e.g. Refs. [9–13]). Here it was generally found that the energy consumption associated with the operation and maintenance stage of a buildings lifetime is the main contributing factor to the environmental impact of a building [9,11,12].

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Andersen et al. [9] found that the use stage contributes to 60–70% of a residential building's GHG emissions and Sharma et al. [12] found that the use stage is responsible for 80–85% of a building's energy consumption. Maslesa et al. [11] found that older buildings have higher environmental impacts during the use stage, while newer buildings have higher embodied impacts in the materials stage. However, all of these studies were generally representative of European or North American conditions. Indeed, most LCA studies on buildings are focused on countries in temperate and sub-tropic regions while building LCAs in Arctic regions are generally not well represented in the literature [10]. An LCA was conducted on a school building in Iceland [14], but the study only evaluated embodied impacts and did not cover the use stage and end-of-life stage.

Indeed, Greenland and the Arctic in general, represents a context that is very different from the conditions in Europe and North America. The weather conditions are more extreme and buildings are worn down faster and the cold climate means that either insulation or heating is needed to maintain an adequate indoor temperature. This means that the existing knowledge about environmental impacts of different buildings and the most contributing materials, processes, and life-cycle stages might be completely different for Arctic and Greenlandic conditions. Thus, there is a need for conducting LCA on buildings situated in Arctic areas in order to support environmentally sound decisions on the type of buildings to be constructed and used in Arctic areas such as Greenland. In addition, the Arctic is very heterogeneous in the availability of natural resources. For instance, part of the Arctic has an abundance of forest that can be used for wood based constructions (e.g. Canada). Greenland does not have forests and generally has fewer materials and technologies available on-site, thus necessitating additional transport of materials. LCA of Greenlandic conditions may therefore not apply for other Arctic regions.

To close this knowledge gap, the purpose of this study was to conduct a comparative LCA to evaluate the environmental performance of four building types in Greenland to identify the environmentally best performing building type. Moreover, an objective was to identify the materials, processes, and life-cycle stages that contribute most to environmental impact across each building type's life-cycle. There is an ongoing discussion on what is most sustainable in Greenland: 1) wood based constructions, as wood in an European context often is seen as the most sustainable building material due to renewability, or 2) concrete constructions as only the cement has to be imported, while all other building materials must be transported to Greenland [15]. Thus, this study is very important for supporting informed decisions on the construction of buildings in Greenland and the Arctic in terms of which building types to prioritize and where to focus to further reduce the environmental impacts of the different building types.

2. Method

2.1. Description of assessed building types

As there is a current discussion on what building type – including building materials - should be the building style of the future in Greenland, it is relevant to compare four main construction types:

1. Main construction of *cross laminated timber (CLT)*. A new building technique in Greenland which is fast to erect and relatively easy to work with, something that is important in a region where the building season is short and there is a lack of skilled workers.
2. *Concrete construction* without organic materials like wood based materials. An emerging building technique because many Greenlandic buildings have mould problems. By only using inorganic materials, mould is expected to be eliminated or at least reduced.
3. *Timber frame construction.* The traditional way of constructing multistory buildings in Greenland. Facades are timber frames, while loadbearing walls, gables, and floor divisions are of in-situ cast concrete (or pre-fab elements which is an aim in future constructions). A well-known method but time consuming.
4. *Renovation of concrete construction.* There is limited tradition for thorough renovation of building envelopes in Greenland. Instead the buildings are demolished or only superficially renovated. This option is only possible if there are existing buildings in need of renovation, and may therefore not always be an alternative to one of the others (see Table 2 for details).

Table 1 shows the key characteristics and differences in building components among the four assessed building types. To make a direct comparison of the four construction types possible, the same layout has been used as a model: a four-story apartment building. Each floor contains three apartments and all floors are assumed to be identical (see Fig. 1). This hypothetical building was selected based on an actual building in Qinngorput in Nuuk, Greenland.

Based on the original drawings of the buildings in Qinngorput estimates of floor and wall areas were extracted (see Supplementary material (SM) 1 Table S1), with subtracted areas for windows and doors (see Table S2). We have identified two types of exterior load bearing walls and two types of interior load bearing walls (see Fig. 1 where these are marked). The exterior walls were classified as either *load bearing* (yellow) or only *stabilizing* walls (blue). The interior walls were classified as either *load bearing partitioning* walls (red) or only *load bearing* walls (green). A number of building parts have been excluded in the assessment as these do not differ among the assessed building types and, therefore, have the same environmental impact. This include the interior non-load bearing walls, the roof, the foundation, and cladding.

2.2. Life-cycle assessment

2.2.1. Goal and scope

An environmental life-cycle assessment (LCA) was performed to quantify the potential environmental impacts of the four building alternatives. LCA is a standardized method [16–18] used for assessing the environmental impacts of product and services, including buildings. LCA provides a holistic overview of a building's environmental performance by taking into account the entire building life-cycle and all relevant environmental impacts [19,20]. Hereby, potentially overlooking of important life-cycle process or environmental impacts can be avoided. This is important for supporting informed decision-making and to avoid unintentional burden-shifting where decisions for reducing impacts in one environmental impact category may lead to even larger impacts in other impact categories [21].

To ensure a fair comparison of the four building types, the LCA and the buildings included in the LCA are all related to a common functional unit (FU). The functional unit in this study was defined as "*Construction, use, and disposal of 1 m^2 of a dwelling in Greenland with a service life of 30 years.*" All results of this study are shown relative to the FU. In accordance with comparative LCAs, the assessment only quantify building parts that differ among the four building types. For instance, roof, doors and windows are the same for all building types and are, therefore, excluded from the LCA. The decision context is defined as Situation A. Here, the implications of the potential decisions made on the basis of this LCA are judged not to lead to large societal changes that will affect e.g. global economy and how products are being produced. Fig. 2 shows an overview of the modelled life-cycle inventory (LCI) and the system boundaries of the LCA. The LCA was modelled in OpenLCA 1.10 [22] and the ecoinvent 3.4 cut-off LCI database [23] was used for modelling the background system and for filling data gaps. Section 2.2.2 provide a more detailed description of the modelling of the foreground system.

The environmental impacts associated with the four building types were estimated using the ReCiPe 2016 (Hierarchist) life-cycle impact assessment (LCIA) method [24] and normalized using the World (2010) normalization reference as implemented in OpenLCA LCIA v. 2.0.4. Elementary flows related to biogenic CO_2 were added to the impact

Table 1
Modelled composition of building components in the four structure types including renovation. All columns and battens are of timber.

	Exterior load bearing wall	Exterior non-load bearing wall	Interior load bearing wall	Interior partition wall	Slab
Cross Laminated Timber	100 mm CLT 175 mm glass wool insulation 12.5 mm gypsum board	80 mm CLT 175 mm glass wool insulation 12.5 mm gypsum board	100 mm CLT	12.5 mm gypsum board 100 mm CLT 12.5 mm gypsum board	50 mm insulation 120 mm CLT 12.5 mm gypsum board
Concrete	200 mm glass wool insulation 200 mm concrete	200 mm glass wool insulation 200 mm concrete	200 mm concrete	200 mm concrete	50 mm glass wool insulation 140 mm concrete
Timber frame	9 mm wind screen 200 × 45 mm columns c/c 600 mm with 200 mm glass wool insulation 45 × 45 mm battens c/c 600 mm with 45 mm glass wool insulation 12.5 mm gypsum board 12 mm OSB board	9 mm wind screen 200 × 45 mm columns c/c 600 mm with 200 mm glass wool insulation 45 × 45 mm battens c/c 600 mm with 45 mm glass wool insulation 12.5 mm gypsum board 12 mm OSB board	100 × 45 mm columns c/c 600 mm with 100 mm insulation	12.5 mm gypsum 100 × 45 mm columns c/c 600 mm with 100 mm glass wool insulation 12.5 mm gypsum board	50 mm glass wool insulation 140 mm concrete
Renovation of concrete building	200 mm glass wool insulation (added) 200 mm concrete (kept)	9 mm wind screen (added) 200 × 45 columns c/c 600 mm with 200 mm glass wall insulation (added) 45 × 45 mm battens c/c 600 mm with 45 mm glass wool insulation (added) 12.5 mm gypsum board (added) 12.5 mm OSB board (added)	200 mm concrete (kept)	200 mm concrete (kept)	50 mm glass wool insulation (added) 140 mm concrete (kept)

Table 2
Overview of removed and added materials for the exterior walls and slab for the renovation of the concrete building. All columns and battens are of timber.

	Removed	Added
Exterior load bearing wall	100 mm glass wool insulation	200 mm glass wool insulation
Exterior non-load bearing wall	9 mm wind screen 100 × 45 mm columns c/c 600 mm with 55 mm glass wool insulation 45 × 45 mm battens c/c 600 mm with 45 mm glass wool insulation 12.5 mm gypsum board 12 mm OSB board	9 mm wind screen 200 × 45 mm columns c/c 600 mm with 200 mm glass wool insulation 45 × 45 mm battens c/c 600 mm with 45 mm glass wool insulation 12.5 mm gypsum board 12 mm OSB board
Slab		50 mm glass wool insulation

categories related to climate change (see Table S8). This was done to express and evaluate the contribution of biogenic CO_2, which is particular important for assessing the building types where timber is a key material in the construction. Results were estimated at both midpoint and damage-level to evaluate the relative importance of the midpoint impact categories to the damage-level impact categories, where the damage-level impact categories represent the three areas of protection, i.e. human health, ecosystem quality and resources [24]. See SM 1 Section S3 and Table S7 for an overview of the covered impact categories.

2.2.2. *Life cycle inventory modelling*

This section provides a description of the modelling of the foreground system for the LCI. A full overview of how the LCI was modelled, including all unit processes used for the LCI are provided in SM 2.

The amounts of building materials needed for the walls and slab for the four building types are provided in Table 3 and were estimated based on the wall compositions presented in Table 1 (additional building data are provided in SM 1 Section S1 and a full inventory of materials used for the different walls and slab for each building type is given in SM 2). All materials and building components (except for aggregates and water used in concrete) are being shipped from Aalborg, Denmark to Nuuk, Greenland. The shipping distance is 4506 km and modelled as shipped on a transoceanic freight ship. Transportation of materials and building components to Aalborg was modelled by identifying relevant suppliers of the materials and components and estimating the transportation distance between the supplier and Aalborg (see Table S3). All suppliers were found to be located in Denmark or Europe and all transportation to Aalborg was modelled as done by lorry. A default material loss of 5% during transport and construction was assumed and modelled as being treated as waste in Greenland.

Infrastructure for water supply, wastewater management, heating and road driving are often not included as part of LCAs on buildings [13, 25] as this is considered outside the scope of the building. However, infrastructure was important to include in this LCA because it includes a comparison between new building projects and a renovation project. Thus, it was important to take into account the added environmental impacts of infrastructure needed for the new building projects. If the buildings are placed in an existing urban area, then the existing infrastructure will be updated with new infrastructure as part of the construction, while if the buildings are constructed in a new urban area, then new infrastructure will also be constructed. This LCA includes new infrastructure for heat supply, roads and parking, sewers and water supply. The total distance of additional infrastructure was estimated to be 95.3 m based on sketches of the projected new building project (see Fig. S2) which amounted to 0.1 m per m^2 new built floor area. The number of parking spaces was similarly estimated based on sketches of the building project and we estimated that about 0.4 m^2 parking and utility area are needed per m^2 new built floor area.

The heat consumption during use of the building types differs due to differences in materials used for the walls. The heat consumption during operation was calculated based on Eq. (1).

$$Energy\ consumption = f_{ThermalBridge} \times \frac{1}{3.6\ \frac{MJ}{kWh}} \times f_{year\ to\ sec} \times Hl_n \times (aT_{in} - aT_{out}) \quad 1$$

Where $f_{\mathrm{ThermalBridge}}$ is a factor added to account for potential thermal bridges in the building structure. $f_{\mathrm{year\ to\ sec}}$ is the number of seconds per

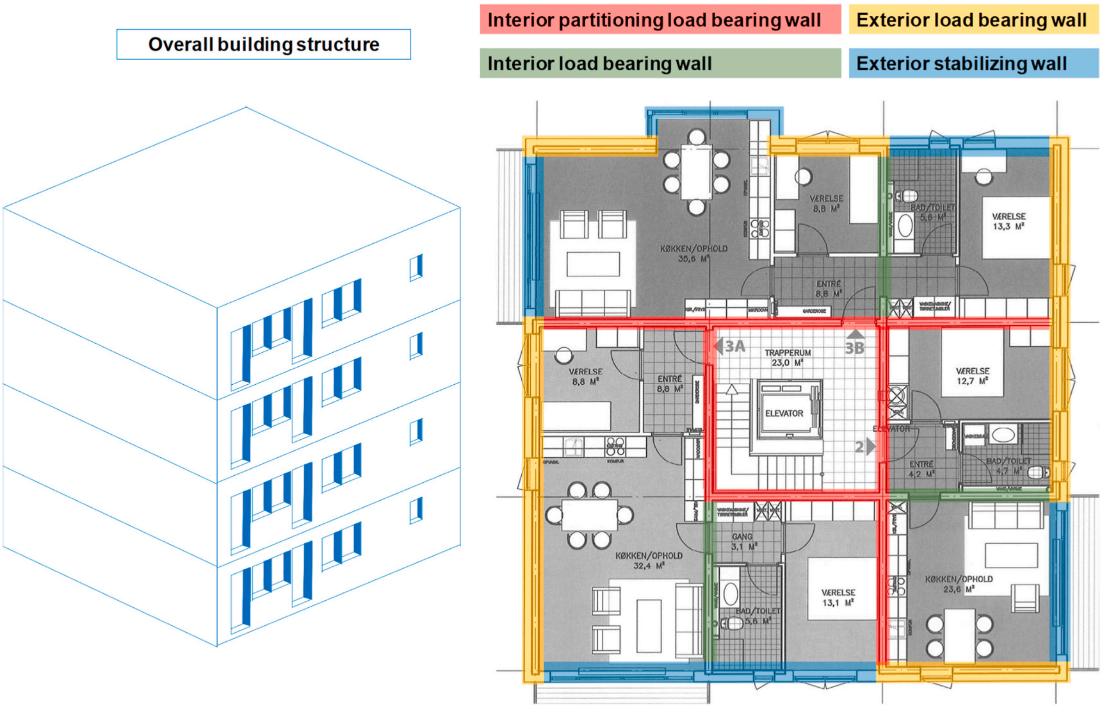

Fig. 1. (Left) Conceptual illustration of the modelled hypothetical four-story building block in Nuuk, Greenland. The hypothetical building is inspired by actual building blocks in Qinngorput, Greenland. (Right) Building floor plan with specification of different wall components evaluated as part of this study. Each floor contains three apartments and all floors are assumed to be identical.

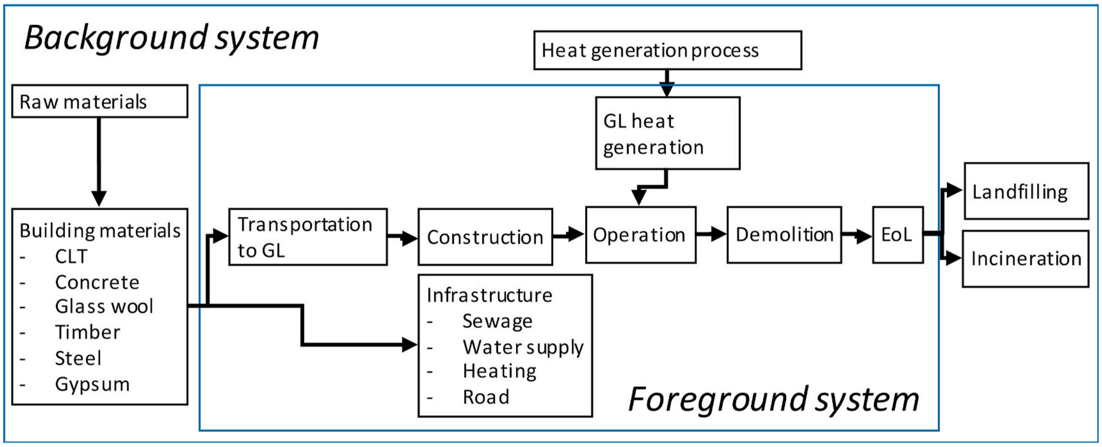

Fig. 2. Overview of system boundaries for the life-cycle assessment.

Table 3
Amounts of new material inputs per m2 floor area for constructing the building types.

Materials [kg/m^2]	Concrete	CLT	Timber frame	Renovated
Concrete	863.8		338.1	
Wood			12.3	4.0
Steel	57.8		22.6	
Glass wool	11.7	11.3	13.9	12.0
Gypsum		19.4	11.0	2.1
Fibre cement			7.7	3.3
CLT		98.8		
TOTAL	**933.4**	**129.5**	**405.7**	**21.3**

year (i.e. 60*60*24*365 s) to estimate the annual heat loss for the buildings. $f_{ThermalBridge}$ was set to 1.6 to indicate an additional heat loss of 60%. This is based on the Danish Building Regulation, which state that thermal bridges will increase the estimated heat loss without accounting for thermal bridges with 50–70% [26]. We apply this factor because the estimation of heat loss from thermal bridges require detailed information on the construction, which was not available in this case, given the conceptual approach to the building type. Hl_n is the heat loss of the specific building type (See Eq. S(2), Section S2.4). aT_{in} (=20 °C) and aT_{out} (=0.38 °C) is the average temperature inside and outside in

Table 4
Operation heat consumption for the four building types.

	Concrete	CLT	Timber frame	Renovated
Heat consumption [MJ/m^2/year]	264.0	264.7	262.3	263.3
Heat consumption [kWh/m^2]	73.3	73.5	72.9	73.1

Greenland, respectively (See Table S4). Table 4 show the estimated energy use for heating of the four building types.

We modelled the energy consumption for heating during building operation to be representative for the heating mix in Nuuk, Greenland. This was based on statistics on total consumption of energy sources for heat production [27] where the heat grid mix is comprised of 8% from municipal waste incineration, 20% from fossil fuels, such as diesel oil, 55% from hydropower, and 17% from residual heat. We acknowledge that this distribution is likely to change during the lifetime of the building. However, specific data or projections on this development are not available. Thus, we keep the distribution constant over time, but will discuss the potential implications of this assumption on the results. The energy usage during construction was modelled based on the report by Danish Energy Agency [28] which estimated energy as a share of annual building energy use (SM 1 Section S2.5). Data on the demolition of the buildings was based on communication with the Danish building demolition company Tscherning [29]. They state that they can demolish 50 m^2 building during a 7 h day. For this work they operate a large diesel driven hydraulic excavator with a water vaporizer that uses 40 L per hour to minimize dust generation.

According to the waste regulations of the Sermersooq municipality, where Qinngorput is located, waste such as concrete, insulation materials, gypsum boards, fibre cement and other inert materials should be landfilled [30]. Clean or lightly treated waste wood should be sent to the Waste Centre in Nuuk, where we assume it is incinerated together with other combustible wastes [31]. All other building materials are assumed to be treated as inert waste in landfills as this is the predominant approach for treatment of building and construction waste in Greenland [31].

2.3. Sensitivity and uncertainty analysis

A sensitivity of the environmental impact scores for each building type relative to the main model input parameters was performed. The sensitivity analysis was performed on independent parameters that were not fixed (see SM 2 Table S15 for list of all parameters included in the sensitivity analysis). Here, we calculated normalized sensitivity coefficients (S_{coef}) according to Eq. (2) [32,33].

$$S_{coef} = \frac{\Delta Out}{Out_0} \Big/ \frac{\Delta a_k}{a_{k,0}} \qquad 2$$

Where $a_{k,0}$ is the default input parameter value for parameter k, Out_0 is the default model output calculated with the value of $a_{k,0}$, Δa_k is the difference between the default input parameter and the perturbed input parameter, ΔOut is the difference between Out_0 and the output calculated for the perturbed parameter value. All continuous parameters included in the analysis were perturbed by a 10% increase. A parameter was considered important if average $|S_{coef}| \geq 0.3$, or if the largest $|S_{coef}| \geq 0.5$, corresponding to a medium and large sensitivity, respectively [34]. The sensitivity analysis and identification of sensitive parameters was used to focus collection of data for specific parameters where more focus was placed on the sensitive parameters. SM 2 Table S15 indicates the maximum absolute S_{coef} for each parameter included in the analysis across all impact categories as well as the average S_{coef} across all impact categories.

To quantify the uncertainty of the final results for each building type and impact category, an uncertainty analysis was performed using Monte Carlo simulation which allow to propagate uncertainty from the life-cycle inventory and parameters to the impact scores for each impact category and for each scenario. The Monte Carlo simulation was performed with 1000 runs where each input parameter was varied within its defined uncertainty distribution (see SM 2). The results of the Monte Carlo simulation were used to express the spread of the results and were used as input to a non-parametric Mann-Whitney *U* test [35] to test for statistically significant ($\alpha = 0.05$) difference in impact category scores between the different building types. Results of the *U* test are given in Table S12 and Table S13.

3. Results

3.1. Comparison of building types

The normalized results of the LCA comparing the four building types is shown in Fig. 3 (characterized results are provided in SM 1 Table S10). The normalized results are expressed as person-equivalents (person.eq; with the metric person.yr), meaning that the characterized impacts scores have been related to the environmental impact of an average person in the World in 2010. The impact categories that appear largest relative to a World person's environmental impact in 2010 was found to be Marine ecotoxicity, Human carcinogenic toxicity, and Freshwater ecotoxicity which all have person-eq. above two across all buildings. Moreover, Human non-carcinogenic toxicity has an impact score of 1.91 and 1.12 person.eq for the Concrete and Timber frame buildings, respectively. All other impact categories has person-eq. less than one. In particular, Mineral Resource Scarcity appear low relative to an average person's impact in 2010. This indicate that impacts on the impact category Mineral Resource Scarcity from the four buildings is almost negligible relative to the annual impact of an average person in 2010.

The results show that across all impact categories it is environmentally preferable to renovate existing concrete buildings compared to construction of new buildings independent of the building type. Indeed, the renovation performs environmentally better than the other three building types across all impact categories. Among the new building types, neither of the alternatives outperform the others across all impact categories. For the new buildings, CLT, Timber frame and Concrete performs best in 10, 7 and 1 out of 18 impact categories, respectively. Thus, the CLT building type generally performs best while the concrete building type appears to be the environmentally worst alternative.

In general, the difference in the building's environmental performance do not vary much. Only for Land use and Mineral resource scarcity, the difference between the building type with the largest and smallest impact score was more than a factor 10 with a factor 30.1 and 18.0, respectively. For Land use, the largest impact score was observed for the CLT building, for Mineral resource scarcity, the Concrete building showed the largest impact score. Across the 18 impact categories, the average difference between the buildings with the largest and smallest impact score was a factor 5.5. When excluding, renovation and only looking at the new buildings, the average difference between largest and smallest impact score was reduced to 3.6 with the largest difference being for Land use with a factor 24.5.

It is evident from Fig. 3 that the 95% confidence interval (indicated by the error bars in the figure) overlap for the different building types for almost all impact categories. Thus, the *U* test was performed to assess for significant difference in impact scores between the different building types for the different impact categories. The results are shown in Table S12 and Table S13. Overall, there are statistically significant differences in the environmental performance of the different building types across all impact categories, except for seven comparisons where a statistically significant difference was not observed based on the *U* test (Table S12). The most prominent was the comparison between the CLT and the timber frame building where a significant difference could not be found for the impact categories: Freshwater ecotoxicity, Global warming, Human non-carcinogenic toxicity and Marine ecotoxicity.

Fig. 4 shows the damage scores for the four building types. Again, it is evident that renovation has the lowest impact across all three damage categories. Regarding the new buildings, none of them are performing better across all three damage categories. CLT was found to be worst for Ecosystem quality due to the land use for CLT production, which account for 46% of the total Damage score for Ecosystem quality (Table S11). The Concrete building performed worst for Human health and Resources. For Human health, this was mainly due to emissions of

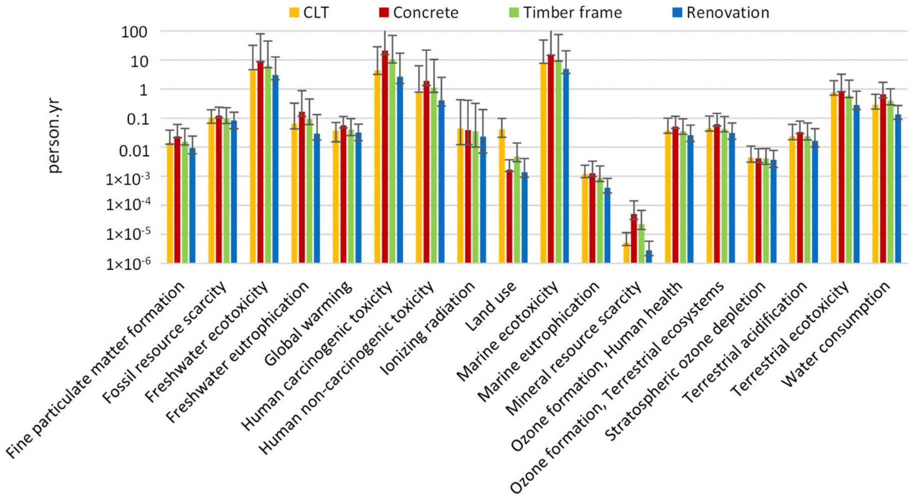

Fig. 3. Normalized impact scores for the four building types. Shown for all assessed midpoint impact categories in ReCiPe 2016 and expressed as person-eq. relative to World per capita impacts in 2010. Error bars indicate the 95% confidence interval as delimited by the 2.5 percentile and 97.5 percentile.

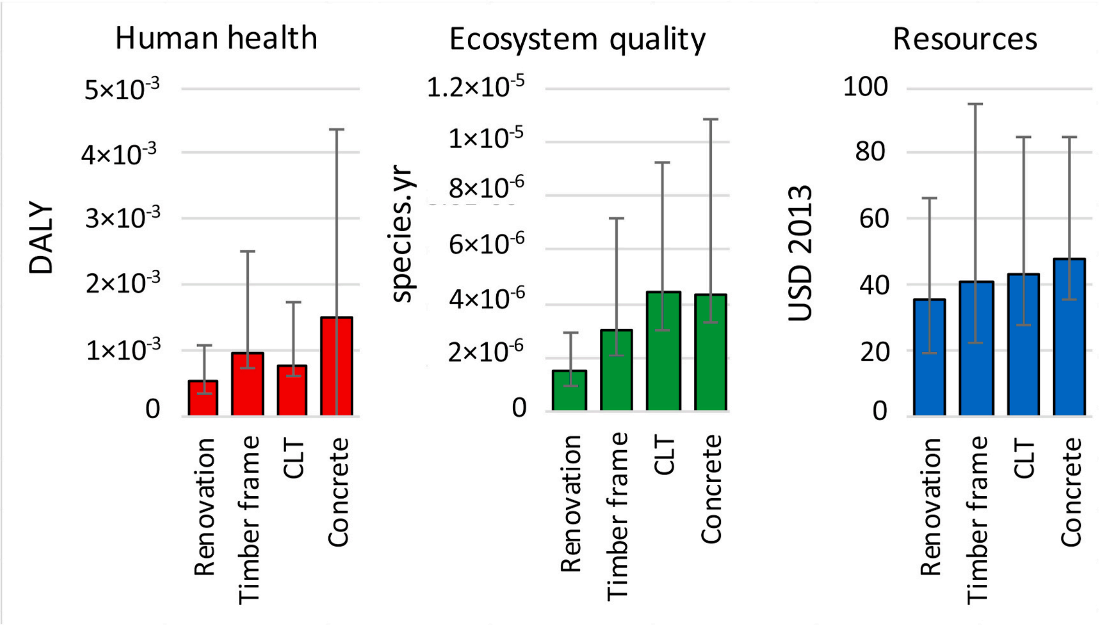

Fig. 4. Characterized damage scores for the four building types shown for potential damages to human health, ecosystem quality and resources. Error bars indicate the 95% confidence interval as delimited by the 2.5 percentile and 97.5 percentile (see SM 1 Table S11 for values).

GHGs, water consumption and emissions of particulate matter which mainly is due to the production of steel reinforced concrete. For Resources, the main contributor is the generation of heat during building operation (and thus is similar for all buildings). Concrete has a larger damage score because of the larger fossil resource requirements for reinforced concrete production.

3.2. Contribution analysis

Fig. 5 shows the contribution of the main life-cycle stages to total deterministic impact scores for each building type and for all assessed impact categories. For the new buildings (i.e. CLT, Concrete and Timber frame), the main contributing life-cycle stages are Use, and Building components which account for at least 35% of the total impacts across all impact categories, the only exception being CLT's global warming impact, where Use and Building components only account for 4% of the total impacts. This is due to storage of biogenic carbon in the CLT elements which means that the contribution from Building components is negative for CLT. Across all impact categories, the average contribution of Use, and Building components was found to be 20%, 54%, respectively, for the new buildings.

For the renovated concrete house, the Use phase dominates with an average contribution of 38% across all impact categories. Infrastructure is 0% as there is no need for new infrastructure in this scenario (although new or updated infrastructure is part of some renovation projects), while Building components is 34%, and is caused by the removal of old building components and addition of new building components as part of the renovation.

In general, Infrastructure, Construction, Demolition, EoL, and Transportation are found to have relatively little contribution to total impact for all four building types across all impact categories with an average contribution of less than 10%. The exceptions being Construction for the renovated concrete house, which amount to about 15% of the total impact score on average across all impact categories and the

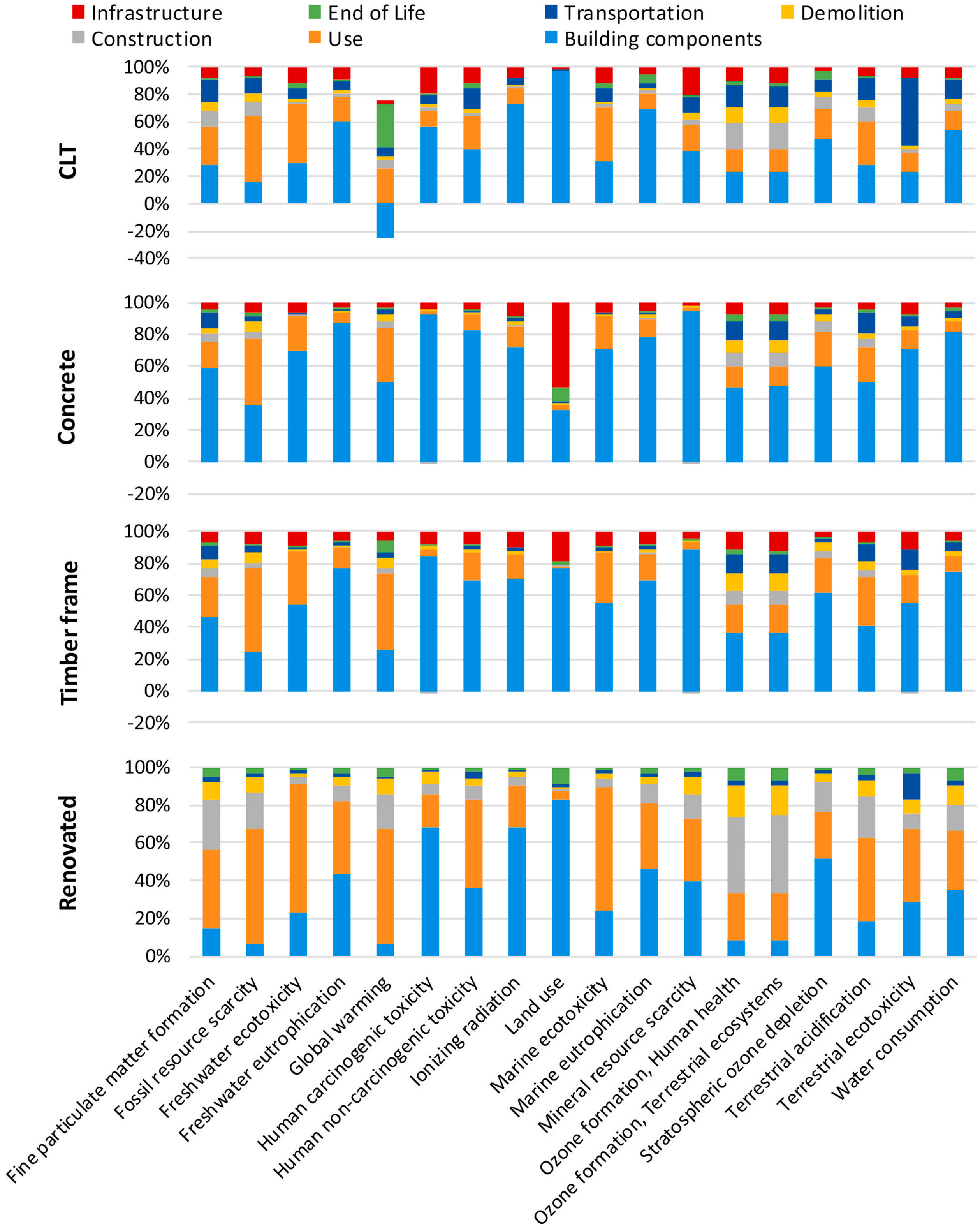

Fig. 5. Percentwise contribution of key life-cycle stages to total deterministic midpoint impact scores for each building types and for all assessed impact categories.

transportation for the CLT building which amount to about 13% of the total impact score on average across all impact categories.

4. Discussion

4.1. Comparison of buildings' environmental performance

The results of this study show that renovation of an existing building is, environmentally speaking, a better solution than construction of a new building independent on the new building type. As indicated in Fig. 5, this was due to the reduced need for production of construction materials for the actual building and the construction of new infrastructure. Indeed, this also underlines the need for including infrastructure as part of the system boundaries in building LCAs if the goal of the LCA involves comparisons between construction of new buildings and renovation of existing buildings.

While there is a difference in the impact scores for the three new buildings, neither of the buildings outperform the others across all midpoint impact categories. Thus, the selection of one building type will inevitably require trade-offs among midpoint- or damage level impact categories. Thus, the choice of building type for construction of new buildings will depend on the decision-makers explicit or implicit preferences for specific impact categories. Overall, the CLT building appears to perform better than the concrete and timber frame building, as it had the lowest midpoint impact scores in 10 out of 18 midpoint impact categories. Furthermore, the damage level assessment shows that CLT is better in terms of reducing impacts on human health. However, the large damage score for ecosystem quality due to the land use is problematic. This illustrate the necessity for sustainable forestry to supply timber for additional demand for e.g. CLT, to minimize impacts on ecosystems and ensure that extraction of timber does not exceed forest growth rate [36].

4.2. Recommendations for improving environmental performance of buildings

The results of the LCA indicate a number of aspects to focus on with regards to improving the environmental performance of the four buildings. Overall, the heat use during operation was found to be the main driver of environmental impact in the building types' lifecycle. This was followed by the impacts related to materials used as part of building components and infrastructure. With regards to the heat consumption during building operation, the environmental impacts are a function of the insulating ability of the building and the composition of the heat grid mix in Greenland.

4.2.1. Building operation

The heating mix in Greenland is already associated with relatively low impacts as 55% of the heating is derived from hydropower via heat pumps. However, the environmental performance could be further reduced by an out phasing of fossil heating sources, such as diesel oil, and the hydropower capacity could be increased to supply the heat demand. These changes and a general decarbonisation of the Greenland heat and power supply appear to be planned already [27,37].

With regards to the buildings' heat consumption, this could be reduced by improving the insulating capability of the buildings. Indeed, there is a large demand for extensive insulation of the buildings due to the climate conditions in Greenland where annual average outdoor temperature is 0.38 °C (Table S4). Thus, increased insulation of the buildings to reduce heat consumption would be a relevant option for reducing the overall environmental impact. Of course, the added impacts from production of more insulation material must be assessed as this extra insulation must not result in a net-increase in environmental impacts. A number of studies have indicated the risk of excess insulation where environmental impacts from extra insulation production are not compensated by reduction in impacts due to reduced energy consumption. This is mainly because environmental impact of energy generation is likely to reduce in the future with the phasing out of fossil fuels [38,39]. We tested the effects of increasing insulation thickness for the concrete building. At present, the buildings are being insulated with 150–200 mm insulating material. We found that increasing insulation up to a thickness of 400–500 mm would generally be preferable for reducing environmental impacts. At higher thicknesses, the tendency starts to reverse. Thus, it appears the optimal insulation thickness, in terms of environmental impact, for these buildings is likely in the range of 400–500 mm (see SM 1 Section S9 for results). However, it is important to notice that in our assessment, we apply a static heating mix. It is likely that the benefits of increased insulation thickness would decrease (or even increase environmental impact) if the heating was fully based on hydropower and not relying on any fossil heat sources.

4.2.2. Building materials

Out of the total environmental impact from production of the building materials and components, the most contributing materials across the four building types were found to be steel reinforced concrete, glass wool insulation, CLT and other construction wood. These materials dominate as they are the main materials used in walls and slabs of the buildings and, in addition, require production associated with substantial environmental impacts. For instance, the production of reinforced concrete has a global warming impact intensity of ca. 0.22 kg CO_2-eq/kg concrete produced. Hence, focus should be placed on these materials to substantially reduce the embodied impacts related to material production. All three materials require considerable energy inputs during production and it is thus important to investigate the potential for using alternative energy sources with lower environmental impacts. Here, it is important not to solely focus on GHG emissions, but also consider other environmental impact categories to ensure alternative energy sources are not simply shifting the problem to a different impact category [21]. With reinforced concrete, CO_2 is also released by the chemical processes in the cement and steel production [40]. Here, implementation of carbon capture and utilization technologies could help reducing CO_2 emissions related to cements and steel production [41–43]. Moreover, it is generally recommended to evaluate material production processes in terms of improving the eco-efficiency of the production (i.e. increase material output/environmental impact) [44,45].

Finally, it is also possible to reduce the environmental impacts through improved building design [46–48]. For instance, by increasing material efficiency in buildings or increasing the life-time of the buildings and materials to allocate the embodied impacts over a longer time period [49,50]. Indeed, we found that the life-time of the buildings is an important parameter for the overall environmental performance (SM 2 Table S15). Currently, the life-time of buildings in Greenland is very short due to a combination of the extreme climate and a building practice where building errors are often discovered [51]. However, if the life-time could be improved e.g. by increased renovation of buildings or repair of materials, then this could help further reduce impacts as shown for renovation in this study.

4.3. Implications for building practice in Greenland

Focus on sustainability is increasing in Greenland. The government of Greenland, one of the biggest clients in Greenland, has in a note on Greenlandic building materials described the principles for planning of sustainable buildings [15]. These general principles include LCA of materials, but in the more detailed description of what consultants should account for in a description of what can be implemented in a specific case, LCA is not mentioned; only that there must be a focus on approved building materials that relate to the environment, both at production and disposal [15]. In reality this means, that LCA is not a commonly used tool when planning buildings in Greenland. Instead, other parts of the note on Greenlandic building materials have attained more attention e.g. a focus on using domestic materials, especially concrete elements, i.e. the building type described as the Concrete building in this study. The point about the predominant use of domestic materials, such as water and sand for concrete production could be questioned. In fact, our assessment shows that the Concrete building has the largest mass of imported materials per m^2 (SM 2 Table S16). This is primarily due to the import of cement for the concrete. On the other hand the Timber frame and CLT building has similar mass of imported materials and both are lower than the Concrete building. The renovated building has, by far, the lowest material import due to the use of the materials already present in the renovated building.

Another focus is to avoid mould growth in buildings. There have been many cases of mould growth in different kinds of buildings, including new buildings. Although it is unknown what mechanisms might be dangerous for the human health when exposed to a group of moulds or what amount may be acceptable, mould and dampness may cause “increased prevalence of respiratory symptoms, allergies and asthma as well as perturbation of the immunological system” [52]. Therefore, mould growth and dampness should be avoided. The health consequences of exposure to mould growth is not part of the LCA, as this only occur when there is some kind of failure in the planning or construction of the building. The traditional way of reducing risk of mould growth is by reducing the dampness, as four parameters are important when it comes to risk of mould growth 1) Temperature, 2) Relative humidity, 3) Nourishment, and 4) Time [53]. In most mould prediction models (e.g. Refs. [53,54]) the risk of mould growth is assessed through a combination of temperature and relative humidity over time, based on the substrate i.e. building material where the mould risk is assessed. The building material can therefore be seen as the nourishment for mould. As organic materials provide nourishment for mould, avoiding organic materials could be one tactic. However, mould are hardy organisms that do not need much nourishment and may live on dust or dirt on surfaces. Consequently, mould can grow on inorganic surfaces e.g. concrete, but the growth rate will be slower than on organic building materials. The traditional way to avoid mould growth is designing the building in a way that temperature and relative humidity do not lead to mould growth. However, the Greenlandic government has as a developer chosen also to focus on not using organic building materials at all. This encourages the use of the concrete building type in this investigation, while CLT buildings are deprioritised. Even though, the use of inorganic materials does not eliminate the risk of mould growth.

Unfortunately, the concrete building type has some weaknesses that makes it less robust towards mistakes at the building site [51]. These mistakes can lead to higher heat loss, reduced comfort and health issues. Parameters that could be included as part of an LCA. However, this is seldom done due to lack of data on errors and their implication. Including effects of building errors would improve the precisions of the LCA. However, this may also introduce a bias towards some buildings because e.g. traditional building types (timber frames) are less prone to construction errors because construction of these is well known in contrast to new building types, such as CLT, where there is a higher risk of errors due to less experience with CLT constructions.

This analysis shows that when the Greenlandic government favours the concrete building type, it is not based on LCA results, but rather on the use of inorganic materials as a way to avoid mould. If focus was only on LCA, renovation of the existing buildings should be given higher priority. Furthermore, the use of CLT or light timber frame buildings should be encouraged. Furthermore, the analysis shows that increasing the insulation thickness would have a substantial positive effect on sustainability. The Greenlandic Building Regulation [55] is relatively old (from 2006) and an update has been planned for several years. Energy requirements are some of the points where substantial changes, in form of increased demands, are expected.

5. Conclusion

This study conducted an LCA on four buildings in Greenland, a concrete building, a CLT building, a light timber frame building, and a renovation of an existing concrete building to compare the environmental performance of the four buildings. We evaluated the environmental impacts at midpoint indicator level and in terms of damages to human health, ecosystem quality, and resources, to identify the building type with the lowest environmental impacts. We found that renovation was the environmentally speaking best solution as it had the lowest environmental impact across all impact categories. Thereby, the findings of this study go against current building practice in Greenland, which is dominated by construction of new concrete buildings while renovation is uncommon. Thus, we recommend reconsidering this practice to lower environmental impacts by increased renovation. For new buildings, we were not able to unanimously identify the best performing building. Overall, the CLT building and the timber frame building performed best in 10 and 7 out of 18 midpoint impact categories, respectively. This was also reflected in the damage level assessments, where the timber frame and CLT building, in general, performed better than the concrete building. Overall, our result show that current Greenlandic building practice, which is predominantly based on construction of new multi-storey concrete buildings, could be revised to include more renovation and also test the use of new buildings based on timber to improve the environmental performance of the building sector in Greenland. In general, it is recommended to apply holistic assessments such as LCA, as part of the decision process, to support more environmentally sound decisions regarding the construction of buildings in Greenland.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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