Life Cycle Environmental Impact Assessment of Contemporary and Traditional Housing in Palestine

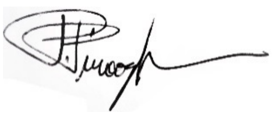
Cover letter

Today, the importance of having a more comprehensive and realistic account of environmental impacts of the buildings and their effect on our limited natural resources are well-researched and widely accepted. The building and construction industry has responded positively to the awareness required in this area and measures have been taken to address this. This, however, is more established in some sectors of the industry and in some countries and construction economies more than the others.

Residential sector has a severe impact on energy and material resources throughout their whole-life cycles with the subsequent greenhouse gases (GHG) emitted in the atmosphere. Projected trends in excessive urbanisation and global population is a major contributor to such impacts. Despite the push for more globalised approaches to and in the building and construction industry, it still is imperative to locally investigate and evaluate the environmental impact of housing in different regions and contexts in order to enable better and more informed decisions. The evidence to support decisions in these specific areas are not as available and accessible as other areas in which LCA research has a more established status.

This is even more urgent in cases where the possibility for urban development is limited or severely constrained. Palestine represents one such areas of the world, and this research focuses on a comparative life cycle assessment (LCA) of contemporary and traditional housing typologies in the region. Primary data has been collected to provide a reliable basis for the LCA, which has been carried out according to the existing international standards. In addition to energy demand and GHG emissions, a range of environmental impact categories has been further evaluated to provide a more holistic sustainability analysis.

The results presented in this article signpost an important starting point in investigating the real mitigation potential of specific materials (e.g. limestone and lime mortar) when employed at scale in specific regions of the world. Our findings can also contribute to developmental policies for the region, with an aim of reducing the anthropogenic pressure on the natural environment.



Dr Poorang PIROOZFAR

On behalf and for the authors

Comments from the editors and reviewers:
-Reviewer 1

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A much needed piece of work that probes and evaluates the Life Cycle Impact of commonly used buildings in a dense urban region. Further work, similar to this in other dense regions of the globe is required, to ensure that we have a better understanding of global building stock and the implications for the natural environment.

Dear Reviewer,

Thank you very much for taking the time to review our manuscript and for your useful comments. We have addressed all of your points and more detailed responses are given below.

The research method and evaluation of the results are appropriate to the task and sensitivity of the results are assessed and considered. Where databases are incomplete, for the purpose of building modelling, appropriate substitutions are considered and made.

Thank you. We have tried to collect as much primary data as possible in a region of the world were the usual issue of data scarcity for life cycle assessment data is even more pressing.

Generally the paper is well written, structured and clear. Very occasionally some of the language used is misguided or loose. For example in the following sentence 'done' should be replaced with a more informative word such as 'completed'.
"Given that some of such processes might have been done using animals, it will immediately decrease the impact due to alternative means of transportation."

While minor, such changes will ensure the paper receives due consideration.

Thank you – we have changed the specific word you suggested and, more generally, we gave a fresh read (and proofread) to the manuscript to remove minor typos and mistakes and to tighten up the language as you suggested in order to improve the reading experience.

With a very minor proof read, to tighten up the language, the work should be accepted.

Thank you very much again for your review – we believe we have addressed your comments.

-Reviewer 2

Exquisitely written and detailed job. If some would be worth mentioning would be the hotspots. That is where the impact categories stem from, which materials or processes are behind the more relevant impact categories.

Dear Reviewer, thank you very much for your positive and encouraging review. We have added a reference to the hotspots as you have requested.

-**Reviewer 3**

The paper "Life Cycle Environmental Impact Assessment of Contemporary and Traditional Housing in Palestine" by P. Piroozfar, F. Pomponi and F. El-Alem applies a comparative life cycle assessment to investigate the eco-profiles of contemporary and traditional housing typologies in Palestine.

Dear Reviewer, thank you for your comments and critique of our paper. We have approached your criticisms constructively and used the revisions as an opportunity to further strengthen and improve our work. We have broken down your review in three sections, linked to the main points for revisions contained in each and have responded in detail to each of them below. We believe we have addressed your comments in full.

If on one hand the subject of the paper could be of relevance for the journal, given the interesting topic and the geographical localization of the research, on the other hand the work fails in giving a useful insights and not trivial understanding of the topic. Thus, unfortunately, I would not recommend such paper for publication on Energy and Buildings in this form.
More in details, authors should extend their knowledge on LCA studies applied on the same subject, not only to increase the bibliographic list of the work (which is not complete respect to all the references cited in the manuscript – see for example the paper by Weidema et al. 2013) but also to compare and better support the selection of the main LCA factors and assumptions for the analysis. In this context, more justification should be given concerning the choice of the functional unit and the LCIA method (which is the reason for choosing two different perspective approaches for the Recipe method? Why not to choose the CML method or extend the analysis of the different results?).

Thank you for your comments. We have clarified our assumptions and choices related to the functional unit for this study (Section 3.2), and increased the bibliographic list of relevant works. As for our choice for the LCIA methods our reasoning is as follows. Firstly, we wanted to focused on energy figures and have therefore chosen an energy-focused method (CED). Secondly, energy can mislead interpretation as it doesn't account for the carbon intensity of the energy carrier. This, combined with the global relevance of climate change and global warming, has led to the choice of including GWP. Thirdly, energy and carbon – whilst a good proxy for other environmental impacts – might still fail to represent the full range of environmental externalities hence our decision to include also results from an impact assessment method based on additional impact categories (ReCiPe). The decision to include two of the ReCiPe perspectives is because we couldn't tell a priori *whether they would've yielded different results, and the different time-horizon of the two perspectives could've been a relevant difference. With regard to your suggestion for the CML method we agree that it would have been a good alternative to ReCiPe. However, the choice of impact assessment methods is one of the many subjective choices that underpin any LCA – and our study is no exception in this.*

Sometimes in the manuscript too long discussion are presented that do not increase the value of the LCA system model (see for example the lucubration about case study to be considered as qualitative research…) nor clarify some assertion (see for example the long explanation why “in an LCA no exact measurement is possible”).

Thank you also for these comments. We have reduced the section on case study research, which we have however retained as we deem it important in the peculiar context of our research. We have also shortened the paper and tightened the language to avoid long discussions that do not add value as your comment reads.

In regard to the exactness of LCAs, we understand that the explanation as to why the LCA is never exact might seem trivial to the expert reader. However, the reality in the LCA community is to believe in overly accurate results with 3-4 significant figures. These numbers are then passed on, enter the grey literature, are used by practitioners and stick around for a long time. This is the reason why we have chosen to dedicate 6 lines of that paragraph to provide an explanation as to why LCA results are estimates rather than exact assessment and referred to some of the latest publications providing a robust evidence for this.

The paper lacks also from technical point of view (see for example the discussion about data collection for which no precise references or personal communication details are provided or the discussion about the “Simapro standard databases”, or missing details about transportation considered in the study). Substantially, section 5 and 6 are a repetition of the same concept and sentences, while a few numeric results are provided to help the reader to follow the reasoning.

Thanks for these comments. We have removed the inappropriate generic reference to SimaPro standard databases and have rephrased and cited the relevant ones accordingly. As for our primary data, we have given full details on the municipalities and libraries visited, the firms that have provided data for our research, and the surveys and other literature sources used. The only thing we did not do is naming specific individuals within the named firms, but this will not be done for confidentiality reasons since it wasn’t mentioned to those interviewees during data collection that their names would’ve been publically published.

We have added a column on the overall comparative performance in tables 13 and 14, which we refer to in order to help the reader follow. Thank you very much for this suggestion. We have also explicitly referred to the comparative performance in terms of GWP to provide a stronger sense of relevance of our results.

We have substantially shortened section 5 and greatly reworked section 6 so that there is no or minimal overlap of the information presented.

Also, the language should be carefully checked, both for typos and for the structure since the manuscript resembles a technical report more than an LCA study.

We have significantly shortened the manuscript, tightened up the language, revised its structure and tone and even removed entire sections (e.g. 4.3). Once again thank you very much for your review and for the opportunity to improve our manuscript.

Life Cycle Environmental Impact Assessment of Contemporary and Traditional Housing in Palestine

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Abstract

Residential buildings consume a vast amount of energy throughout their whole-life cycles with the subsequent greenhouse gases (GHG) emitted in the atmosphere. This phenomenon will only be exacerbated by projected trends in excessive urbanisation and global population. It is therefore imperative to investigate and quantiatively evaluate the environmental impacts of housing in different regions and contexts in order to enable better and more informed decisions.

This is even more urgent in cases where the possibility for urban development is limited or severely constrained. Palestine represents one such areas of the world, and this research focuses on a comparative life cycle assessment (LCA) of contemporary and traditional housing typologies in the region. Primary data has been collected to provide a reliable basis for the LCA, which has been carried out according to the existing international standards. In addition to energy demand and GHG emissions, ~~a range of~~additional environmental impact categories ~~has~~ have been further evaluated to provide a more holistic sustainability analysis.

Results~~, which have been~~—strengthened ~~strengthened~~ by ~~undertaking~~ an uncertainty analysis—show ~~, show~~ that environmental impacts, energy use, and global warming potential for contemporary houses are for the most much higher than those for traditional houses. This is mainly due to the high impact of concrete and steel, but further exacerbated by the low impact of limestone as a suitable building material for the region. The results presented in this article signpost an important starting point in investigating the real mitigation potential of specific materials (e.g. limestone and lime mortar) when employed at scale in specific regions of the world. Our findings can also contribute to developmental policies for the region, with an aim of reducing the anthropogenic pressure on the natural environment.

Keywords

life cycle assessment (LCA); housing; Palestine; limestone; natural materials; comparative analysis.

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1. Introduction

Buildings are ubiquitous. The increasing number of people living in cities will lead by 2030 to an increase of 1,527,000 km^2 of new urban land area (Seto, Fragkias, Güneralp, & Reilly, 2011). In turn urbanisation and construction activities exacerbate the pressure on the natural environment, through the use of finite resources, emissions of greenhouse gases (GHG) to the atmosphere, energy demand, and waste generation (Pomponi & Moncaster, 2018). It is therefore imperative for a quicker transition to a fairer and more sustainable future to accurately evaluate the environmental impacts of buildings and construction activities in order to enable better and more informed decisions in line with life cycle thinking and the UN Sustainable Development Goals.

If this holds true globally, it is particularly urgent and timely to evaluate such environmental impacts in densely populated areas or parts of the world where spatial expansion of urban sprawling is severely constrained. Palestine is one of such cases, and the focus of this paper. ~~Specifically,~~ Palestine presents a rather mixed residential built environment where, however, two main typologies emerge: contemporary vs. traditional houses. The former follows ~~more~~ modern trends in building and construction technologies as well as material use whereas the latter reflects long-standing traditions based on the availability of local materials. Although traditional and contemporary houses have been studied in Palestine previously (Assi, 2001; Barakat et al., 2004; Hussein et al., 2010), no systematic research or comparative analysis of housing from a life cycle perspective has been carried out to date. This represents a significant gap, particularly in terms of supporting developmental decisions in such a delicate area of the world.

This ~~research will therefore conduct~~article presents a comparative life cycle assessment (LCA) between traditional and contemporary Palestinian houses. Within our scope, ~~In this study~~ ~~t~~traditional houses are ~~considered~~ those built ~~from~~ in the 1900-1930 period, and contemporary houses are ~~the houses or apartment buildings~~those built ~~mainly~~ from the 1990s onwards. The next section contextualises the scope and remit of ~~this~~ the research whereas section 3 introduces the research design and methodology. Section 4 details the data underpinning the LCA, whose results are ~~extensively~~ presented in Section 5. Section 6 discusses the main findings from this work and concludes the article.

2. The Study Background, Context and Case

2.1. Geography and Climate

As a historical Mediterranean territory, Palestine has hosted many cultures for thousands of years, and the remnants of those cultures can be found around the region. Tradition and modernity co-exist in most cities and villages around Palestine ~~to-date~~, and housing is no exception in such amalgamation, where both traditional and contemporary houses can be found side-by-side.

Palestine is located in the Western Asia, south of Lebanon, and west of Jordan, with the Mediterranean Sea on the west. The climate in Palestine is categorised as Mediterranean, with hot, dry, and relatively long summers, and rainy but short winters (Abdul-Hadi, 2013). During the British mandate (before 1948), it was around 430km by 70-80km. Now the West Bank area is around 120km by 40-50km (Abdul-Hadi, 2013). Figure 1 shows the Palestinian territory in 1947 compared to it at present time. The cases selected for primary data collection for this research are ~~both~~ located ~~within the territory~~in Palestine within its present time boundaries.

~~The climate in Palestine is categorised as Mediterranean climate, with hot, dry, and relatively long summers, and rainy but short winters (Abdul-Hadi, 2013).~~

2.2. Housing Typology

The change in building typology is mainly due to ~~the~~ changes in construction technology and building materials, but with rapid growth in settlement in main cities, the transition phase between the two typologies has been lost, and the traditional building methods and material have been disregarded.

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Commented [2]: Barakat, S., Elkahlout, G. and Jacoby, T., 2004. The reconstruction of housing in Palestine 1993–2000: a case study from the Gaza strip. *Housing Studies*, *19*(2), pp.175-192.

Commented [3]: Hussein, M.H., Barlet, A. and Semidor, C., 2010. Socio-Environmental Dimensions of Private Outdoor Spaces in Contemporary Palestinian Housing. *Open House International*, *35*(2), p.67.

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~~Thus, a~~A trend of building large reinforced concrete apartment blocks has therefore started as they were allegedly most cost- and time-effective, and eas~~y~~ier to construct, maintain, repair and reconstruct in case this was needed. Although many traditional houses and buildings still exist, due to the expansion of cities and villages, many of the old structures are being demolished to ~~build~~ be replaced by modern houses.

~~On the other hand the loss of transition in the housing typology is also exacerbated by the rapid change in lifestyle.~~ New construction methods and building materials (e.g. from limestone to reinforced concrete) ~~experienced a drastic change from limestone as prevailing building material in traditional housing at the beginning of C20th to reinforced concrete structures and concrete block walls in contemporary modern housing nowadays~~have exacerbated this lack of transition between housing typologies, further increased by the switch from~~. A shift from~~ single houses to apartment ~~buildings~~ blocks, which has probably been the most significant change that the housing industry in Palestine has experienced.

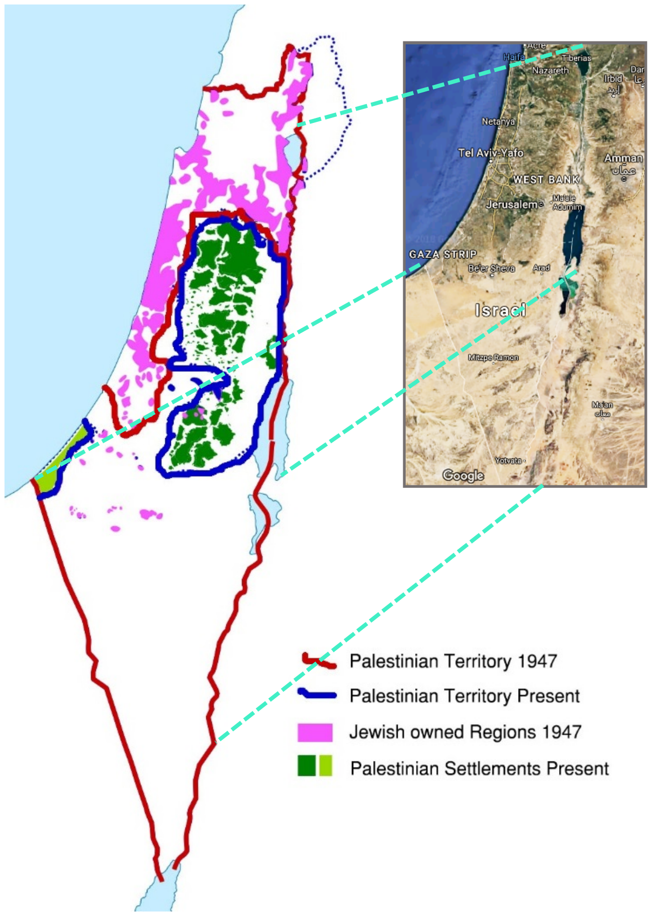

Figure 1: Palestinian Territory 1947 and Present
Source of satellite inset: Google Maps

An architectural styles survey in Palestinian Territories, classified residential buildings into two main categories: 1) Separate Houses, including Single Houses and Villas, and 2) Apartments, including Low Apartment Building, Block-Apartment, and Apartment Building (Hadid, 2002).

In an attempt to classify traditional houses, the Palestinian National Information Centre published an article entitled ‘Architectural Model for Residential Buildings in Palestine in the Ottoman Empire’ (2011). It offers multiple classification systems for traditional houses, and provides key information across several building elements and characteristics, such as the building materials, roof typology, roof bearing techniques, and room allocation and organization among others.

Commissioned by the EU and supported by the Ramallah Municipality Centre, the “Guide to Preservation of the Historic City Centre in Ramallah” (Issa & Juda, 2014) is probably the most comprehensive study of housing typology in Ramallah and can be generalised to Palestinian territories. Issa and Juda (2014) divide house typologies into five periods including: Late C19th, Early to mid C20th, 1950s-1960s, 1970s-1980s and ~~finally~~ 1990s onwards, each with a distinguishing characteristic. Around 1850, ~~the~~ living style ~~with~~in Ramallah started to change due to agricultural and land reforms. By the end of the C19th, ~~the~~ urban areas were taking shape and simple village huts were starting to expand into a ‘Housh’; a number of simple houses built adjacent to or on top of each other, with a private open space. At the beginning of the C20th, ‘Liwan’ became the common typology as a result of urban growth and stabilization, where single houses with large spaces and gardens were formed. The British mandate (1920-1948), regulated the new cities where building permits and plans were required. During the 1950-60s period, in addition to single residential houses, multi-story residential buildings started to appear, sometimes with commercial spaces on the ground floors. The new typology which began in 1970s was in large housing developments initiated by NGOs. Modern single houses and villas were still being built with almost no clues which could be traced back to traditional housing. The building typology from the 1980s continued on into the 1990s onwards, but large residential buildings were the main typology, with fewer housing projects being built. Furthermore, new private residential suburbs were developed, where a mixture of villas, multi-story residential projects, and semi-detached and terraced houses typically consisting of 2 to 4 units, could be found.

~~Within the scope of this research, traditional houses will be defined as Palestinian houses built before 1930 and contemporary houses are the ones built from 1990s onwards.~~

2.3. Construction Methods and Building Materials

In the interest of consistency and to fulfil the aim of this research, a common typology of each category – traditional and contemporary – has been chosen to elaborate on their building materials and construction methods. This will be used as a basis for the LCA at the analysis stage.

Contemporary housing

In-situ reinforced concrete, steel, and hollow concrete blocks are the most common materials used in contemporary buildings. The contemporary houses are made of reinforced concrete floor slabs with steel or concrete column and beam structures, hollow core concrete blocks as external walls and solid lightweight concrete blocks for partitions. Stone is still used in contemporary buildings, but only as a cover material (finishing) for the façade (Hadid, 2002) which acts as a rainscreen.

Traditional housing

Traditional houses built before 1930 were mostly using two prevailing construction methods and materials. Stone houses used limestone for walls and foundations, and lime mortar as a binding material. Rows of limestone were set, forming an inner ~~course~~ and an outer course. “The gap between outer and the inner courses, is filled with small rubble stone and mortars…” (Hadid, 2002, p.20). The limestone walls were of considerable depth with “Good walls used to have a thickness that varies from 80 to 120cm” (Hadid, 2002, p.20). Stone walls in traditional Mediterranean Architecture are known to have binding mortar varying between 4-25% of the wall volume (CORPUS, n.d.).

The other prevailing typology pre-1930, is known as ‘Mud House’ where adobe bricks made of local red soil, sand, water, and natural earth material were used. Mud houses were popular in the Gaza Strip and Jordan Valley especially in Jericho (Hadid, 2002). Mud houses are not within the focus of this study, because due to the heavy maintenance requirements and other disadvantages, they have almost totally been abandoned and are no longer ~~are~~ in use or in demand.

3. Research Design and Methodology

This research ~~uses a multiple-case study with a multiple-unit of analysis to investigate different housing typology in Mediterranean climate~~is based on case studies across multiple units of analysis in Palestine. Case study is ~~primarily~~ often considered qualitative research but can utilize both qualitative and quantitative methods (Bryar, 1999); what is the case in this research due to the nature of the data used. While the primary strength of case study research is its reliance on data enquiry from different sources and multiple data collection techniques, which increases the validity of the findings (Ridenour & Newman, 2008), the common criticism about case study as a method appears to be about the generalizability ~~ation methods~~ of its knowledge claims. Yin (2009, p. 38) emphasizes the methodological legitimacy of case studies where he suggests that ~~‘~~“fatal flaw in doing case studies is to conceive of statistical generalization as the method of generalizing the results of the case ~~study’~~ study” because case studies are not sampling units and therefore should not be treated as such but rather as experiments ~~instead~~ (Tsang, 2014). ~~This research therefore, uses four standardized stages of LCA i.e. i) Goal and Scope, ii) Life Cycle Inventory (LCI), iii) Life Cycle Impact-Assessment (LCIA) and, iv) Interpretations, as set in BS EN ISO 14040.~~LCA of buildings can take many forms: process based analysis (e.g. Monahan and Powell, 2011; Moncaster et al., 2018), input-output analysis (e.g. Nässén et al., 2007; Pomponi and D'Amico, 2018), or hybrid analysis (Treloar et al. 2000; Baynes et al., 2018). There are considerable methodological variations in how the method is applied across industry (De Wolf et al., 2018), and it is still debated which approach yields the best results (Yang et al., 2017; Pomponi and Lenzen, 2018). This research is based on the standardized approach to LCA, which consists of four phases: i) Goal and Scope, ii) Life Cycle Inventory (LCI), iii) Life Cycle Impact-Assessment (LCIA) and, iv) Interpretation, as set in the EN ISO 14040 (ISO, 2006).

3.1. Goal and Scope

The goal of this research is to determine the environmental impacts and energy consumption of two building typologies ~~used in~~representing traditional and contemporary houses in Palestine. The former is represented by a single house made with limestone while the latter is an apartment ~~in a typically~~ in a ~~4-~~5~~-~~story reinforced concrete building representing a contemporary house. ~~The goal is to be achieved by conducting a life cycle assessment for both typologies in order~~The scope is to determine:

a. The comparative analysis of impacts ~~of~~ across different life cycle stages of the two typologies.
b. The typology with the lowest environmental impacts overall.

3.2. Functional Unit, Systems and System Boundaries

This research focuses on two complete dwellings, one for each typology. However, due to their inherently different overall sizes ~~The~~ the functional units ~~in this research~~for our analysis is taken as 1m^2 of the built area of each house typology to ensure comparability of results. The system boundary is set according to BS EN 15978:2011 "Sustainability of Construction Works" (BSI, 2011), ~~setting it~~and covers stages from A1 to A4, which ~~mainly~~ denotes cradle to gate (A1- A3) processes, ~~in addition to~~and transportation to the construction site (A4). ~~Material inputs for each building typology is only taken into consideration, from raw material extraction, to site transportation.~~ Nevertheless, the LCI does take into account excavation, thus partially covering the impacts incurred in the A5 stage. The A1 to A4 system boundary (i.e. cradle to site) was mainly ~~chosen~~ due to lack of reliable information on, and the great variability and uncertainty about, ~~demolition and recycling~~post-construction life cycle stages in Palestine.

~~4.~~ Data ~~Query~~

4. ~~This section describes the procedures followed to help building up the LCI for this study.~~

4.1. Data Collection

Data was collected in three different steps. Initially, research on Palestinian structures and houses was carried out in the UK. Building on this first step, two trips to Palestine followed where further research was conducted by visiting libraries at Birzeit University in Birzeit and Al Najah University in Nablus, and visits to different local firms and organizations such as Riwaq, and Sakakini & Partners (architecture and engineering consultancy company) and government institutes including Palestinian Central Bureau of Statistics and Ramallah Municipality to obtain more information on, and drawings of, building typologies. ~~Last but not least, was t~~The third stage of data ~~enquiry~~ collection was carried out via formal and informal interviews with industry professionals and university professors in Palestine, to conclude on the housing typologies, building materials, material sourcing and construction methods in Palestine.

4.2. Data Generation

The data generation was carried out in two different steps. Firstly, the primary data collected informed the design of the building models that were created in SketchUp as a reference typology

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for traditional (Figure 2) and contemporary (Figure 3) houses in order to calculate the areas or weights of the materials in the house, which are needed to perform an LCA.

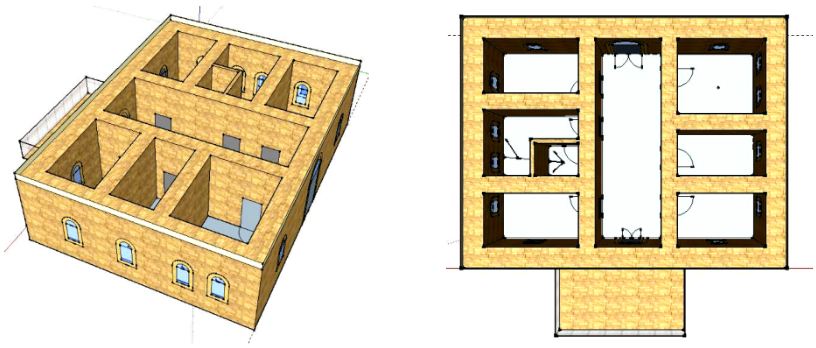

Figure 2: Traditional house reference typology

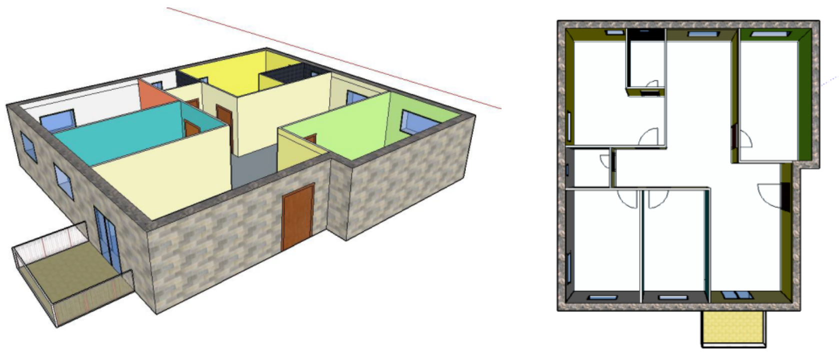

Figure 3: Contemporary house reference typology

~~To carry out an LCA, taking the ISO 14040 LCA requirements into consideration, LCI was required to be built for the developed reference typologies~~When primary data was not sufficient to cover the need of this research, we resorted to the large datasets provided within~~.~~ SimaPro ~~provides a large dataset from different sources~~ such as ecoinvent 3.0 (Moreno Ruiz et al., 2013) and Input-Output database (e.g. Rueda-Cantuche et al., 2009) where generic information for tens of thousands process and products can be found. ~~However~~Still, some material and processes ~~might not be available in SimaPro standard databases~~could not be found in such datasets, ~~in which case relevant impact assessment data about the process will be sought through other datasets outside SimaPro e.g. The~~and in rare cases we have therefore resorted University of Bath's inventory of carbon and energy database (Hammond and Jones, 2011). The ICE database is strictly UK focused but its information on the embodied energy of building materials is a useful starting point that can then be matched with appropriate carbon conversion coefficients, which are representative of the geographical context under examination (Pomponi and Medina Campos, 2018). The extra figures and numbers can be then added to the results found through SimaPro.

It is however important to note that "… LCA software tools can be used for the calculation of the embodied energy and carbon in buildings. However, their data and calculation often do not cover the whole lifecycle of buildings thus, only partial estimation is possible" (Moncaster & Song, 2012, p.32). This study is no exemption and rather provides an estimate of the environmental impacts of both contemporary and traditional Palestinian houses. This approach follows a growing community ~~which is~~ formally moving from the calculation of embodied carbon in buildings to its estimation

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(Gantner, Fawcett, & Ellingham, 2018; Mendoza Beltran, Pomponi, Guinée, & Heijungs, 2018; Richardson, Hyde, & Connaughton, 2018) after a clear understanding that ~~due to the~~ many assumptions are involved in an LCA ~~no exact measurement is possible~~and that these affect results (Moncaster et al., 2018). Assumptions were also a necessary step in this research, the most important of which is that ~~and are presented in the next section.~~

~~4.3. Assumptions~~

~~It is assumed that~~ both house typologies are built in the present day ~~due to two reasons~~. The means of transportation and the supply chain of building materials from over 100 years ago were unclear and unlikely to be replicated in modern times. Given that some of such processes might have been ~~done~~ completed using animals, it will immediately decrease the impact due to alternative means of transportation. ~~Taking that into consideration, the second reason for making this assumption is to increase the reliability of the study, given that if the conventional typology is to be reused, modern day technology will be utilized to build it.~~

~~Due to lack of documentation and research of building materials in Palestine, there were certain assumption when creating and preparing the models, and calculating the materials inputs. This can be relatively disregarded though because for both house typologies, the main material inputs are accounted for, and the chosen functional unit does accommodate for the uncertainty in the material inputs, given that the main ratios for mass/m² are adhered to.~~

Commented [18]: Moncaster, A.M., Pomponi, F., Symons, K.E. and Guthrie, P.M., 2018. Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system. *Energy and Buildings*, *173*, pp.389-398.

5. Data Analysis

5.1. Life Cycle Inventory

~~The LCA data used was sourced mainly from SimaPro databases~~As explained most LCI data was sourced from within SimaPro; we chose~~. Most of the~~ materials with ~~had~~ a general representation, and a unit process was used for all of them. The LCI and the source of materials for traditional and contemporary house typologies can be found in tables 1 and 2 correspondingly.

Table 1: Life Cycle Inventory and Sources for Traditional House Reference Typology

Material	Mass (Kg)	Process Chosen	Source
Binding Mortar	292.87	Non-Hydraulic Lime Mortar	---
Copper Wire	4.57	Copper wire, technology mix, consumption mix, at plant, cross section 1 mm² EU-15 S	ELCD 3.0
Doors	884.8	Pine wood, timber, production mix, at saw mill, 40% water content DE S	ELCD 3.0
Glass	60.72	Flat glass, coated (RoW)| production | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Lime Plaster	21295	Lime Plaster	---
Limestone	1796911.1	Limestone, unprocessed (RoW)| limestone quarry operation | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Metal Railing	326.9	Cast iron (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
PVC	19.66	PVC pipe f	---

Table 2: Life Cycle Inventory and Sources for Contemporary House Reference Typology

Material	*Mass (Kg)*	*Process Chosen*	*Source*
Aluminium	31.2	Aluminium, cast alloy (GLO)| market for | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Bitumen	52	Bitumen adhesive compound, hot (GLO)| market for | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)

Concrete	504855.54	Concrete, normal (RoW)| production | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Copper Wire	5.1	Copper wire, technology mix, consumption mix, at plant, cross section 1 mm² EU-15 S	ELCD 3.0
Doors	540.12	Pine wood, timber, production mix, at saw mill, 40% water content DE S	ELCD 3.0
Glass	90.13	Flat glass, coated (RoW)| production | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Hollow Concrete	53332	Concrete block (RoW)| production | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Metal Railing	143.5	Cast iron (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Plaster	25**	Base plaster (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Polystyrene	159.75	Polystyrene foam slab (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
PVC	58.18	PVC pipe f	---
Steel	31729.25	Reinforcing steel (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Stone Face	19473.92	Natural stone plate, cut, Lime (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)

For the materials used in traditional buildings which were not available in SimaPro ~~databases~~, Riwaq's 'Guide for the Maintenance and Restoration of Historic Buildings in Palestine' (Khaldoun, 2004) was used as a source to obtain the processes and ingredients for each material. Those materials were the non-hydraulic lime-based binding mortar and lime plaster for internal finishing. The Non-hydraulic lime mortar had the following ratio; for 1.2 kg of mortar, there is 0.9 kg of sand, 2.5 kg of lime, 0.25 kg of clay, and 0.25 kg of cement. For the lime plaster, the ratio is 2/3 Lime and 1/3 water. The material input for SimaPro for those two are shown in tables 3 and 4.

Table 3: Composition of Non-Hydraulic Lime Mortar Process

Known Outputs	*Non-Hydraulic Lime Mortar*	*1 Kg*
Known inputs from nature	Sand	0.75 kg
	Clay, unspecified	0.208 kg
Known inputs from techno-sphere	Lime (Row) [Production, milled loose] Alloc, Def, U	2.083 kg
	Cement, Portland (Row) [Production,] Alloc, Def, U	0.208 kg

Table 4: Composition of Lime Plaster

Known Outputs	*Lime Plaster*	
Known inputs from nature	Water, well in ground, Row	1/3000 m^3
Known inputs from techno-sphere	Lime (Row) [Production, milled loose] Alloc, Def, U	2/3 kg

Furthermore, for the PVC pipes, a system process was found. The impacts of the PVC pipes were calculated, then entered into a unit process as emissions or impacts for 1 kg of PVC pipes. Thus the new process created "PVC pipe f" was used for PVC, as seen in table 5.

Table 5: Obtaining PVC Pipe f

	For the Process of PVC pipe f	
	PVC pipe E	Industry Data 2.0
Emissions to air	Carbon Dioxide Fossil	3.32 kg

Also the natural limestone plates, used for the stone finishing of the contemporary houses, was modified for limestone stone plates instead of granite by changing the input material (table 6).

Table 6: Obtaining Natural Limestone Plate

Known Outputs	*Natural stone plate, cut, Lime (RoW)| production | Alloc Def, U*
Known Inputs from Nature(Resources)	Water, rive, (Row) Limestone (in ground)
Known inputs from techno-sphere	Limestone Quarry Infrastructure

5.2. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) was conducted using three calculation methods: Recipe Mid-point (I&H), Cumulative Energy Demand (CED), and IPCC Global Warming Potential (GWP), for a 100-year time frame. Tables 7 and 8 show the characterisation and normalisation values calculated using ReCipe midpoint I (20 years) and ReCipe midpoint H (100 years). The impact calculated per category is for 1m^2 for each house typology.

~~The results calculated through Recipe Midpoints I and H are quite close. Recipe midpoint I (Individualist perspective) taking 20 years into account, shows slightly higher value for climate change than that calculated for Recipe H (Hierarchist Perspective) for the next 100 years. This is probably due to CO_2 removal from the atmosphere by nature or man-made processes.~~

The results calculated through Recipe Midpoints I and H are quite close. Recipe midpoint I (Individualist perspective) taking 20 years into account, shows slightly higher value for climate change than that calculated for Recipe H (Hierarchist Perspective) for the next 100 years.

Table 7: Recipe Midpoint (I) Characterisation and Normalisation Values for total Impact per m^2 of contemporary and traditional houses (20 years)

Impact category	*Unit*	*Recipe Midpoint (I) Characterisation Values*		*Recipe Midpoint (I) Normalisation Values*	
		Contemporary House	Traditional House	Contemporary House	Traditional House
Agricultural land occupation	m^{2}a	18.77	3.608	0.003	0.000664
Climate change	kg CO_2 eq	1157.59	231.224	0.122	0.024278
Fossil depletion	kg oil eq	206.37	72.155	0.160	0.055992
Freshwater ecotoxicity	kg 1,4-DB eq	9.80	1.061	2.283	0.247212
Freshwater eutrophication	kg P eq	0.27	0.019	0.939	0.066497
Human toxicity	kg 1,4-DB eq	58.92	4.915	0.279	0.023248
Ionising radiation	kBq U235 eq	38.66	6.160	0.089	0.014231
Marine ecotoxicity	kg 1,4-DB eq	7.37	0.687	3.507	0.326937
Marine eutrophication	kg N eq	0.18	0.076	0.025	0.010398
Metal depletion	kg Fe eq	334.83	11.965	0.753	0.026921
Natural land transformation	m^2	0.16	0.061	0.013	0.005093
Ozone depletion	kg CFC-11 eq	0.00	0.000	0.001	0.000376
Particulate matter formation	kg PM10 eq	3.18	1.006	0.226	0.071549
Photochem oxidant formation	kg NMVOC	4.63	2.058	0.081	0.036219
Terrestrial acidification	kg SO_2 eq	4.28	1.217	0.120	0.034072
Terrestrial ecotoxicity	kg 1,4-DB eq	0.06	0.020	0.011	0.003437
Urban land occupation	m^{2}a	15.91	11.203	0.021	0.014452
Water depletion	m^3	2090.58	321.722	0	0

Table 8: Recipe Midpoint (H) Characterisation and Normalisation Values for total Impact per m² of contemporary and traditional houses (100 years)

Impact category	Unit	*Recipe Midpoint (H) Characterisation Values*		*Recipe Midpoint (H) Normalisation Values*	
		Contemporary House	Traditional House	Contemporary House	Traditional House
Agricultural land occupation	m^2a	18.770	3.61	0.004	0.00066
Climate change	kg CO_2 eq	1057.890	215.24	0.094	0.03121
Fossil depletion	kg oil eq	206.375	72.15	0.133	0.05599
Freshwater ecotoxicity	kg 1,4-DB eq	9.800	1.06	0.891	0.24615
Freshwater eutrophication	kg P eq	0.272	0.02	0.656	0.06650
Human toxicity	kg 1,4-DB eq	319.251	29.00	0.508	0.08903
Ionising radiation	kBq U235 eq	62.243	16.42	0.010	0.01247
Marine ecotoxicity	kg 1,4-DB eq	9.941	1.19	1.143	0.48325
Marine eutrophication	kg N eq	0.182	0.08	0.018	0.01040
Metal depletion	kg Fe eq	334.827	11.96	0.469	0.02692
Natural land transformation	m^2	0.155	0.06	0.960	0.00509
Ozone depletion	kg CFC-11 eq	0.000	0.00	0.002	0.00038
Particulate matter formation	kg PM10 eq	3.180	1.01	0.213	0.07155
Photochem oxidant formation	kg NMVOC	4.629	2.06	0.081	0.03622
Terrestrial acidification	kg SO_2 eq	4.519	1.36	0.132	0.03553
Terrestrial ecotoxicity	kg 1,4-DB eq	0.064	0.02	0.008	0.00342
Urban land occupation	m^2a	15.913	11.20	0.039	0.01445
Water depletion	m^3	2090.578	321.72	0	0

~~On the other hand,~~ Recipe midpoint H has higher values in regards to Human Toxicity, Ionising Radiation, Marine Ecotoxicity, and Terrestrial Acidification. ~~Furthermore, the normalisation results~~Normalised results for both typologies seem to convey the same results, but with smaller numbers due to the fact that it is the total impact per m² per person ~~(given a world population of 6.055 billion)~~. Thus the characterisation results will be ~~mostly~~ used for clarity. The two categories with highest impacts are Water Depletion, and Climate Change, for both conventional and contemporary houses. Tables 9 and 10 show the total energy consumption calculated through CED per 1m² of the built area. Weighing for CED is done by assuming a value of 1 for all categories, thus the results found represent the same relationship as what the characterisation values would. Furthermore, weighing and single score results are equal, and were thus represented in a single table.

Table 9: CED Characterisation values for total energy use per m²

Impact category	*Unit*	*Contemporary House*	*Traditional House*
Non-renewable, fossil	MJ	9219.955	3228.977
Non-renewable, nuclear	MJ	549.520	79.305
Non-renewable, biomass	MJ	0	0.000
Renewable, biomass	MJ	0.008	0.007
Renewable, wind, solar, geothermal	MJ	27.170	41.991
Renewable, water	MJ	0.028	0.032

Table 10: CED values for total energy use per m²

Impact category	*Uni t*	*Contemporary House*	*Traditional House*
Total	TJ	0.009797	0.00335
Non-renewable, fossil	TJ	0.009220	0.00323
Non-renewable, nuclear	TJ	0.0005495	7.93051E-05
Non-renewable, biomass	TJ	0	0
Renewable, biomass	TJ	7.6309E-09	6.56979E-09
Renewable, wind, solar, geothermal	TJ	2.717E-05	4.19912E-05
Renewable, water	TJ	2.7865E-08	3.15896E-08

CED results for contemporary houses are much higher when considering non-renewable sources (fossil & nuclear), where in the case of nuclear it is around 3 times ~~higher than~~as high as that of traditional. On the other hand, the traditional house seems to have higher use of renewable energy (wind, solar, geothermal, & water).

Table 11 shows results for the IPCC GWP calculation method, giving only a single value for global warming potential ~~for the next~~over 100 years. GWP for contemporary houses is nearly five times as much that of traditional houses. This can be interepreted in different ways. For instance, traditional houses could be a suitable mitigation strategy to reduce embodied carbon in the built environment given their lower GWP100. Alternatively, given fixed carbon budgets, traditional houses can be a way to providing housing to more people (nearly in a ratio of 5:1), leaving greater carbon allowances to other sectors.

Table 11: IPCC GWP (100 years) Characterisation Values per m^2

Impact category	*Unit*	*Contemporary House*	*Traditional House*
IPCC GWP 100a	kg CO_2 eq	1063.51	215.72

5.3. Uncertainty

Table 12 presents the scores given to both house typologies using the LCI Pedigree Matrix (Weidema et al., 2013) with justifications behind the assigned values.

Commented [19]: Hi, Rev3 was right – not all references in the text are in the bibliography. Can I leave this to you, and can you perhaps switch to the numbered format used in Energy and buildings? This will give us an idea of the overall number of references (we should be around 25-30 I think at the moment which is OK) – thank you!

Using the LCI Pedigree Matrix, the uncertainty values calculated for contemporary houses is 1.24, and for traditional houses it is 1.34. The higher uncertainty for traditional houses is justified by the lack of record of building materials and methods at the time, thus giving the model a higher uncertainty value.

Table 12: Score for Pedigree Matrix for LCI

	Contemporary House	*Traditional House*	*Reasoning*
Reliability	**2 –** Verified Data partly based on assumptions OR none verified data based on measurements.	**3-** Non verified data partly based on qualified estimates.	More verified data about RC structures, than for limestone structures.
Completeness	**4 –** Representative data from only one site relevant for the market considered OR some sites but from shorter periods.	**4 –** Representative data from only one site relevant for the market considered OR some sites but from shorter periods.	Each typology has 1 house model.

Temporal Correlation	**1 –** Less than 3 years of difference than our reference year.	**4 –** Less than 15 years of difference to our reference year.	Data found for contemporary houses is more recent, and time-specific, whilst data for contemporary houses was collected for a more general time-frame.
Geographical Correlation	**1 –** Data from area under study.	**1 –** Data from area under study.	Both models are within area of study.
Further Technological Correlation	**3 –** Data on related processes or materials but same technology, OR data from processes and materials under study but from different technology.	**3 –** Data on related processes or materials but same technology, OR data from processes and materials under study but from different technology.	Simapro data is based mostly on EU or USA technology, it is thus assumed that the technology found in Palestine is more outdated.
Total Value for Uncertainty Coefficient	**1.24**	**1.34**	

5.4. Uncertainty Analysis Results

SimaPro is used to directly calculate the uncertainty of the results using the coefficients 1.24 for contemporary houses, and 1.34 for traditional houses. The uncertainty analysis was conducted via a Monte Carlo simulation with 1000 samples, which has been proven to be a sufficient threshold for good convergence (Pomponi et al., 2017). ~~which~~ This produced values for mean, median, standard deviation (SD), and coefficient of variation (CoVar). The CoVar is defined as:

$$CoVar = \frac{\sigma}{\mu} * 100$$

Tables 13-16 indicate, for both house typologies, the calculated values of mean, median, SD, and CoVar for Recipe I, Recipe H, CED and IPCC GPW (100 years)—respectively.

Table 13: Uncertainty Results for Recipe I Characterisation results for Contemporary and Traditional Houses (20 years)

Impact category	*Unit*	*Contemporary House*				*Traditional House*				*Δ (Contemporary vs. Traditional)*
		Mean	Median	SD	CoVar	Mean	Median	SD	CoVar	[Mean values]
Agricultural land occupation	m^2a	18.886	17.633	6.745	35.70%	3.970	3.663	1.594	40.10%	376%
Climate change	kg CO_2 eq	1151.474	1137.021	151.282	13.20%	252.970	249.010	39.455	15.60%	355%
Fossil depletion	kg oil eq	205.242	202.833	27.847	13.60%	78.713	76.238	19.307	24.50%	161%
Freshwater ecotoxicity	kg 1,4-DB eq	8.913	8.817	28.522	321.00 %	1.252	0.941	10.149	808.00 %	612%
Freshwater eutrophication	kg P eq	0.274	0.238	0.146	53.50%	0.021	0.019	0.011	52%	1205%
Human toxicity	kg 1,4-DB eq	53.479	54.924	152.245	284%	5.792	5.198	53.960	937.00 %	823%
Ionising radiation	kBq U235 eq	36.953	20.669	50.106	136.00 %	6.683	3.767	9.901	148%	453%
Marine ecotoxicity	kg 1,4-DB eq	6.649	6.601	23.222	349%	0.832	0.614	8.218	985%	699%
Marine eutrophication	kg N eq	0.181	0.179	0.023	13%	0.084	0.082	0.015	18.40%	115%
Metal depletion	kg Fe eq	332.434	324.244	79.495	24%	13.119	12.129	4.668	35.50%	2434%
Natural land transformation	m^2	0.155	0.152	0.063	40.70%	0.070	0.068	0.057	81.50%	121%

Commented [20]: Pomponi, F., D'Amico, B. and Moncaster, A., 2017. A method to facilitate uncertainty analysis in LCAs of buildings. *Energies*, *10*(4), p.524.

Ozone depletion	kg CFC-11 eq	3.60E-05	3.35E-05	1.27E-05	35%	1.57E-05	1.35E-05	9.55E-06	61.10%	129%
Particulate matter formation	kg PM10 eq	3.161	3.098	0.449	14.20%	1.104	1.064	0.259	23.50%	186%
Photochemical oxidant formation	kg NMVOC	4.596	4.495	0.737	16.00%	2.248	2.208	0.415	18.50%	104%
Terrestrial acidification	kg SO_2 eq	4.245	4.201	0.569	13.40%	1.332	1.307	0.238	18%	219%
Terrestrial ecotoxicity	kg 1,4-DB eq	0.057	0.060	0.196	342.00 %	0.023	0.022	0.072	314.00 %	148%
Urban land occupation	m^2a	15.851	15.128	4.461	28.20%	12.079	10.396	7.178	59%	31%
Water depletion	m^3	2081.326	2028.329	288.109	14%	350.990	342.574	61.881	17.60%	493%

Table 14: Uncertainty Results for Recipe H Characterisation results for Contemporary and Traditional Houses (100 years)

Impact category	*Unit*	*Contemporary House*				*Traditional House*				Δ (Contempo
		Mean	Median	SD	CoVar	Mean	Median	SD	CoVar	[Mean values]
Agricultural land occupation	m^2a	18.982	17.923	6.263	33.00%	4.005	3.639	1.668	41.60%	374%
Climate change	kg CO_2 eq	1059.934	1050.299	138.273	13.10%	233.168	230.198	34.554	14.80%	355%
Fossil depletion	kg oil eq	206.205	203.796	27.028	13.10%	77.228	74.752	19.109	24.70%	167%
Freshwater ecotoxicity	kg 1,4-DB eq	9.058	9.828	29.630	327.00%	1.262	1.267	9.851	778%	618%
Freshwater eutrophication	kg P eq	0.264	0.233	0.127	48.10%	0.020	0.018	0.012	58.60%	1220%
Human toxicity	kg 1,4-DB eq	88.167	279.437	7949.509	9.03E+01	60.396	51.980	2648.515	4.40E+01	46%
Ionising radiation	kBq U235 eq	64.078	48.661	60.705	94%	17.376	14.901	11.089	63.90%	269%
Marine ecotoxicity	kg 1,4-DB eq	9.347	9.973	24.041	257.00%	1.381	1.361	7.970	578%	577%
Marine eutrophication	kg N eq	0.182	0.180	0.022	12%	0.084	0.082	0.015	18.40%	117%
Metal depletion	kg Fe eq	335.807	322.316	81.422	24.20%	12.871	12.079	4.411	34.20%	2509%
Natural land transformation	m^2	0.158	0.155	0.063	39.60%	0.069	0.068	0.051	73.40%	129%
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	33.80%	0.000	0.000	0.000	59.00%	N/A
Particulate matter formation	kg PM10 eq	3.185	3.117	0.465	14.60%	1.094	1.054	0.274	25.10%	191%
Photochemical oxidant formation	kg NMVOC	4.620	4.534	0.713	15.40%	2.238	2.193	0.419	18.70%	106%
Terrestrial acidification	kg SO_2 eq	4.524	4.457	0.622	13.70%	1.480	1.460	0.261	17.70%	206%
Terrestrial ecotoxicity	kg 1,4-DB eq	0.058	0.065	0.204	351%	0.023	0.023	0.070	307%	152%
Urban land occupation	m^2a	15.995	15.032	4.601	28.80%	12.129	10.050	7.723	63.70%	32%
Water depletion	m^3	2095.780	2066.872	280.401	0%	350.990	344.554	62.871	17.90%	497%

Table 15: Uncertainty Results for CED Characterisation results for Contemporary and Traditional Houses

Impact category	*Unit*	*Contemporary House*				*Traditional House*			
		Mean	Median	SD	CoVar	Mean	Median	SD	CoVar
Non-renewable, biomass	MJ	0.000	0.000	0.000	0%	0.000	0.000	0.000	0%

Non-renewable, nuclear	MJ	554.057	525.149	173.444	31.40%	86.634	77.723	38.812	44.80%
Non-renewable, fossil	MJ	9250.337	9153.980	1247.832	13.50%	3524.752	3410.891	881.188	24.90%
Renewable, biomass	MJ	0.008	0.008	0.001	16.10%	0.007	0.007	0.001	14.70%
Renewable, water	MJ	0.028	0.028	0.003	11.10%	0.035	0.034	0.004	10.60%
Renewable, wind, solar, geothermal	MJ	27.173	27.028	4.129	15.20%	45.792	44.950	6.733	14.80%

Table 16: Uncertainty Results for IPCC GWP (100 years) Characterisation results for Contemporary and Traditional Houses

Impact category	*Unit*	*Contemporary House*				*Traditional House*			
		Mean	Median	SD	CoVar	Mean	Median	SD	CoVar
IPCC GWP 100a	kg CO_2 eq	227.886	225.959	34.352	15.10%	1089.109	1074.257	148.020	13.60%

5.5. Life Cycle Assessment Interpretation and Analysis

The results for environmental impacts, energy use, and global warming potential for contemporary houses were much higher than those for traditional houses~~ in most categories~~. Specifically, contemporary houses are three times more energy intensive (Table 10), five times more carbon intensive (Table 11), and with varying degrees of higher intensity across other environmental impact categories (Tables 13 and 14). These range from around 30% for urban land occupation, through 120% for natural land transformation and around 500% for water depletion, to four-digit figures for freshwater eutrophication (~1200%) or metal depletion (~2500%). These~~is~~ results ~~is~~ are mainly due to ~~the known high impact of~~ concrete and steel production, which represent the impact hotspots in this case. However, ~~the results~~they also show the low impact of limestone as a building material, compared to ~~reinforced~~ concrete. This is mainly due to the fact that limestone is a natural material, but concrete and steel are produced using energy and carbon intensive processes. In fact,

~~The results found through Recipe Midpoint (I & H) attribute the biggest environmental impact of contemporary houses to Water Depletion, Climate Change, and then Metal and Fossil Depletion. For traditional houses, the same order of impacts applies, but with less Metal Depletion than Fossil. The environmental impacts calculated were highest for steel and concrete, followed by limestone then lime plaster. T~~the impacts associated with steel and concrete were mainly due to the actual production process of each building material, whilst the environmental impact of limestone is mainly due to its transportation.

Cumulative Energy Demand results attribute most of the energy use to non-renewable fossil, then non-renewable nuclear. The renewable energy sources were used by the wooden doors and copper wire production only, for both houses. As mentioned earlier, the contemporary house has a much higher total energy use compared to the traditional house~~, mainly due to the production of steel and concrete~~. Nevertheless, the energy required for the transportation of limestone is equal to the energy needed for concrete production. This is due to the large heavy volumes transported. Even though the contemporary house has a higher energy use, the high values of energy use due transportation of limestone within the West Bank only show that this could be drastically increased with an increase in transportation distance. ~~The global warming potential over 100 years calculated through IPCC GWP for contemporary houses (1063.51 kg CO_2-eq) was around 5 times higher than for traditional houses (215.72 kg CO_2-eq).~~

An uncertainty analysis was conducted for ~~coefficients of 1.24 and 1.34 for contemporary and traditional houses correspondingly~~both houses. The mean, median, and ~~SD~~ standard deviation results seem to coincide with the main results found, but the ~~CoVar~~ coefficient of variation seems to fluctuate a lot in value, and in some cases it is higher for the contemporary house. For both contemporary and traditional houses, CoVar values found in relation to the results seem to make no difference. Even if the values of the impact do vary around 20% for contemporary houses, it is still significantly higher than the values of traditional houses and vice versa. The uncertainty in an LCA is due to multiple factors (Pomponi et al., 2017) but in the case of this research the chief component is the lack of high-quality data for some categories which affected the model. Nevertheless, the basic uncertainty coefficient related to each category is shown to have an effect on certain categories more than the others.

Commented [21]: This is also missing from the bibliography but have given the fresh reference to this paper earlier in my comments.

6. ~~Discussion of Findings and Concluding Comments~~Conclusions

The aim of this research was to conduct a comparative LCA for contemporary and traditional houses in order to quantify the environmental impact, and energy use of both house typologies. ~~The research in hand~~ We measured the environmental impacts, energy use, and global warming potential of two house typologies found in Palestine: contemporary houses primarily made of reinforced concrete, and concrete blocks, and traditional houses chiefly made of limestone and lime mortar. Traditional houses showed reduced overall energy demand, lower embodied carbon, and consistently lower environmental impacts across the range of categories considered. One exception for the traditional houses was~~An LCA was conducted for both houses, comparing the results found through Recipe midpoint I and H, CED, & IPCC GWP 100. The traditional house was found to have a significantly lower impact compared to the contemporary houses. The high impacts of the contemporary house are mainly due to the production of steel and concrete, but also those of other materials such as hollow concrete blocks, and the stone finishing, which adds to the total impact calculated. Recipe mid-point I and H assessment showed Water Depletion (m^3) to impact categories of greatest concern, followed by climate change (kg CO_2 eq). Most of the energy used is sourced from non-renewable fossil fuels, and overall, the GWP for contemporary houses is five times that of conventional houses.~~

~~Whilst conventional houses were proven to have less of an impact than contemporary houses, but~~ limestone transportation, which ~~n~~ showed to have surprisingly high environmental impacts and energy requirements. This is explained by the great quantities needed, and therefore transported, in such house typology.

With the current unprecedented rates of global population growth and urbanisation, it is likely that the construction industry will keep promoting cheap and quick housing solutions, such as those represented by the contemporary house in this research. However, the anthropogenic stress on the natural environment has also reached unprecedented and unsustained levels and different approaches will be needed to reduce and mitigate the environmental impacts caused by buildings. This research has shown that traditional houses in Palestine have a significantly lower environmental impact than the conventional alternative. The results presented in this article can therefore represent an important starting point in investigating the real mitigation potential of specific materials (e.g. limestone and lime mortar) when employed at scale in specific regions of the world.

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Life Cycle Environmental Impact Assessment of Contemporary and Traditional Housing in Palestine

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Abstract

Residential buildings consume a vast amount of energy throughout their whole-life cycles with the subsequent greenhouse gases (GHG) emitted in the atmosphere. This phenomenon will only be exacerbated by projected trends in excessive urbanisation and global population. It is therefore imperative to investigate and quantiatively evaluate the environmental impacts of housing in different regions and contexts in order to enable better and more informed decisions.

This is even more urgent in cases where the possibility for urban development is limited or severely constrained. Palestine represents one such areas of the world, and this research focuses on a comparative life cycle assessment (LCA) of contemporary and traditional housing typologies in the region. Primary data has been collected to provide a reliable basis for the LCA, which has been carried out according to the existing international standards. In addition to energy demand and GHG emissions, additional environmental impact categories have been further evaluated to provide a more holistic sustainability analysis.

Results—strengthened by an uncertainty analysis—show that environmental impacts, energy use, and global warming potential for contemporary houses are for the most much higher than those for traditional houses. This is mainly due to the high impact of concrete and steel, but further exacerbated by the low impact of limestone as a suitable building material for the region. The results presented in this article signpost an important starting point in investigating the real mitigation potential of specific materials (e.g. limestone and lime mortar) when employed at scale in specific regions of the world. Our findings can also contribute to developmental policies for the region, with an aim of reducing the anthropogenic pressure on the natural environment.

Keywords
life cycle assessment (LCA); housing; Palestine; limestone; natural materials; comparative analysis.

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1. Introduction

Buildings are ubiquitous. The increasing number of people living in cities will lead by 2030 to an increase of 1,527,000 km^2 of new urban land area [1]. In turn urbanisation and construction activities exacerbate the pressure on the natural environment, through the use of finite resources, emissions of greenhouse gases (GHG) to the atmosphere, energy demand, and waste generation [2]. It is therefore imperative for a quicker transition to a fairer and more sustainable future to accurately evaluate the environmental impacts of buildings and construction activities in order to enable better and more informed decisions in line with life cycle thinking and the UN Sustainable Development Goals.

If this holds true globally, it is particularly urgent and timely to evaluate such environmental impacts in densely populated areas or parts of the world where spatial expansion of urban sprawling is severely constrained. Palestine is one of such cases, and the focus of this paper. Palestine presents a rather mixed residential built environment where, however, two main typologies emerge: contemporary vs. traditional houses. The former follows modern trends in building and construction technologies as well as material use whereas the latter reflects long-standing traditions based on the availability of local materials. Although traditional and contemporary houses have been studied in Palestine previously [3-5], no systematic research or comparative analysis of housing from a life cycle perspective has been carried out to date. This represents a significant gap, particularly in terms of supporting developmental decisions in such a delicate area of the world.

This article presents a comparative life cycle assessment (LCA) between traditional and contemporary Palestinian houses. Within our scope, traditional houses are those built in the 1900-1930 period, and contemporary houses are those built from the 1990s onwards. The next section contextualises the scope and remit of the research whereas section 3 introduces the research design and methodology. Section 4 details the data underpinning the LCA, whose results are presented in Section 5. Section 6 discusses the main findings from this work and concludes the article.

2. The Study Background, Context and Case

2.1. Geography and Climate

As a historical Mediterranean territory, Palestine has hosted many cultures for thousands of years, and the remnants of those cultures can be found around the region. Tradition and modernity co-exist in most cities and villages around Palestine, and housing is no exception in such amalgamation, where both traditional and contemporary houses can be found side-by-side.

Palestine is located in the Western Asia, south of Lebanon, and west of Jordan, with the Mediterranean Sea on the west. The climate in Palestine is categorised as Mediterranean, with hot, dry, and relatively long summers, and rainy but short winters [6]. During the British mandate (before 1948), it was around 430km by 70-80km. Now the West Bank area is around 120km by 40-50km [6]. Figure 1 shows the Palestinian territory in 1947 compared to it at present time. The cases selected for primary data collection for this research are located in Palestine within its present time boundaries.

2.2. Housing Typology

The change in building typology is mainly due to changes in construction technology and building materials, but with rapid growth in settlement in main cities, the transition phase between the two typologies has been lost, and the traditional building methods and material have been disregarded. A trend of building large reinforced concrete apartment blocks has therefore started as they were allegedly most cost- and time-effective, and easier to construct, maintain, repair and reconstruct in case this was needed. Although many traditional houses and buildings still exist, due to the expansion of cities and villages, many of the old structures are being demolished to be replaced by modern houses.

New construction methods and building materials have exacerbated the lack of transition between housing typologies, further increased by the switch from single houses to apartment blocks, which has probably been the most significant change that the housing industry in Palestine has experienced.

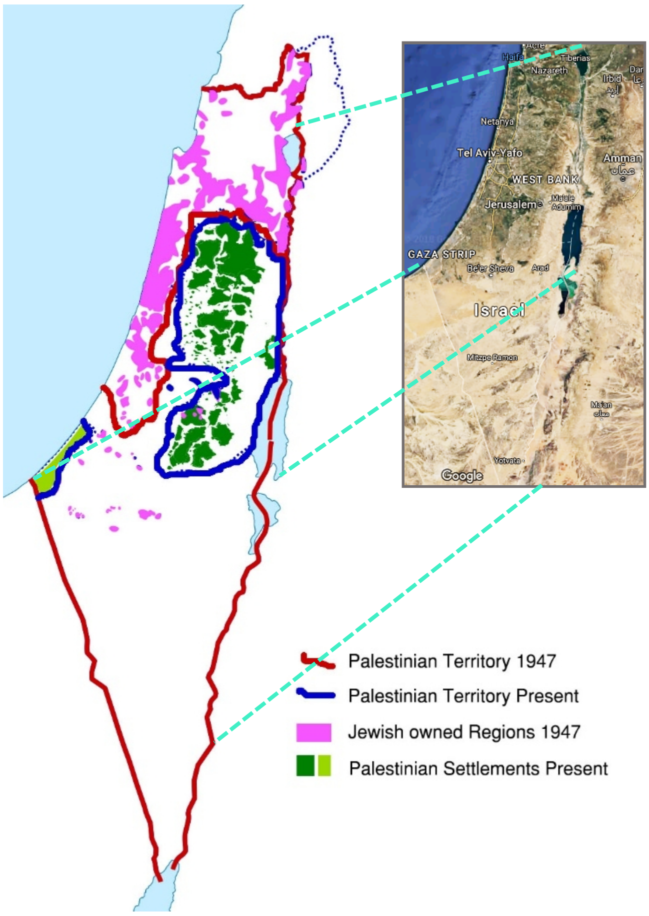

Figure 1: Palestinian Territory 1947 and Present
Source of satellite inset: Google Maps

An architectural styles survey in Palestinian Territories, classified residential buildings into two main categories: 1) Separate Houses, including Single Houses and Villas, and 2) Apartments, including Low Apartment Building, Block-Apartment, and Apartment Building [7].

In an attempt to classify traditional houses, the Palestinian National Information Centre published an article entitled ‘Architectural Model for Residential Buildings in Palestine in the Ottoman Empire’ (2011). It offers multiple classification systems for traditional houses, and provides key information across several building elements and characteristics, such as the building materials, roof typology, roof bearing techniques, and room allocation and organization among others.

Commissioned by the EU and supported by the Ramallah Municipality Centre, the “Guide to Preservation of the Historic City Centre in Ramallah” [8] is probably the most comprehensive study of housing typology in Ramallah and can be generalised to Palestinian territories. Issa and Juda [8] divide house typologies into five periods including: Late C19th, Early to mid C20th, 1950s-1960s, 1970s-1980s and 1990s onwards, each with a distinguishing characteristic. Around 1850, living style in Ramallah started to change due to agricultural and land reforms. By the end of the C19th, urban areas were taking shape and simple village huts were starting to expand into a ‘Housh’; a number of simple houses built adjacent to or on top of each other, with a private open space. At the beginning of the C20th, ‘Liwan’ became the common typology as a result of urban growth and stabilization, where single houses with large spaces and gardens were formed. The British mandate (1920-1948), regulated the new cities where building permits and plans were required. During the 1950-60s period, in addition to single residential houses, multi-story residential buildings started to appear, sometimes with commercial spaces on the ground floors. The new typology which began in 1970s was in large housing developments initiated by NGOs. Modern single houses and villas were still being built with almost no clues which could be traced back to traditional housing. The building typology from the 1980s continued on into the 1990s onwards, but large residential buildings were the main typology, with fewer housing projects being built. Furthermore, new private residential suburbs were developed, where a mixture of villas, multi-story residential projects, and semi-detached and terraced houses typically consisting of 2 to 4 units, could be found.

2.3. Construction Methods and Building Materials

In the interest of consistency and to fulfil the aim of this research, a common typology of each category – traditional and contemporary – has been chosen to elaborate on their building materials and construction methods. This will be used as a basis for the LCA at the analysis stage.

Contemporary housing

In-situ reinforced concrete, steel, and hollow concrete blocks are the most common materials used in contemporary buildings. The contemporary houses are made of reinforced concrete floor slabs with steel or concrete column and beam structures, hollow core concrete blocks as external walls and solid lightweight concrete blocks for partitions. Stone is still used in contemporary buildings, but only as a cover material (finishing) for the façade [7] which acts as a rainscreen.

Traditional housing

Traditional houses built before 1930 were mostly using two prevailing construction methods and materials. Stone houses used limestone for walls and foundations, and lime mortar as a binding material. Rows of limestone were set, forming an inner and an outer course. “The gap between outer and the inner courses, is filled with small rubble stone and mortars…” [7, p.20]. The limestone walls were of considerable depth with “Good walls used to have a thickness that varies from 80 to 120cm” [7, p.20]. Stone walls in traditional Mediterranean Architecture are known to have binding mortar varying between 4-25% of the wall volume [9].

The other prevailing typology pre-1930, is known as ‘Mud House’ where adobe bricks made of local red soil, sand, water, and natural earth material were used. Mud houses were popular in the Gaza Strip and Jordan Valley especially in Jericho [7]. Mud houses are not within the focus of this study, because due to the heavy maintenance requirements and other disadvantages, they have almost totally been abandoned and are no longer in use or in demand.

3. Research Design and Methodology

This research is based on case studies across multiple units of analysis in Palestine. Case study is often considered qualitative research but can utilize both qualitative and quantitative methods [10]; what is the case in this research due to the nature of the data used. While the primary strength of case study research is its reliance on data enquiry from different sources and multiple data collection techniques, which increases the validity of the findings [11], the common criticism about case study as a method appears to be about the generalizability of its knowledge claims. Yin [12, p. 38] emphasizes the methodological legitimacy of case studies where he suggests that “fatal flaw in doing case studies is to conceive of statistical generalization as the method of generalizing the results of the case study” because case studies are not sampling units and therefore should not be treated as such but rather as experiments [13]. LCA of buildings can take many forms: process-based analysis (e.g. [14, 15]), input-output analysis (e.g. [16, 17]), or hybrid analysis (e.g. [18, 19]). There are considerable methodological variations in how the method is applied across industry [20], and it is still debated which approach yields the best results [21, 22]. This research is based on the standardized approach to LCA, which consists of four phases: i) Goal and Scope, ii) Life Cycle Inventory (LCI), iii) Life Cycle Impact-Assessment (LCIA) and, iv) Interpretation, as set in the EN ISO 14040 [23].

3.1. Goal and Scope

The goal of this research is to determine the environmental impacts and energy consumption of two building typologies representing traditional and contemporary houses in Palestine. The former is represented by a single house made with limestone while the latter is an apartment in a 5-story reinforced concrete building representing a contemporary house. The scope is to determine:

a. The comparative analysis of impacts across different life cycle stages of the two typologies.
b. The typology with the lowest environmental impacts overall.

3.2. Functional Unit, Systems and System Boundaries

This research focuses on two complete dwellings, one for each typology. However, due to their inherently different overall sizes the functional units for our analysis is taken as 1m^2 of the built area of each house typology to ensure comparability of results. The system boundary is set according to BS EN 15978:2011 “Sustainability of Construction Works” [24], and covers stages from A1 to A4, which denotes cradle to gate (A1- A3) processes, and transportation to the construction site (A4). Nevertheless, the LCI does take into account excavation, thus partially covering the impacts incurred in the A5 stage. The A1 to A4 system boundary (i.e. cradle to site) was mainly due to lack of reliable information on, and the great variability and uncertainty about, post-construction life cycle stages in Palestine.

4. Data

4.1. Data Collection

Data was collected in three different steps. Initially, research on Palestinian structures and houses was carried out in the UK. Building on this first step, two trips to Palestine followed where further research was conducted by visiting libraries at Birzeit University in Birzeit and Al Najah University in Nablus, and visits to different local firms and organizations such as Riwaq, and Sakakini & Partners (architecture and engineering consultancy company) and government institutes including Palestinian Central Bureau of Statistics and Ramallah Municipality to obtain more information on, and drawings of, building typologies. The third stage of data collection was carried out via formal and informal interviews with industry professionals and university professors in Palestine, to conclude on the housing typologies, building materials, material sourcing and construction methods in Palestine.

4.2. Data Generation

The data generation was carried out in two different steps. Firstly, the primary data collected informed the design of the building models that were created in SketchUp as a reference typology for traditional (Figure 2) and contemporary (Figure 3) houses in order to calculate the areas or weights of the materials in the house, which are needed to perform an LCA.

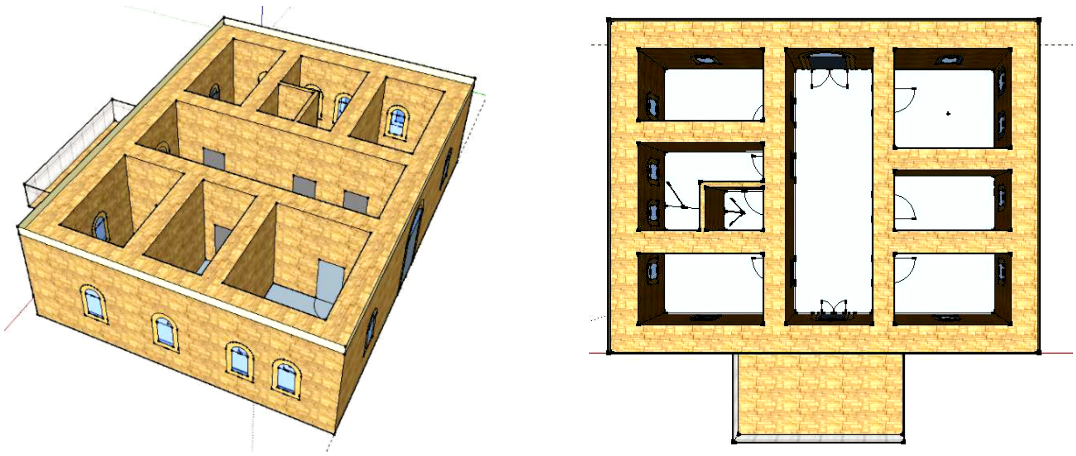

Figure 2: Traditional house reference typology

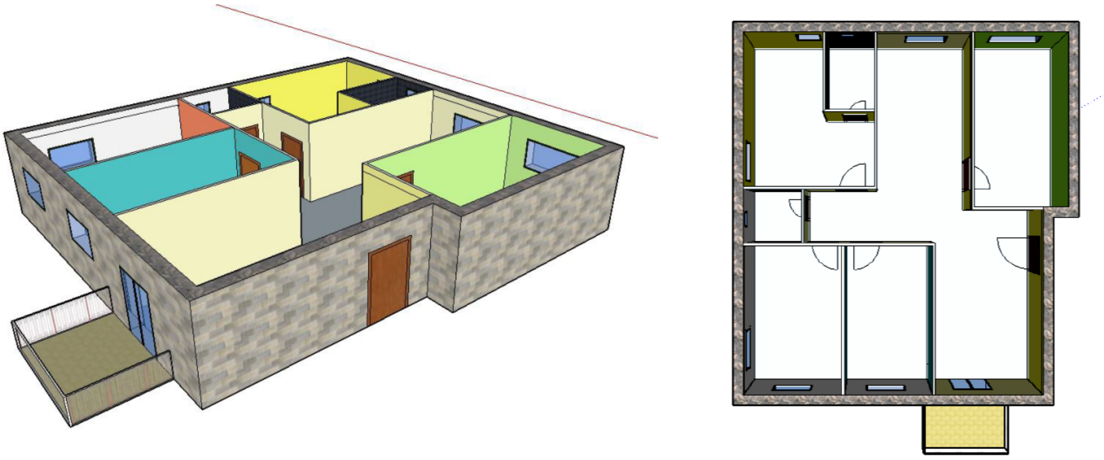

Figure 3: Contemporary house reference typology

When primary data was not sufficient to cover the need of this research, we resorted to the large datasets provided within SimaPro such as ecoinvent 3.0 [25] and Input-Output database (e.g. [26]) where generic information for tens of thousands process and products can be found. Still, some material and processes could not be found in such datasets, and in rare cases we have therefore resorted to University of Bath's inventory of carbon and energy database [27]. The ICE database is strictly UK focused but its information on the embodied energy of building materials is a useful starting point that can then be matched with appropriate carbon conversion coefficients, which are representative of the geographical context under examination [28]. The extra figures and numbers can be then added to the results found through SimaPro.

It is however important to note that "… LCA software tools can be used for the calculation of the embodied energy and carbon in buildings. However, their data and calculation often do not cover the whole lifecycle of buildings thus, only partial estimation is possible" [29, p.32]. This study is no exemption and rather provides an estimate of the environmental impacts of both contemporary and traditional Palestinian houses. This approach follows a growing community formally moving from the calculation of embodied carbon in buildings to its estimation [30-32] after a clear understanding that many assumptions are involved in an LCA and that these affect results [15]. Assumptions were also a necessary step in this research, the most important of which is that both house typologies are built in the present day. The means of transportation and the supply chain of building materials from over 100 years ago were unclear and unlikely to be replicated in modern times. Given that some of such processes might have been completed using animals, it will immediately decrease the impact due to alternative means of transportation.

5. Data Analysis

5.1. Life Cycle Inventory

As explained most LCI data was sourced from within SimaPro; we chose materials with a general representation, and a unit process was used for all of them. The LCI and the source of materials for traditional and contemporary house typologies can be found in tables 1 and 2 correspondingly.

Table 1: Life Cycle Inventory and Sources for Traditional House Reference Typology

Material	Mass (Kg)	Process Chosen	Source
Binding Mortar	292.87	Non-Hydraulic Lime Mortar	---
Copper Wire	4.57	Copper wire, technology mix, consumption mix, at plant, cross section 1 mm² EU-15 S	ELCD 3.0
Doors	884.8	Pine wood, timber, production mix, at saw mill, 40% water content DE S	ELCD 3.0
Glass	60.72	Flat glass, coated (RoW)| production | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Lime Plaster	21295	Lime Plaster	---
Limestone	1796911.1	Limestone, unprocessed (RoW)| limestone quarry operation | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Metal Railing	326.9	Cast iron (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
PVC	19.66	PVC pipe f	---

Table 2: Life Cycle Inventory and Sources for Contemporary House Reference Typology

Material	*Mass (Kg)*	*Process Chosen*	*Source*
Aluminium	31.2	Aluminium, cast alloy (GLO)| market for | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Bitumen	52	Bitumen adhesive compound, hot (GLO)| market for | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Concrete	504855.54	Concrete, normal (RoW)| production | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Copper Wire	5.1	Copper wire, technology mix, consumption mix, at plant, cross section 1 mm² EU-15 S	ELCD 3.0
Doors	540.12	Pine wood, timber, production mix, at saw mill, 40% water content DE S	ELCD 3.0
Glass	90.13	Flat glass, coated (RoW)| production | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Hollow Concrete	53332	Concrete block (RoW)| production | Alloc Def, U	'Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Metal Railing	143.5	Cast iron (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Plaster	25**	Base plaster (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Polystyrene	159.75	Polystyrene foam slab (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
PVC	58.18	PVC pipe f	---
Steel	31729.25	Reinforcing steel (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)
Stone Face	19473.92	Natural stone plate, cut, Lime (RoW)| production | Alloc Def, U	Ecoinvent v3.01' (Ecoinvent 3 - allocation, default - unit)

For the materials used in traditional buildings which were not available in SimaPro, Riwaq's 'Guide for the Maintenance and Restoration of Historic Buildings in Palestine' (Khaldoun, 2004) was used as a source to obtain the processes and ingredients for each material. Those materials were the non-hydraulic lime-based binding mortar and lime plaster for internal finishing. The Non-hydraulic lime mortar had the following ratio; for 1.2 kg of mortar, there is 0.9 kg of sand, 2.5 kg of lime, 0.25 kg of clay, and 0.25 kg of cement. For the lime plaster, the ratio is 2/3 Lime and 1/3 water. The material input for SimaPro for those two are shown in tables 3 and 4.

Table 3: Composition of Non-Hydraulic Lime Mortar Process

Known Outputs	*Non-Hydraulic Lime Mortar*	*1 Kg*
Known inputs from nature	Sand	0.75 kg
	Clay, unspecified	0.208 kg
Known inputs from techno-sphere	Lime (Row) [Production, milled loose] Alloc, Def, U	2.083 kg
	Cement, Portland (Row) [Production,] Alloc, Def, U	0.208 kg

Table 4: Composition of Lime Plaster

Known Outputs	*Lime Plaster*	
Known inputs from nature	Water, well in ground, Row	1/3000 m^3
Known inputs from techno-sphere	Lime (Row) [Production, milled loose] Alloc, Def, U	2/3 kg

Furthermore, for the PVC pipes, a system process was found. The impacts of the PVC pipes were calculated, then entered into a unit process as emissions or impacts for 1 kg of PVC pipes. Thus the new process created "PVC pipe f" was used for PVC, as seen in table 5.

Table 5: Obtaining PVC Pipe f

	For the Process of PVC pipe f	
	PVC pipe E	Industry Data 2.0
Emissions to air	Carbon Dioxide Fossil	3.32 kg

Also the natural limestone plates, used for the stone finishing of the contemporary houses, was modified for limestone stone plates instead of granite by changing the input material (table 6).

Table 6: Obtaining Natural Limestone Plate

Known Outputs	*Natural stone plate, cut, Lime (RoW)| production | Alloc Def, U*
Known Inputs from Nature(Resources)	Water, rive, (Row)
	Limestone (in ground)
Known inputs from techno-sphere	Limestone Quarry Infrastructure

5.2. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) was conducted using three calculation methods: ReCiPe Mid-point (I&H), Cumulative Energy Demand (CED), and IPCC Global Warming Potential (GWP), for a 100-year time frame. Tables 7 and 8 show the characterisation and normalisation values calculated using ReCiPe midpoint I (20 years) and ReCiPe midpoint H (100 years). The impact calculated per category is for 1m^2 for each house typology. The results calculated through ReCiPe Midpoints I and H are quite close. ReCiPe midpoint I (Individualist perspective) taking 20 years into account, shows slightly higher value for climate change than that calculated for ReCiPe H (Hierarchist Perspective) for the next 100 years.

Table 7: ReCiPe Midpoint (I) Characterisation and Normalisation Values for total Impact per m^2 of contemporary and traditional houses (20 years)

Impact category	*Unit*	*ReCiPe Midpoint (I) Characterisation Values*		*ReCiPe Midpoint (I) Normalisation Values*	
		Contemporary House	Traditional House	Contemporary House	Traditional House
Agricultural land occupation	m^2a	18.77	3.608	0.003	0.000664
Climate change	kg CO_2 eq	1157.59	231.224	0.122	0.024278
Fossil depletion	kg oil eq	206.37	72.155	0.160	0.055992
Freshwater ecotoxicity	kg 1,4-DB eq	9.80	1.061	2.283	0.247212
Freshwater eutrophication	kg P eq	0.27	0.019	0.939	0.066497
Human toxicity	kg 1,4-DB eq	58.92	4.915	0.279	0.023248
Ionising radiation	kBq U235 eq	38.66	6.160	0.089	0.014231
Marine ecotoxicity	kg 1,4-DB eq	7.37	0.687	3.507	0.326937
Marine eutrophication	kg N eq	0.18	0.076	0.025	0.010398
Metal depletion	kg Fe eq	334.83	11.965	0.753	0.026921
Natural land transformation	m^2	0.16	0.061	0.013	0.005093
Ozone depletion	kg CFC-11 eq	0.00	0.000	0.001	0.000376
Particulate matter formation	kg PM10 eq	3.18	1.006	0.226	0.071549
Photochem oxidant formation	kg NMVOC	4.63	2.058	0.081	0.036219
Terrestrial acidification	kg SO_2 eq	4.28	1.217	0.120	0.034072
Terrestrial ecotoxicity	kg 1,4-DB eq	0.06	0.020	0.011	0.003437
Urban land occupation	m^2a	15.91	11.203	0.021	0.014452
Water depletion	m^3	2090.58	321.722	0	0

Table 8: ReCiPe Midpoint (H) Characterisation and Normalisation Values for total Impact per m^2 of contemporary and traditional houses (100 years)

Impact category	*Unit*	*ReCiPe Midpoint (H) Characterisation Values*		*ReCiPe Midpoint (H) Normalisation Values*	
		Contemporary House	Traditional House	Contemporary House	Traditional House
Agricultural land occupation	m^2a	18.770	3.61	0.004	0.00066
Climate change	kg CO_2 eq	1057.890	215.24	0.094	0.03121
Fossil depletion	kg oil eq	206.375	72.15	0.133	0.05599
Freshwater ecotoxicity	kg 1,4-DB eq	9.800	1.06	0.891	0.24615
Freshwater eutrophication	kg P eq	0.272	0.02	0.656	0.06650
Human toxicity	kg 1,4-DB eq	319.251	29.00	0.508	0.08903
Ionising radiation	kBq U235 eq	62.243	16.42	0.010	0.01247
Marine ecotoxicity	kg 1,4-DB eq	9.941	1.19	1.143	0.48325
Marine eutrophication	kg N eq	0.182	0.08	0.018	0.01040
Metal depletion	kg Fe eq	334.827	11.96	0.469	0.02692
Natural land transformation	m^2	0.155	0.06	0.960	0.00509
Ozone depletion	kg CFC-11 eq	0.000	0.00	0.002	0.00038
Particulate matter formation	kg PM10 eq	3.180	1.01	0.213	0.07155
Photochem oxidant formation	kg NMVOC	4.629	2.06	0.081	0.03622
Terrestrial acidification	kg SO_2 eq	4.519	1.36	0.132	0.03553
Terrestrial ecotoxicity	kg 1,4-DB eq	0.064	0.02	0.008	0.00342
Urban land occupation	m^2a	15.913	11.20	0.039	0.01445
Water depletion	m^3	2090.578	321.72	0	0

ReCiPe midpoint H has higher values in regards to Human Toxicity, Ionising Radiation, Marine Ecotoxicity, and Terrestrial Acidification. Normalised results for both typologies seem to convey the same results, but with smaller numbers due to the fact that it is the total impact per m^2 per person. Thus the characterisation results will be used for clarity. The two categories with highest impacts are Water Depletion, and Climate Change, for both conventional and contemporary houses. Tables 9 and 10 show the total energy consumption calculated through CED per 1m^2 of the built area. Weighing for CED is done by assuming a value of 1 for all categories, thus the results found represent the same relationship as what the characterisation values would. Furthermore, weighing and single score results are equal, and were thus represented in a single table.

Table 9: CED Characterisation values for total energy use per m^2

Impact category	*Unit*	*Contemporary House*	*Traditional House*
Non-renewable, fossil	MJ	9219.955	3228.977
Non-renewable, nuclear	MJ	549.520	79.305
Non-renewable, biomass	MJ	0	0.000
Renewable, biomass	MJ	0.008	0.007
Renewable, wind, solar, geothermal	MJ	27.170	41.991
Renewable, water	MJ	0.028	0.032

Table 10: CED values for total energy use per m^2

Impact category	*Unit*	*Contemporary House*	*Traditional House*
Total	TJ	0.009797	0.00335
Non-renewable, fossil	TJ	0.009220	0.00323
Non-renewable, nuclear	TJ	0.0005495	7.93051E-05
Non-renewable, biomass	TJ	0	0
Renewable, biomass	TJ	7.6309E-09	6.56979E-09
Renewable, wind, solar, geothermal	TJ	2.717E-05	4.19912E-05
Renewable, water	TJ	2.7865E-08	3.15896E-08

CED results for contemporary houses are much higher when considering non-renewable sources (fossil & nuclear), where in the case of nuclear it is around 3 times as high as that of traditional. On the other hand, the traditional house seems to have higher use of renewable energy (wind, solar, geothermal, & water).

Table 11 shows results for the IPCC GWP calculation method, giving only a single value for global warming potential over 100 years. GWP for contemporary houses is nearly five times as much that of traditional houses. This can be interepreted in different ways. For instance, traditional houses could be a suitable mitigation strategy to reduce embodied carbon in the built environment given their lower GWP100. Alternatively, given fixed carbon budgets, traditional houses can be a way to providing housing to more people (nearly in a ratio of 5:1), leaving greater carbon allowances to other sectors.

Table 11: IPCC GWP (100 years) Characterisation Values per m^2

Impact category	*Unit*	*Contemporary House*	*Traditional House*
IPCC GWP 100a	kg CO_2 eq	1063.51	215.72

5.3. Uncertainty

Table 12 presents the scores given to both house typologies using the LCI Pedigree Matrix [33] with justifications behind the assigned values. Using the LCI Pedigree Matrix, the uncertainty values calculated for contemporary houses is 1.24, and for traditional houses it is 1.34. The higher uncertainty for traditional houses is justified by the lack of record of building materials and methods at the time, thus giving the model a higher uncertainty value.

Table 12: Score for Pedigree Matrix for LCI

	Contemporary House	*Traditional House*	*Reasoning*
Reliability	**2 –** Verified Data partly based on assumptions OR none verified data based on measurements.	**3-** Non verified data partly based on qualified estimates.	More verified data about RC structures, than for limestone structures.
Completeness	**4 –** Representative data from only one site relevant for the market considered OR some sites but from shorter periods.	**4 –** Representative data from only one site relevant for the market considered OR some sites but from shorter periods.	Each typology has 1 house model.
Temporal Correlation	**1 –** Less than 3 years of difference than our reference year.	**4 –** Less than 15 years of difference to our reference year.	Data found for contemporary houses is more recent, and time-specific, whilst data for contemporary houses was collected for a more general time-frame.
Geographical Correlation	**1 –** Data from area under study.	**1 –** Data from area under study.	Both models are within area of study.
Further Technological Correlation	**3 –** Data on related processes or materials but same technology, OR data from processes and materials under study but from different technology.	**3 –** Data on related processes or materials but same technology, OR data from processes and materials under study but from different technology.	Simapro data is based mostly on EU or USA technology, it is thus assumed that the technology found in Palestine is more outdated.
Total Value for Uncertainty Coefficient	**1.24**	**1.34**	

5.4. Uncertainty Analysis Results

SimaPro is used to directly calculate the uncertainty of the results using the coefficients 1.24 for contemporary houses, and 1.34 for traditional houses. The uncertainty analysis was conducted via a Monte Carlo simulation with 1000 samples, which has been proven to be a sufficient threshold for good convergence [34]. This produced values for mean, median, standard deviation (SD), and coefficient of variation (CoVar). The CoVar is defined as:

$$CoVar = \frac{\sigma}{\mu} * 100$$

Tables 13-16 indicate, for both house typologies, the calculated values of mean, median, SD, and CoVar for ReCiPe I, ReCiPe H, CED and IPCC GPW (100 years)—respectively.

Table 13: Uncertainty Results for ReCiPe I Characterisation results for Contemporary and Traditional Houses (20 years)

Impact category	*Unit*	*Contemporary House*				*Traditional House*				*Δ (Contemporary vs. Traditional)*
		Mean	Median	SD	CoVar	Mean	Median	SD	CoVar	[Mean values]
Agricultural land occupation	m^2a	18.886	17.633	6.745	35.70%	3.970	3.663	1.594	40.10%	376%
Climate change	kg CO_2 eq	1151.474	1137.021	151.282	13.20%	252.970	249.010	39.455	15.60%	355%
Fossil depletion	kg oil eq	205.242	202.833	27.847	13.60%	78.713	76.238	19.307	24.50%	161%
Freshwater ecotoxicity	kg 1,4-DB eq	8.913	8.817	28.522	321.00%	1.252	0.941	10.149	808.00%	612%
Freshwater eutrophication	kg P eq	0.274	0.238	0.146	53.50%	0.021	0.019	0.011	52%	1205%
Human toxicity	kg 1,4-DB eq	53.479	54.924	152.245	284%	5.792	5.198	53.960	937.00%	823%
Ionising radiation	kBq U235 eq	36.953	20.669	50.106	136.00%	6.683	3.767	9.901	148%	453%
Marine ecotoxicity	kg 1,4-DB eq	6.649	6.601	23.222	349%	0.832	0.614	8.218	985%	699%
Marine eutrophication	kg N eq	0.181	0.179	0.023	13%	0.084	0.082	0.015	18.40%	115%
Metal depletion	kg Fe eq	332.434	324.244	79.495	24%	13.119	12.129	4.668	35.50%	2434%
Natural land transformation	m^2	0.155	0.152	0.063	40.70%	0.070	0.068	0.057	81.50%	121%
Ozone depletion	kg CFC-11 eq	3.60E-05	3.35E-05	1.27E-05	35%	1.57E-05	1.35E-05	9.55E-06	61.10%	129%
Particulate matter formation	kg PM10 eq	3.161	3.098	0.449	14.20%	1.104	1.064	0.259	23.50%	186%
Photochemical oxidant formation	kg NMVOC	4.596	4.495	0.737	16.00%	2.248	2.208	0.415	18.50%	104%
Terrestrial acidification	kg SO_2 eq	4.245	4.201	0.569	13.40%	1.332	1.307	0.238	18%	219%
Terrestrial ecotoxicity	kg 1,4-DB eq	0.057	0.060	0.196	342.00%	0.023	0.022	0.072	314.00%	148%
Urban land occupation	m^2a	15.851	15.128	4.461	28.20%	12.079	10.396	7.178	59%	31%
Water depletion	m^3	2081.326	2028.329	288.109	14%	350.990	342.574	61.881	17.60%	493%

Table 14: Uncertainty Results for ReCiPe H Characterisation results for Contemporary and Traditional Houses (100 years)

Impact category	*Unit*	*Contemporary House*				*Traditional House*				*Δ (Contemporary vs. Traditional*
		Mean	Median	SD	CoVar	Mean	Median	SD	CoVar	[Mean values]
Agricultural land occupation	m^2a	18.982	17.923	6.263	33.00%	4.005	3.639	1.668	41.60%	374%
Climate change	kg CO_2 eq	1059.934	1050.299	138.273	13.10%	233.168	230.198	34.554	14.80%	355%
Fossil depletion	kg oil eq	206.205	203.796	27.028	13.10%	77.228	74.752	19.109	24.70%	167%
Freshwater ecotoxicity	kg 1,4-DB eq	9.058	9.828	29.630	327.00%	1.262	1.267	9.851	778%	618%
Freshwater eutrophication	kg P eq	0.264	0.233	0.127	48.10%	0.020	0.018	0.012	58.60%	1220%
Human toxicity	kg 1,4-DB eq	88.167	279.437	7949.509	9.03E+01	60.396	51.980	2648.515	4.40E+01	46%
Ionising radiation	kBq U235 eq	64.078	48.661	60.705	94%	17.376	14.901	11.089	63.90%	269%
Marine ecotoxicity	kg 1,4-DB eq	9.347	9.973	24.041	257.00%	1.381	1.361	7.970	578%	577%
Marine eutrophication	kg N eq	0.182	0.180	0.022	12%	0.084	0.082	0.015	18.40%	117%
Metal depletion	kg Fe eq	335.807	322.316	81.422	24.20%	12.871	12.079	4.411	34.20%	2509%
Natural land transformation	m^2	0.158	0.155	0.063	39.60%	0.069	0.068	0.051	73.40%	129%
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	33.80%	0.000	0.000	0.000	59.00%	N/A
Particulate matter formation	kg PM10 eq	3.185	3.117	0.465	14.60%	1.094	1.054	0.274	25.10%	191%
Photochemical oxidant formation	kg NMVOC	4.620	4.534	0.713	15.40%	2.238	2.193	0.419	18.70%	106%
Terrestrial acidification	kg SO_2 eq	4.524	4.457	0.622	13.70%	1.480	1.460	0.261	17.70%	206%
Terrestrial ecotoxicity	kg 1,4-DB eq	0.058	0.065	0.204	351%	0.023	0.023	0.070	307%	152%
Urban land occupation	m^2a	15.995	15.032	4.601	28.80%	12.129	10.050	7.723	63.70%	32%
Water depletion	m^3	2095.780	2066.872	280.401	0%	350.990	344.554	62.871	17.90%	497%

Table 15: Uncertainty Results for CED Characterisation results for Contemporary and Traditional Houses

Impact category	*Unit*	*Contemporary House*				*Traditional House*			
		Mean	Median	SD	CoVar	Mean	Median	SD	CoVar
Non-renewable, biomass	MJ	0.000	0.000	0.000	0%	0.000	0.000	0.000	0%
Non-renewable, nuclear	MJ	554.057	525.149	173.444	31.40%	86.634	77.723	38.812	44.80%
Non-renewable, fossil	MJ	9250.337	9153.980	1247.832	13.50%	3524.752	3410.891	881.188	24.90%
Renewable, biomass	MJ	0.008	0.008	0.001	16.10%	0.007	0.007	0.001	14.70%
Renewable, water	MJ	0.028	0.028	0.003	11.10%	0.035	0.034	0.004	10.60%
Renewable, wind, solar, geothermal	MJ	27.173	27.028	4.129	15.20%	45.792	44.950	6.733	14.80%

Table 16: Uncertainty Results for IPCC GWP (100 years) Characterisation results for Contemporary and Traditional Houses

Impact category	*Unit*	*Contemporary House*				*Traditional House*			
		Mean	Median	SD	CoVar	Mean	Median	SD	CoVar
IPCC GWP 100a	kg CO_2 eq	227.886	225.959	34.352	15.10%	1089.109	1074.257	148.020	13.60%

5.5. Life Cycle Assessment Interpretation and Analysis

The results for environmental impacts, energy use, and global warming potential for contemporary houses were much higher than those for traditional houses. Specifically, contemporary houses are three times more energy intensive (Table 10), five times more carbon intensive (Table 11), and with varying degrees of higher intensity across other environmental impact categories (Tables 13 and 14). These range from around 30% for urban land occupation, through 120% for natural land transformation and around 500% for water depletion, to four-digit figures for freshwater eutrophication (~1200%) or metal depletion (~2500%). These results are mainly due to concrete and steel production, which represent the impact of hotspots in this case. However, they also show the low impact of limestone as a building material, compared to concrete. This is mainly due to the fact that limestone is a natural material, but concrete and steel are produced using energy and carbon intensive processes. In fact, the impacts associated with steel and concrete were mainly due to the actual production process of each building material, whilst the environmental impact of limestone is mainly due to its transportation.

Cumulative Energy Demand results attribute most of the energy use to non-renewable fossil, then non-renewable nuclear. The renewable energy sources were used by the wooden doors and copper wire production only, for both houses. As mentioned earlier, the contemporary house has a much higher total energy use compared to the traditional house. Nevertheless, the energy required for the transportation of limestone is equal to the energy needed for concrete production. This is due to the large heavy volumes transported. Even though the contemporary house has a higher energy use, the high values of energy use due transportation of limestone within the West Bank only show that this could be drastically increased with an increase in transportation distance.

An uncertainty analysis was conducted for both houses. The mean, median, and standard deviation results seem to coincide with the main results found, but the coefficient of variation seems to fluctuate a lot in value, and in some cases it is higher for the contemporary house. For both contemporary and traditional houses, CoVar values found in relation to the results seem to make no difference. Even if the values of the impact do vary around 20% for contemporary houses, it is still significantly higher than the values of traditional houses and vice versa. The uncertainty in an LCA is due to multiple factors [34] but in the case of this research the chief component is the lack of high-quality data for some categories which affected the model. Nevertheless, the basic uncertainty coefficient related to each category is shown to have an effect on certain categories more than the others.

6. Conclusions

The aim of this research was to conduct a comparative LCA for contemporary and traditional houses in order to quantify the environmental impact, and energy use of both house typologies. We measured the environmental impacts, energy use, and global warming potential of two house typologies found in Palestine: contemporary houses primarily made of reinforced concrete, and concrete blocks, and traditional houses chiefly made of limestone and lime mortar. Traditional houses showed reduced overall energy demand, lower embodied carbon, and consistently lower environmental impacts across the range of categories considered. One exception for the traditional houses was limestone transportation, which showed to have surprisingly high environmental impacts and energy requirements. This is explained by the great quantities needed, and therefore transported, in such house typology.

With the current unprecedented rates of global population growth and urbanisation, it is likely that the construction industry will keep promoting cheap and quick housing solutions, such as those represented by the contemporary house in this research. However, the anthropogenic stress on the natural environment has also reached unprecedented and unsustained levels and different approaches will be needed to reduce and mitigate the environmental impacts caused by buildings. This research has shown that traditional houses in Palestine have a significantly lower environmental impact than the conventional alternative. The results presented in this article can therefore represent an important starting point in investigating the real mitigation potential of specific materials (e.g. limestone and lime mortar) when employed at scale in specific regions of the world.

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Declaration and Conflict of Interest Statement

We, the authors of the abovementioned paper, confirm that there are no known conflicts of interest associated with this publication.

We confirm that the manuscript has been read and approved by all the named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

We also confirm that we have given due consideration to the protection of intellectual property associated with this work and that there is no impediment to publication, including the timing of publication, with respect to intellectual property. In so doing, we confirm that we have followed the regulations of our institutions concerning intellectual property.

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On behalf and for the authors;

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