INTEGRATION OF LIFE CYCLE ASSESSMENT INTO STRUCTURAL INTERVENTION SCENARIOS FOR ASSESSING ENVIRONMENTAL IMPACTS OF VULNERABLE BUILDINGS

by

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A thesis submitted to the University of Birmingham
for the degree of DOCTOR OF PHILOSOPHY

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February 2021

ABSTRACT

Recent developments in the construction industry have led to a growing awareness about sustainable buildings. However, due to negligence in building construction, including inadequate building regulations and incorrect design, structural integrity remains a primary issue of the construction sector. Furthermore, an increasing number of disasters in recent years is another critical factor that has triggered a rise in the number of existing vulnerable buildings. Thus, building durability must become a priority factor required to 'sustain' buildings. However, current studies on structural strengthening mostly focus on only one aspect of building performance without referring to the interrelation between the multiplicities of design, construction, and maintenance deficiencies.

This research aims to examine the improvement of vulnerable buildings; not only in terms of structural performance but also in consideration of a wider set of sustainability challenges. Therefore, this study proposes an integrated and sustainable structural intervention method for vulnerable buildings. The method is based on the concept of "structural intervention", which refers to structural retrofitting and reconstruction of buildings. Using this concept, sustainability metrics are expanded beyond environmental impacts throughout design and service life of buildings to also include a reduction in structure vulnerability and inefficient use of resources. The proposed method is based on scenarios that refer to the scale of damage inflicted on vulnerable buildings. The scenarios' sustainable performance is evaluated by using Life Cycle Analysis, which includes life cycle inventory analysis and life cycle impact assessment. The LCA concept is adapted and reshaped to make it specifically tailored to vulnerable buildings by covering the entire life cycle of scenarios, also referred to herein as, "customised stages". The method was applied to two case studies of vulnerable buildings with low and medium damage, each constructed according to different local and national building codes.

Results of the study suggest that the fulfilment of sustainability criteria in buildings can be significantly improved by implementing the sustainable structural intervention method. Findings indicate that avoiding new build construction by strengthening the structure of existing vulnerable buildings can decrease construction-related environmental burdens and overuse of resources. Further, it was found that although embodied environmental effects have a lesser impact than a building’s operational impacts, reducing them also help conserve natural resources. Additionally, the use of recyclable strengthening materials contributes to both the reduction of resource demand and environmental impacts. The service life also has a considerable impact on results when comparing the total and annual environmental impacts of intervention scenarios. Since the strengthening techniques are unique and the design options are limited, the environmental impacts should be evaluated on a project basis and the proposed method should be followed accordingly. The method can serve as a reference for the sustainable transformation of the vulnerable building stocks, and it can be further improved for regional building regulations.

ÖZET

İnşaat sektöründeki son gelişmeler, sürdürülebilir binalar konusunda artan bir farkındalığa yol açmıştır. Bununla birlikte, yetersiz bina yönetmelikleri ve yanlış tasarımlar dahil olmak üzere bina inşaatındaki ihmaller nedeniyle, yapısal bütünlük inşaat sektörünün birincil sorunu olmaya devam etmektedir. Ayrıca, son yıllarda artan afetler, mevcut dayanımı yetersiz binaların sayısındaki artışı tetikleyen bir başka kritik faktördür. Bu nedenle, yapının dayanıklılığı, binaları "sürdürmek" için gereken öncelikli bir faktör haline gelmelidir. Fakat, yapısal güçlendirme ile ilgili mevcut çalışmalar, tasarım, inşaat ve bakım eksikliklerinin çokluğu arasındaki karşılıklı ilişkiye değinmeksizin çoğunlukla bina performansının yalnızca bir yönüne odaklanmaktadır.

Bu araştırma, dayanımı yetersiz binaların iyileştirilmesini sadece yapısal performans açısından değil, aynı zamanda daha geniş, sürdürülebilirliğe dair bir dizi zorlukları da göz önünde bulundurarak incelemeyi amaçlamaktadır. Bu nedenle, bu çalışma, dayanımı yetersiz binalar için entegre ve sürdürülebilir bir yapısal müdahale yöntemi önermektedir. Yöntem, binaların yapısal güçlendirme ve yeniden inşasına atıfta bulunan "yapısal müdahale" kavramına dayanmaktadır. Bu kavramı kullanarak, sürdürülebilirlik ölçütleri, yapıların dayanıksızlığının azaltılması ve kaynakların verimsiz kullanımını da içerecek şekilde, binaların tasarım ve hizmet ömrü boyunca çevresel etkilerinin ötesine genişletilir. Önerilen yöntem, dayanıksız binalara verilen hasarın derecesine atıfta bulunan senaryolara dayanmaktadır. Senaryoların sürdürülebilir performansı, yaşam döngüsü envanter analizi ve yaşam döngüsü etki değerlendirmesini içeren Yaşam Döngüsü Analizi kullanılarak değerlendirilir. YDA kavramı, senaryoların tüm yaşam döngüsünü kapsayacak şekilde özellikle dayanıksız binalara uygun hale getirilmesi için uyarlanır ve yeniden şekillendirilir, burada ayrıca "özelleştirilmiş

aşamalar" olarak da ifade edilir. Yöntem, her biri farklı yerel ve ulusal bina yönetmeliklerine göre inşa edilmiş, düşük ve orta hasarlı, dayanıksız binaların iki vaka çalışmasına uygulanmıştır.

Çalışmanın sonuçları, binalarda sürdürülebilirlik kriterlerinin karşılanmasının, sürdürülebilir yapısal müdahale yönteminin uygulanmasıyla önemli ölçüde iyileştirilebileceğini göstermektedir. Bulgular, mevcut dayanıksız binaların yapısını güçlendirerek yeni inşaat yapımından kaçınmanın, inşaatla ilgili çevresel yükleri ve kaynakların aşırı kullanımını azaltabileceğini göstermektedir. Ayrıca, gömülü çevresel etkilerin bir binanın işletim etkilerinden daha az etkiye sahip olmasına rağmen, bunların azaltılmasının da doğal kaynakların korunmasına yardımcı olduğu bulunmuştur. Ek olarak, geri dönüştürülebilir güçlendirme malzemelerinin kullanımı hem kaynak talebinin hem de çevresel etkilerin azaltılmasına katkıda bulunmuştur. Müdahale senaryolarının toplam ve yıllık çevresel etkileri karşılaştırıldığında hizmet ömrünün de sonuçlar üzerinde önemli bir etkisi vardır. Güçlendirme tekniklerinin kendine özgü ve tasarım seçeneklerinin de sınırlı olmasından dolayı, çevresel etkiler proje bazında değerlendirilmeli ve önerilen yöntem buna göre takip edilmelidir. Yöntem, dayanıksız bina stoklarının sürdürülebilir dönüşümü için bir referans görevi görebilir ve bölgesel inşaat yönetmelikleri için daha da iyileştirilebilir.

to all survivors

Earthquakes do not kill people; ***vulnerable buildings*** *do.*

ACKNOWLEDGEMENTS

With the scholarship I got six years ago, I have reached nearly the end of a full PhD life by seizing opportunities that I could not even imagine. Now, I hope to contribute to the academy with my works. So, I would like to thank my country Republic of Turkey and the Ministry of National Education, for offering me this opportunity.

I would like to thank both my supervisors Professor Charalampos Baniotopoulos and Dr Pedro Martinez-Vazquez, for guiding and supporting me throughout my PhD challenge and COVID-19 and giving me valuable feedback on all drafts, papers, chapters and what more. I am especially grateful to Dr Pedro for helping me to find case studies when I get stuck and Turkey case study project engineer Durmus Meydanli. I would like to extend my thanks to my annual year examiners, especially for Dr Dexter Hunt and Dr Sakdirat Kaewunruen, for their support and guidance during reviews. I would like to take this opportunity to thank to my examiners, Dr Evangelos Efthymiou and Dr Dexter Hunt for an intellectually stimulating viva and for their very helpful suggestions. Sincere thanks also go to the Liveable Cities team for their valuable feedbacks, help and for broadening my horizon in sustainable cities and resilience. I also wish to thank Giovani Palafox for helping me overcome the language barrier of my case study located in Mexico, and Dennis for inspiring me. I would like to express my deepest thanks and appreciation to Grant from Athena Institute for his supportive and helpful replies to my every single mail patiently. Some parts of this thesis were proofread for the conventions of language, grammar and spelling by Janet's Proofreading Service; thank you Janet.

I know that the challenging path of PhD has succeeded thanks to many others. I would like to thank my office (F59B and N420) and school mates, in particular Yang, Dennis, Ryan, Rafael, Hasan, and Chayut for their help and support every time, but also all those who gave me good company away from home, especially Nour, Anam, Karen, Leonor, Tuba, and Fatima. Also, thanks to all those who provided continuous encouragement from my home country, including Assoc Prof Salih Taner Yildirim, Rumeysa Cakan, Umit Isik and Sema Cil.

Finally, I wish to heartfelt thanks to my parents Halis and Fatma, my sisters Filiz and Figen, my brother Furkan, and my nieces and nephews and other family members for their patience and unconditional support on my endless education and another adventure abroad. Life is a journey, and I wish to receive further patience and support from my loved ones to be able to continue my future adventures.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
AFAD	Earthquake Department Disaster Management and Emergency Presidency
AIEB	Athena Impact Estimator for Buildings
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineering
BBL	Beyond Building Life
BEES	Building for Environmental and Economic Sustainability
BIM	Building Information Modelling
BOM	Bill-of-materials
BS	British Standards
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
CEN	European Committee for Standardisation
CO_2	Carbon dioxide
CSA	Canadian Standards Association
EIO	Economic Input Output
ELSA	European Laboratory of Structural Assessment
EN	European Standards
EnvISA	Environmental Impact Seismic Assessment
EPBD	European Energy Performance in Buildings Directive
EPD	Environment Product Declaration
ESSIM	Environmentally Sustainable Structural Intervention Method
EU	European Union
FEM	Finite Element Method
FEMA	Federal Emergency Management Agency
FFC	Fossil Fuel Consumption
FRP	Fibre-reinforced Plastic
GFRP	Glass Fibre-reinforced Plastic
GHG	Greenhouse gas
GWP	Global Warming Potential
G20	Group of Twenty

HAZUS	Hazards U.S.
HAZUS-MH	Hazards U.S. Multi-Hazard
HVAC	Heating, ventilation, and air conditioning
HH	Human Health
ICE	Inventory of Carbon & Energy
IEA	International Energy Agency
IECC	International Energy Conservation Code
Idemat	Industrial Design & Engineering Materials Database
LCA	Lifecycle assessment
LCI	Lifecycle Inventory Analysis
LCIA	Lifecycle Impact Assessment
LEED	Leadership in Engineering and Environmental Design
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
OECD	Organisation for Economic Co-operation and Development
ODP	Ozone Depletion Potential
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
MATLAB	Matrix Laboratory
MCDM	Multi-Criteria Decision Making
Mw	Moment Magnitude
NA	Not Available
NDCs	Nationally Determined Contributions
NIST	National Institute of Standards and Technology
NRE	Non-Renewable Energy
nZEB	Nearly Zero Energy Buildings
PACT	Performance Assessment Calculation Tool
PBEE	Performance-based Earthquake Engineering
PBD	Performance-based design
PEER	Pacific Earthquake Engineering Research
PV	Photovoltaics
RC	Reinforced concrete
REDI	Resilient Earthquake Design Initiative
SAP2000	Structural Analysis and Design Software
SSD	Sustainable Structural Design

sPBA	Simplified Performance-based Assessment
TBSC	Turkish Building Seismic Code
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
TurComDat	Turkish Construction Materials Database
UK	United Kingdom
US, USA	United States of America

LIST OF PUBLICATIONS

- Keskin, F.S., Martinez-Vazquez, P., & Baniotopoulos, C. (2020). Sustainable structural intervention methodology for vulnerable buildings from a lifecycle perspective. *IOP Conference Series: Earth and Environmental Science*, *410*, 012051. https://doi.org/10.1088/1755-1315/410/1/012051
- Keskin, F. S., Martinez-Vazquez, P., & Baniotopoulos, C. (2020). An overview of sustainability policies and strategies on buildings in Turkey. *International Journal of Sustainable Energy*, 1–24. https://doi.org/10.1080/14786451.2020.1768094

Under review:

- Keskin, F. S., Martinez-Vazquez, P., & Baniotopoulos, C. (2021). An integrated method to evaluate sustainability for vulnerable buildings addressing life cycle embodied impacts and resource use. *Manuscript submitted for publication.*

1. INTRODUCTION

1.1 Background

1.1.1 Vulnerable buildings

Vulnerability is a multi-dimensional concept determined by physical, institutional, human and economic factors and is estimated based on the buildings database (Pavić, Bulajić and Hadzima-Nyarko, 2019). Physical vulnerability is defined for buildings as the degree of loss resulting from a hazard at a certain severity level (Coburn, Sspence and Pomonis, 1994) and depends on reduction in resistance and the level of decay in the structures as a result of constant exposure to such environmental factors (such as seismic actions) (Pîrvănuș, 2020). Such exposure to hazards has increased with the most destructive disasters in the last years that caused significant damages even to the collapse of the buildings.

The frequency of disasters has more than quadrupled between 1970 and 2018. As shown in Figure 1-1, while the number of disasters per continent was 90 on average in the 1970s, this value exceeded 400 after 2000, although the number seems to have declined between 2000 and 2018 (EM-DAT, 2019). The disasters are directly affecting human life and cause fatalities and injuries. But also, disaster effects on buildings are not negligible (Guha-Sapir and Hoyois, 2015), especially seismic effects on buildings are responsible for many physical substantial damages (Wei, Shohet, *et al.*, 2016). For instance, in the 2011 Tohoku Earthquake (9.0 Mw (moment magnitude)), the number of fatalities was about 16,000, while nearly 130,000 houses were collapsed and 240,000 heavily damaged (Kazama and Noda, 2012). In 2010, the Haiti earthquake (7.0 (Mw)) killed 230,000 people and destroyed or damaged 280,000 buildings (Miyamoto and Gilani, 2012). The magnitude 7.6 (Mw) Kashmir earthquake struck Pakistan, with over 72,000 people killed by the collapse of over 270,000 buildings, while 180,000 buildings were partially damaged, and 2.8 million people were left homeless after the earthquake (Rossetto and Peiris, 2009). The data based on EM-DAT (2014) is presented in Figure 1-2, which highlights the number of homeless people caused by disasters between 2000-2017. Homelessness data includes the number of people whose house is heavily damaged or destroyed and so need a shelter, that can give information on damaged and destroyed living spaces of people. The most devastating impact of disasters in the last twenty years was recorded in 2005 and 2006 when the homes of more than 6 million people were either destroyed or heavily damaged. Whereas flooding is the most prevalent type of disaster causing homelessness, earthquakes are the deadliest (Bhattacharya, Nayak and Dutta, 2014). This is not due to ground motions directly, but because of the collapse of vulnerable structures. It was estimated that between 75% and 90% of these casualties are caused by the collapse of buildings between 1970 and 1999 (Papanikolaou and Taucer, 2004). These results are examples of how natural hazards can turn into a disaster by human action.

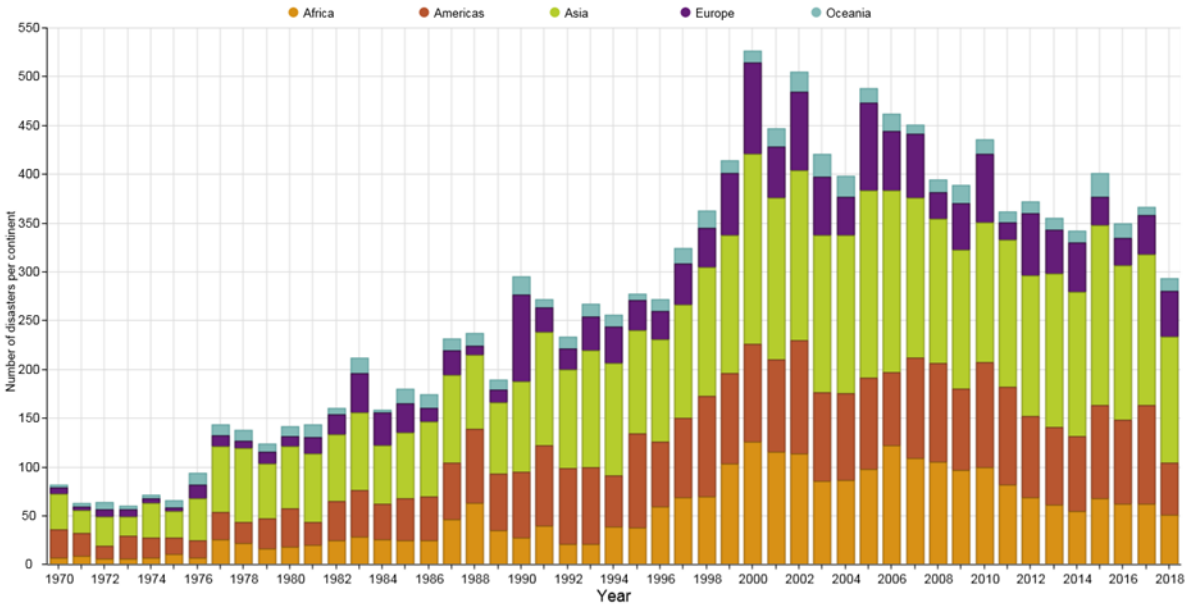


Figure 1-1 Total number of reported disasters 1970-2018 (EM-DAT, 2019)

Vulnerable structures create significant problems and need an urgent solution to act early after disasters. New buildings need to meet adequate safety requirements to avoid these problems. In the last decade, building codes have been renewed in developed countries to prevent the collapse of buildings; however, the necessary progress has not yet been made in developing countries (Bhattacharya, Nayak and Dutta, 2014). Besides pre-disaster preparedness, post-disaster preparedness is also rare in developing countries (Tucker, 2013). Developed countries have also considerably reduced the social, physical and economic losses caused by earthquakes with the enforcement of building codes and incentives of building retrofits (Spence, 2004; Ploeger, Atkinson and Samson, 2010). Bilham (2009) states that an additional 1 billion residences are needed in the next 50 years to house the increasing population. Since these will likely be mostly concentrated in urban areas, a possible earthquake may potentially cause 1 million deaths in just one megacity. This indicates that the current stock of vulnerable buildings will increase exponentially in the future. The safety of these buildings is crucial to reduce the hazard intensity and losses from disasters.

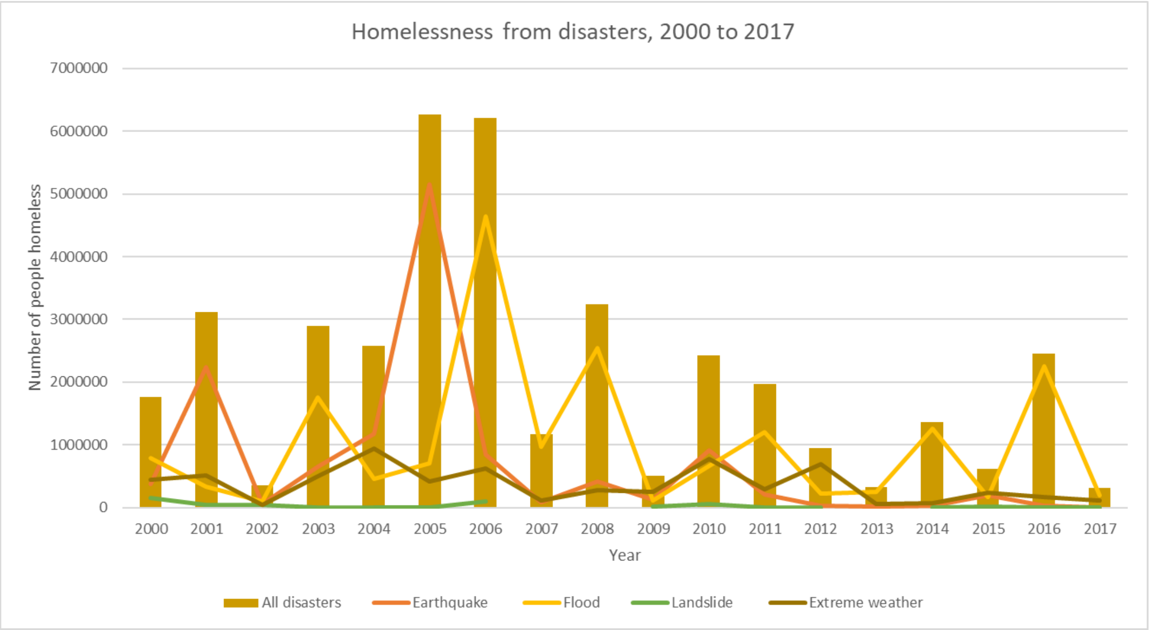


Figure 1-2 Total number of homelessness reported from disasters 2000-2017 (Ritchie, 2014)

To reduce the risk of collapse, there are two main interventions: either increasing the structural strengthening of a building or replacing the entire building. The main aim in the structural intervention of the buildings is to offer resistance to a disruptive event so that the structure can recover to the pre-determined performance objectives rapidly. Such interventions in buildings also help to shift the accepted lifespan of buildings to a new service life. Therefore, in this study, the vulnerable building is identified by considering the deficiencies on buildings that require structural interventions. These deficiencies may occur due to damaging effects of disasters, visible defects, changing the intended purpose of building and the need of upgrading the structure according to renewed building code (Santos *et al.*, 2010).

Overall, the increasing number of disasters and the vulnerable building stock show that preparedness and early actions for all possible disasters will be critical issues for future cities.

1.1.2 Sustainable buildings[1]

Sustainability has many definitions and interpretations. According to White (2013), even about 2,000 different definitions might appear when different experts in this arena need to make a definition to develop a shared vision. The most common and first definition of sustainability is "development which meets the needs of the present without compromising the ability of future generations to meet their own needs", which defined in the World Commission on Environment and Development's report, Our Common Future in 1987 and refers to sustainable development (Brundtland, 1987). Sustainable development was elaborated in the commission within two concepts; "needs" to ensure equitable opportunities for all and "limitations" on the environment's ability to meet needs in the present and future. Therefore, the concept

[1] Some part of this section has been already published in Keskin, Martinez-Vazquez and Baniotopoulos (2020a). Fatma Seyma Keskin wrote the major parts of the paper, while Pedro Martinez-Vazquez and Charalampos Baniotopoulos contributed with reviewing, editing and supervising the paper.

interconnects social, economic and environmental aspects known as the triple bottom line of sustainability (Elkington, 1997). Sustainable Development Goals is a universal call made by United Nations in 2015, covering global goals by 2030. These goals address the three pillars of sustainability; such as ending poverty and improving well-being, reducing inequalities, achieving universal access to clean water and sanitation, improving energy efficiency and access to clean energy, growing economy, developing resilient infrastructure, increasing resource-use efficiency, enhancing sustainable urbanisation, reducing waste generation and increasing recycling, and preventing climate change and marine pollution (UNDP, 2021). Sustainable construction also addresses these three aspects of sustainability and applies them to buildings (Kibert, 2016). Sustainability is mostly perceived in the construction industry as energy, material and water savings, improving environmental quality and innovative designs (U.S. Green Building Council, 2009; Hossain and Gencturk, 2016). Green buildings, on the other hand, are the result of a sustainable construction approach and involve the creation of a sustainable built environment (Kibert, 2016). Kibert (1994) defined green building as "healthy facilities designed and built in a resource-efficient manner, using ecologically-based principles" (p.3). Much effort and importance have put into green buildings in recent years, but now attention has shifted to sustainable buildings (Boyle, 2005). According to Boyle (2005), all impacts of a sustainable building have to be considered throughout its entire life span, from the extraction of its material to construction and from building operation to disposal, as a component in a system. In developed countries, buildings have become a priority for achieving energy efficiency due to their energy consumption levels, longevity, and the number of technological items and services developed under older environmental frameworks. Thus, sustainable construction has become a primary focus to achieve sustainable development goals.

The building sector has become the biggest sector responsible for world energy consumption and carbon dioxide (CO_2) emissions (IEA, 2019b). The latest evidence shows that the total energy generation of construction industries reached 36% of global final energy use in 2018. This consists of energy use during operation and construction. Moreover, the sector is responsible for almost 40% of the world's CO_2 emissions (IEA, 2019b). This is due to the construction sector's inability to keep up with other sectors in enforcing and developing sustainable methods, technologies, and procedures. Considering these worrying factors, to achieve energy efficiency in buildings, a holistic set of tools, design and assessment methodologies there exist for optimising the energy performance of buildings, primarily targeting energy consumption and reductions of polluting emission. Saving in energy use is mostly achieved by building envelope elements, heat sources, building design and energy generation systems. That is because improving energy efficiency is widely accepted as a relatively economical way to reduce total energy consumption through its CO_2 emissions (Azhar Khan *et al.*, 2014). These visions encourage maximising reductions in energy consumption and CO_2 emissions associated with any stage of the construction chain. Although the continuous growth of population combined with an ever-increasing demand of sophistication to managing buildings impose barriers to that movement, it manifests via technological development and policies. The way forward to mitigate the current trends on CO_2 emissions attached to the built environment is, therefore, through the identification and enhancement of performance optimisation methods, standards and further regulations (Azhar Khan *et al.*, 2014).

International communities set conditions for developing policies and procedures, which are implemented and enforced by countries; hence actions are taken regionally as opposed to globally (Al-Tamimi, 2017). Evidently, there is no unique global perspective on how sustainable development can be realised with the best practices. The fact that various sustainability perspectives exist reflects the referred global asymmetries. Examples of the numerous sustainability frameworks include those formulated by countries affiliated to the OECD, UNFCCC, Kyoto Protocol, IEA, and UNEP. A more sustainable and cleaner environment for everyone requires a higher level of participation from all stakeholders. These would include the ISO, IECC, ASHRAE, CEN standards, NDCs under Paris Agreement, and the EPBD, to cite but a few (IEA, 2019a).

In recent years, countries around the world have been attempting to combat the global warming problem. Global warming is the long-term warming of the world climate due to fossil fuel use, which increases greenhouse gas (GHG) levels due to human use, while climate change refers to both human and nature-induced warming and its effects on the world. For instance, melting glaciers, sea-level rise, floods, wildfires, and hurricanes are only some impacts of climate change in the world (NASA, 2020). Therefore, to reduce global warming impacts, the Paris Agreement had set targets of 1.5°C by reducing 7.6% of emissions (32 gigatonnes of CO_2 equivalent) annually between 2020 and 2030, and 2°C by reducing 2.7% of emissions (15 gigatonnes of CO_2 equivalent) annually. However, it has recently been stated that, even if all the unconditional commitments in Paris are fulfilled, these goals hardly seem possible to reach because the temperature is expected to rise by 3.2°C (UN, 2019). On the other side, GHG emissions are one of the sources of air pollution, and buildings are individually responsible for more than half of emissions by the built environment. This air pollution caused by energy use in building kills half a million people each year (C40, 2020). This shows that more destructive climate impacts, increasing disasters and more air pollution await us. This horrific picture is proof that zero-emissions targets should be pursued more broadly, and more concrete targets need to be set. The Emissions Gap report (2019) states that energy-efficient measures and efficient use of resources by building materials offer opportunities for reducing emissions. Therefore, tangible examples and evidence are needed to respond to climate change so that one knows where and how improvements can be made. At this point, lifecycle assessment (LCA) comes out and estimates the impacts on nature, taking into account the lifetime flows between nature and building from cradle-to-grave (O'Connor, 2020).

The LCA facilitates balancing the share of operating and embodied energy and provides certainty regarding the overall environmental impact (Chastas, Theodosiou and Bikas, 2016). ISO standards namely, (ISO 14040, 2006) and (ISO 14044, 2018), establish a framework for the assessment that is aligned with (EN 15978, 2011) and (EN 15804, 2013) and provide guidance for the assessment of buildings. Buildings consist of energy consumption and emissions throughout their lifespan as operational and embodied energy and carbon. According to this, while the operational impacts of buildings should conveniently cover the building's use, embodied impacts cover from manufacturing to the end of life stages of a building (Chastas, Theodosiou and Bikas, 2016). Figure 1-3 illustrates the life cycle stages of a building and its operational and embodied impacts throughout system boundaries, including its representative modules according to EN 15978 (2011) and Annex 57 (2016). Although a significant part of the LCA refers to operational impacts, embodied and operating CO_2 emissions release clearly at each stage of the chain (Chwieduk, 2003).

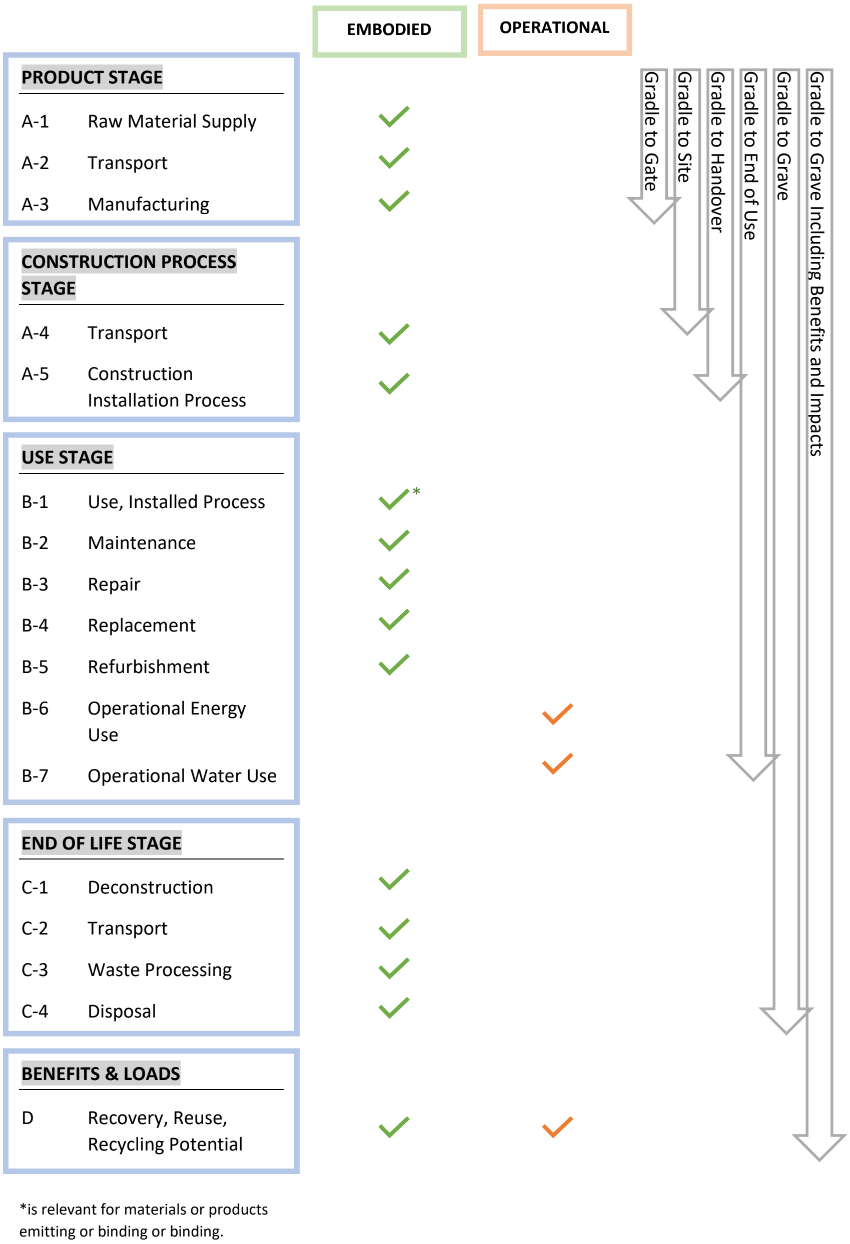


Figure 1-3 Building lifecycle stages and relevant embodied and operational impacts (EN 15978, 2011; Lützkendorf, Balouktsi and Frischknecht, 2016)

Embodied impacts load on the environment in various forms, such as resource depletion and pollution of water, air and soil. For instance, during manufacturing, on-site construction, repair and deconstruction of buildings, a massive amount of CO_2 emissions and energy occurs, which is partially caused by a large amount of energy consumption, especially during the construction phase (Shrivastava and Chini, 2011). This embodied energy can form up to 10-20% of the total energy use of a building (can be both residential and office buildings) from cradle-to-grave (Ramesh, Prakash and Shukla, 2010). In addition to that, the manufacturing of building materials is responsible for 20% of the world's fuel consumption (Dixit *et al.*, 2010) and nearly 18% of carbon emissions for any construction project (Ibn-Mohammed *et al.*, 2013). The embodied carbon can directly impact human health as toxic emissions also occur during the manufacturing phase, while operating of building causes the highest energy consumption and accompanying GHG emissions (Rajagopalan, Bilec and Landis, 2012). Therefore, currently, most techniques aim at cutting down the operational energy to nearly zero while excluding embodied energy due to the higher impacts of operating energy and related carbon in a building's life cycle. These techniques are mostly directed towards energy upgrading of buildings, even though some of these upgrading techniques can increase the embodied impacts of the building, which is the case when, for instance, applying thermal insulation. Therefore, a balance is required between these two (Ji *et al.*, 2020). Besides that, in the case of reducing the operational energy, the total impact of the building will have shifted to the materials related embodied impacts (Rossi, Marique and Reiter, 2012).

On the other hand, building construction causes a considerable amount of depletion in natural resources during manufacturing and also a significant amount of debris from demolition. Approximately 89 billion tonnes (Gt) of natural resources were consumed in 2017 globally. The construction sector shared 44 Gt of this consumption for only non-metallic materials. This amount is estimated to increase to 86 Gt in 2060 (OECD, 2018).

1.2 The relevance of the research

Although Chapter 2 will more clearly describe the research gaps that this study aimed to fill, this section outlines some of the aspects demonstrating the relevance of the research.

The importance of the increasing number of disasters, their impact on buildings and producing sustainable buildings have been emphasised in the background section. Vulnerable buildings contain multiple deficiencies, and that better insight is required into the resilience of these buildings in response to a disaster. In this research, these deficiencies are investigated from an environmental sustainability perspective to understand the life cycle impacts of vulnerable buildings. This is based on relevant scenarios according to different damage scales and local codes on structures. Instead of focusing only on the resilience or sustainability of structures, an integrated method is developed on vulnerable buildings as there is an urgent need for a practical approach.

The main advantage of this approach is that it gives a simplified and improved framework for alternative scenarios on the vulnerable buildings, including Pre-LCA and LCA stages. Vulnerable buildings do not have a straightforward LCA process as other buildings; it includes complex LCA stages, and that complexity reduced by customised LCA stages and intervention scenarios based on the vulnerability of structures. Such complex assessments need long-term solutions that are more important than inefficient solutions; therefore, these assessments are done throughout the building life span. Pre-LCA highlights the design process of the intervention scenarios, which leads to the pursuit of sustainable construction. In LCA stages, the proposed method adapted and reshaped the standard LCA stages for vulnerable buildings from cradle-to-grave according to their extended service lives with linking life cycle impact assessment (LCIA) as well as the life cycle inventory analysis (LCI), that factors are often ignored in existing studies. The method proposed in this research can be used in multiple contexts, as it is not developed according to the local codes of one specific region. This study applies it to two distinct regions: Mexico and Turkey. This is the first study that investigates, in an integrated way, the sustainability of vulnerable buildings in these two regions. It is expected that the method presented herein can serve as a model for other countries or regions with a vulnerable building stock.

This study mostly focuses on possible scenarios for vulnerable buildings and life cycle impacts, including embodied impacts and resource use, and evaluates these results according to LCA stages and building service life, which can provide more in-depth insight and a compact framework for the sustainability of vulnerable buildings. This research explores the potential and advantage of the existing vulnerable building stock, which is mostly considered as a burden environmentally and structurally in the built environment.

1.3 Aim and objectives

The main aim of this research is:

- To develop a more efficient sustainability assessment method that incorporates structural interventions for vulnerable buildings within the LCA framework and addresses structural safety, environmental impacts, and resource use throughout the building life cycle.

In order to fulfil the presented aim, the following objectives are set in this research, in chronological order:

- State the importance of a sustainable structural intervention method (Chapter 1 and 2).
- Propose an integrated method for life cycle environmental impacts of structural interventions, considering different damage scales, local conditions, and service periods (Chapter 3).
- Apply the proposed method for a low-damaged building to the entire life cycle of selected structural retrofits (Chapter 4).

- Apply the proposed method for a medium-damaged building to the whole life cycle for both the retrofitted and a new building when considering service life (Chapter 5).
- Investigate the effects of the proposed method on building sustainability performance (Chapter 4-5-6).

1.4 Thesis layout

The thesis is composed of six chapters. The next chapters are structured as follows. Chapter 2 explores trends on retrofit approaches to vulnerable buildings, some general concepts about policy actions of countries, and then critically reviews the relevant literature to evaluate the key aspects for environmental sustainability of vulnerable buildings. After that, research gaps are defined according to the literature. The proposed method is provided in Chapter 3. Structural intervention in vulnerable buildings and its incorporation into LCA methodology is described. The proposed integrated method is applied to a low-damaged building in Chapter 4. This chapter provides LCI and LCIA of the case building with a critical discussion.

Similarly, Chapter 5 presents analysis and discussions on a medium damaged building. Finally, Chapter 6 reflects on the research objectives as set in Section 1.3, and the key findings of the research are presented. Then the chapter finishes with future research and recommendations for the transformation of vulnerable buildings. A flow chart of the overall structure of the thesis is presented in Figure 1-4.

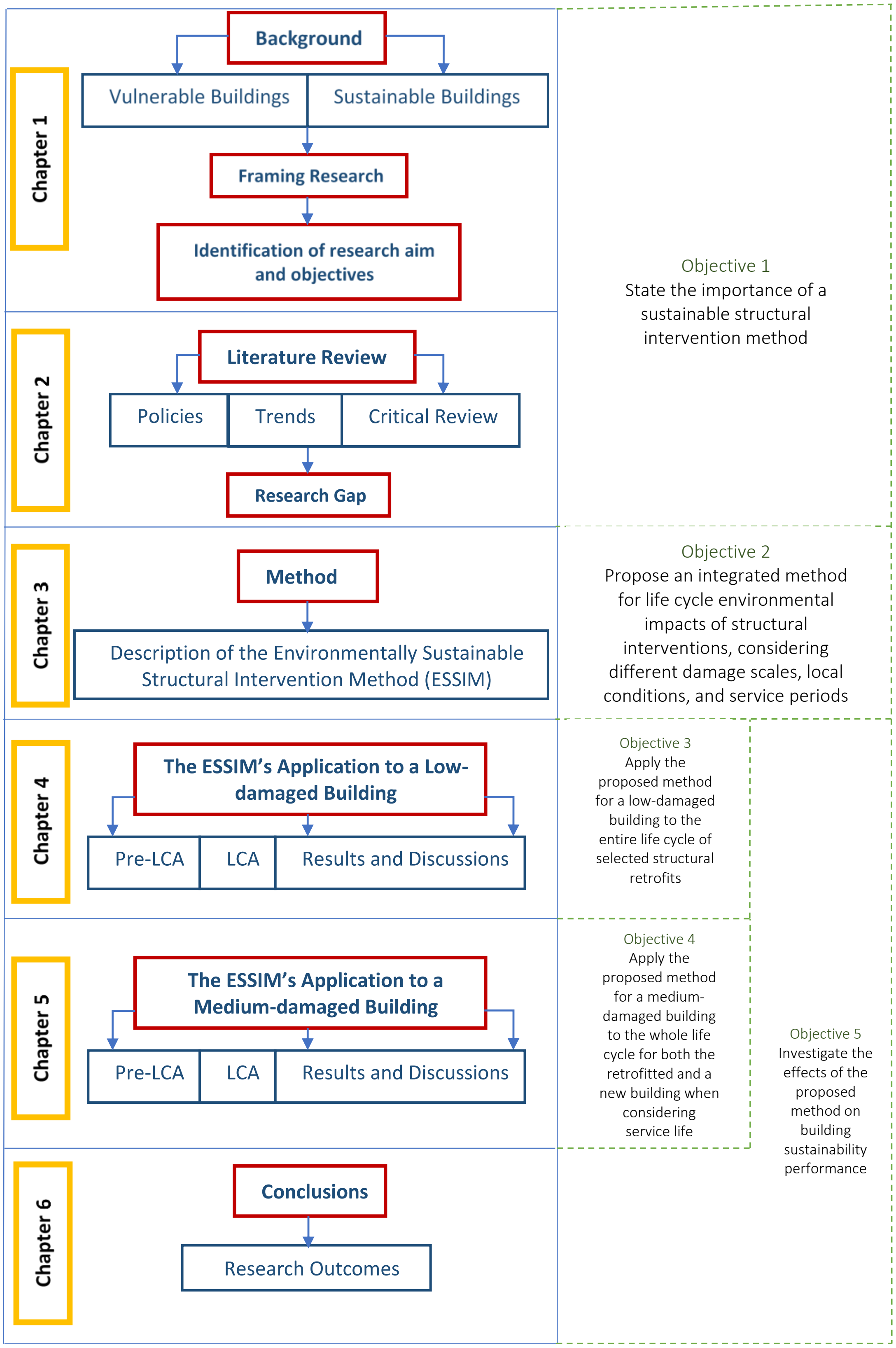


Figure 1-4 Flow chart showing the organisation of thesis and research objectives addressed in each of the chapters

2. LITERATURE REVIEW

2.1 Foreword

This chapter reviews the key literature on sustainability approaches to vulnerable buildings and aims to understand what sort of sustainability aspects are in trend and why. The mean of sustainable buildings concepts was investigated for countries by looking at policies and strategies. Which factors need to be considered in assessing the environmental impacts of vulnerable buildings has been explored through current methodologies. Finally, a critical literature review was conducted focusing on the evaluation of environmental sustainability for vulnerable buildings from a life cycle perspective. In this study, since country policies and academic studies have different data sources and databases, reviewing these two concepts is divided into sections 2.2 and 2.3. This review led to the development of the concepts that form the basis of the method presented in Chapter 3.

2.2 General outlook to policy and strategy actions on sustainable buildings at a global level [2]

This section scrutinises globally established policy and strategic actions. It includes an overlook on current measures on sustainability and focuses on the evaluation of state policies and goals set to achieve sustainability goals generated through international agreements.

Countries are in a renewal process and continuous improvement regarding sustainability policies. The design and construction of building is regulated under the building regulations to ensure the safety of people within the built environment. Environmental sustainability concept on buildings in policies mostly covers energy code (includes energy efficiency, thermal

[2] Major part of this section has been already published in Keskin, Martinez-Vazquez and Baniotopoulos (2020a). Fatma Seyma Keskin wrote the major parts of the paper, while Pedro Martinez-Vazquez and Charalampos Baniotopoulos contributed with reviewing, editing, and supervising the paper.

building regulations, or energy standards of buildings (Nejat *et al.*, 2015)) policies and that generally focus on the building envelope to reduce energy consumptions from buildings since the energy-saving potential from improved building envelope performance is huge (IEA, 2017). Building regulations and certifications on the environmental sustainability of buildings mostly includes energy consumption and relevant emissions. To date, many regulations came into force for energy saving in buildings; however, building energy codes still do not exist in about 2/3 of the countries worldwide (IEA, 2018), and the level of stringency of the energy codes in law enforcement varies as "mandatory" or "voluntary" from country to country (Iwaro and Mwasha, 2010). According to Berardi (2015), developing countries' energy policies have only been established recently, while developed countries have relatively more advanced policies in comparison. It is noted that during the period 2000–2017 and beyond, there has been a steady increase in the number of practices adopted that promote energy efficiency around the world (IEA, 2019a). However, many countries fall behind in implementing energy policies which directly affects the growing building stock in those regions.

Energy certification for buildings includes a set of mandatory policies and voluntary programs created by both governments and organisations. As of 2017, more than 80 countries have buildings energy certificates; 36 of these have mandatory certification policies, and another 20 countries have widespread voluntary building energy certification programs or policies (IEA, 2017). Energy efficiency has been carried out in three key steps, including assessment, rating, and certifying (Aktas and Ozorhon, 2015) and numerous building certification systems are available today, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) certifications; these are voluntary building sustainability rating systems. These building assessment systems performed a successful effort (Kibert, 2016). For instance, 2.2 million buildings have been registered for BREEAM certification, and over 500,000 have been successfully awarded (BREEAM, 2019). Regarding LEED, a total of 80,000 buildings had been certified (Tufts, 2016). Throughout the world, building certification targets and procedures are updated regularly, and which is based on city or region wide performance standards or regulations such as Low-Energy (30-60 kWh/m^2), Passive Energy (15-20 kWh/m^2) and Plus Energy Buildings (able to produce more energy than its needs and sell it) (Spiegelhalter, Architect and Planner, 2010). In the EU, those procedures are driven by energy performance and optimisation as covered by 2010/ 31/EU EPBD (EPBD, 2010). The energy performance of a building is calculated according to the energy needed to meet the energy demand associated with typical use of the building, which includes energy used for hot water, cooling, heating, lighting and ventilation, among others (EPBD, 2010). Such policies manifest themselves in different forms in member states. However, as a common goal in the EU, long-term energy renovation for existing buildings encourages achieving nearly Zero Energy Buildings (nZEB) stock by 2050 as recently revised in EPBD (EPBD, 2018). In 2010/ 31/EU EPBD (2010), nZEB is defined as highly energy efficient and decarbonized buildings, through deep renovations and/ or renewable sources and passive systems. The renovation decision is mostly related to thermal performance applied to envelopes, windows, and roofs, which are recommended as passive improvements by the EU (Rodrigues *et al.*, 2018). Till present, such energy renovations of existing buildings to save energy through energy retrofitting have provided considerable benefits to the world, resulting in 50-90% (in-use) energy-saving after refurbishment. With advances in technique, design and technology, these reductions in energy requirements in existing and new buildings have been largely achieved low cost and sometimes even with net negative costs (Lucon and Ürge-Vorsatz, 2014).

The Asian continent is also proactive in enforcing developments of sustainable buildings. For example, South Korea uses the Green Building Certification system for the rating of building energy efficiency (Koo *et al.*, 2014; Nejat *et al.*, 2015). Japan also uses a green building rating system, namely CASBEE (Laustsen, 2008) and Top Runner, for achieving high-energy performance (Kimura, 2010). In North America, energy efficiency is promoted through the IECC 2004, guidance provided by the ASHRAE, and the Canadian National Building. Their building energy performance plan, ENERGY STAR, strengthens capacity by enabling energy savings on the order of 20% (Nejat *et al.*, 2015).

Recently, a decrease in energy investments in buildings fell from 11% in 2016 to 4.7% in 2017 globally (IEA, 2018). Additionally, most of the aforementioned energy code policies focus on the building envelope (IEA, 2017) rather than focusing on other building deficiencies.

In line with the above, specific emission and energy targets on buildings are required in buildings to produce more strict and effective sustainability policies. Local targets address local requirements that are naturally different from international practices (Deringer, Iyer and Yu Joe Huang, 2004). Similarly, such great effort relies on decreasing energy consumption from buildings with envelope insulation, relevantly space heating and cooling. However, renewable energy is seen as indispensable in energy-saving targets (EPBD, 2018) rather than building envelope. Technological clean energy solutions with low-carbon power generation can decrease the world's CO_2 emissions by about 90% by 2050. For instance, solar power technology could supply carbon-free heat to approximately 3 billion people worldwide by 2050 (IEA, 2019c).

The energy performance and structural renovation of existing buildings are also under the support of many international organisations and governments (Napolano *et al.*, 2015). For example, in addition to the energy retrofitting of buildings in the EU, structural retrofitting in earthquake-prone areas is also evaluated by integrating it alongside other sustainability metrics (Lucon and Ürge-Vorsatz, 2014). Japan also integrated its energy code with structural performance codes in its building certification (IEA, 2018). (The next section presents these enhanced integrated sustainable approaches). Examples of the impact of having implemented ambitious goals include EU nZEB and decarbonisation, which enabled decreasing energy consumption at beyond 2% per year across some EU members (Romanian, Polish, and Estonian households) (Berardi, 2015). The challenges in reaching global targets, however, remain. According to IEA, the global average building-related energy use per person needs to shift from 5 MWh (megawatt-hour) to 4.5 MWh to meet global temperature raising below the 2°C target by 2025, which is equivalent to a 30% reduction in global average building energy intensity (in terms of energy use per square metre) by 2030. This reduction means that the energy performance improvements of existing buildings will need to be nearly doubled to more than 2% each year by 2030 (IEA, 2017).

The inadequacies and challenges of reducing energy and emissions from buildings prompted research to investigate "what is real zero" as up until now, net-zero buildings have only reached zero for operational carbon. In this context, an initiative called Architecture 2030 aims to achieve a stable decline of carbon neutrality by using no fossil fuel GHG emitting energy to operate (Architecture 2030, 2014). Another zero carbon target is from C40 cities; they aim to develop net-zero carbon new buildings by 2030 and all buildings by 2050 (C40, 2020). The Net Zero Carbon Buildings Commitment also aims to reduce operational carbon from buildings and aims to include embodied carbon in future (WGBC, 2020). At the moment, it is difficult to highlight that concrete progress has been made since only five members of the G20 countries, which make up 78% of all emissions in the world, have committed to the long-term zero-emission target (UNEP, 2020).

Nevertheless, how realistic these goals are a matter of debate. The need for integrated designs and the inclusion of several factors such as new technologies are emphasised to achieve such massive savings. Besides that, buildings' operational impact is still the largest part of the lifetime carbon pie and needs to be balanced against embodied impacts (O'Connor, 2020). Therefore, the more success is achieved in the operational energy, the more breakthroughs in reducing the embodied energy are needed for this balance to occur (Feese, Li and Bulleit, 2015). On the other hand, Comber and Poland (2013) are optimistic about the possibility of the net-zero operational energy buildings and attribute this to the encouragement of the AEC industry. In addition, it is believed that better construction practices have the potential to reduce energy demand worldwide by nearly 30% by 2050 (IEA, 2019c) and can help reduce embodied impacts and high demand in construction materials.

Overall, countries are merging policy and legislation into concise strategies in order to progress their financial targets and focus on sustainable buildings. However, the building sector's energy-saving and emission reduction approach, both from the building operation and the construction and demolition stages, is critical and still lacks adequate research approaches.

2.3 Reviewing the relevant literature on the environmental sustainability of vulnerable buildings

LCA's applications to assess the environmental impact of interventions, including repair, strengthening, and replacement in vulnerable buildings, is reviewed in the literature broadly. In this section, the most common databases were searched to complete the literature. Firstly, the keywords were selected as "retrofitting", "disaster", "earthquake", "buildings", and "sustainability" for Google Scholar and Research Gate. However, it was challenging to find relevant research since retrofit studies mostly cover energy retrofitting, and disaster-related research includes social issues. Nevertheless, energy retrofitting (as trend approach of sustainability studies because of the nZEB targets for existing buildings) and building safety-related studies are presented in section 2.3.1. Although these studies mainly focus on energy retrofitting and its operational energy, it also contributes to the safety of buildings. The remainder of the studies (21 documents) include structural retrofitting/repair and their life cycle environmental impact presented in section 2.3.2.

In order not to overlook any study, another literature review was done in Scopus, and the keywords[3] changed to: "sustainab*", "building*", "environment*", "structural retrofit*" or "seismic" or "disaster". The results (384 documents) were limited to the relevant subject area, conferences, articles and review papers in the English language. Titles and abstracts of these documents were screened to include in the relevant literature. The same documents with first selection were eliminated, and ten records were left apart from the first database. Finally, 31 studies were selected for review.

2.3.1 Trends on sustainability approaches for vulnerable buildings[4]

In recent years, there has been an upward trend in retrofitting approaches aimed primarily at energy recovery to reduce emissions and energy consumption caused by the heating and cooling of buildings. To achieve this, the focus was on the existing building stock, which could not provide sufficient energy saving. For instance, 60% of the EU's residential buildings were built before the first thermal regulation and will be 50 years old by 2021 (Eurostat, 2001; Lamperti Tornaghi, Loli and Negro, 2018). This situation directly affects the energy consumption of existing EU buildings' stock and relevant CO_2 emissions by about 40% and 36%, respectively (Economidou *et al.*, 2011; Lamperti Tornaghi, Loli and Negro, 2018). It also affects the

[3] (*) can represent any character(s)

[4] Some part of this section has been already published in Keskin, Martinez-Vazquez and Baniotopoulos (2020b). Fatma Seyma Keskin wrote the major parts of the paper, while Pedro Martinez-Vazquez and Charalampos Baniotopoulos contributed with reviewing, editing and supervising the paper.

depletion of raw materials representing 50% of total depletion, and waste generation at 35% of EU total numbers (Marini *et al.*, 2014).

However, most crucially, this expansive building stock exhibits structural problems and deterioration in materials and can be vulnerable to seismic motions (Marini *et al.*, 2017). Furthermore, unplanned urbanisation in hazard-prone regions and increasing frequency and intensity of hazards due to climate change are other factors that increase the destruction of the built environment (Li, Ahuja and Padgett, 2012). It should be noted that it is unachievable to reach the sustainability target if the building cannot show sufficient resistance against natural hazards (Gencturk, Hossain and Lahourpour, 2016). In this context, some studies suggested that green building practices might compromise building safety design (Padgett and Li, 2016). Other studies found that the effects of disaster damage were unsustainable, given the high rebuilding costs and dangers to human life. Figure 2-1 outlines some examples of energy investments that failed once the safety of these buildings was overlooked during the implementation of such mechanisms (Caruso, Lamperti Tornaghi and Negro, 2017). As seen in the figure, energy investments for buildings can be wasted by hazard risks due to the structural vulnerability in hazard-prone areas (Lamperti Tornaghi, Loli and Negro, 2018). This evidences that human safety should be overseen during energy or other retrofit types (Marini *et al.*, 2017; Georgescu *et al.*, 2018).

a) Roof collapse with solar panels of a library building in Italy for gravity loads, in 2015

b) Roof collapse with solar panels of a building in Italy after Emilia earthquake in 2012

c) Building collapse with thermal insulation in Turkey after Izmir Earthquake in 2020

d) The collapse of an industrial warehouse renovated with photovoltaic panels in Italy after the Emilia earthquake in 2012

Figure 2-1 Failed energy investments made on vulnerable buildings (a and b: (Caruso, Lamperti Tornaghi and Negro, 2017), c: (Guardian, 2020), d: (Marini et al., 2015))

This situation highlights that the renovation of existing buildings in Europe is done according to the solutions for the “episodic” and “contingent” problems exhibited by the buildings (Marini *et al.*, 2015). These methods have produced limited solutions, neglecting the complexity of building deficiencies and their interrelationship (Feroldi *et al.*, 2013). Marini et al. (2014) stated that the only way to reduce energy consumption from buildings and secure the existing vulnerable building stock is through the renovation of building stock. To address this, two solutions were considered: new building construction or the refurbishment of the existing building stock. However, it was emphasised that the existing buildings should be protected and renewed with high technology since the construction of new buildings will significantly affect the environment. Resultantly, systems that integrate energy efficiency and structural safety have been proposed for this renovation solution. The National and European Standards and Directives also encourage seismic and energy regeneration actions. For this reason, future studies are aimed at developing approaches that combine seismic and energy regeneration techniques. At the same time, it is aimed to transform these buildings, which show poor performance in terms of energy and structure, into nZEB seismic-resistant buildings, which refer to energy-efficient and seismically upgraded (Georgescu *et al.*, 2018). Seismic upgrading is applied if the seismic response of the structure does not meet the standard required by the regulation; Georgescu et al. (2018) investigate Italian and Romanian codes in this review.

2.3.1.1 Energy and Seismic Retrofit Studies

There are different approaches to this subject because existing buildings are more challenging to energy upgrading than new buildings and a uniform standard approach is inconvenient. Therefore, Belleri and Marini (2016) investigated the PBEE-Green framework over scenarios, including impacts of solely energy retrofit versus energy with seismic retrofit for vulnerable buildings. Annual embodied carbons of seismic retrofitting constituted 10% compared to operational carbon after energy retrofitting. In comparison, in the case of not implementing seismic retrofit, annual embodied carbon increased to 87% because of the probability of future earthquakes. The results showed that solely energy retrofit applications do not guarantee a reduction in environmental impacts because of the repairs caused by seismic damages.

Numerous research embedded safety aspects with sustainability practices into energy retrofitting methods, and they mostly used exoskeletons that allow more control on thermal and operational energy optimisation. For instance, Feroldi et al. (2013) used double-skin façades to provide thermal comfort and reduce primary energy and included seismic hazard and vulnerability data for urban scale analysis. Similarly, Mora et al. (2015) investigated panels inside and outside of external walls to improve thermal performance and structural tightening.

Marini et al. (2017) investigated self-supported independent exoskeleton (glazed façades with solar greenhouses, thermal insulation layers, windows and shading systems) as camouflage upgraded energy efficiency and structural performance, and these are reduced GHG emissions. Later, an expanded life cycle thinking approach discussed such renovations (Marini, Passoni and Belleri, 2018). Effects of retrofits (including envelope, windows, walls, shadings, PV panels, so on) on the RC buildings' energy efficiency are also discussed by Georgescu et al. (2018) for two seismic areas in Italy. Basiricò and Enea (2018) also investigated the building envelope's energy performance and vulnerability according to Italian codes.

Building function is also a factor that should be considered during the implementation of seismic energy retrofits. De Vita et al. (2018) investigated historical buildings and their thermal properties for the strengthening of masonry walls such as grout injections, reinforced plaster, and artificial cement on the outer walls. However, this study demonstrated that such interventions might affect the thermal performance of a historical building negatively. Mora et al. (2018) also investigated structural and non-structural retrofit by adopting primary energy consumption of combined systems for energy and seismic retrofit. The combined interventions (120 scenarios) were selected as a thermal envelope, energy generators, and electrical systems (PV systems and light bulbs) to estimate energy use. Regarding seismic retrofit, they chose the most cost-effective and energy-saving intervention and so anchorage with ties rods and fibre-reinforced plastic (FRP) reinforcement is chosen as the best solution due to cost-benefit (7% increase) and unchanged primary energy consumption during a 30-years life span. Impacts of seismic retrofit on energy use is negligible during the use of the building; however, a combination of energy and seismic retrofit is still economically profitable because of the saving in energy consumption and its cost. These studies include seismic retrofits but do not include their embodied environmental impacts.

In a study by Lamperti et al. (2018), the effects of embodied carbon were also investigated on building construction regarding precast and cast-in-situ building systems, including seismic resilience and energy improvement. Energy improvement was provided by implementing wall systems with similar thermal transmittance and HVAC systems (electricity and heating). Its operational carbon was added to embodied carbon from construction and demolition emissions of building systems with energy-efficient wall systems. The results showed that the cast-in-situ building has 20% more CO_2 emissions because its construction (differences between materials and quantities in the structural skeletons) caused more emissions than precast. Then, damage costs are calculated for four seismic limit states to add over energy cost and CO_2 cost of these different building types. This study only focuses on construction with different structural systems and their lifetime financial loss, excluding environmental impacts of damage repair.

Energy retrofitting projects also aimed to reduce the operational energy to nearly zero with retrofitting with innovative interventions and prefabricated panels. ProGETonE is a European project that proposes prefabricated retrofit solutions to save energy , reduce cost, and improve seismic safety by applying new external envelopes to resist the horizontal seismic loads (Ferrante *et al.*, 2018). These envelopes can be used to design room extensions, balconies, or sun-spaces (PROGETONE, 2020). The TES-Façade project considers fire safety for existing buildings and applies timber-based element systems to façades (Loebus, Ott and Winter, 2014). Additionally, the More-Connect project was developed in Europe to adapt 250 million homes to a zero-energy performance target by 2020 and is aimed to retrofit 20% of all houses to zero-energy. To achieve this, innovative approaches have been developed, such as prefabricated modular multifunctional renovation elements for the building façade and roof, and new building services to lower energy expenses and reduce on-site construction works (MORE-CONNECT, 2020). Further, the IMPRESS project also developed pre-fabricated panels considering corrosion, solar reflectance properties, ageing, energy-saving, and aesthetics (IMPRESS, 2020). Similar projects are also available for existing school buildings such as the ENTRANZE, RENEW SCHOOL, ZEMeds, School of the Future and VERYSchool projects (Mora *et al.*, 2018).

Energy retrofitting projects progressively help current environmental performance assessment methods come into effect when comparing building solutions, noting that structural performance was not initially embedded in those assessment methods (Loli, Lamperti Tornaghi and Negro, 2017). These energy retrofitting studies do not include life cycle embodied carbon and/or energy caused by structural deficiencies.

Overall, most techniques aim at reducing the operational energy to nearly zero while excluding embodies. This highlights the lack of well-defined systematic approaches and methods for incorporating procedures to deal with disaster damage to sustainability metrics (Wei, Shohet, *et al.*, 2016).

2.3.2 Critical reviews of the relevant literature on structural interventions to vulnerable buildings and their life cycle environmental impacts

The primary consideration in building design is the buildings' safety; therefore, engineering methods for building performance tend to focus less upon other factors such as environmental impacts (Welsh-Huggins and Liel, 2017). In recent years, disasters such as the Tohoku Earthquake and Hurricane Sandy have shown the importance of integrating building resilience into a sustainable design concept (Hossain and Gencturk, 2016). For instance, 1.12 million buildings collapsed or were damaged after the 2011 Great East Japan Earthquake and rehabilitation of this building stock is estimated to cause 26.3 million tons CO_2 emissions that correspond to 2.1% of GHG emissions of Japan in 2010 (Pan *et al.*, 2014; Wei, Skibniewski, *et* *al.*, 2016). The concept of resilience "defines the capacity to adapt to changes and threats (Pelling and High, 2005), being able to recover from their impacts (Timmerman, 1981), and to transform into more desirable states (Milman and Short, 2008)" (Ismail, Halog and Smith, 2017). The resilience of buildings refers to structures designed to withstand natural and man-made disasters, according to Structural Engineering Community. However, recently, the already-established discussion of disaster resilience has had the opportunity to expand to include environmental aspects and apply existing strategies in modern methods to meet growing challenges (Comber and Poland, 2013). Therefore, it has been possible to incorporate resilience into sustainability assessment frameworks, as these two concepts mostly work in parallel and focus on survivability (Roostaie, Nawari and Kibert, 2019; Almulhim, Hunt and Rogers, 2020).

Many studies have previously investigated the social impacts of post-disaster buildings, such as mortality, shelter needs, or post-disaster economic impacts (Wei, Shohet, *et al.*, 2016). Nevertheless, the lack of preparedness for disasters has economic consequences for the governments; for instance, in the 2011 Great East Japan Earthquake, 1.12 million buildings were damaged and recovering them cost $122 billion (Norio *et al.*, 2011), while in Italy, rebuilding cost €3600 million between 1968 and 2016 (Marini *et al.*, 2017). The lack of preparedness, need for urgent action after a disaster, and resource limitations may cause low priority on the whole bottom line of sustainability (Ismail, Halog and Smith, 2017). Therefore, the reason why environmental impacts are ignored could be due to the lack of well-defined criteria and measurement methods (Wei, Shohet, *et al.*, 2016). Ismail et al. (2017) stated that the mere repair or rebuilding of vulnerable buildings is insufficient to provide a disaster-resistant built environment. Because waste generation, air and water pollution during the recovery process can lead to unsustainable practices, harmful effects on the socio-ecological systems, and a failed post-disaster construction project. This indicates that disaster risks should be included in building sustainability, and integrated systems can increase hazard resistance of buildings and achieve sustainable improvement (Hossain and Gencturk, 2016; Wei, Skibniewski, *et al.*, 2016).

Structures are designed and built to provide enough strength to survive the most severe earthquakes accepted in the local building regulations that specific to a particular region or country and seismic events. Compliance with these regulations is foreseen to minimise the direct and indirect effects of hazard (Gencturk, Hossain and Lahourpour, 2016). In this respect, Lamperti, Loli and Negro (2018) considered building safety as a pillar of social sustainability. On the other hand, traditional LCA frameworks have been partially insufficient to assess buildings' environmental performance accurately in the face of environmental loss due to destructive disasters (Wei, Skibniewski, *et al.*, 2016). A practical, resilient, and sustainable practice needs a comprehensive, systematic, and precise sustainability assessment framework, and for this, sustainability should be represented by quantifiable units.

According to Boyle (2005) "the complexity of sustainability is recognised but not yet fully understood". In addition to that the quantification of buildings is complicated compared to other products. For that, it includes parameters such as complex production and construction processes, multiple materials, varying functions, long service period in contrast with design period of components, continuous interaction of users with the environment, inadequate data, and non-standardised processes (Hossain and Gencturk, 2016). Such LCA frameworks that consider the quantified sustainability assessment can more accurately evaluate sustainability over the life cycle of buildings subject to damage. Table 2-1 lists the studies concerning the structural intervention of the building considering life cycle environmental assessment. It focuses on studies that include environmental impact analysis over the building's life cycle. Social and cost assessments were not included in the table as both of these sustainability aspects are outside the scope of this research project. The table provides information on the selected building and hazards type, structural performance methods, and environmental impact categories and assessments. The critical results regarding structural retrofit and environmental impacts are also included in the table.

Table 2-1 Overview of studies concerning structural intervention in vulnerable buildings and their life cycle environmental impacts

Study	Building Type	Structural Intervention – Analysis	Environmental Impact Categories - Method – System Boundary	Software Tool - Database	Result
Dattilo et al. (2010) Campedei, Italy	RC* Building (3-storey)	GFRP* wrapping and RC jacketing – Seismic analysis	CO_2* emissions – IPCC* – Manufacturing, construction, end of life (disposal and recycling) stages	SimaPro* 7.1.8 – Idemat* 2001, Ecoinvent*, BUWAL* 250	GFRP wrapping has higher CO_2 emissions than RC.
Menna et al. (2013) NA*	RC Building (5-storey/100-year service)	Structural elements and non-structural components: Rehabilitation and replacement – Seismic risk/based time-dependent expected loss	Climate change, ecosystem quality, human health, resource depletion, operational impacts – IMPACT* 2002+ – Whole lifecycle	NA – DEQ 2010 database	Overall, a 25% reduction was received from rehabilitation.
Chiu et al. (2013) Taipei, Taiwan	RC Building (low-rise/15-20-30-year service)	Seismic retrofit – Seismic performance and damage and earthquake occurrence	CO_2 emissions - Construction of retrofits, the whole lifecycle of the building	NA	Repair activities constituted about 11% of carbon emissions from new building construction.
Comber and Poland (2013) California, USA	NA (Two-storey)	Upgrading seismic code requirements: Base isolation, steel frame and buckling/restrained braced frame - Loss Estimation (HAZUS*) and performance-based seismic design	GWP* emissions – EnvISA* and hybrid EIO* model – Manufacturing and construction Stage	NA	Overall, a 9-11% reduction was received from rehabilitation.

Study	**Building Type**	**Structural Intervention – Analysis**	**Environmental Impact Categories - Method – System Boundary**	**Software Tool - Database**	**Result**
Sarkisian (2014) California, USA Shanghai and Shenzhen, China	High rise steel structure (13-storey/25-year service) RC office tower (27-storey/50-year service) Mid-rise RC building Steel Tower (71-storey)	Seismically isolated braced frame, plastic materials, Pin-Fuse Frame – Damage Estimation (HAZUS)	Carbon emissions – NA	Environmental Analysis Tool – NA	Overall, a 10-30% reduction was received from rehabilitation.
Welsh-Huggins and Liel (2014) California, USA	Commercial building (4-storey/60-year service)	Repair and green roof design – Probabilistic seismic loss estimation (PACT*), dynamic analysis, structural seismic analysis (OpenSEES*)	Climate change potential and fossil fuel consumption – NA – Production, construction, operations and maintenance (repair and reconstruction) and end-of-life stages.	AIEB*	While the low level of damage was achieved by implementing green roof design which caused higher environmental impacts because of the higher amount of concrete use.
Terracciano et al. (2015) Italy	Masonry Buildings (1-3 storey)	Vertical Additions; RC, glued laminated, hot-rolled steel, timber, cold-formed steel – Dynamic Analysis (FEM*)	Related to materials production - MCDM TOPSIS* method – NA	NA	Cold-formed steel solutions were selected as the best vertical addition system.
Feese et al. (2015) California, USA	Steel and RC office buildings (low-rise/60-year)	Building elements - Potential damage and repair cost under various seismic events (HAZUS-MH*)	Embodied Energy – NA – Initial construction and end of life stages	Athena Eco Calculator	About 14% reduction can be received from repair energy by upgrading building code.

Study	Building Type	Structural Intervention – Analysis	Environmental Impact Categories - Method – System Boundary	Software Tool - Database	Result
Simonen et al. (2015) California, USA	RC Building (42-storey)	Different structural designs: Fixed-base, base-isolated, and damped-outrigger. Seismic repair and replacement of structural components – Earthquake performance (FEMA P-58, 2012), High perform design (REDI*)	GHG* Emissions – TRACI* method – Manufacturing of buildings and repair materials	NA – Carnegie Mellon University's Economic Input-Output LCA database	14-20% improvement can be achieved from high performing buildings due to the less seismic repair.
Napolano et al. (2015) Italy	Masonry Building	Seismic retrofit: Local replacement damaged mortar, mortar injection, grid-reinforced mortar application, steel chain installation – Italian National Code	GWP, ozone depletion, oxidation, eutrophication, acidification, non-renewable energy – EPD* Procedure – Cradle to grave	SimoPro 7.3 software – Ecoinvent 2.2, SimaPro 7.3 and literature database	Recycling of materials provided benefit in all categories.
Zhao and Qin (2015) NA	Super-tall buildings (68- storey)	Improved design by integrating the energy dissipation devices (for wind and seismic resistant): Viscoelastic coupling dampers (VCDs) – Dynamic time history method, Chinese standard	Embodied carbon – NA – Construction of the building (excluding retrofits)	NA – ICE* database	Integrating the optimal design method is lower the embodied impacts.
Ferreira et al. (2015) Lisbon, Portugal	Ancient building (3-storeys/50 years)	Seismic refurbishment: Exterior façade, shotcrete, concrete elements, steel columns and beams, epoxy resin, steel roof with insulation, new construction (RC building option and clay brick walls) – NA	Primary Energy, GWP, ozone layer depletion, acidification potential, eutrophication potential, waste generated, water – NA – Manufacturing and Construction Stage	GaBi* – GaBi databases	The saving was achieved by the retrofit application at 13% in GWP, 34% in acidification potential, 10% in primary energy and 266% in eutrophication potential.

Study	Building Type	Structural Intervention – Analysis	Environmental Impact Categories - Method – System Boundary	Software Tool - Database	Result
Dong and Frangopol (2016) California, USA	Steel buildings (3-storey)	Structural-non-structural components: Conventional and base-isolated designs – Seismic Performance (PEER*) repair loss, downtime, Finite element model (OpenSEES)	Embodied energy, CO_2 emissions – NA – Manufacturing and construction stages	Monte Carlo – NA	Base-isolated building was reduced to 40.5% of that conventional building repair loss, which is equal to a 45% reduction in CO_2 emissions.
Padgett and Li (2016) California, USA	RC and Steel Office Building (4-storey/50 years)	Concrete and steel building design alternatives – Performance-based assessment (FEMA*), simulating earthquake responses(OpenSEES)	Embodied energy, and CO_2 of sustainability – NA – Manufacturing and construction of building and repair	AIEB	Impacts from repair constituted 20% and 23% of steel and concrete buildings' initial construction, respectively.
Belleri and Marini (2016) Italy	RC Building (50 years)	Structural and non-structural assessment: Lateral load resisting system, epoxy, placing concrete forms and steel for columns, window, wall and floor repair, masonry infills, replacing tiles and stairs, painting – Loss and Damage analysis (PACT), structural analysis of retrofitted building	Embodied carbon, operational energy and carbon – PBEE-GREEN* Method – Building and retrofit manufacturing and disposal stages	NA – ICE database	Nearly 90% reduction achieved in annual embodied carbon by implementing seismic retrofit.

Study	Building Type	Structural Intervention – Analysis	Environmental Impact Categories - Method – System Boundary	Software Tool - Database	Result
Hossain and Gencturk (2016) California, USA	RC Building (4-Storey/60 year)	Seismic repair: Injecting epoxy resin, patching with shotcrete, RC jacketing, replacement – Seismic environmental loss (PEER PBEE*)	GWP, acidification and eutrophication potentials – TRACI method – Cradle to the grave (excluding use stage)	NA – Berkeley Lab Building Materials Pathways (B-PATH) and EcoInvent 2.0 Databases	Overall, a 5-40% reduction was received from rehabilitation.
Wei et al. (2016) Israel	RC Building (40 years)	Seismic repair: Epoxy resin, shotcrete patching, RC jacketing, replacement – Loss estimation (HAZUS)	CO_2 emissions – NA – Construction stages of building and repair and demolition stage	NA – Huberman and Pearlmutter (2008) and (TCR, 2008; U.S. EPA., 2008, 2014; U.S. EIA, 2010) Databases	Overall, a 1.1-117.8% reduction was received from rehabilitation and replacement of building according to damage levels.
Menna et al. (2016) Italy	Masonry Building (2-storey/60-year)	Seismic retrofit of the masonry walls (GFRP, steel grid and basalt FRP*), flat roof replacement (RC, polystyrene and steel flat roof) – Italian Structural Code	GWP, photochemical oxidation, eutrophication, ozone layer depletion, acidification and non-renewable fossil – EPD method – Whole lifecycle	SimaPro 7.3 – Ecoinvent 3.0 Database	Minimum impacts were achieved by using RC roof replacement with steel grid walls.
Vitiello et al. (2016) Naples, Italy	RC Buildings (3-storey)	Seismic Retrofit: FRP and RC jacketing, RC shear walls, base isolation – Italian National Building Code, Eurocode 8*, SAP2000* tool	Climate change, ecosystem quality, human health and resource depletion – IMPACT 2000+ – Cradle to gate	SimaPro 7.3 – Ecoinvent 2.2 Database	The most environmentally sustainable retrofit strategy was determined.

Study	Building Type	Structural Intervention – Analysis	Environmental Impact Categories - Method – System Boundary	Software Tool - Database	Result
Gencturk et al. (2016) California, USA	RC Building (4-storey/50-year)	Seismic repair: Epoxy injection, patching, repair/replacement of concrete/cover, longitudinal rebar and transverse rebar, reconstruction – Damage and loss assessment (HAZUS and PEER PBEE), and dynamic analysis (ZEUS NL*).	Environmental emissions and waste generation, GWP, climate change potential, human health effects, eutrophication, acidification, ozone depletion, eco-toxicity, smog formation, fossil fuel depletion, water use – NA – Manufacturing, construction, and end-of-life (demolition, disposal, and recycling) stages	NA - Lawrence Berkeley National Laboratory and EcoInvent v2.0 Database	More resilient designs can reduce the repair activities of buildings by two times.
Wei, Shohet, et al. (2016) Israel	RC Building (20 years)	Seismic Repair: Epoxy resin, concrete jacketing, shotcrete patching, hydro-jetting, cleaning of reinforcement, replacement of concrete frame – Loss estimation (HAZUS) and PBD*.	CO_2 emissions – NA – Construction, Repair activities and demolition	NA	Cost and social benefit results give a 1% reduction from CO_2 emissions.
Alirezai et al. (2016) NA	Office building (2-storey)	NA – Damage estimation (PACT), Building modelling (BIM*), Structural analysis (OpenSEES), Damage probabilities (HAZUS –MH)	Embodied energy – HAZUS-MH method – Only repair activity	NA	Repair energy can be found by using the damage ratio.
Gervásio (2017) NA	Steel Structure (multistorey)	Structural systems: Concentrically braced frames, dual-system concentrically braced frames, eccentrically braced frames, and dual-system eccentrically braced frames – NA	GWP, use of natural resources, primary energy demand – EPD procedure – Material production, demolition and recycling stages	NA – Gabi Database	With high strength steels, a reduction of up to 27% in carbon emissions can be achieved.

Study	Building Type	Structural Intervention – Analysis	Environmental Impact Categories - Method – System Boundary	Software Tool - Database	Result
Loli et al. (2017) Italy	RC Office building (3-storey)	Cast-in-situ and precast structures, replacement (brick walls, concrete panels, glass facades, windows) – Damage estimation (sPBA* and SAP2000 tool), Eurocode 8	CO_2 emissions, embodied, operational and demolition energy – IPCC 2007 – Manufacturing and demolition stages	SimaPro – NA	The precast structure was selected in terms of being the most sustainable and economical.
Formisano et al. (2017) Naples, Italy	RC School Building (2-storeys)	Retrofit: RC shear walls, Eccentric bracing frames, Concentric bracing frames, Steel plate shear walls, Buckling restrained braces – In-situ surveys for the seismic-volcanic vulnerability analysis, seismic retrofit modelling (FEMA and SAP2000 tool), Italian Building Code	Human health, ecosystem quality, climate change and resources – MCDM TOPSIS method and Impact 2002+ – Cradle to gate	SimaPro 7 – Ecoinvent and Idemat Databases	The implementation of Steel plate shear walls achieved the best environmental performance.
Uzun and Secer (2017) Kocaeli, Turkey	RC Building (6 storeys)	Structural retrofits: Shear wall (different thickness), partitioning wall –Turkish Earthquake Code, (STA4CAD* tool)	Energy consumption and CO_2 emissions – NA – Retrofit construction	NA	While the partitioning wall revealed the least emissions and energy, the shear wall had the highest and changed the impacts according to the thickness of application.
Welsh-Huggins and Liel (2017) California, USA	Office Building (4-storey/50 years)	Different seismic design considerations: Green roof application (shallow, deep and green roof retrofits) and repair (glazing and plywood) – ASCE* and OpenSEES, Loss analysis (PACT)	CO_2 emissions, operating energy – TRACI method – Manufacturing stage	SimaPro – Ecoinvent database	The green roof requires more additional repair material to support its behaviour against possible earthquake movements and is, therefore, less green than other options.

Study	Building Type	Structural Intervention – Analysis	Environmental Impact Categories - Method – System Boundary	Software Tool - Database	Result
Ribakov et al. (2018) Mediterranenan region	RC Building (5-storey /50 years)	Seismic Retrofit: Concrete diaphragms, high-damping rubber bearing, seismic isolation – Seismic evaluation under four real earthquake and calculations (MATLAB*)	Environmental score – NA – Production, construction, maintenance and demolition stages	SimaPro 7.3.3 – Ecoinvent Database	Retrofit reduced environmental impacts by about 10%.
Chhabra at al. (2018) California, USA	Steel building (9-storey/50 years)	Non-structural and structural repair actions (wallboard) – Hazard, structural, damage and loss analyses (PACT and OpenSEES)	GWP – Unit process method, TRACI 2.1 – Manufacturing and transportation of repair materials	NA – Ecoinvent 3.0 database	Non-structural components have mostly higher GWP due to seismic repair compared to structural components, and GWP from lifetime repairs accounts for about 3% of the building replacement.
Welsh-Huggins and Liel (2018) California, USA	RC buildings (4-12 storey/50 years)	Enhanced seismic designs: Lateral strength and ductility capacity for different code designs, including structural and non-structural components – ASCE, OpenSEES, Loss estimation (SP3, 2020)	Embodied Carbon – TRACI method – Manufacturing building materials and repairs	SimaPro – Ecoinvent database	Embodied carbon is higher for high performing buildings, and it is lower for post-seismic repair activities than less durable buildings.

Study	Building Type	Structural Intervention – Analysis	Environmental Impact Categories - Method – System Boundary	Software Tool - Database	Result
Simonen et al. (2018) USA	Building components (structural and non-structural)	Building components: Structural steel elements, RC elements, masonry walls, exterior enclosure light frame structural elements, roof elements, partitions, stairs. non-structural components – Damage estimation (FEMA), the vulnerability of structural and non-structural components (PACT)	Embodied carbon and energy, eutrophication, ozone depletion potential, acidification and smog – TRACI 1.0 – Manufacturing Stage	NA –Carnegie Mellon University's Economic Input	The highest environmental impacts caused by non-structural and architectural finishes components of buildings.

*__AIEB__, Athena Impact Estimator for Buildings; **ASCE**, American Society of Civil Engineers (Standard - Minimum Design Loads for Buildings and Other Structures (ASCE, 2010)); **BIM**, Building Information Modelling; **BUWAL**, (Lifecycle inventory database); **CO_2**, Carbon Dioxide; **EIO**, Economic Input Output; **EnvISA**, Environmental Impact Seismic Assessment; **EPD**, Environment Product Declaration; **Eurocode 8**, European Standard, Design of Structures for Earthquake Resistance (Eurocode, 2005); **FEM**, Finite Element Method; **FEMA**, Federal Emergency Management Agency; **FRP**, Fibre-reinforced Plastic; **GaBi**, (LCA software (GaBi, 2020)); **GHG**, Greenhouse Gas; **GFRP**, Glass Fibre-reinforced Plastic; **GWP**, Global Warming Potential; **HAZUS**, Hazards U.S. (Geographic information system-based natural hazard analysis tool); **HAZUS-MH,** Hazards U.S. Multi Hazards; **ICE**, Inventory of Carbon & Energy; **Idemat,** Industrial Design & Engineering Materials Database; **IMPACT**, (A lifecycle impact assessment methodology); **IPCC**, (A method developed by Intergovernmental Panel on Climate Change); **MATLAB**, Matrix Laboratory (Programming and numeric computing platform); **MCDM TOPSIS**, Multi-Criteria Decision Making Technique for Order Preference by Similarity to Ideal Solution; **NA**, Not Available; **OpenSEES**, the Open System for Earthquake Engineering Simulation (PEER, 2014); **PACT**, Performance Assessment Calculation Tool; **PBD**, Performance-based Design; **PBEE-Green**, (Integrating PBEE in environmental analysis); **PEER**, Pacific Earthquake Engineering Research; **PEER PBEE**, Pacific Earthquake Engineering Research Performance-based Earthquake Engineering); **RC**, Reinforced Concrete; **REDI**, Resilient Earthquake Design Initiative; **SAP2000**, Structural Analysis and Design (Software) **SimaPro**, (LCA software (SimaPro, 2020)); **sPBA**, Simplified Performance-based Assessment; **STA4CAD**, Structural Analysis for Computer-Aided Design; **TRACI**, Tool for the Reduction and Assessment of Chemical and other Environmental Impacts; **ZEUS NL**, (Frame analysis software).

2.3.2.1 Structural Performance Methods for Assessing Environmental Impacts

Overview of the Studies (Study and Building Type)

As can be seen from the table above, this field of study is a field that begun to be studied closely in 2010, and most of the studies chose to examine buildings in the USA. On the other hand, RC buildings have been the most preferred type of building, and their service period is generally chosen as 50 and 60 years. Also, various methods have been used to examine the structure's structural performance and its components, and these methodologies have focused on the dangerous effects of earthquakes because of their high damaging effects on buildings.

Overview of the Structural Performance Methods (Structural Analysis)

One of the most common methods in building performance analysis was produced by FEMA (Federal Emergency Management Agency). The relevant road maps and guidelines FEMA (2006) and FEMA P-58 (2012) address performance metrics in seismic design and consider uncertainty associated with seismic events, and HAZUS (Hazards U.S.) is a regional seismic-loss estimation tool. This tool determines the damage probability of building and converts these probabilities into the number of damaged buildings under four damage levels (Feese, Li and Bulleit, 2015). The determined damage levels give information about the building's repair cost, and this repair is determined according to the cost ratio specific to each damage level according to the total replacement cost of the building. These repair cost ratios are derived from historical earthquake loss data for different buildings (Wei, Shohet, *et al.*, 2016). Performance Assessment Calculation Tool (PACT) is another tool also developed by FEMA (FEMA P-58, 2012) which models probabilistic structural seismic damage, performs a probabilistic analysis of seismic performance, and evaluates measurements such as repair cost, methods and time, loss of life, and other measures (Simonen *et al.*, 2018). The most useful feature of this software is repair cost and time since possible repair action to specific building component types is specified for each damage state. That is adopted to calculate environmental impacts (Welsh-Huggins and Liel, 2017).

Similarly, performance-based engineering (PBE) formalises hazard-resistant design to meet performance objectives (Welsh-Huggins and Liel, 2017). Performance-Based Earthquake Engineering (PBEE) also provides an assessment of seismic losses probabilistically, and Performance-Based Design (PBD) is another method for building seismic performance, including performance criteria, the magnitude of the earthquake, or return period (Simonen *et al.*, 2018).

A comprehensive methodology that includes the structure’s response to seismic motion and the environmental impacts or loss of the structural damage has not been developed (Hossain and Gencturk, 2016). However, seismic losses that determine the damage of structure caused by hazards will be decisive in selecting a repair scheme and environmental load due to repair activity (Gencturk, Hossain and Lahourpour, 2016). Tapia and Padgett (2012), one of the first authors in this field, stated that current practices and research to integrating sustainability and disaster risk reductions were in their infancy.

FEMA presented the seismic design guideline for evaluating life cycle environmental impacts caused by seismic damage (FEMA P-58-4, 2012) by referring to FEMA P-58 (FEMA P-58, 2012). This method includes a framework for sustainable design of new buildings considering FEMA P-58 and PACT to estimate potential earthquake damage (the similar application available in studies) and also considers retrofit versus replacement. However, these designs do not include sustainable retrofit selection. Also, although current studies generally use FEMA guidelines, they needed to develop and propose integrated environmental performance assessment methods. Since there is a need for a comprehensive method to measure the sustainability of buildings in which natural hazards are included, there is a growing group of researchers: (Comber and Poland, 2013; Welsh-Huggins and Liel, 2014, 2018; Feese, Li and Bulleit, 2015; Napolano *et al.*, 2015; Vitiello *et al.*, 2016; Wei, Shohet, *et al.*, 2016; Wei, Skibniewski, *et al.*, 2016; Dong and Frangopol, 2016; Gencturk, Hossain and Lahourpour, 2016; Hossain and Gencturk, 2016; Menna *et al.*, 2016; Padgett and Li, 2016; Uzun and Secer, 2017; Chhabra *et al.*, 2018; Ribakov, Halperin and Pushkar, 2018) who have developed framework to include environmental assessment with building seismic resilience.

Studies Focusing on Pre-design Objectives for Assessing Environmental Impacts

Environmental impacts calculations are challenging because of the complexity of environmental modelling data, labour, and time, although PBD includes repair cost, downtime, and fatalities. For these reasons, many studies in the literature have used economic data to estimate environmental impacts probabilistically (Chhabra *et al.*, 2018). For instance, Arroyo et al. (2012) introduced the environmental cost losses in the framework of existing seismic design methods and highlighted the importance of designing buildings under seismic codes. Alirezaei et al. (2016) used HAZUS-MH (Hazards U.S. Multi Hazards) (developed by FEMA) for energy consumption per replacement cost (MJ/$), the total cost replacement value ($/SF) and PACT for damage estimation method. Therefore, the total repair energy was found by multiplying the damage ratio, area of the building (SF), and embodied energy of the building (MJ/SF). Belleri and Marini (2016) evaluated seismic repair cost results based on Pacific Earthquake Engineering Research Performance-based Earthquake Engineering (PEER-PBEE), PACT software which was used to determine the environmental impacts caused by these repairs. Figure 2-2 shows the PEER-PBEE methodology that divides loss assessment into four steps.

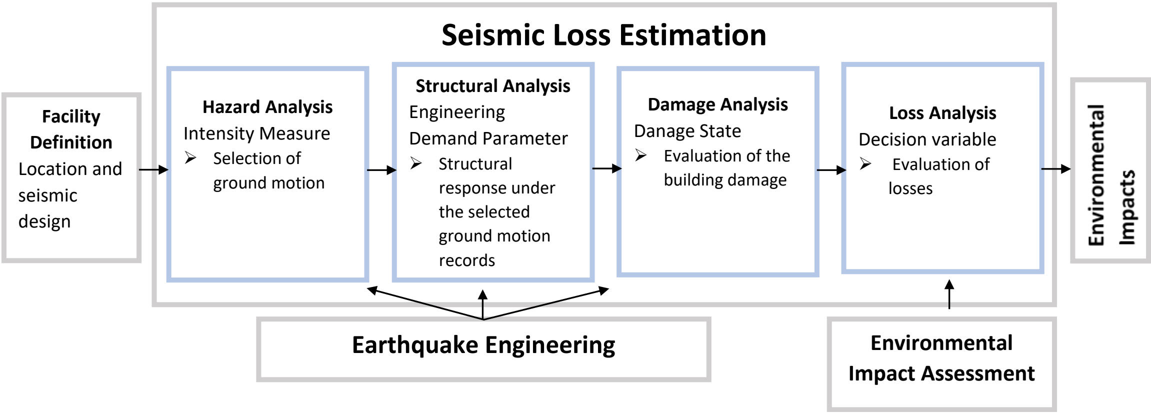


Figure 2-2 PBEE methodology and environmental impact assessment (adopted from (Belleri and Marini, 2016)

Moreover, Gencturk et al. (2016) also adopted the PEER PBEE method and PACT for evaluating structural damage from five building designs. Simonen et al. (2018) narrowed down the focus on building components subjected to five seismic damage levels by using PACT to create a database, and Welsh-Huggins and Liel (2014) also used PACT for probabilistic seismic loss estimation. Chhabra et al. (2018) used PACT for damage and loss analysis of non-structural and structural repair actions. Menna et al. (2013) also investigated environmental impacts by evaluating expected damages on structural and non-structural components, focusing mainly on different structural limits according to FEMA (FEMA 273, 1997). Comber and Poland (2013) focused on seismic upgrading of buildings according to building code requirements by FEMA and lifetime environmental impacts caused by seismic damage according to loss estimation by using HAZUS. Feese et al. (2015) also evaluated seismic design code levels for upgrading the building structural performance, used HAZUS-MH for multi-hazard loss estimation, and chose three seismic design code levels (Pre-code, moderate, high). Then, the program provided a repair cost ratio for these damage levels and building types.

Similarly, Hossain and Gencturk (2016) investigated high and low performed buildings subject to five seismic damages. They preferred the PEER PBEE methodology for seismic analysis, structural response evaluation, damage assessment, and loss analysis to incorporate environmental impact assessment. Different design alternatives for buildings, also studied by Padgett and Li (2016), steel and concrete buildings were selected to estimate hazard-related impacts considering four damage levels by using PBD assessment of FEMA. Wei, Shohet et al. (2016) and Wei et al. (2016) also used PBD and HAZUS for loss estimations. Differently, Chiu, Chen and Chiu (2013) followed the Poisson process for estimating expected costs according to the probability of seismic damage and estimated environmental payback period (considering retrofit and non-retrofit of buildings) over the building's service period.

These studies include whole building earthquake-resistant designs rather than a structural retrofit and compare the repairs for different damage scales during the use of the building. In other words, pre-design objectives are targeted to achieve satisfied hazard resistant design along the design period of the building (Welsh-Huggins and Liel, 2014), rather than post-seismic recovery of existing damaged buildings. Feese et al. (2015) recommended real-world applications for assessing environmental impacts caused by seismic damage rather than probability estimations. Additionally, the shortcomings related to direct modelling of the environmental impacts of structural and non-structural components and the calculation of seismic effects throughout the building service life includes uncertainties (Chhabra *et al.*, 2018). For instance, Hossain and Gencturk (2016) accounted damage assessment procedure, including uncertainties and assumptions. Also, uncertainties in the environmental impact data basis on assumptions were considered by Dong and Frangopol (2016) and Belleri and Marini (2016).

Studies Focusing on Structural Retrofits (Interventions) for Assessing Environmental Impacts

Some studies focus on structural retrofits and their environmental impacts without using probabilistic analysis for damage loss. Terracciano et al. (2015) investigated vertical additions for the strengthening of masonry buildings. Further, Napolano et al. (2015) and Menna et al. (2016) also conducted a systematic approach for assessing the environmental impacts of retrofit options for the wall of masonry structures. Similarly, Ferreira et al. (2015) focused on the seismic refurbishment of ancient buildings. Retrofit options for damaged RC buildings were also investigated by Belleri and Marini (2016), Vitiello et al. (2016), Formisano et al. (2017), Uzun and Secer (2017) and Ribakov et al. (2018).

Another method, Sustainable Structural Design (SSD), combines basic structural design and sustainability requirements and compares them with economic terms, as seen in Figure 2-3 (Marini *et al.*, 2014; Tsimplokoukou, Lamperti and Negro, 2014). The SSD method developed by EC for assessment of the seismic performance of buildings addresses sustainability and energy efficiency by implementing simplified Performance-Based Assessment (sPBA) (Romano, Negro and Taucer, 2014). The EC generates policy frameworks that provide inclusive and guidance within the sustainable development goals. This method is one of the supporting tools developed for the building design process in the Joint Research Centre. The sPBA simply originated from the PBEE PEER method to estimate expected losses and cost (Loli, Lamperti Tornaghi and Negro, 2017). The energy consumption during the use phase converts from kWh or m^3 (natural gas) to total energy price (€/kWh or €/m^3 gas), environmental impacts as global warming potential (GWP) (CO_2 equivalent) and embodied energy (MJ or kWh or m^3) converts to price of CO_2 and total cost of the building. The cost calculated as the sum of the initial construction cost and expected loss (repair cost and repairing actions costs, e.g., removal, rent, so on) (Lamperti Tornaghi, Loli and Negro, 2018).

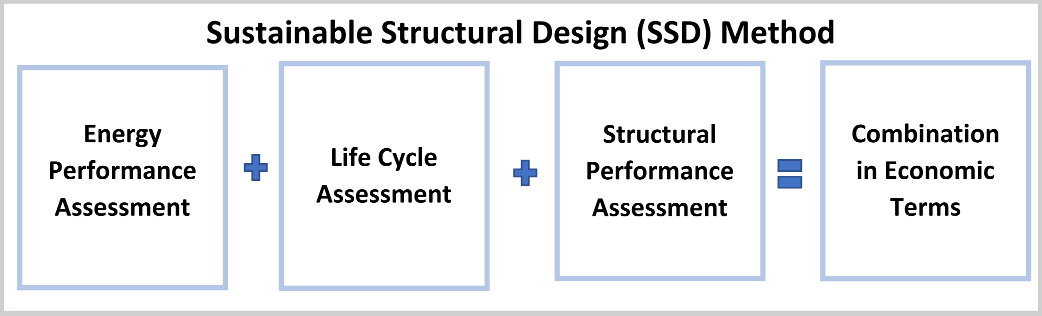


Figure 2-3 SSD method's steps (Marini et al.*, 2014; Tsimplokoukou, Lamperti and Negro, 2014)*

In some studies, it has preferred to give environmental results by converting them into monetary units. For example, Loli et al. (2017) implemented the SSD method for precast and cast-in-situ buildings at the ELSA laboratory to determine the most sustainable and resilient solution. The PBA method was implemented to assess costs and expected losses of structural solutions. Expected losses were evaluated for heavy damage, severe damage, and near collapse state, which needed demolition and reconstruction of non-structural elements, replacement of non-structural elements and damaged beam retrofit, and new building construction. Repair costs were assessed for these interventions. Results were presented in monetary units, and the most sustainable option has less damage and environmental costs but higher construction cost. Dattilo et al. (2010) also conducted research at ELSA laboratory for evaluating environmental impacts caused by structural interventions. CO_2 emission results were also converted to monetary terms in this study. Wei, Shohet et al. (2016) also used monetary terms to represent optimum results of three metrics of sustainability: environmental, cost, and social.

The integrated methodologies that combine sustainability and structure are specific methods for assessing seismic performance (such as FEMA or national building codes) of buildings and intend to make them specific according to the target region (Loli, Lamperti Tornaghi and Negro, 2017). Menna et al. (2013) recommended the application of local practices for buildings structural performance assessments. As we know, building performance objectives may vary with the selected performance level, or conversely, performance-based standards may target different objectives (FEMA, 2006). As is seen, the development in the refurbishment of the existing buildings increases the attention of the governmental and scientific arenas (Menna *et al.*, 2016). However, even with such sustainability measures applied to disaster-resistant design, there is still a lack of well-defined systematic approaches and methods to integrate disaster damage in whole bottom lines of sustainability metrics. This issue causes less attention to measure buildings' sustainable performance (Wei, Shohet, *et al.*, 2016). Namely, integrated methods and frameworks are required to reduce disaster risk and create the most effective interventions. The process of renovating existing buildings is based on integrated multidisciplinary approaches, but it is crucial to identify ongoing interactions (De Vita *et al.*, 2018).

2.3.2.2 Assessment of Environmental Impacts

Building materials consume a significant amount of energy during production and transportation due to the high-energy demand. Besides, earthquake damages also considerably affect the building's environmental performance (Menna *et al.*, 2013). Ribakov (2018) investigated non-retrofitted and retrofitted options of buildings. The damage index was used to evaluate the damage, and the necessary recovery material for each building component was estimated. Park and Ang (1985) proposed the damage index, which is hypothetically calculated by multiplying the consumption of rehabilitation materials required for each building element by the consumption of construction materials. The environmental impacts of the non-retrofit building estimated as 13-5% of the construction of the whole building and the impact was reduced by up to 55% by implementing seismic retrofit.

The building environmental impacts calculation includes the entire process from construction to maintenance and replacements (Menna *et al.*, 2013). There is no such ratio for post-disaster repair or reconstruction of buildings as the repair cost ratio because environmental impacts associated with the damage repair have not been recorded yet in the historical loss data (Wei, Shohet, *et al.*, 2016). Therefore, many existing studies have estimated the probabilistic environmental impacts derived from repair cost, as aforementioned in the previous section. In this context, Wei, Shohet, et al. (2016) proposed to directly calculate emissions from repair measures, taking into account the CO_2 coefficients corresponding to parameters such as the relevant material or equipment, as Feese et al. (2015) suggested the real-world applications. Based on this, the author defined an estimated emission rate as the ratio of emissions from repair to emissions from the building's replacement (Wei, Shohet, *et al.*, 2016). However, this study is also limited by pre-design objectives, selected repair activity, and cradle-to-gate system boundary.

Embodied and Operational Impacts (Environmental Impact Categories)

During maintenance or replacement of building materials, a substantial amount of recurring embodied energy is released, which indicates the necessity and importance of complete life cycle analysis for embodied impacts. Also, the end-of-life stage affects embodied impacts. However, it is considered a minor impact; recycling or reusing potential can lead to a 30-40% embodied energy reduction from low and zero energy buildings' life cycle (Chastas, Theodosiou and Bikas, 2016). Therefore, at the centre of the full LCA of a building is the bill-of-materials (BOM), referred to as primary inventory data or life cycle inventory. This data includes many elements such as material types, quantity, manufacture of the product, transportation, disposal of materials, maintenance, and many others (ATHENA, 2019a). On the other hand, the availability and quality of primary inventory data associated with different augmentation techniques are among the main problems of environmental analysis (Menna *et al.*, 2016). Moreover, the completeness and accuracy of this information are limited, so there are uncertainties in the environmental analysis (Chhabra *et al.*, 2018).

BOM provides information for calculating embodied carbon; it has been chosen as the determining criterion of environmental impacts in studies. Simonen (2018) verified that embodied carbon is a suitable representative for other relevant environmental impact measures for assessing LCA of repair activities in their study. Because retrofitting buildings are most relevant with embodied carbon when assessing their environmental impacts, and the highest environmental impacts are caused by non-structural and architectural finishes components of buildings. Furthermore, embodied carbon is also related to resource use, and Construction Products Regulation (EU Regulation No. 305/ 2011 (EU, 2011)) has determined the sustainable use of natural resources as an essential requirement for construction works (Gervásio, 2017).

Apart from embodied impacts, operational impacts also have significant impacts, and results showed that the highest environmental impacts occurred during the usage stage because of the energy use, including heating fuel, electricity and water (Menna *et al.*, 2013). For this reason, some studies have aimed to reduce the operational impacts of buildings as well as seismic improvement. For instance, Belleri and Marini (2016) aimed to assess the effectiveness of energy refurbishments in reducing emissions by implementing thermal insulation and renewable energy. Similarly, Terracciano et al. (2015) aimed at winter heating and the impacts of glass facades and windows investigated by Loli et al. (2017). Welsh-Huggins and Liel (2014) also investigated integrating assessment of hazard resilience design and green design as a green roof. The high seismic level (2% occurrence probability in 50 years) caused 98% damaged partitions in the reference model, while only 58% for the green model. However, the higher amount of concrete used in the green model caused a high amount of environmental impacts (10%) compared to the reference model. Therefore, it is not the green roof that leads to a more seismic resilient structure it is the use of more concrete (interior partitions) to support the roof that provides this. Green roofs have a positive effect on building operating energy; however, it is a minor impact. They provide more benefits in lowering ambient air temperatures around a building and counteract urban heat island effects (Welsh-Huggins and Liel, 2014). This study has shown that the repair's environmental impacts also need to be calculated, as each possible repair scenario brings additional environmental impacts. Later, the authors expanded the idea by improving the green-resilience framework, including uncertainty and variability to results (Welsh-Huggins and Liel, 2017). Finally, the authors investigated the environmental impacts of enhanced seismic pre-designs and suggested increasing lateral strength buildings (lateral load-resisting RC frame lines) in high seismic areas that can reduce embodied emissions from post-seismic repairs (Welsh-Huggins and Liel, 2018).

The Impacts of the Building Performance Design on the Environmental Impacts

It is a fact discovered by many studies that different building code design levels (such as Pre-code, moderate and high design code levels in HAZUS-MH according to code requirements by FEMA) have a significant impact on environmental impacts. More resilient designs of buildings cause less damage to the building in possible earthquakes and the environmental impacts due to its repair. For instance, repair loss can be reduced to 40.5% by implementing advanced building designs for seismic areas, leading to a 45% reduction in carbon emissions from structural and non-structural components (Dong and Frangopol, 2016). While structural components require partial repair (not full replacement) caused by damage, non-structural components often need a full replacement. Therefore, investing more in structural components to increase their resilience produces less environmental impacts.

Comber and Poland (2013) found that a building's initial design in accordance with the required building code provided approximately 34% environmental benefit from repairing activities. Likewise, it has saved about 14% from repair energy by upgrading the building with codes (Feese, Li and Bulleit, 2015). Advanced structural systems provided about 10-30% reduction from repair activities (Sarkisian, 2014), high performing buildings 14-20% (Simonen *et al.*, 2015), and similar savings also achieved by (Zhao and Qin, 2015; Gencturk, Hossain and Lahourpour, 2016; Hossain and Gencturk, 2016). Padgett and Li (2016) compared the concrete and steel buildings, and the repair of steel building constituted 20% of the embodied impacts of building construction. It resulted in 23% for concrete building repair. These two buildings do not have the same design and were designed according to different building codes.

The Impacts of the Life Cycle Stages (System Boundary)

Since the post-disaster repair of buildings includes many factors, the assumptions and pre-design alternatives may not be sufficient for sustainable transformation of existing damaged buildings. Like LCA of buildings, repair of buildings also includes specific stages such as the production of repair materials, installation, use, and waste. Material production has been the most cited subject as it has the most impacts on buildings life cycle (Gencturk, Hossain and Lahourpour, 2016). According to results, 84% of the CO_2 emissions occurring in the retrofitting construction resulted from material use (Wei, Skibniewski, *et al.*, 2016). In the study of Chiu et al. (2013), repair activities corresponded to 11% of the emissions from new building construction (low-rise RC building), while Wei et al. (2016) found that new building construction (RC building) estimated to be equal to 117.8% of building construction. Menna et al. (2013) found that only rehabilitation activities constitute approximately 25% of environmental impacts from the building construction (RC building) and 6% of total life cycle impacts. In addition to that, building material production and rehabilitation have a significant impact representing just over 40% in resource depletion. Gervasio (2017) also proofed that using strength materials with a small scale to reduce resource use, such as high strength steel, led to a decrease (up to 27%) in carbon emissions and energy demand (up to 25%) of different static systems as seismic-resistant building frames.

Regarding other stages, Menna et al. (2013) stated that the construction process and transportation have the lowest impact and shares around 6% of the total impacts. Napolano et al. (2015) highlighted the environmental benefit of recycling materials. Wei et al. (2016) investigated emissions from demolition activities of retrofit at the end-of-life stage, and it found to be equal to 2.4% of total rehabilitation emissions while debris was 4.1%. However, in the study of Pan et al. (2014), the impacts from demolition and debris disposal at the end-of-life stage were statistically estimated to be equivalent to 42 and 58% of the total impacts of rehabilitation, respectively. This is because all LCA stages include many criteria and parameters (such as intervention type), thus causing results to differ due to uncertainties regarding the data. Therefore, the LCA of building retrofits need to be investigated more comprehensively and in detail, and methods should be developed accordingly.

In addition to the life cycle stages, some studies have also included the buildings' service life in analyses, and a significant impact has been discovered. For example, seismic upgrading a building according to the new code increased the construction effects by an additional 2%, but a 9% reduction was achieved in the building's lifetime CO_2 effects (Comber and Poland, 2013). Belleri and Marini (2016) also investigated the annual embodied carbon of seismic retrofits, and it helped reduce about 90% of the building's annual impacts.

Environmental Performance Classification (Method)

Based on the above facts, some studies to combine seismic retrofit techniques with environmental considerations have emerged for a more robust criterion for upgrading building performance. This is accompanied by upgraded environmental criteria for setting up the sustainable rating systems currently in use (Comber and Poland, 2013). These systems form part of national or international standards and regulations, whether mandatory or voluntary (Caruso *et al.*, 2017). However, these sustainable rating systems do not consider building resilience in their assessments (Welsh-Huggins and Liel, 2017), and the environmental effect is also ignored in the structural performance perspectives (Simonen *et al.*, 2018).

The environmental impacts arising from post hazard rehabilitation have also been proposed as performance metrics in earthquake design procedure (FEMA, 2006) (Hamburger *et al.*, 2012) and sustainability rating systems (Comber and Poland, 2013). Therefore, Envision Sustainability Rating System (ISI, 2020) includes credits for hazard preparedness for sustainability ratings of infrastructures (Padgett and Li, 2016). Furthermore, Comber and Poland (2013) also investigated the benefits of developed methodologies for building certifications like LEED by following design and innovation credits. In the study of Comber and Poland (2013), it is estimated that many LEED buildings are likely to suffer damage in future, especially in California. Therefore, although possible precautions are not taken in these buildings' design, fully carbon emission measures are also missed. Pre-disaster preparedness and post-disaster resilience can be correlated, and building service time can be optimized to minimize material usage (Kneer and Maclise, 2008; Sarkisian, Hu and Shook, 2012; Comber and Poland, 2013).

In the study of Gencturk et al. (2016), environmental impacts categorised according to the USA's annual per capita environmental impact as an environmental performance score. Such studies always have limitations regarding the definition of damage states that need more detailed local numerical modelling. According to results given in environmental performance score metrics, a higher-performing building can increase the environmental impacts by 192%; however, more resilient designs can reduce buildings' repair activities two times. Simonen et al. (2015) and (2018) used The Building for Environmental and Economic Sustainability (BEES) Environmental Performance Score, which is developed by the National Institute of Standards and Technology (NIST) in the US, to determine the relative importance and quantity of environmental impact categories. They found that LCA studies, including whole building assessment, can be rewarded by green building rating systems. Ribakov (2018) also analysed environmental impacts over points that were evaluated from environmental performance scores on the damage level using Eco Indicator 99. The method provides an option to evaluate the percentage difference between two values of environmental damage of compared mitigation measures (impacts of retrofits and total impacts of building). As Gervasio (2017) recommended, an acceptable and targeted environmental performance for buildings similar to actual and acceptable performance in structural analysis of buildings should be developed.

Some researchers have used a multi-criteria decision-making process, as they included different criteria in their study. Formisano et al. (2017) used Multi-Criteria Decision Making Technique for Order Preferences by Similarity to Ideal Solutions (MCDM TOPSIS) for defining the criteria as safety, the feasibility of function, human health, reversibility of the retrofit, and its cost. TOPSIS is a simple MCDM technique for selecting the best choice between various alternatives. Terracciano et al. (2015) also used the MCDM TOPSIS method to compare the vertical addition systems in terms of structural, environmental, energy, and economic performance parameters. However, as there is still insufficient data and no historical loss data related to environmental impacts of a structural intervention for vulnerable buildings, studies addressing particularly environmental impacts are still open to development. That also helps improvement in the multi-criteria decision-making process to be examined under all pillars of sustainability.

2.4 Research gap

Structural interventions offer a useful option in strengthening existing vulnerable buildings. Due to retrofitted existing buildings being characterised by an extended lifespan, including versatile and interactive design procedures and solutions, data collection, and interpretations, LCA studies to be carried out in this area will encourage the retrofitting solutions of existing buildings (Menna *et al.*, 2016).

Studies above indicated that, in general, environmental impacts occur less in the rehabilitation of high-performed (robust) buildings. Therefore, these studies emphasize the precautions taken before a disaster for the buildings to be built. Also, they do not fully consider existing buildings, their avoiding environmental impacts, debris from applied retrofit techniques, and total impacts of retrofit over the building service period, including extended service life after the retrofit. Furthermore, the net benefits of structural improvement, its customised LCA stages, and impacts remained incomplete for existing vulnerable buildings. Apparently, although numerous studies have sustainably assessed the building seismic resilience, the full transformation of the destructive effects of disasters on buildings into sustainability criteria continues to be investigated due to the lack of any systematic method (Wei, Shohet, *et al.*, 2016).

Regarding proposed methods by current studies, no study has systematically analysed by comparing both environmental impacts associated with the various design of retrofitting scenarios and retrofit versus non-retrofit option for existing buildings, including direct calculating (real-world applications) environmental impacts from retrofit options. However, researching the most sustainable option among the strengthening options may contribute to developing strengthening techniques. Some studies investigated the environmental impacts of structural retrofit techniques by implementing different materials or techniques to make them more sustainable. For example, Das (2011) investigated carbon fibre polymer composites, FRP by Moliner et al. (2013) and sustainable alternatives for RC jacketing by Miyauchi et al. (2012).

In addition to the deficiencies above the current literature regarding post-disaster building sustainability, most studies have limited the research methodology to only specific to seismic events and discussed the structural performance of particular building types in certain regions. In order to estimate the impacts of building rehabilitation, considering the increase of other disasters, methods should be developed which include relevant scenarios with a scope and flexibility that take into account the local building codes. An opportunity can be taken by developing existing local structural practices and regulations with sustainability concepts to track countries' zero-emission targets.

A more compressive and systematic framework would be thus required (is still necessary) for assessing the quantifiable effects of life cycle processes on building retrofits and their impacts. Besides, structural strengthening methodologies for renewing the building stock need further scrutiny to synchronise with sustainable developments that strive to modernise construction practices. Therefore, with the thought of discovering the benefit of structural interventions on buildings' environmental sustainability over their whole life cycle, this study aims to propose a comprehensive method. That can incorporate the vulnerability of building into the sustainability concept by generating scenarios related to damage scales and customising LCA stages according to these scenarios, considering intervention techniques and local conditions. The proposed method also evaluates the environmental benefits of the strengthening, which includes environmental impact categories, embodied carbon and energy and resource use caused by selected scenarios considering extended service life after the retrofit.

The study is intended to provide an integrated method for vulnerable buildings, thereby providing a suggestion and a comprehensive perspective on decisions affecting society as well as the environment, particularly in disaster-prone areas. Moreover, the results obtained from this study will contribute to the historical loss data associated with the environmental impacts of post-disaster recovery.

3. METHOD

3.1 Foreword

This chapter[5] dissects how structural interventions and life cycle environmental analysis can be integrated together to explain and justify the methods used to achieve the objectives and the research gaps identified in Chapter 1 and 2. Section 3.2 outlines general information about the method, followed by section 3.3 with a more detailed description.

3.2 General information on outline methodology

In order to develop a comprehensive method, structural interventions implemented in vulnerable buildings were investigated, and the environmental consequences were assessed. The Environmentally Sustainable Structural Intervention Method (ESSIM) prioritises different ways to measure the environmental benefits of structural retrofit. More broadly, ESSIM aims at embedding structural retrofit impacts into the standard LCA framework. This proposed method was developed on two pillars:

- Pre-LCA Stages: Structural intervention in vulnerable buildings
- LCA Stages: LCA of relevant structural intervention scenarios for vulnerable buildings

The framework was expanded to produce scenarios related to the structural interventions of the buildings according to their vulnerability. The proposed methods are applied using two criteria: (1) to determine which retrofit designs reduce environmental impacts and (2) which decisions for retrofitted or non-retrofitted designs are achieving the lowest environmental impact. As a result of the analyses, the method sheds light on the decisions which determine the building's life cycle footprint. The method also demonstrates that structural intervention is an integrated

[5] Major part of this section has been already published in Keskin, Martinez-Vazquez and Baniotopoulos (2020a). Fatma Seyma Keskin wrote the major parts of the paper, while Pedro Martinez-Vazquez and Charalampos Baniotopoulos contributed with reviewing, editing and supervising the paper.

process that includes sustainability in existing frameworks. In this context, LCA stands as the primary vehicle to assess environmental impacts of retrofits under the following criteria:

- Sustainability considerations to determine the type of intervention to use: Including structural retrofit scenarios
- Sustainability considerations to select the end-of-life procedure: Including both structural retrofit and new building scenarios

Interventions are expected to extend the building's service life; hence the extended service life needs to be considered in the LCA (FEMA P-58-4, 2012). To build on this idea, these two criteria developed to consider the different impacts of the selected scenarios on service life and the environmental impacts. The first one explores retrofitting alternatives that fulfil the best practices for environmental sustainability. In the case of demolition or the high cost of intervention, end-of-life procedures (second criterion) becomes increasingly relevant due to the construction of the new building and its long service life. Thus, annual environmental impacts for end-of-life procedures should be considered (FEMA P-58-4, 2012). Either path will require progressive environmental impact study and initiatives to ensure each link in the chain addresses sustainability goals.

These two criteria define the two-stage process shown in Figure 3-1, while each criterion is discussed in sections 3.2.1 and 3.2.2, respectively. Once the viable techniques of structural interventions are selected, as per section Pre-LCA, the corresponding LCA can be carried out. The framework of ESSIM represented in Figure 3-1 is recalled and explained in Section 3.3. Therefore, the objective of the proposed method is to acknowledge the implications of decisions made during the planning, design, and implementation of structural intervention with a sustainability perspective which can lead to evidence-based decision making under the LCA

(FEMA P-58-4, 2012). Sustainable design decisions made using these considerations satisfies sustainability and structural safety requirements.

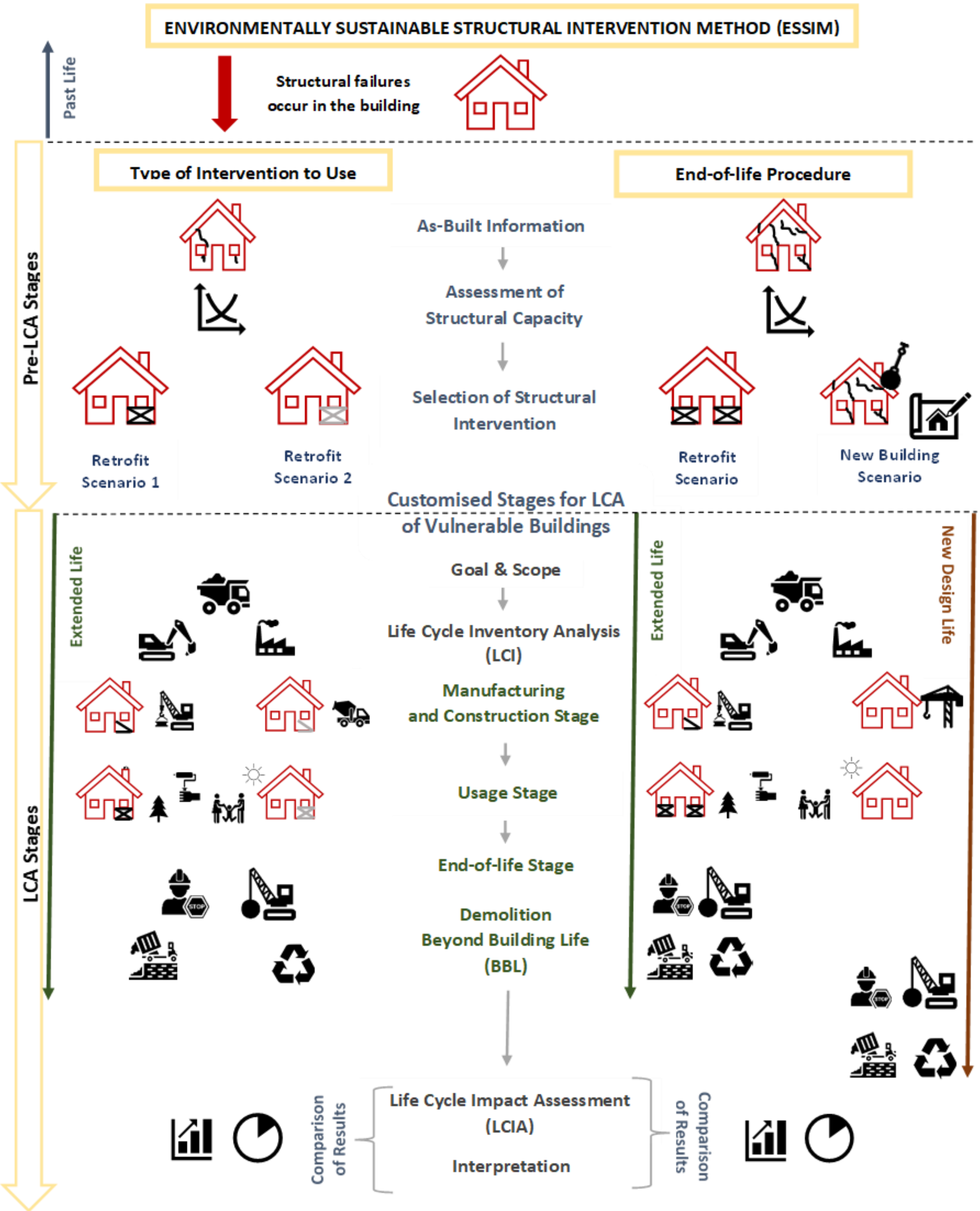


Figure 3-1 Simplified framework of the proposed method

3.2.1 Sustainability considerations to define the type of intervention use

The main idea behind resilient buildings is that they do not collapse even if damaged during a disruptive event. Recently, building design and adequate implementation of building codes have considerably improved and the occurrence of medium or low-damaged buildings became more frequent after disasters. This situation leads to a single decision that requires the structural strengthening of these damaged buildings. Furthermore, the development of construction technology has enabled various strengthening techniques to be implemented during the design and planning stage. In this process, LCA emerges as a tool that can be used to make a choice between these various techniques. The LCA compares the environmental impacts of intervention scenarios through the building's LCA stages. This process can exclude the existing building's embodied impacts as they do not change through the interventions. Regarding operational impacts, according to Georgescu et al. (2018), seismic retrofits often can have no effect on the energy performance of the building but may have detrimental or beneficial impacts as well.

3.2.2 Sustainability considerations to select the end-of-life procedure

Demolition is perhaps the most common end, result to remove vulnerable buildings such as those with deteriorated materials or unrepairable damage. The higher cost and the complexity of retrofitting limits the solutions to salvage the structure as safety cannot be overlooked at any cost. In this study, the intervention scenarios also consider the demolition of the building due to the replacement intervention. This criterion is to support that buildings can remain safe and serve longer by retrofit methods before making demolition decision and to present the difference in environmental impacts between the new and retrofitted building. The proposed framework now includes assessing the building's sustainable performance, including the end-of-life adopted method. The assessment process should include a qualitative evaluation of alternatives such as demolition versus retrofit - bearing in mind new design life and the extended service life provided by the latter. It thus seems convenient to discretise the environmental assessment of buildings into annual impact assessments (FEMA P-58-4, 2012).

3.3 Description of incorporating structural intervention in the LCA

3.3.1 Pre-LCA Stages: Structural intervention in vulnerable buildings

The vulnerability of existing buildings is usually investigated if one or more of the following conditions occur (Santos *et al.*, 2010);

- Damage after a disaster,
- Visible defects,
- Changing the intended purpose of the building (such as removing column),
- Structural changes implemented under new building codes, i.e. the existing design standard, resulted in structural design flaws during design and installation.

The presence of one or more combination of defects prevents the building from meeting its objected performance. It is important to note that disasters on their own do not warrant structural reinforcement; however, the damage caused becomes a factor that must be integrated into the decision-making process of strengthening. By implementing or installing new reinforcements, the expected performance can be matched or improved and are subject to local (national) procedures and practices, which can be subjected to various interpretations.

Notwithstanding that, building performance objectives may vary with the selected performance level, or conversely, performance-based standards may target different objectives (FEMA, 2006). Building vulnerabilities and interventions can also vary according to the type of building. For example, RC and masonry buildings have structural and qualitative differences; non-ductile adobe buildings (a masonry building is made of organic materials such as earth) exhibit great resistance to lateral earthquake movements due to the heavy walls (Bhattacharya, Nayak and Dutta, 2014) while RC buildings have ductile behaviours. As a result, this situation gives rise to different structural assessments and intervention methods. In this study, the ESSIM is developed bearing in mind the referred variability of local practices (e.g., Mexico building regulation differs from the one in Turkey). Furthermore, this study does not include hazard probability during the lifetime of the building due to a variety of uncertainties. It focuses on exploring environmental impacts of real applications of retrofit options, not predictive retrofit possibilities. Therefore, the layout of this section is purposefully general so that it aligns with existing research that proposes generalisation, so that the design framework can be used for any type of building, can be adapted for different types of disasters inducing damage and local performance codes.

The process includes three stages (adapted from FEMA 356 (2000) and BS EN 1998-3 (2005)):

- Obtaining as-built information of the damaged building
- Assessment of the building's structural capacity
- Selection of structural intervention and its design

3.3.1.1 Obtaining As-built Information of the Damaged Building

Obtaining the as-built information of the damaged building is necessary to understand the stability and robustness of the structure. This information will provide the critical elements which will progress into the second stage.

Location

The geographic location gives information about the seismic history and the vulnerability of the area to disasters. This information is also used in the LCA to select the origin of the products.

Original Drawings

Available plans and drawings are essential to understand the building geometry and also changes and additions to buildings after its initial construction. It also provides information about possible reasons for design failures, especially for a building that does not comply with new building regulations and design standards. This information also forms the basis of the LCA.

Characteristics of the Building

The structure of a building contains columns, foundation, beams, diaphragms and load-bearing walls to withstand lateral and gravitational loads, which are transferred to the foundation and the ground to preserve structural stability and integrity. A non-structural system may include the building's architectural and mechanical parts like windows and HVAC systems that do not have a primary role in withstanding seismic and other loads of the building (Comarazamy, 2005). In this section, the number of floors, overall dimensions, physical properties of building components, structural frame, system's geometry and foundations, roof (EN 15978, 2011), soil characteristics, age of the building and related building data are collected to be able to model the building. Also, the accuracy of the obtained information should be cross-checked against original drawings, if available. Therefore, to determine the structural characteristics, focusing on only the structural components of the building would be enough while assessing the structural strengthening of the building.

Building Function

The collected data would also factor the function of the building (office, residential, industrial), occupancy, relevant functional and technical requirements, refurbishment information, change in the use of the facility and required service life (detailed in below section) (EN 15978, 2011).

This information also feeds into the LCA stage since building types affect the maintenance activities during the use of the building.

Field Investigation

The first is assessing existing conditions to determine what could have induced structural failure and consequent material degradation. Destructive and/or non-destructive test records of the materials should be conducted and reviewed (FEMA 356, 2000), including foundation to upper structure and the soil. Because the response of the soil affects the motion of the structure during the disaster, and that depends on the characteristic of the underlying soil. Therefore, the interaction between the structure with foundation and the soil is necessary to consider to assess structural performance of the building (Jayalekshmi and Chinmayi, 2016). The non-destructive tests could take the form of a visual inspection, physical (e.g. rebound and flat-jack hammer), thermal imagining (e.g. infrared thermography), sound (e.g. ultrasonic pulse velocity, impact-echo method), and radar (e.g. ground penetration radar) methods to identify structural damage (Hussain and Akhtar, 2017). These records include cracks, irregularities, existing crushing of concrete, and it can usually be observed as buckling, yielding and rupture of steel, and the size or level of the damage is assessed further. Figure 3-2 illustrates two types of damage observed in RC and masonry buildings (Ilki *et al.*, 2012; Güney, Kuruşcu and Arun, 2016). The scrutiny of the material collected could inform engineers about the severity and level of the damage, while a portion of it could feed into posterior stages of damage evaluation.

a) Beam-column joint failure due to low shear strength of beams, inadequate shear capacity of columns and poor concrete quality (Ilki *et al.*, 2012)

b) Cracks on non-load-bearing wall (in the middle) due to insufficient connection in roof-floor joints and out-of-plan motion caused by height and thickness of the wall (Güney, Kuruşcu and Arun, 2016)

Figure 3-2 Damage types observed in RC and masonry buildings after Van Earthquake in Turkey (Ilki et al., 2012; Güney, Kuruşcu and Arun, 2016)

Regarding destructive tests, samples are taken from the building; these can be laboratory tests, in-situ test, field test, and soil tests (Ungureanu and Georgescu, 2013), for instance core tests and pull-out and pull-off tests (Malek and Kaouther, 2014). These tests would help to determine the expected building performance. Regarding masonry buildings, the survey is done as an inspection of the building that can be a visual inspection and/or by opening up the exterior surface to determine the material and damage (Santos *et al.*, 2010). Figure 3-3 displays two photographs of destructive test examples from two different building type.

a) Core sample taking for concrete quality control

b) The concrete surface removing for determining structural material

Figure 3-3 Destructive testing of RC and masonry two vulnerable buildings located in Kocaeli, Turkey

Vulnerability State

The visible defects and laboratory tests are identified and recorded in the field investigation process to determine the vulnerability state that considers only the structural part of the vulnerable building in this study. Data from the highly developed seismic design guidelines can be integrated to assess the vulnerability. Evaluating the extent or scale of the damage is vital to be able to select strengthening techniques. Failure to determine the damage classes will negatively impact the assessment and may lead to catastrophic results to life and property. There are several differences between damage level definitions in different codes and methods. For instance, FEMA 445 classifies these levels as slight (1), moderate (2), extensive (3) and complete (4) (FEMA 445, 2006); Turkish Building Seismic Code (TBSC) classifies performance levels based on structural damages, which are classed as uninterrupted use (negligible damage) (1), limited damage (2), controlled damage (can be economically strengthened or demolished) (3), collapse prevention (before collapse) (4) (AFAD, 2018b;

Güler and Celep, 2020); the SSD method (sPBA) defines the damage limit states as low (1), heavy (2), severe damages (3) and building collapse (4) (Caruso, Lamperti Tornaghi and Negro, 2017). The structural intervention can take the form of repair and/or strengthening. The former is executed to recover the building element's load-bearing capacity without upgrading structural resistance, while the latter implies increasing the load-bearing capacity and upgrading structural resistance (Santos *et al.*, 2010). In this study, either repair or strengthening and building replacement are referred to as intervention. Generally speaking, the levels of damages define repairable (can be repaired and/or can be strengthened) (1, 2 and 3 levels) and non-repairable conditions of the building, and so the highest level of damage (level 4 e.g., complete level in FEMA, collapse prevention level in TBSC and building collapse level in SSD) requires the building to be demolished. Destruction can also be considered for extensive (3) (e.g., controlled damage level in TBSC and severe damage level in SSD) damage, as well. Cost is often a decisive factor in retrofitting or reconstruction to buildings with extensive damage, and this value has been suggested as 40% in previous studies. In other words, if the repair cost is more than 40% of the rebuilding cost, the repair is not preferred (FEMA P-58-1, 2012; Chhabra *et al.*, 2018). Other factors may also lead to the demolition decision. For instance, difficulties in the installation process of the retrofit, its negative impact on the building function, long period of the construction timescale, and the need for occupants to relocate may trigger the demolitions decision.

In the proposed method, these damage scales provide an appropriate process for assessing retrofits' environmental impact. The first criterion includes the damaged buildings that require retrofitting, and the second criterion considers buildings that can be both reinforced or demolished, as in extensively damaged buildings. The generalised damage levels to which the criteria can be met are shown in Figure 3-4. (To be able to reflect these criteria, the case studies defined as low and medium-damaged refer to “type of intervention to use” and “end-of-life procedure”, respectively.)

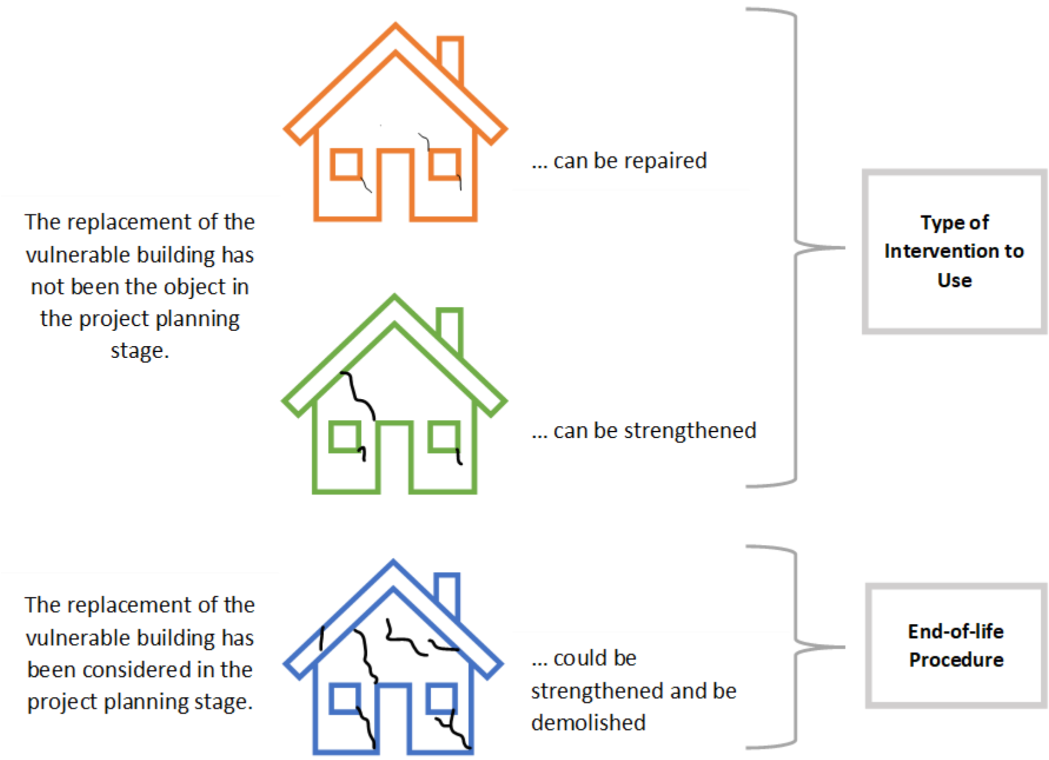


Figure 3-4 Generalised damage levels to corresponding criteria of the proposed method

Service Life

The service life is defined as the period after installation to the component meets or exceeds performance requirements (Jernberg *et al.*, 2004). The service life analysis of structural materials and components determine how the selected performance values change over time. Therefore, building service life can be estimated according to the service lives of its products by using the factor method based on ISO 15686-8 (2008) (Anand and Amor, 2017). The material degradation is taken into account to determine the service life and, therefore, necessary to determine the allowable degradation limits and performance requirements. However, the limit state is a complex issue that needs to be investigated economically, technically and environmentally. The building industry typically focuses on the first two issues; environmental impacts have mostly neglected. The characteristic performance over time varies according to the selected character and shows a statistical distribution (Jernberg *et al.*, 2004); therefore, service life is a function that cannot be expressed as a single deterministic value and shows a big scatter.

Today, with standardised methodologies, advances in the science of building materials, and the inclusion of this information in the building design, the service life estimation of building materials and components are possible (Jernberg *et al.*, 2004). For instance, ISO 15686-1.3 (1997), ISO 15686-2.3 (1998), BS 7543 (1992) and CSA S-478 (2001) are worldwide standards to estimate and predict the service period of building and its materials/components (Jernberg *et al.*, 2004). According to ISO 15686-1.3 (1997), an estimated service life method developed based on various factors such as; quality of materials and workmanship, level of building facility, environmental conditions for materials and location, the service life of similar materials and maintenance level (AIJ, 1993; Hernández-Moreno, 2012). These factors are based on empirical information and may change upon different statistical distributions (Hernández-Moreno, 2012). The assignment of these qualitative values are subjective values interpreted by the designer, so the designer must have all the necessary information to be reliable in the method implementation (ISO 15686-1.3, 1997; ISO 15686-2.3, 1998; Hernández-Moreno, 2012). Since this method gives an approximate service life, it is recommended to use it for a useful and fast estimation for the entire building.

Sustainable design implementation in the construction of buildings provides sustainability and advantages for planning service life, and increasing durability (Hernández-Moreno, 2012) while the LCA covers the entire period from the installation to the demolition of the building.

The service life begins with the use of the building, and some factors, such as predicting the service life and the durability of the building taken into account in the preliminary design process (Hernández-Moreno, 2012). Then, maintenance, repair or replacement of building components in a periodic cycle are included in the process. However, a decrease in the building's durability shortens its service life. Therefore, interventions to increase the service life are amongst the first steps that can be taken to sustain the building, and the effect of the chosen intervention on the service life should also be taken into account from a life cycle perspective (FEMA P-58-4, 2012). The intervention's impact involves uncertainties depending on the service life and impact category (i.e. corrosion, physical deterioration). For example, building location, such as rural or industrial areas, affects materials degradation depending on the carbonation rate. Therefore, estimation of the service life for retrofitted buildings, is challenging and quantitative studies are not available. However, such methods exist for long-lasting bridges and roads that require continuous maintenance and deformed continuously, such as (Kong and Frangopol, 2003; Karbhari, 2009; Mirza *et al.*, 2017). Results showed that appropriate maintenance could extend the bridge's service to 120 years from 70 years (Kong and Frangopol, 2003); this means that regular maintenance can increase the service life of a bridge by about %70.

3.3.1.2 Assessment of the Building's Structural Capacity

The information collected in the previous stage should inform the modelling of the structure. The analysis of the model should yield details on deformation of members and internal forces as well as on global performance indicators such as whether sections exhibit elastic or inelastic behaviour to determine their capacity level accurately. In the design and analysis of the original building, various analytical approaches and stress detection and strength comparisons are made (Ungureanu and Georgescu, 2013). Code procedures for the strengthening of buildings should also be looked at to confirm a reliable assessment of the building's capacity. The assessment procedure should link safety with performance criteria specified in the relevant code of practice (Arya and Agarwal, 2007). Regarding the seismic performance of buildings, there exist several methodologies with developments in analytical approaches, such as FEMA 356 (2000), FEMA 445 (2006), Eurocode 8 (2005), TBSC (2018b); these include different assumptions for seismic movements, input factors, assessment of vulnerability and building types (Bertogg, Hitz and Schmid, 2002; Alam, Alam and Tesfamariam, 2012). Therefore, the performance objective of a building may vary according to the selected performance level, or performance-based standards, selected building codes, and standards targeting different objectives (FEMA, 2006).

3.3.1.3 Selection of Structural Intervention and its Design

There are structural and functional choices to be made in the retrofit design process. When considering retrofit solutions and design options, the retrofitting process often has mandatory prerequisites stipulated in codes and standards, and these conditions include mechanical and functional requirements (Menna *et al.*, 2016). The selection of the type of intervention is directly related to the structural irregularities, initial rigidity and geometry of structure, if any, of the vulnerable building (Marini *et al.*, 2017). Therefore, the assessment results of the structure inform the selection of the type of intervention. The retrofitting should be capable of going through higher or similar loads than those that caused the damage without collapsing while ensuring that the building meets the acceptable limits and desirably improve the performance level.

The classic forms of strengthening and/or modifying structural ductility occur at a local and global level (Georgescu *et al.*, 2018). Local interventions aim at increasing resistance, ductility, and stiffness of structural elements and joints (Ferrante *et al.*, 2018), whereas global interventions aim at increasing the lateral stiffness of the overall system, for instance, through the addition of structural elements like shear walls and bracing (Georgescu *et al.*, 2018). Two examples of local and global interventions are presented in Figure 3-5 (Kaygısız, 2015).

a) Local intervention: Rehabilitation of concrete member with RC jacketing

b) Global intervention: New RC additions to the façade of the building

Figure 3-5 Two reinforced concrete examples of local and global intervention applications (Kaygısız, 2015)

Some of intervention techniques are;

Wrapping (Jacketing): This is the local level of strengthening (Marini *et al.*, 2017), which can be implemented to improve the shear or/and flexural strength and also ductility of RC members (Georgescu *et al.*, 2018). The typical applications are RC, steel and FRP wrappings (jackets) to increase stiffness, ductility, resistance (PAHO, 2000), and improve joint connections (FEMA, 2006)

Additional: Extra structural elements such as beams, pillars, foundation, shear wall and interior structural walls (PAHO, 2000) increase lateral strengthening (Georgescu *et al.*, 2018).

Energy dissipation devices: These are usually in the form of base isolators to control vibrations. Base isolation protects the structure from the damaging effects of an earthquake by improving the structure's dynamic response and significantly reducing the seismic demand and displacement. This method is used by using different types of base isolator devices to install in the foundation part of the building (Vitiello *et al.*, 2016; Haghpanah, Foroughi and Behrou, 2017; Georgescu *et al.*, 2018), and can be installed just below the first floor, under columns or shear walls, such as rubber bearing (Kawamura *et al.*, 2000). Dampers are also used to reduce seismic demand, and such dampers (viscous, hysteretic, viscoelastic, etc.) can be inserted between an external reaction structure and the building prior to retrofit or it can be embedded in the structure (Georgescu *et al.*, 2018). One of the examples of the base isolations and dampers is presented in the *Figure 3-6* (Buckle, 2000; Kawamura *et al.*, 2000; Agrawal and Shrikhande, 2006).

Epoxy Injection: This material is a kind of adhesive, mortar, and sealant, and it works as a stabiliser for new concrete (Traykova and Chardakova, 2014).

Others: Braced frames, external steel braced frame, frame walls, buttresses, and construction of a new framed system (PAHO, 2000).

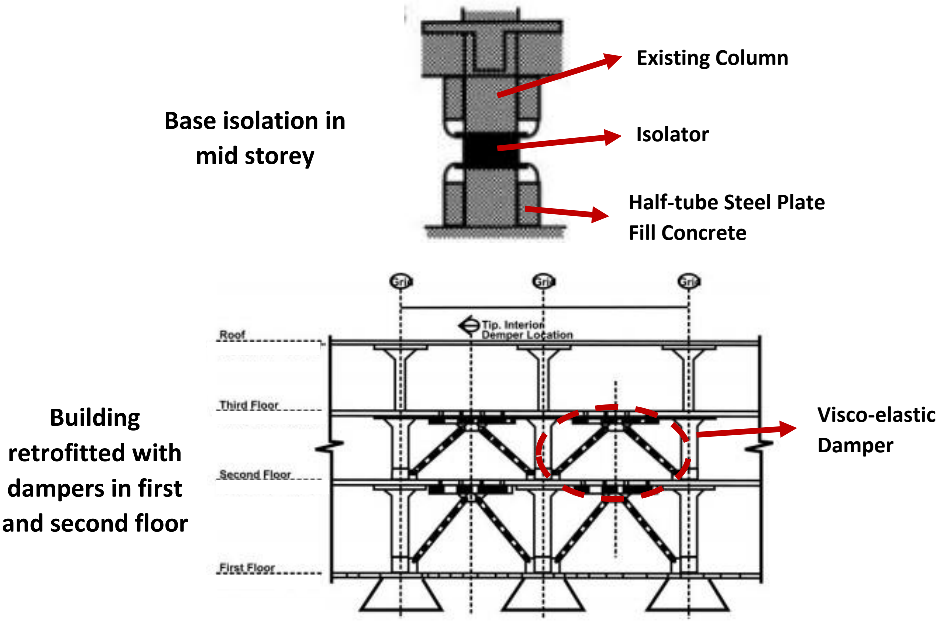


Figure 3-6 Base isolation retrofit of building supported by columns (Kawamura *et al.*, 2000) *and building retrofitted with dampers* (Buckle, 2000)

Building type also determines the strengthening technique that can be chosen. For instance, masonry buildings have different intervention applications such as surface treatment, steel chain installation, mesh reinforcement, shotcrete, and seismic wallpaper. The option to take would depend on the type of material used in the main construction, e.g., concrete, timber, steel, and masonry. An interim between stages would be for designers to figure out what type of retrofit to use. There is no single solution, but different intervention techniques have their own specific installation process and timescales. The recovery time also depends on the functionality of the building and the maximum acceptable time, which may differ for different occupancies and buildings (FEMA P-1050, 2015). The local level of interventions is focused on the demolition of schedule-timeline, downtime, and relocation of the habitants. These interventions are not adequate for some building component designs, such as shallow beams, because of their installation difficulties (Marini *et al.*, 2017). The global level of interventions consists of additional structural elements like shear walls and bracings; however, these approaches have some architectural considerations and need to appropriately installed and connected to the existing structural fittings for seismic resistance (Georgescu *et al.*, 2018). These techniques require good workmanship quality and need to be designed accordingly to the original purpose of the building.

If the demolition is included in the structural intervention scenario, the end-of-life procedure is applied. In this case, the life cycle of the new building is also included. While the new building is constructed according to code requirements and preferred design parameters, a building demolition depends on many other criteria such as structural characteristic, demolition equipment, and safety and site conditions.

As mentioned above, functional choices should be made in addition to structural interventions. Comparable considerations that take into account the functionality of the retrofits can contribute to the construction sector's sustainable development goals and should be evaluated using appropriate criteria (Menna *et al.*, 2016). The following aspects would ideally feed into the analysis of sustainability study to achieve its targets (Santos *et al.*, 2010); structural safety, quality of workmanship, type of technique, level of integration with other parts or components of the structure, relocation of inhabitants, noise and vibrations induced, aesthetics, cost, time, and investigation of product satisfaction. It is not always possible to combine or keep control of all these aspects and would require optimization of various partial procedures. Therefore, this research focuses on safety and environmental impacts only.

3.3.2 LCA Stages: Incorporating structural intervention into the LCA framework

The importance given to environmental protection due to concerns has increased, and the methods in this field have also developed accordingly (ISO 14040, 2006). One of the methods developed to understand better and address environmental impacts or burdens is the LCA (ISO 14040, 2006). In recent years, existing methods, tools and databases have been under continuous development and renewal (Caruso, Lamperti Tornaghi and Negro, 2017) to standardise the LCA and generate more precise results. Although the LCA framework is product-based, significant developments are underway under ISO, ASM and CEN standards to develop LCA methods for buildings (FEMA P-58-4, 2012). LCA's general guidelines were issued by ISO 14040 and ISO 14044, forming a structured, comprehensive and internationally standardised method (EC, 2010). This method aims to identify the environmental performance of the building and its materials throughout its life span (FEMA P-58-4, 2012). Annex 57-1 (2016) recommends the standards ISO 21929-1 (2011) and EN 15978 (2011) to be used for assessing specifically for embodied impacts. As a result of developments, ISO 14044 (2018) and ISO 14040 (2006) now frame LCA into the following four steps, which are described in detail in the ILCD Handbook (2010):

- Goal and Scope
- Life cycle Inventory Analysis (LCI)
- Life cycle Impacts Assessment (LCIA)
- Interpretation

These steps work based on iterative procedures that define how each step affects the preceding. (ISO 14040, 2006; ASMI, 2011). In this proposed methodology, developed structural intervention scenarios evaluate environmental performances once the safety limits are satisfied. Therefore, this framework is considered as an assessment method for selecting or deriving the most sustainable solutions. LCA could also feed into decision-making processes to promote sustainability in the construction sector for addressing environmental concerns (Ortiz, Castells and Sonnemann, 2009).

3.3.2.1 Goal and Scope

The goal and scope include motivations for the implementation and completion of an LCA (ISO 14040, 2006). The scope includes the system, system boundaries, impact categories, quality of data, assessment parameters (data sources) and functions of the system. In this study, the goal of the proposed method is to produce a way to achieve the most sustainable solution in terms of the facility and the feasibility of the method. The scope includes as-built information and structural performance of the building, implementation of strengthening techniques, determining service period, LCI inventory assessment, and LCIA analysis throughout the building life cycle. The goal and scope should be defined in more detail, according to the presented in Chapters 4 and 5. LCA quantifies the environmental impacts, including extraction and manufacturing of materials, transportation, use, maintenance, demolition, disposal and recycling, and the selected stages determine the system boundary (Consoli, 1993; Menna *et al.*, 2013). The system boundary is limited by the period of the life cycle. This research defines the whole life cycle as a system boundary, in other words, from cradle-to-grave. Functional units are determined in relation to a particular material or building component (Anand and Amor, 2017). This research includes retrofits and building materials represented by m, m^2, m^3, tonne, and kWh as functional units.

3.3.2.2 Life Cycle Inventory Analysis (LCI)

LCI includes collecting the necessary data for analysis, such as energy, resources and water (ISO 14040, 2006). The input and output flow of collected data refers to various processes in the life cycle stages inside the selected system boundary, and the outcome of the LCI is revealed as a life cycle inventory (Gencturk, Hossain and Lahourpour, 2016). LCA could be achieved either as a unit process, economic input-output (EIO), or hybrid process. EIO quickly estimates repair cost, which is available in PACT and FEMA P-58 (2012). The unit process is traditional and arguably the most precise approach (FEMA P-58-4, 2012). Since the present study is based on the bill-of-materials (BOM), the unit process is adopted to complete the inventory.

BOM signifies the quantity of materials (e.g. concrete - m^3, steel - tonnes, electricity- kWh, etc.) that can be measured from drawings or exported from Building Information Modelling (BIM), 3D CAD or quantity experts (Annex 57-1, 2016). BOM is crucial data for LCA buildings and needs to be accurate and comprehensive (ASMI, 2020b). While collecting data, concepts such as the location, age, scope and diversity of the data should be considered in terms of data quality. Therefore, collecting the data can be challenging and time-consuming. For this reason, the as-built information in the Pre-LCA stage also feeds into this step. If the direct measurement is not possible, data can be obtained from other sources as secondary data such as the production of materials, construction works, transport operations, maintenance and demolition. Therefore, the database would include the whole life cycle of materials impacts through manufacturing to end of life (FEMA P-58-4, 2012).

Building inventory data for LCA of the whole building is highly dependent on LCA data of building components and materials, and this data is obtained from the building industry, databases or Environmental Product Declaration (EPD) (Anand and Amor, 2017). Several databases and tools exist, such as the BEES Database (U.S.) (BEES, 2011), U.S. Lifecycle Inventory database (USLCI, 2012), Ecoinvent (Europe, Global) (Ecoinvent, 2020), some of the tools are AIEB (Athena Impact Estimator for Buildings) (ASMI, 2019a), OpenLCA (OpenLCA, 2020), SimaPro (SimaPro, 2020) and GaBi (GaBi, 2020). If national data is inaccessible, EPD, a standardised procedure defined in ISO 14025 (2006), and EN 15804 (2013) and EN 15942 (2011) can be used (Lützkendorf, Balouktsi and Frischknecht, 2016). These tools help eliminate the continuous change in the LCA process, including transport and manufacturing, that minimise disparities by increasing standardised practice with third-party centralised data sources and review. Nevertheless, it should be noted that LCA is a rigorous science that does not give an absolute result and certainty and contains various variables (ASMI, 2020a). Also, variations exist in generic data of products and EPD's due to the data sources and insufficient data collection methods. In this case, product-level data quality control can be performed using data quality indicators in databases and EPDs (Anand and Amor, 2017).

In this study, the LCI database would contain retrofitting and new building materials, and that could be comparable, employing the same assumptions and data sources. Since this study deals with structural interventions, only embodied impacts are focused. LCA stages are constrained by system boundaries as cradle-to-grave in ISO 14040. However, the details in the system boundaries are shaped with the goal of the study (ISO 14040, 2006). EN 15978 (2011) presents specific LCA stages regarding building components and construction; however, these stages need further scrutiny to cover specific conditions of damages and its recovery. Life cycle impacts related to disaster damages can be added to the life cycle impacts of building construction and can be assessed separately with customised stages (FEMA P-58-4, 2012). In this way, particular requirements derived from interventions can become part of an integrated approach (Romano, Negro and Taucer, 2014). For this reason, LCA stages for structural interventions should stand alone hence allowing space for proper reflection of vulnerability in buildings. This is reflected in Figure 3-7 and detailed in the below sections, where structural intervention branches out into a specific parameterisation spanning between raw material extraction and the end of life. Three posterior stages of the remaining life cycle of the building are derived from these customised LCA stages. Detailed parameters of each stage reveal more clearly how to get LCI of the structural interventions.

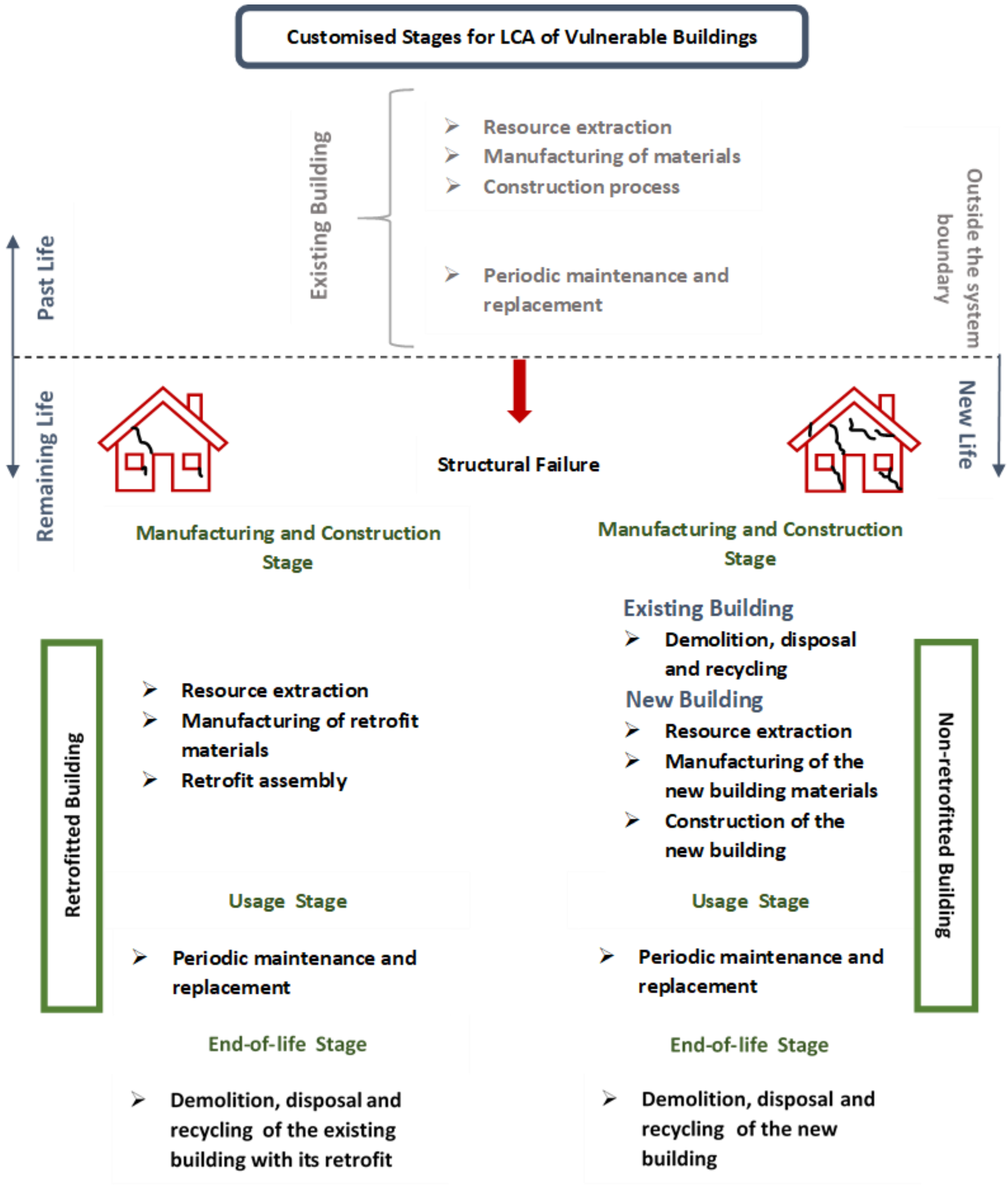


Figure 3-7 Customised LCA stages to cover specific conditions of the vulnerable buildings

Manufacturing and Construction Stage

LCI of this stage for a complete LCA is primarily related to data from the building's materials and components and includes many parameters, variations, and assumptions (Anand and Amor, 2017). The critical details require precise evaluation of the manufacturing and construction stages of the retrofitting and building. For this reason, these two stages have been presented under a joint heading, considering the life cycle stages and their distribution over the service period of the buildings. There are plenty of parameters related to retrofitting or rebuilding construction; assumptions can be made to reduce missing data. Since this method is based on scenarios and their comparison, it can minimise uncertainties and predictions by eliminating the same factors in these scenarios, which provides practicality in practice. The factors to be considered during the manufacturing and construction stage also presented in some publications such as FEMA P-58-4 (2012), EN 15978 (2011) and, ISO14040 (2006). Considering the scenarios in this proposed method, the parameters evaluated as in Table 3-1 takes into account the variety of retrofitting techniques and building designs.

Table 3-1 Summarised specific parameters of manufacturing and construction stage

Scenarios	Parameters	
Retrofit Scenario	Retrofitting materials	Type of materials and quantities for manufacturing
	Transportation	Transportation distance and modes for materials, disposal, and labours
	Construction works	Construction equipment use, retrofit assembly (scaffolding, preparing, and cleaning for retrofit implementation)
New Building Scenario	Demolition of vulnerable building	Demolition equipment use, material type and quantities for disposal
	New building materials	Type of materials and quantities for manufacturing
	Transportation	Transportation distance and modes for disposal and new building materials and labours
	Construction works	Construction equipment use, assembly of the new building (scaffolding, site preparation)

Usage Stage

The usage stage includes maintenance, repair, periodic renewal, replacement of end-of-life materials, transport and installation of new materials, and cleaning (preparation) waste (Annex 57-1, 2016). However, the emissions of these applications may change over time, and new technologies may be developed. This creates uncertainties about how to combine these emissions over time with a time-defined inventory. The application of such dynamic aspects to LCA is called dynamic LCA. Dynamic LCA is a new field and includes uncertainties related to technological forecasting and changes according to time, such as energy mixes over the building's lifetime (Anand and Amor, 2017). However, existing LCA and repair studies that consider the dynamic aspects of processes and the time-dependent changes in the environmental impacts are not yet available (Hasik *et al.*, 2018). Therefore, this study considered environmental impacts as a constant for the whole life cycle.

Operational energy and water consumed are also included in this stage; however, these factors will be the same for the selected structural retrofit scenarios and so can be neglected from the report. Embodied impacts are relevant to structural interventions, and this research does not relate with intervention on the building's operational impacts. Nevertheless, these should be considered for a new building scenario due to its longer service life rather than a retrofitted building. Therefore, estimating and including the information on the extended service period of the retrofitted building and the long service period of the new building is necessary for LCA to estimate operational environmental impacts. As a final point, both scenarios' annual impacts can be estimated to make a precise comparison.

End-of-life Stage

Buildings are demolished at the end of their useful life. Retrofitted buildings demolish as a whole building together with their retrofits at the end of life. However, this process does not require the inclusion of the main building due to the same activities of both scenarios. On the other hand, retrofit and new building scenarios need a demolition process because there are differences. In the demolition process, firstly, the reinforced elements on the exterior are demolished, followed by the use of special demolition equipment. Building demolition can be done mechanically or manually via cranes, excavators, hydraulic breakers, or bulldozers.

Demolition of high-rise buildings may require wrecking balls; however, this method is not useful for controlling the process. Another method is breakers and rotational hydraulic shears used to break concrete. Explosives are also another option to demolish high-rise buildings. In brief, demolition requires a high level of diesel and electricity (Talukhaba, Phungula and Manchidi, 2013), so it should be included in the scenarios at the end of life.

After the demolition process is completed, the rubble waste is transported to the relevant plants for disposal, landfill, reuse or recycling. This transportation distance and mode, and then the environmental impacts from disposal to recycling are calculated (EN 15978, 2011). BOM of recycled materials is determined based on assumptions of recycling rates and operations of materials derived from industry and manufacturers (Annex 57-1, 2016). This stage is considered as Beyond Building Life (BBL); this system boundary includes reuse, recycling and energy recovery that are considered as a potential resource to use in the future (EN 15978, 2011). The BBL process assumptions are also inevitable due to changes and developments between current and future technologies (Gervásio, 2010). Since recycling is not well developed and can be expensive, the recycling process results in the production of different materials of lower quality called downcycling, such as concrete as filler material and concrete aggregate. One of the most common waste disposal methods is incineration. During that energy is produced (export energy) and at the same time CO_2, such as wooden waste incineration (Hauke and Siebers, 2011). Calculation of export energy is beyond the scope of this study. Analyses in this study follow the closed-loop recycling process or avoided burden method for metals recycling, which quantifies the net environmental benefit and loads of the process, subtracting the impacts of the products (secondary material) produced in recycling (EN 15978, 2011). Regarding intervention scenarios, in case of demolition of the existing building and replacing it with the new one, the demolition process includes disposal and recycling processes of the existing building and the net benefit from that process is reflected in environmental impact results (e.g., environmental impact results from construction stage of the new building). However, the new building construction is considered apart from that demolished building's impacts because the recycling materials may not use in that new building, but its benefit still exists.

3.3.2.3 Life Cycle Impact Assessment (LCIA)

At the LCIA step, the inventory outcome obtained in LCI is processed and converted into environmental impacts. The environmental impact is indicated by the category indicators calculated from the LCI results with characterisation factors. The characterisation includes the conversion of LCI results into common units. These factors help compile many chemical emissions according to their corresponding environmental effects and calculate the equivalent effect of 1 kg of emissions into the environment that allows converting the common units and aggregating results in the same impact category. For instance, climate change impact covers CO_2 as a reference substance, and methane is one of its contributors. The climate change characterisation factor of the 1 kg methane is 23, giving a figure of 23 kg CO_2 equivalent impact for the impact category of climate change (BRE, 2021). Figure 3-8 displays summarised process of calculating the life cycle values of embodied environmental impacts (Annex 57-1, 2016). For instance, BOM is multiplied by the embodied carbon coefficients (kgCO_2 per kg of material) stored in the LCI database or LCA software databases (Annex 57-1, 2016). Therefore, LCIA connects the LCI results to environmental impact category indicators (midpoint); such as global warming, and environmental damage indicators (endpoints); such as damage to human health or decrease in fish population (ISO 14040, 2006; Ortiz, Castells and Sonnemann, 2009). However, currently, these indicators cannot directly address the ultimate effects on endpoints because of the uncertainty and challenges in assessment (ASMI, 2020a). Depending on the available impact assessment methodology in the LCA software, various impact categories become available (Anand and Amor, 2017).

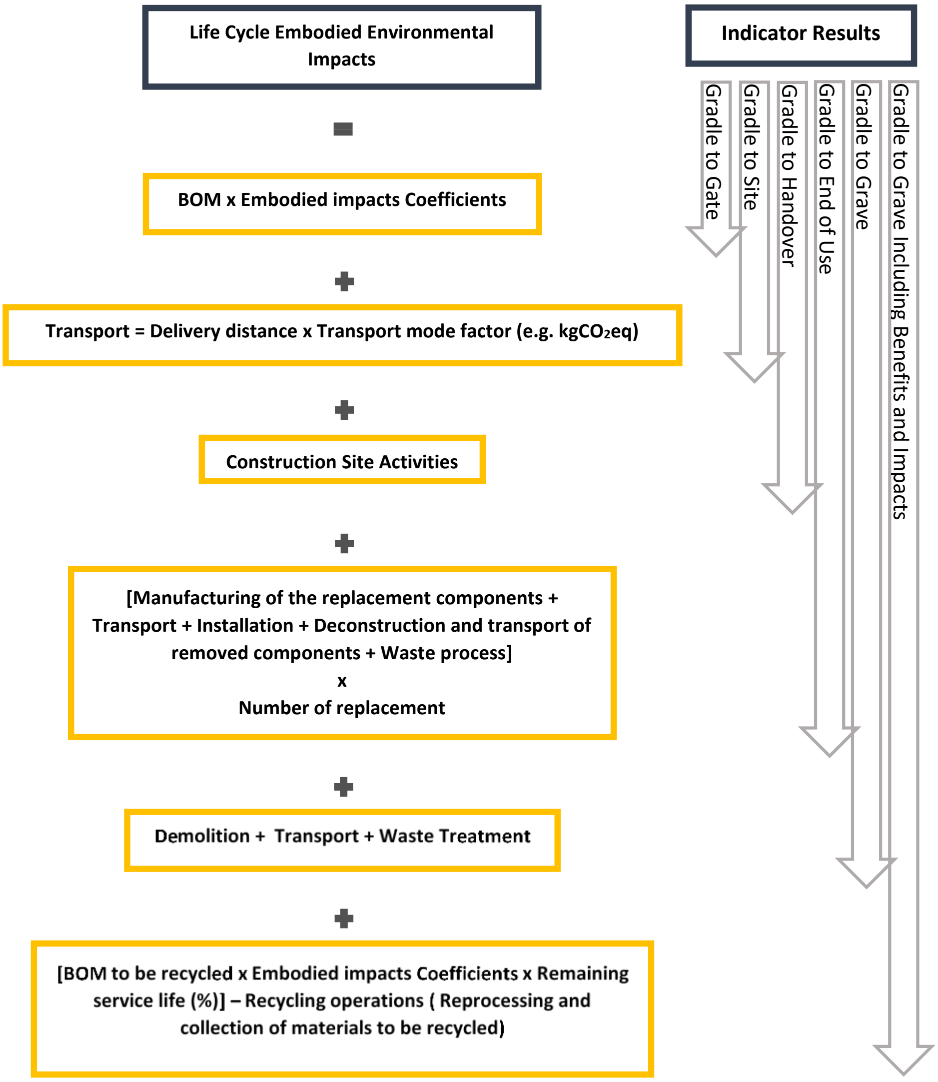


Figure 3-8 Summary of the typical calculation process of cradle-to-grave embodied impacts (Annex 57-1, 2016)

Overall, the data outputs show that damage may be caused to the environment, including air, water, land and non-renewable resources (ISO 14040, 2006). Therefore, inventory flow contributing to the same impact categories can be grouped according to appropriate characterisation factors recommended by various LCIA methods (Gencturk, Hossain and Lahourpour, 2016). For instance, TRACI (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) (2011) use characterisation factors published by US Environmental Protection Agency (EPA) (Simonen *et al.*, 2015). Another method IPCC (International Panel on Climate Change) uses CO_2 to determine weighting GHGs and lists GWP for different time horizons (Anand and Amor, 2017). The IMPACT 2002+ methodology links LCI results to damage categories by linking midpoint categories (Jolliet *et al.*, 2003). In this field, databases, methodologies and software are continuously updated. In the LCA of the building, the choice of indicators has generally depended on the comparison related to the goal and the one that can be easily understood and interpreted (Anand and Amor, 2017).

Life cycle impact results are calculated on a probabilistic basis. The most common environmental impacts are embodied carbon and energy. These would generally be reported as a part of the contribution to GWP or climate change and primary energy resources, respectively (Lützkendorf, Balouktsi and Frischknecht, 2016). GWP is a relative measure of GHG mass measured against carbon dioxide equivalents (kg CO_2eq) for time horizon (e.g. 50, 80, 100 years represents a deterioration of gas concentration in the atmosphere over time), that affects climate change and represents carbon footprint (Annex 57-1, 2016; Lützkendorf, Balouktsi and Frischknecht, 2016). The cause and effect pathway of climate change that started with the release of GHG emissions and ended with global warming is illustrated in Figure 3-9 (Huijbregts *et al.*, 2014). Primary energy includes all direct or indirect energy consumption to produce or transport products and is measured in megajoules (MJ) (ATHENA, 2019b). There are a broad set of life cycle environmental impacts representing environmental footprint that are more established when compared to the carbon footprint. An overview of the link between the inventory, midpoints, endpoints and areas of protection is presented in Figure 3-10 according to ILCD Handbook (EC, 2010).

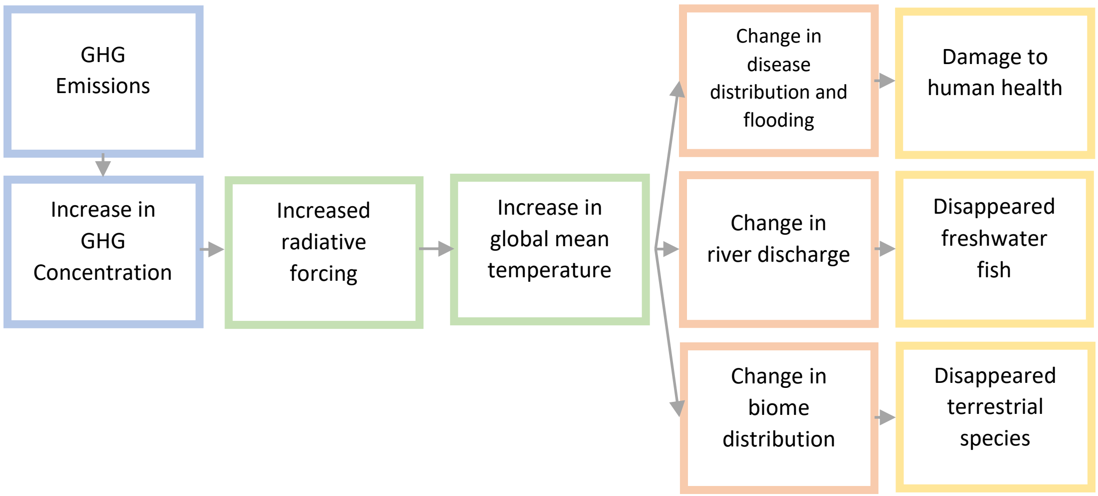


Figure 3-9 Cause and effect pathway of climate change (Huijbregts *et al.*, 2014)

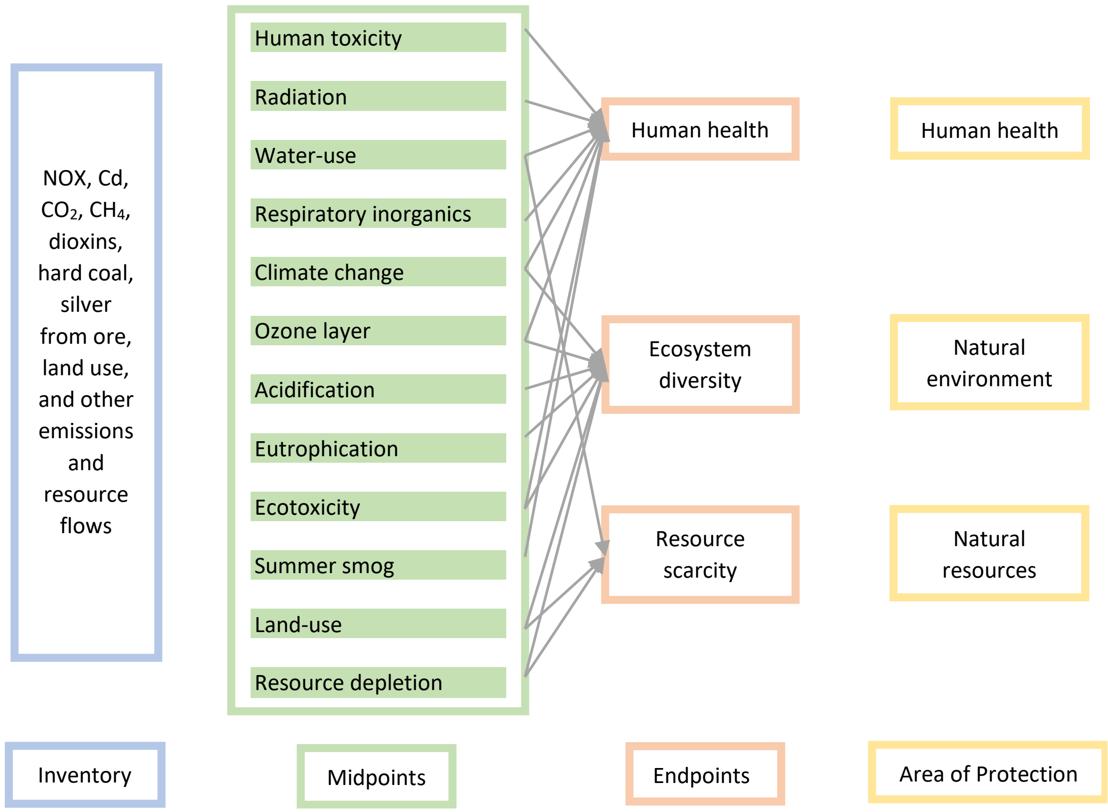


Figure 3-10 Schematic steps of life cycle impact assessment (EC, 2010)

According to ISO 14044 (2006), there exist some optional steps in LCIA. For instance, normalisation estimates the magnitude of category indicators, and it helps to compare results on reference value (reference impact) such as per unit basis. Therefore, normalisation helps to determine the most impactful categories between the impact categories that have different units. For instance, the reference value for an Environmental Profile of BRE (Building Research Establishment) is determined as the impact of a European citizen over a year (e.g., the environmental impact of one citizen is 12.3 tonnes CO_2 equivalent for normalisation factor of climate change) (BRE, 2008). Weighting aggregates and converts results based on value-choices according to the importance of factors. For example, Environmental Profile uses weightings to create a single score for total environmental impacts, called Ecopoint Score, which refers to the environmental impacts of one Western European citizen for one year (e.g., climate change has the most significant importance with 21.6% weightings rate) (BRE, 2008). Therefore, this procedure can include subjective and regional factors. Data quality analysis assesses the reliability of the results to satisfy determined requirements. Sensitivity analysis is a procedure that estimates how changes in method and data selection affect impact results. LCA results are associated with a probabilistic manner. FEMA P-58-4 (2012) describes the uncertainties as follows; lack of LCI data corresponding to specific materials, assumptions in the calculation of repair materials, material transportation, variety of repair work, site complexities, constantly changing industrial data, and so changes in the environmental impacts. Uncertainty analysis can be applied to estimate the uncertainties in the calculation and data and their effect to impact the reliability of the results (FEMA P-58-4, 2012). Although LCA is in the process of development, it has limitations; using foreign databases instead of local sources, lack of comprehensive guidelines or selected system boundaries can be examples of limitations in LCA studies (ATHENA, 2019a). Several methods exist that assess life cycle impacts; however, there are currently no guidelines for performing LCA according to internationally accepted methods or precise comparison of results (Anand and Amor, 2017).

3.3.2.4 Interpretation

Interpretation is the last stage of LCA and includes evaluations of results, defining important environmental impacts, conclusion and recommendation (ISO 14040, 2006) based on assessment results underpinned by the Goal and Scope. In this research, comparisons of selected scenarios are also included in this stage. While embodied impacts can be selected as proxy measures for environmental impacts, other impact categories can also be presented to interpret the impacts on relevant damage categories. The results can be plotted for each life cycle stage of the selected scenarios and over their whole life cycle. The extended service life of the retrofitted building should be reflected in the results. Even if the retrofits have extended the building's service life, the service life of a new building is usually longer. However, in this case, the environmental impacts of the new building's construction will be decisive. Therefore, the total environmental impacts are distributed over the service lives so that the annual impact can be determined for both scenarios from a life cycle perspective.

Figure 3-11 shows the cumulative distribution of embodied and operational energy consumption of a building systematically during its life cycle (O'Connor and Bowick, 2014). The segment of the curves associated with embodied energy caused by construction and repair are flat; the inverse is true for the operational stage showing fluctuations. However, with the application of the proposed method to a retrofitted or reconstructed building, this plot will change because complete construction is avoided, and for the latter, demolition is adopted for a vulnerable building. Furthermore, the service period of these scenarios will not remain the same. Therefore, considering these factors, the environmental impact of a vulnerable building after retrofitting or new construction can be determined over its life cycle stages and its extended service life with the proposed method.

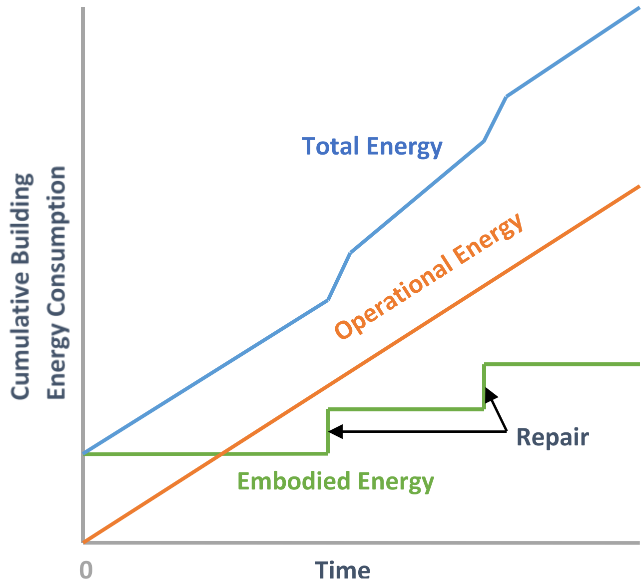


Figure 3-11 Cumulative energy consumption of a building over time (O'Connor and Bowick, 2014)

3.4 Summary of the proposed method

This chapter presented the proposed sustainable structural intervention method over the building life cycle stages. Primarily, the two-stage process was developed, which are demonstrated as Pre-CA and LCA stages, to integrate structural interventions into the standard LCA procedure. The framework was detailed, considering the structural interventions that vulnerable buildings can be exposed. Therefore, the method was developed based on two criteria by evaluating the possibility of retrofitting or the reconstruction of vulnerable buildings. In the following sections, the steps of the Pre-LCA and LCA stages, the guidelines, standards, and parameters to be considered were detailed to explain how to determine the scenarios and how the assessment will be carried out.

The following two chapters present the applications of the defined criteria. Chapter 4 assesses a low-damaged building where the criterion for the type of intervention to use is selected and applied for two determined structural intervention scenarios. Chapter 5 considers a medium-damaged building where the criterion for end-of-life procedure is applied for retrofit and non-retrofit scenarios.

4. THE ESSIM'S APPLICATION TO A LOW-DAMAGED BUILDING

4.1 Foreword

This chapter applies the ESSIM described in Chapter 3 to a low-damaged building. The building is a residential building and was constructed in 2001. The majority of Turkey's buildings, nearly 87%, constitute residential buildings (NEEAP, 2018) and 66% of these buildings are located in the seismic zone (Ergunay, 2007). Turkey is located in one of the seismically active regions of the world, and almost every part of the country is in the seismic zone. In the event of a destructive earthquake (7.25 Mw), it is estimated that in Istanbul, which hosts one million buildings, approximately 34% of buildings will receive low damage, 15% medium damage and 4% heavy damage or collapse. To avoid possible losses in Turkey, about 7 million vulnerable buildings, mostly residential, are being demolished and rebuilt with the urban renewal program (Erdik, 2013). As a result of the painful experiences in recent years, the earthquake code has been changed three times in the last 25 years: 1998, 2007 and most recently in 2018. The current seismic design code and other building codes have been prepared following global standards. For instance, dynamic analysis and mode superposition methods were introduced, and minimum cross-sectional dimensions were renewed in 1998 (RTOG, 1998). Then, performance analysis for the retrofitted structures was included as a new section in the 2007 earthquake code (RTOG, 2007). Regarding the 2018 building seismic code, seismic acceleration values of soil that include updated information from renewed seismic hazard map of Turkey (AFAD, 2018a) was improved, and new sections were added about such as precast and cast-in-place RC buildings, seismically isolated buildings and design of structural and non-structural elements (AFAD, 2018b; Atmaca *et al.*, 2020).

The case building is located in the Ercis district of Van, Tukey. It is a settlement where earthquake movements have been observed frequently, and there have been many damaging earthquakes in the past. In 2011, the 7.2 Mw earthquake with an epicentre in Van caused heavy damage to 30% of the buildings in the area (Beyhan, Keskinsezer and Kafadar, 2019). Most of the heavy damage and collapses were observed in the Ercis district due to structural and design errors in some buildings, such as failures in beam-column connection, inadequate anchorage, lap-splice lengths, hoop reinforcement, column dimensions and expansion joints (Ozden, Akpinar and Meydanli, 2011). The fact that the retrofitting works in the area started in 2012, right after earthquake, has made the city one of the exemplary places for the retrofitting techniques applied in the region recently. The case study building combines the retail store on the ground and mezzanine floors, and apartments on the upper floors. This type of building is quite common in Turkey, especially in city centres; they have widened openings to showcase the retail stores on the ground floor. Similar designs have caused significant caustic effects in past earthquakes in Turkey (Atay, 2010).

The energy-saving potential of residential buildings in Turkey is 46% (ATCMP, 2014). With the new energy certification regulation, most dwellings are planned to be at least a C (A is the highest energy consumption level and G is the lowest) energy level by 2023 (Gurlesel, 2012). This energy and related GHG levels are determined according to the reference indicator values determined for each building type and four regions specified in the regulation (RTOG, 2008, 2010). The building is placed at an energy level between A and G by comparing it with the indicator values expressed in coefficients. Depending on the increasing number of buildings and the potential to save energy, sustainable interventions have become significant in new and existing buildings. Therefore, integrating safety and sustainability in Turkish buildings is essential in regards to their susceptibility to seismic motions.

Therefore, this chapter investigates a damaged residential building where two different strengthening techniques can be applied. These two techniques are assessed from a life cycle perspective to ensure their relative environmental performances. The flow chart in Figure 4-1 below can be followed for the sustainable design of a vulnerable building with the selected retrofit scenario.

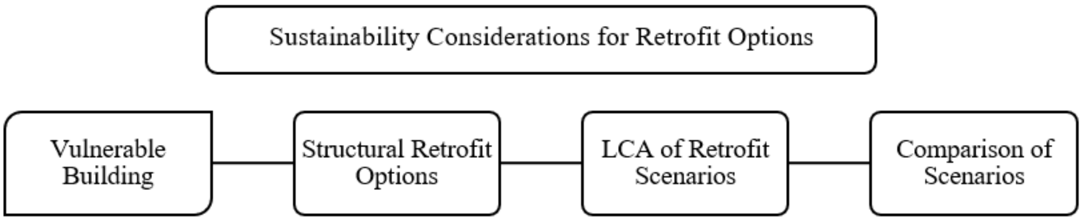


Figure 4-1 Flow chart of a vulnerable building assessed considering different retrofit options for a low-damaged building

The objectives set for this chapter:

- To describe and investigate the vulnerability conditions of the low-damaged building.
- To incorporate the LCA stages according to the defined intervention scenarios.
- To assess the environmental impacts of selected scenarios to minimise life cycle emissions.

4.2 Pre-LCA stages

In this section, two feasible scenarios were generated for a vulnerable building based on the proposed method. The vulnerable building was investigated in three stages. Architectural and structural details of the project were outsourced by the project engineer.

4.2.1 Obtaining as-built information

4.2.1.1 Location

The case study building is located in the Ercis district of Van and was damaged due to a consecutive earthquake called the Van earthquake that occurred in 2011 (M_W=7.2) (Erdik *et al.*, 2012). Van is located in the 1st and 2nd degree earthquake zone of Turkey. According to the AFAD (Earthquake Department Disaster Management and Emergency Presidency) interactive web application, the district's ground acceleration corresponds approximately to 0.3 g, that location is displayed on Turkey's Seismic Hazard Map in Figure 4-2 (AFAD, 2018a). The ground acceleration value defines the earthquake level of 10% probability of exceedance within the period of 50 years.

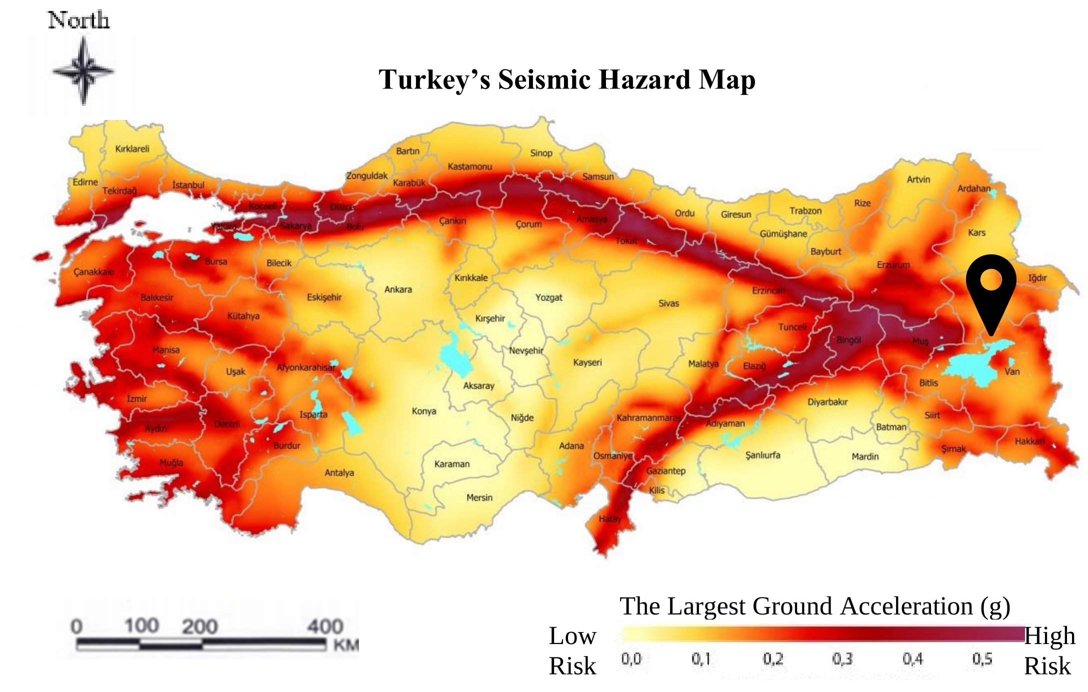


Figure 4-2 Location of the district Ercis on Turkey's Seismic Hazard Map (AFAD, 2018a)

4.2.1.2 Original Drawings

The building has an architectural plan which includes each floor plan, section views, elevations, the plot plan, window and door schedules, and other details. However, this architectural plan did not match the existing building, so a new plan was obtained in parallel with data provided by the site investigation. Therefore, there is no available information about any changes and additions to the building after its initial construction.

4.2.1.3 Characteristics of the Building

The structure represents the most common system in Turkey; a construction practice of rigid frames formed by an RC beam-column connection with slabs. The building consists of seven floors in total. All floors have a height of 2.80 m, except the ground floor, which is 2.70 m. The columns are 60 x 100 cm, and the beams are of different sizes because of the hollow flooring (which is made with light filling material, used to fill the gap between the beams, so a flat ceiling is provided for the users) and the balconies. The beams' sizes vary at: (width x depth) 80 x 32 cm, 70 x 32 cm, 40 x 32 cm 60 x 32 cm, 40 x 80 cm, 60 x 52 cm, 90 x 32 cm, 70 x 32 cm, 25 x 30 cm, 25 x 40 cm, and 25 x 50 cm. Shear walls were used for the basement walls and the lift. The foundations are 110 cm wide, and 100 cm in depth, with a slab thickness of 15 cm for each floor. Table 4-1 shows the dimensions on each floor of the building.

Table 4-1 Dimensions on each section

Level	**Dimensions (x,y)**
Foundation	18.10 x 25.63 m^2
Basement	17.00 x 24.60 m^2
Ground	17.00 x 25.65 m^2
Mezzanine	17.00 x 26.90 m^2
1	17.00 x 27.15 m^2
2	14.00 x 27.15 m^2
3	14.00 x 27.15 m^2
4	14.00 x 27.15 m^2

4.2.1.4 Building Function

The building was built in 2001 as a semi-detached apartment building; however, it has different functions with the basement being used as a storage area, the ground and mezzanine floors as a retail store, and the other four floors as apartments. As seen in Figure 4-3, the building has a different view and designs for the upper floors and the lower floors because of these different functionalities. After retrofitting in 2011-2012, the building’s apartment floors were used as a hotel without any structural change, and the retail store remained the same. Therefore, the selected retrofit also needed to be designed according to the hotel building and the store’s functionality.

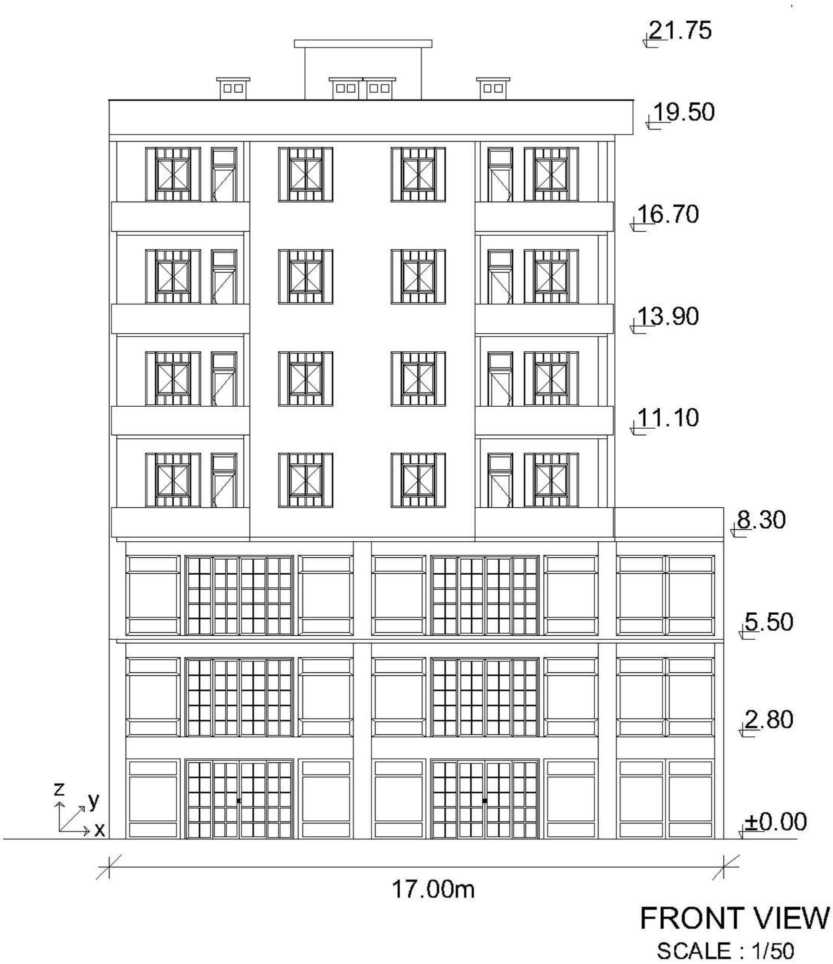


Figure 4-3 Front elevation of the case study building

4.2.1.5 Field Investigation

A visual inspection was primarily conducted by the technical team in the field study, and details of the distress and design deficiencies were recorded according to measurements. In visual research, the building's geometry, existing damage, damage type, depth, and location were determined, and the architectural plan was drawn. Then, relevant tests were performed to identify the durability of the building. One of the destructive tests applied to the building was core sampling, to determine the concrete’s strength. The field crews took a sufficient number of core samples (at least three samples from each floor), and concrete quality control was carried out with impact testing apparatus. Then, a concrete hammer test was conducted as a non-destructive approach.

The rebar control was done by removing the concrete cover from certain places to check. At least one on each floor, 10% of the shear walls and columns and 5% of the beams' covers needed to be removed, and the reinforcement and reinforcement overlap length needed to be determined. Then a digital photometer was used for 20% of the rest of the elements.

Geotechnical revision of the foundations was carried out, and samples from the subsoil were taken to determine the soil class. The workmanship quality of the structural system of the building was found to be sufficient.

4.2.1.6 Vulnerability State

During the field investigation, it was found that the load-bearing system's physical appearance was at a sufficient level and not destroyed. Horizontal cracks were observed at the lower and upper ends of the columns of the basement, ground, and mezzanine floors. Some of these cracks were found to be between 0.5 mm and 3 mm. There were also other cracks in the upper floor slabs and deflections in the beams. The main reason for these cracks was the geometry of the building. There are local floor openings that make it difficult to safely transfer earthquake loads to vertical bearing elements such as columns. The floor opening was chosen for an easy view of the retail store's interior area from outside and inside the building. At the same time, beams were not placed in this area for aesthetic reasons. These failures caused low stiffness at the ground and mezzanine floors and prevented the earthquake energy from being distributed nearly equally to all floors, causing the damage to occur in the columns in the store area. Therefore, the building was damaged during the earthquake due to the insufficient capacity of the building's components. Regarding the foundation, no damage was observed, the footing type was not damaged after the earthquake.

4.2.1.7 Service Life

The building was constructed in 2001, and so was ten years old during the earthquake. After the retrofitting, the store was still used, but the apartment floors became a hotel. Residential and hotel buildings are designed for at least 50 years of use, and relevant maintenance and repair activities further increase their service life. In this study, considering that the building was constructed following the 1998 earthquake codes and the quality of the materials is sufficient, it is assumed that the structural retrofit would increase the building's service life by approximately 50% according to project engineer, so serving for another 65 years after retrofitting.

4.2.2 Assessment of the building's structural capacity

The concrete samples showed 25 MPa, 20 MPa and 16 MPa compression resistance for the columns and beams. The slap and foundations showed 25 MPa and 20 MPa, respectively; thus, the concrete quality of the building was at a sufficient level. Also, the rebars were in a sufficient condition, and their strength was 250 kg/cm^2. The concrete quality inhibits corrosion of the steel reinforcement and no corrosion effect has been observed on the reinforcements after the stripping of the concrete cover. The ground classification was found to be loose and soft soil. There was no deflection problem on the floor coverings. The foundation was constructed as continuous footing, which is sufficiently applicable for that soil type. Its concrete strength was determined as 20 MPa, and this strength and original design of the foundation was considered in the structural assessment.

The building carrier system must continuously and safely transfer the loads that will occur during an earthquake through its building elements down to its foundation. Therefore, the building must provide sufficient durability and rigidity for this load transfer. However, in this building, the load transfer failed and caused distress. The main reason for this concerns the deformation capacity of the damaged building components due to the floor openings and irregularity in the building's geometry; which is called soft storey irregularity.

As a result of all these findings, the building was modelled according to the design and tests' results. The case study building was constructed in line with the 1998 Regulation on Buildings to be Constructed in Disaster Areas. However, the main reason for the damages in the building was failing to comply with the regulations and standards of the period in construction. The building's earthquake safety analysis was carried out in 2012 by the project engineer following the 2007 Earthquake Regulations in force (RTOG, 2007). It has been observed that the current state of the investigated building does not meet the conditions stipulated by the 2007 Earthquake Regulation for Van and will not show the expected performance in the event of a possible earthquake. A system improvement is required to ensure the safety of the building under possible earthquake effects. It is characterised as a limited damaged building because it affects around 15% - 35% of the earthquake performance according to damage states defined in TBSC (AFAD, 2018b; Güler and Celep, 2020). In this study, this limited damage can be matched with low damage corresponding to "type of intervention to use" criteria of the proposed method.

4.2.3 Selection and design of structural interventions

The strengthening principles and techniques were determined by considering the vulnerability of the building. Due to the columns' insufficient bearing capacity, the over-stressed columns transfer loads exceeding their capacities to the beams in accordance with the principle of force distribution. The capacity of building elements can be strengthened by concrete, steel and FRP jacketing methods. Also, it has been determined that the best way to improve soft storey irregularity is by adding beams to support the transferring of the loads. Some deformation was recorded in the beams and cracks in the slabs of the upper floors; therefore, this area also needs to be strengthened. Foundation had a sufficient condition; therefore, no changes or reinforcement have been made to the original foundation.

The reinforced structure prepared in line with these evaluations was analysed, and the analyses were renewed until the most economical and statically correct system was selected by the project engineer. The Structural Analysis for Computer-Aided Design (Sta4CAD) program was used to determine the building's earthquake performance. The nonlinear analysis was preferred as the static analysis method, and dynamic analysis was used as the earthquake calculation method. According to these methods, parameters that determine the equivalent static earthquake load to be affected by the earthquake zone, local soil class and properties of the structure (geometry, ground properties and the purpose of use) are entered to the software. The Ercis District is located in the 1st-degree earthquake zone according to the 2007 Earthquake Regulation. Since the building is used as a residential building, its building importance coefficient is I = 1.0, which represent residences, workplaces, hotels, etc. As a result of the ground study, the ground class was determined as Z4, representing loose and soft soils. The concrete class of the original structure was taken as the average value of the core samples and concrete test hammer results, and the class of the rebar that was found out as a result of the tests was used. These values are the corresponding expression of the technical terms in the software and regulation. Table 4-2 lists related information used during the structural analysis presented in **Appendix A** and **B**.

Table 4-2 Data used in the structural analysis

Relevant Data for the Structural Analysis	
Building Type	Residential
Floors	8
Concrete Class	20 MPa
Rebar Class	420 MPa
Earthquake Zone	1^{st} Zone
Ground Zone	Z4
Earthquake Coefficient	0.4
Building importance coefficient	I = 1.0.
Building Performance Level	Life Safety Level
Static analyses Method	Non-Linear Analysis + P Delta (2.Stage) + Cracked Section
Earthquake Standard	TDY2007 Code
Reinforced Concrete Calculation Method	Load Bearing Capacity Method TS500-2000
Earthquake Calculation Method	Mode Superposition with Dynamic Analysis

Steel and RC jacketing applications are common retrofit techniques in Turkey for increasing strength and stiffness of damaged columns. Therefore, these two techniques were separately applied to the building to assess the performance. New beam additions were selected according to the jacketing materials and two types of beams were generated: RC and steel. Regarding the deflected beams and weak slabs on the first floor, only the CFRP technique is applied because of easy applicability and sufficient resistance; this technique is the most appropriate for slabs and beams compared to RC and steel. Therefore, two different retrofit projects are created, and Table 4-3 details these two selected scenarios for this vulnerable building.

Table 4-3 Selected structural strengthening scenarios for the damaged building

RC Scenario	**Steel Scenario**
RC jacketing for weak columns	Steel jacketing for weak columns
RC beam additions for the ground floor	Steel beam additions for the ground floor
CFPR application to deflected beams and cracked ceiling concrete	CFPR application to deflected beams and cracked ceiling concrete
Epoxy application to cracks	Epoxy application to cracks

These two scenarios were developed to increase construction resistance against earthquakes in accordance with the 2007 earthquake regulation code for Turkey, and the two strengthening solution suggestions are applicable techniques in terms of architectural and reinforcement detail. A sufficient level of improvement was achieved in the strength of the structure with both strengthening scenarios. Therefore, this structure's damage level, which is expected to sustain major damages in subsequent earthquakes, was reduced to minimum levels with the applied strengthening technique — the details of both scenarios are presented below.

4.2.3.1 The RC Scenario: RC Jacketing and Beams

The RC jacketing was applied to the damaged and insufficient capacity columns specified in the project. The retrofitted structure was modelled in 3D with the Sta4CAD program and analysed according to the 2007 Turkish earthquake code, see **Appendix A**. The results from observations on the building and field tests were evaluated. During the retrofitted structure analysis, the existing elements were modelled with their material properties, and the retrofit elements with C25 (fck: 20 MPa) concrete and S420 (fyk: 420 MPa) steel properties. This RC technique provided additional supports to the building by increasing the shear and compression strength of the columns with an enlarged column section. Transverse reinforcements that were applied along with the column height increased the axial compressive strength of the columns. The sufficient compressive and shear strength was determined according to the RC jacketing dimensions and the concrete design strength; the result was then reduced by multiplying by 0.9.

Using RC jackets to the column-beam joints is very laborious and not a preferred method. Therefore, the thickness of the RC jacketing was kept at an appropriate level to provide sufficient support to the joints. Another issue that can affect the jacket's effectiveness is the connection between the existing column and the new reinforcement; thus, it is important that the jacket is applied with adequate workmanship. Four additional RC beams were placed so that they were supported by two columns on the ground floor. The dimensions of three of the beams were 40 x 40 cm, and the fourth beam was 70 x 32 cm because of hollow flooring. These beams help in transferring the load to the columns and eliminate any irregularity of the soft storeys. The RC scenario retrofit plan is presented in **Appendix C** for the basement, ground and mezzanine floors. The CFRP application to the deflected beams and cracked ceiling surface contributes to the building's strength and increases the shear force. Therefore, the beams' bending capacity is increased by applying the CFRP.

4.2.3.2 The Steel Scenario: Steel Jacketing and Beams

The Steel scenario was also modelled in 3D with the Sta4CAD program and analysed according to the 2007 Turkish earthquake code, the analysis results are presented in **Appendix B**. The designers decided to apply steel retrofits to the building as it would be easier to implement and worker errors would be minimized compared to the RC retrofits. Therefore, it was also analysed in the SAP2000 (Structural Analysis and Design) software for cross-checking and more detailed analysis results. Steel jackets were applied to selected columns with continuous steel plates, and these steel plates were also extended towards the beam and slab to prevent failure from the plastic hinge zone in the beam-column joints. The steel jackets had a 16-mm thickness and were connected with welding. Along with the retrofitted columns on the mezzanine floor, steel jacketing was also required at the beam-column joints, which had a 30-cm length. These steel plates in the joint had a U shape, which increases shear and bending strength. The additional steel beams were hollow structural steel with a 10-mm thickness, their sizes were 20 x 30 cm. Two more columns were also wrapped with steel jacketing on the mezzanine floor to connect the beams to the columns. The Steel scenario retrofit plan is presented in **Appendix D** for the basement, ground and mezzanine floors. The steel jacketing provides easy applicability and a low margin of workmanship error. The CFRP has high linear elastic behaviour and strength; this material was also applied to the beams' and ceiling surfaces by the same method as in the RC scenario.

4.3 LCA stages

This process includes the LCA of the selected scenarios. The "type of intervention to use" procedure of the proposed method then followed to assess the environmental impacts of the two structural retrofit scenarios. Firstly, the same applications in both scenarios were removed. Therefore, the CFRP application to the deflected beam and cracked ceiling surfaces was removed from both scenarios as it would not make a difference for the comparison. Then, the proposed method conducted the following four steps of the LCA framework.

4.3.1 Goal and scope

This case study's goal is a comparative sustainability performance for the two presented scenarios of the damaged residential building. The analysis scope includes two types of structural retrofitting, and both have brought the building performance level to a sufficient level. The retrofitted building's life cycle run from the materials' production to the end-of-life stage in the LCA boundary system, excluding the same materials and activities in both scenarios, such as scaffolding installation. The functional unit includes the retrofit materials of the selected scenarios.

4.3.2 Life cycle inventory analysis (LCI)

The LCI includes quantifying the retrofit materials, construction works, transportation, maintenance, and end-of-life of the materials throughout the retrofit's customised LCA stages. The unit process method was selected for the LCA. A flow chart in Figure 4-4 is drawn to explain the case study's steps over its selected scenarios during their life cycle.

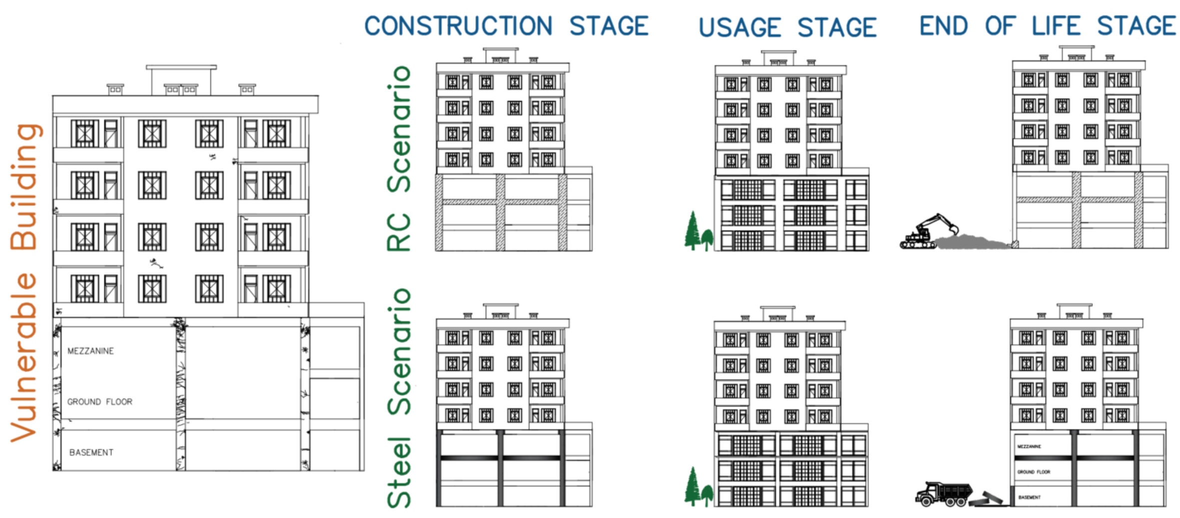


Figure 4-4 Schematic representation of a low-damaged building's LCA stages over the two selected scenarios

The necessary data was collected from the actual drawings of the RC and Steel scenarios, and some assumptions were applied. Some data was also provided from the Athena Impact Estimator for Buildings (AIEB) tool, such as on-site construction, related transportation, replacement and maintenance effects, demolition, disposal and recycling according to the BOM, and the building's service life and building location. Then quantities of each material were calculated for each LCA stage as presented in the sections below. The customised stages developed for the structural retrofit scenarios, as seen in Figure 4-5, illustrate the organisation of the LCA with associated modules which represent specific parameters (considerations) related to vulnerable buildings under customised stages from cradle-to-grave. In the following sections, firstly, the LCI of the RC scenario is presented and then that of the Steel scenario.

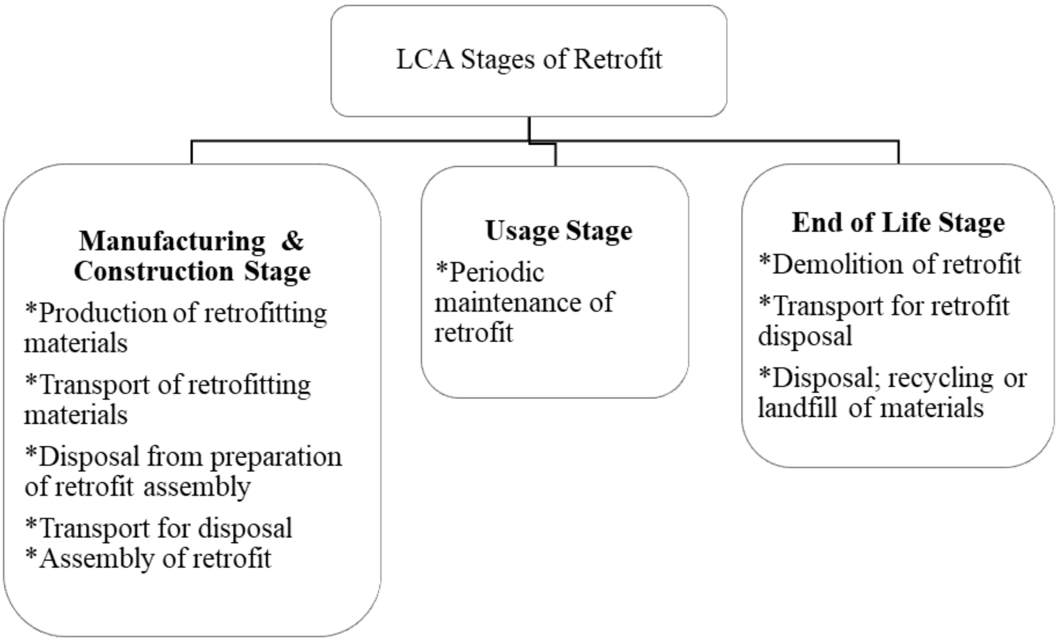


Figure 4-5 Specific parameters of the LCA stages for the structural retrofits using the unit process method

4.3.2.1 LCI of the RC Scenario

Manufacturing and Construction Stage

In the RC scenario, two types of retrofit were applied to the damaged building: RC jacketing and RC beam addition. Three RC jackets were applied to each of the basement, ground and mezzanine floors, and four beams were added to the ground floor. Because of the building design changes, there are some differences in the application of these retrofits (**see Appendix C**). Below, Figure 4-6 shows details of the RC jacketing and beam from one example.

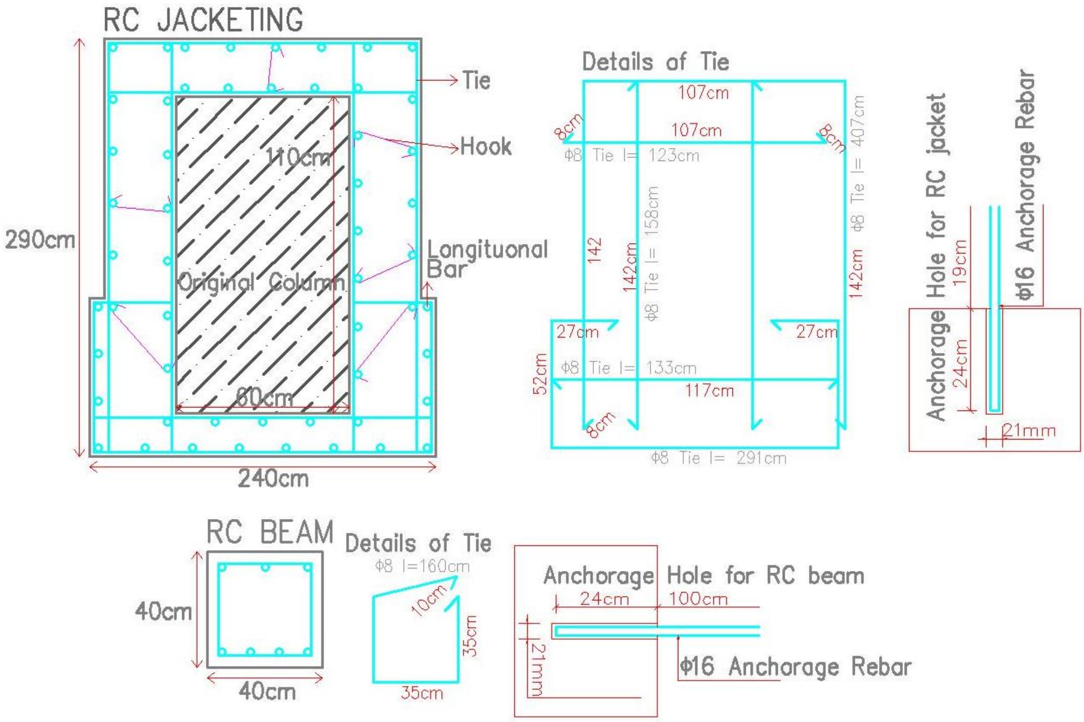


Figure 4-6 The RC jacket and beam reinforcement

During the LCA calculations, the entire retrofitting process was included while some assumptions were made as there was limited knowledge about the case study building. Since the transport distance of the material is unknown, the available data was used from the AIEB that assumes an average transport distance. The collected data is shown in Table 4-4 as a step-by-step RC retrofit application for each floor and each stage, and the steps below explain the assembly of one RC jacket:

- Preparation of column surfaces for the retrofit includes cleaning the column surface of plaster (m^3 or kg); drilling anchorage holes for the anchorage rebars; and drilling the slab (kg or m^3) for pouring the concrete of the RC jackets and beams shown in the project. The RC jacket was applied from the lower floor slab to the upper floor slab. A magnetic drill (h) was used for drilling works; another magnetic drill was applied to the slab and column surfaces for roughening (h-neglected), and transportation of all the waste (km). The cleaning process was then completed with an air pressure device (h-neglected) to improve the adherence between the original column and the retrofit.

- The anchorage rebars (kg) (that transfer the incoming force to the concrete with the adherence formed in its depth) were placed in the holes with epoxy mortar (m^3 or kg) (as a binder), and epoxy was applied to the drilled slab and cleaned surface columns (m^3 or kg) along the columns.
- The steel reinforcement (kg) was prepared in the iron cutting machine (h) and assembled and transported (km) to the site.
- Timber formworks (kg) were assembled; the concrete mixture (kg) was cast and its transport (km).
- Finally, mortar (kg or m^3) was applied to the surface, then the surface was painted (kg or L).

Table 4-4 The collected data from the RC scenario for the manufacturing and construction stage

Basement	RC jackets were applied to three damaged columns.		
Work	**Characteristic**	**Unit**	**Amount**
Cleaning the column surfaces	Nearly 2 cm-thickness waste was removed from the entire surface of the columns.	m^3	0.54 m^3
Drilling anchorage holes	Magnetic drilling was used to drill each hole, and it took 1 minute. The magnetic drill is 120-volt, 6.25 amp and 750 watts. In total, 145 holes were drilled.	h	2.4 h
Waste from drilling	Each hole is 21 mm wide and 24 cm in depth. The thickness of the drilled slab is 2.5 cm. In total, 12035 cm^3 hole was drilled and 22313 cm^3 slab. Concrete density is 2400 kg/m^3 for disposal.	m^3	0.034 m^3
Mortar application	6-mm thickness epoxy mortar was applied to the cleaned columns, the drilled holes and slabs, and cracked surfaces.	m^3	0.341 m^3

Steel reinforcement	The steel waste and wires were calculated for Φ8, Φ14 and anchorage rebars Φ16, separately.	Kg	1864 kg
Iron cutting machine	The machine has 380 volts, 1450 rpm, 1.5 kW. 1-tonne iron is prepared in 2 hours.	h	3.53 h
Wooden formwork	The same material was used for each floor. The total area was 41.3 m^2. 1 m^2 area takes 0.0123 m^3 timber, and 1 m^3 timber is 1000 kg.	Kg	510 kg
	0.10 kg nail was used for 1 m^2 area.	Kg	4 kg
Casting the concrete mixture	Concrete is C25=20MPa. Winding concrete was applied to the 3 columns with different sizes.	m^3	6.85 m^3
Mortar	Mortar was applied to the concrete surface of the jacket. 2.8 cm-thickness mortar was applied to 41.3 m^2 area.	m^3	1.16 m^3
Paint	One-layer paint application is 7 m^2/L, and three layers was applied to the RC jacketing, that is 41.3 m^2.	L	17.7 L
Ground Floor	RC jackets were applied to three damaged columns, and four new RC beams were added.		
Work	**Characteristic**	**Unit**	**Amount**
Cleaning the column surfaces	Nearly 2 cm-thickness waste was removed from the entire surface of the columns and for new beams.	m^3	0.68 m^3
Drilling anchorage holes	Magnetic drilling was used to drill each hole, and it took 1 minute. The magnetic drill is 120-volt, 6.25 amp and 750 watts. In total, 205 holes were drilled.	h	3.4 h
Waste from drilling	Each hole is 21 mm wide and 24 cm in-depth for the columns and beams. In total, 205 holes were drilled. Concrete density is 2400 kg/m^3 for disposal.	m^3	0.02 m^3
Mortar application	6-mm thickness epoxy mortar was applied to the cleaned columns, the drilled holes, and cracked surfaces.	m^3	0.38 m^3
Steel reinforcement	The steel waste and wires were calculated for Φ8, Φ12, Φ14 and anchorage rebars were used for columns and beams with 43 cm and 124 cm-lengths Φ16.	Kg	2339 kg

Iron cutting machine	The machine has 380 volts, 1450 rpm, 1.5 kW. 1-tonne iron is prepared in 2 hours.	h	4.7 h
Wooden formwork	The same material as on the basement floor was used. New wooden formwork was prepared for beams. The total area was 21.42 m^2. 1 m^2 area takes 0.0123 m^3 timber, and 1 m^3 timber is 1000kg.	Kg	265 kg
	0.10 kg nail was used for 1 m^2 area.	Kg	2.1 kg
Casting the concrete mixture	Concrete is C25=20MPa. Winding concrete was applied to the 3 columns with different sizes. The dimensions of three of the beams were 40 x40 cm, and the fourth beam was 70 x 32 cm.	m^3	8.77 m^3
Mortar	Mortar was applied to the concrete surface of the jackets and beams. 2.8 cm-thickness mortar was applied.	m^3	1.76 m^3
Paint	One-layer paint application is 7 m^2/L, and three layers were applied to the jacket and beam surfaces, which are 41.3 m^2 and 21.42 m^2, respectively.	L	27 L
Mezzanine Floor	RC jackets were applied to three damaged columns.		
Work	**Characteristic**	**Unit**	**Amount**
Cleaning the column surfaces	Nearly 2 cm-thickness waste was removed from the entire surface of the columns.	m^3	0.54 m^3
Drilling anchorage holes	Magnetic drilling was used to drill each hole, and it took 1 minute. The magnetic drill is 120-volt, 6.25 amp and 750 watts. In total, 25 holes were drilled.	h	0.4 h
Waste from drilling	Each hole is 21 mm wide and 24 cm in depth. The thickness of the drilled slab is 2.5 cm. Concrete density is 2400 kg/m^3 for disposal.	m^3	0.02 m^3
Mortar application	6-mm thickness epoxy mortar was applied to the cleaned columns, the drilled holes and slabs, and cracked surfaces.	m^3	0.33 m^3
Steel reinforcement	The steel waste and wires were calculated for Φ8, Φ14 and anchorage rebars Φ16, separately.	Kg	1266 kg

Iron cutting machine	The machine has 380 volts, 1450 rpm, 1.5 kW. 1-tonne iron is prepared in 2 hours.	h	2.5 h
Casting concrete mixture	Concrete is C25=20MPa. Winding concrete was applied to the 3 columns with different sizes.	m^3	6.85 m^3
Mortar	Mortar was applied to the concrete surface of the jacket. 2.8 cm-thickness mortar was applied to 41.3 m^2 area.	m^3	1.16 m^3
Paint	One-layer paint application is 7 m^2/L, and three layers were applied to the RC jacketing, that is 41.3 m^2.	L	17.7 L

Usage Stage

During the usage stage of buildings, various repair and maintenance operations take place. In this case study, the necessary maintenance was considered for the selected retrofit scenarios, and the other parameters were neglected. Therefore, it assumed that the RC scenario only needs paint during the 65 years' service period of the hotel building, repeated every five years. Table 4-5 presents the maintenance activities and assumptions that applied only to the retrofit, and Figure 4-7 displays a photograph of the current condition of the building in use (Google Map, 2015).

Table 4-5 The maintenance activities of the RC scenario

Works	**Description**	**Service Life**	**Unit**
Painting the RC jackets and beams	The total area of application is 145.32 m^2.	5 years	Kg or L

Figure 4-7 Retrofitted hotel building during use (front and right elevations) (Google Map, 2015)

End-of-life Stage

This stage only includes demolition of the retrofit scenarios, the whole building is excluded because it is the same process for both scenarios. Therefore, only retrofit materials, their deconstruction and final disposal were considered for the analysis. Demolition and transport energy are consumed during deconstruction according to amount of building materials and their transport distance. Also, the building materials determine the final disposal, such as landfill or recycling.

4.3.2.2 LCI of the Steel Scenario

Manufacturing and Construction Stage

In the Steel scenario, two types of retrofit were applied to the damaged building: steel jacketing and steel beam addition. Three steel jackets were applied to each of the basement, ground, and mezzanine floors, and four beams were added to the mezzanine floor. Because of the changes in the design, there are some differences in the application of these retrofits (see **Appendix D**). Figure 4-8 below shows details of the steel jacketing and beam from one example.

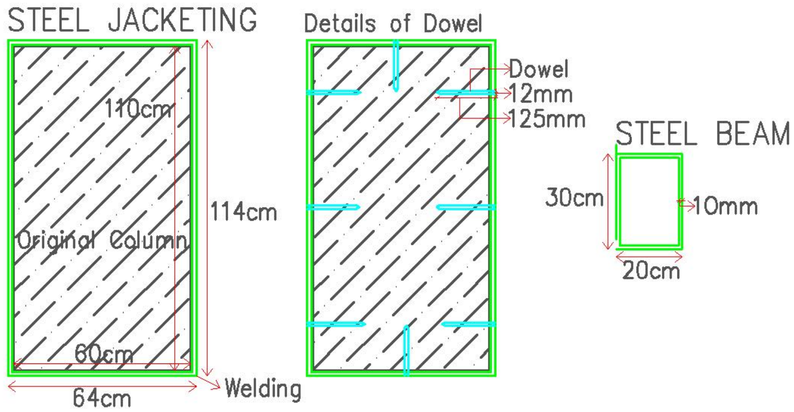


Figure 4-8 The steel jacket and beam reinforcement

Some assumptions were also made in this scenario to be able to include as much of the retrofit process as possible. Therefore, the collected data and assumptions for the Steel scenario are presented in Table 4-6 separately for each floor. The steps below explain one steel jacket assembly:

- The column surface was cleaned of plaster (m^3 or kg); then the magnetic drill was applied to the column surfaces for roughening (h-neglected); and all the waste was transported (km). The cleaning process was then completed with an air pressure device (h-neglected) to increase the adherence.
- Mortar and epoxy (m^3 or kg) were applied to the cleaned column's surface.
- Steel elements were transported (km) to the site. Steel plates were prepared in the iron cutting machine (h-neglect) and they (kg) were assembled continuously on four faces

of the column; with hollow structural steel (beam) and U plates for the column-beam joints applied on the ground floor.

- The plates were tightened with vice (press) (neglected) and each connection was welded (h), while steel was cooled with an air compressor (h-neglected). Dowels(kg) were applied to avoid any gaps and provide load transfer without any problems between steel and the column.
- Mortar (kg or m^3) was applied to the steel surfaces to protect them from corrosion (it also prevents fire on the steel plates). Bitumen (kg) was applied to the jackets on the basement floor to protect them from the soil. Finally painting (kg or L) was applied to all retrofits.

Table 4-6 The collected data from the Steel scenario for the manufacturing and construction stage

Basement	Steel cover was applied to 3 damaged columns.		
Work	**Characteristic**	**Unit**	**Amount**
Cleaning of column surfaces	The entire surface of the columns was removed nearly 2cm thickness waste.	m^3	0.54 m^3
Mortar application	Mortar applied to clean columns with 6mm thickness, 6mm epoxy application and cracks over other surfaces.	m^3	0.46 m^3
Steel plates	16 mm thickness of steel jacketing, and its weight is 125.1 kg/m2. Three columns have 22.77m2.	Kg	2848.5 kg
Welding	The welding is chosen as a long weld (>250 mm) and 8 mm continuous fillet with 0.5 h/m for the structural purpose (Watson *et al.*, 1996). The welding machine has 230 V and 2200watts.	h	7.7 h
Dowels	12x125mm dowels applied with 25cm gap. Dowels selected as M10 type and have 72.8 gr each (Makro Teknik, 2020).	Gr	19656 gr

Mortar application over retrofit	Mortar applied to the steel surface of jacketing with 6mm thickness.	m^3	0.154 m3.
Asphalt	Asphalt applied to jackets to protect from the soil. $23m^2$ can be done with 14 kg asphalt and applied to 8.1 m^2 area.	Kg	4.9 kg
Paint	One layer paint application is 7 m^2/L and three layers applied to 14.65 m^2 surface.	L	6.3 L
Ground Floor	Steel cover was applied to 5 damaged columns, and new steel beams added 4 in total.		
Work	**Characteristic**	**Unit**	**Amount**
Cleaning of column surfaces	The entire surface of the columns was removed nearly 2cm thickness waste.	m^3	0.62 m^3
Mortar application	Mortar applied to clean columns with 6mm thickness, 6mm epoxy application and cracks over other surfaces.	m^3	0.52 m^3
Steel plates	16mm thickness of steel jacketing, and its weight is 125.1 kg/m^2. Five columns have $30m^2$.	Kg	3753 kg
Steel beams	Steel rectangular beams were used with 10 mm thickness. Weight is 75.06 kg in total 23.2 m^2.	Kg	1741 kg
Welding	The welding is chosen as long weld (>250mm) and 8mm continuous fillet with 0.5 h/m for the structural purpose from (Watson *et al.*, 1996). The welding machine has 230 V and 2200watts. 42.6m welding applied to columns and beam.	h	21.4 h
Dowels	12x125 mm dowels applied with 25 cm gap. Dowels selected as M10 type and have 72.8 gr each (Makro Teknik, 2020).	Gr	22859 gr
Mortar application over retrofit	Mortar applied to the steel surface of jacketing. 6mm thickness applied to columns and beams 53.2 m^2.	m^3	0.32 m^3
Paint	One layer paint application is 7 m^2/L and three layers applied to 53.2 m^2 surface.	L	22.8 L
Mezzanine	Steel cover was applied to 3 damaged columns with beam additions		
Work	**Characteristic**	**Unit**	**Amount**

Cleaning of column surfaces	The entire surface of the columns was removed nearly 2cm thickness waste.	m^3	0.64 m^3
Mortar application	Mortar applied to clean columns with 6mm thickness, 6mm epoxy application and cracks over other surfaces (0.153m^3). Mortar and epoxy application to addition beams.	m^3	0.52 m^3
Steel plates	16 mm thickness of steel jacketing, and its weight is 125.1 kg/m2. Three columns have 25.5 m^2.	Kg	3190 kg
Steel plates to beams	12 mm thickness of steel jacketing has 95 kg/m2 weight.	Kg	475 kg
Welding	The welding is chosen as long weld (>250mm) and 8mm continuous fillet with 0.5 h/m for the structural purpose from (Watson *et al.*, 1996). The welding machine has 230 V and 2200watts. 30m welding applied for columns and 28.8m for beams.	h	29 h
Dowels	12x125 mm dowels applied with 25 cm gap. Dowels selected as M10 type and have 72.8 gr each (Makro Teknik, 2020).	Gr	20238 gr
Mortar application over retrofit	Mortar applied to the steel surface of jacketing.	m^3	0.154 m^3
Paint	One layer paint application is 7 m^2/L and three layers applied to 30.5 m^2 surface.	L	13.2L

Usage Stage

Only retrofitting related maintenance activities were included in this scenario as well. Therefore, only painting work was included for this stage. Table 4-7 shows the maintenance activities and assumptions that applied to only the retrofit.

Table 4-7 The maintenance activities of the Steel scenario

Works	**Description**	**Service Life**	**Unit**
The paint of Steel jacketing and beams	The total area of application is 98.35 m^2.	5 years	Kg or L

End-of-life Stage

Similar to the other scenario, the demolition of the entire building was also ignored in the Steel scenario. The demolishing and disposal process of this scenario includes scrap collection, processing, and transport to steel plants.

4.3.2.3 LCI Results

The author tested several LCA software programs, and the AIEB was selected to develop the LCA models to assess the environmental burdens created by both scenarios' material and energy consumption. This is the only tool which assesses the whole of the building's environmental impacts and the building assemblies (ASMI, 2011). The relevant data from the tool covers 90-95% of the envelope and structural system suitable for different building types (ASMI, 2019b).

The AIEB allows users to model the building by describing the building's components and their dimensions. The assemblies section provided by the program helps when entering data and modelling the building. These assemblies are the foundation, floors, walls, columns and beams, roof and extra basic materials. Then a tree is generated to view and edit each assembly. Therefore, the tool provides BOM data by modelling the building in case of the absence of material knowledge (which helped analyse existing and new buildings in Chapter 5). In this case study, the collected data were analysed using the extra basic material assembly only, since only the building's retrofit was considered. There was no need to model the entire building.

The LCA results of the building were generated in relation to the building's life cycle stages, and **Appendix E** summarises the system boundary capacity of AIEB. Modules in the LCA stages include generalised items; however, they should be customised according to the structural intervention scenarios. Therefore, the LCA of the retrofitted buildings could not be analysed in a straight forward manner. For instance, during the retrofit assembly, some construction waste is generated, and it must be removed during the construction process; therefore, the construction process also involves demolition and disposal aside from material waste. In addition, the construction stage of the original building usually present in building LCA assessments is not included in these retrofitted scenarios, as existing buildings are used, and the building construction stage has already occurred. Because of these specific situations in the structural interventions to vulnerable buildings, the scenario requires to be analysed with discretion. Thereby, the system boundary of the AIEB was incorporated into the customised stages of the LCA scenarios, presented in Figure 4-5 above. Figure 4-9 summarises which of the information modules cover which processes of the LCA stages of the structural retrofit scenarios.

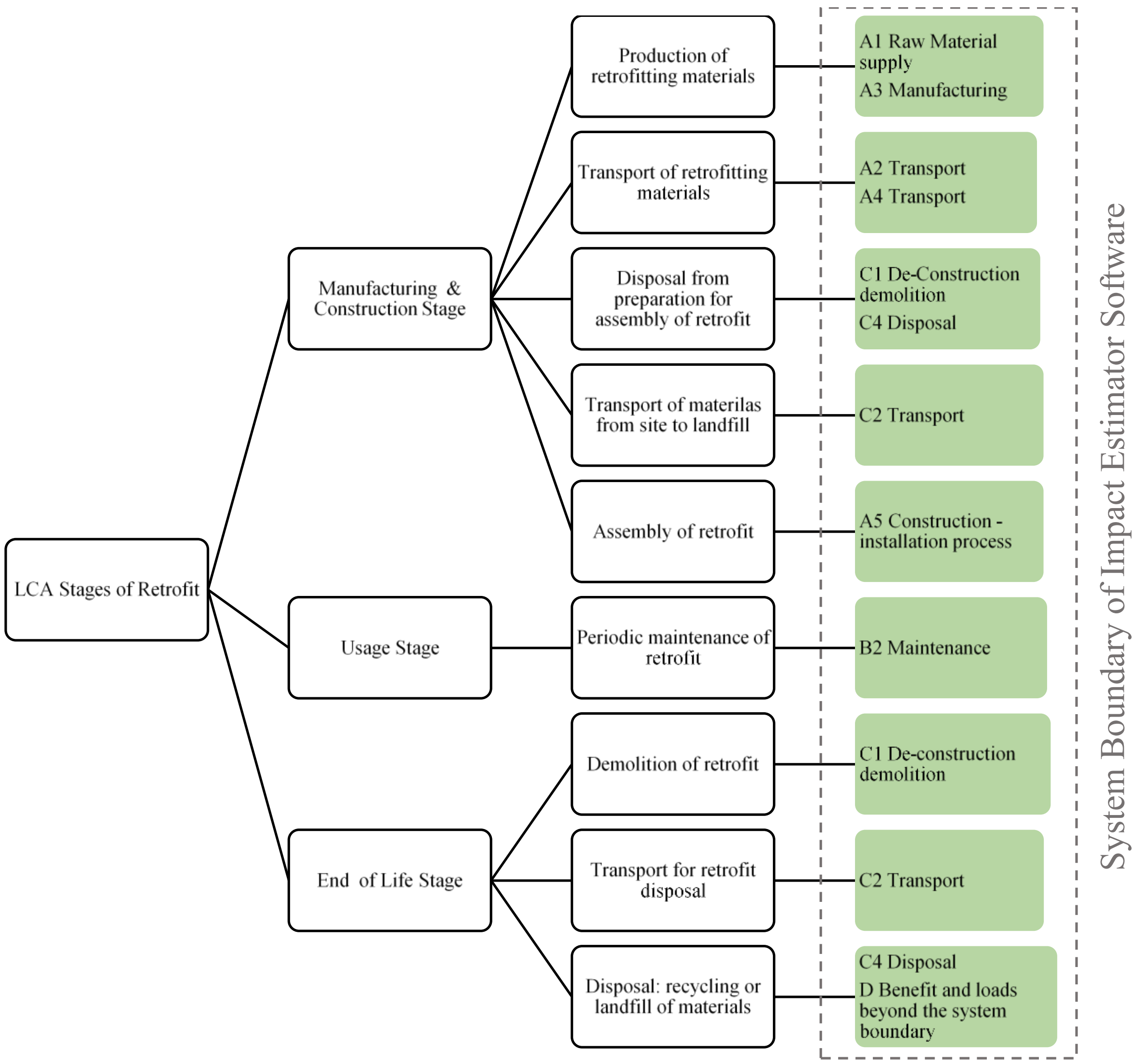


Figure 4-9 LCA stages of the retrofits and their corresponding modules in the AIEB software

The given material quantities, building type, assumed lifespan and location affect the building's environmental impacts and help the tool to complete an LCA. The location determines the electricity grids and transportation matrices, the assumed lifespan and building type determine the maintenance schedule. Electricity is used during the operation of the building and as embodied energy during the construction, maintenance, and end-of-life stages. Material manufacturing includes resource extraction and transport. The tool also considers material waste by assigning a construction waste factor for each construction material. The construction waste factor is included in the calculation of the net amount of material, taking into account lost, wasted or damaged materials (ATHENA, 2019b), the formula is presented in Equation 4-1 (ASMI, 2019b). For instance, the net amount of 1 m^3 of Concrete Benchmark 25 MPa with 0.05 construction waste factor is equivalent to 1.05 m^3. Concrete benchmark is a mix design of ready mixed concrete products varying compressive strengths, fly ash and slag cement concentrations. For instance, the concrete used in this case study is limited to the available database in the AIEB; therefore, a 25Mpa Portland cement mix with a combined 4% fly ash and 6% slag cement concrete in use in Canada (CAN) was selected (ASMI, 2016). Table 4-8 presents the construction waste factor and converted units for each material corresponding to the BOM of the scenarios. The input materials' information gives the BOM based on simplified algorithms to complete the take-off process. Material information can be entered into the program in two ways; the first is the automatic calculation of the BOM according to previously defined assemblies in the software, including sufficient details. The second way is the transfer from other resources, which can be from BIM models, drawing take-offs, and cost estimates (ASMI, 2020b). The second option is considered as the more accurate BOM. The first one calculates the BOM within +/- 10% of the second option, and in general, 15% difference is an acceptable level for comparative impacts, according to ATHENA (2013). In this case study, the BOM was calculated by using existing drawings of the case study, information from the literature, and compensating missing data with well-accepted assumptions, described in section 4.4.2. All this information then refers to AIEB's database to create an LCI profile. The case study was adhered to, and the corresponding materials were selected accordingly; hence specific mixtures for reducing environmental impacts did not consider. The tool filters these LCI results through a set of characterisation factors based on the TRACI methodology (ASMI, 2011). **Appendix F** presents a detailed framework of the working plan of the AIEB software program.

The Net Amount = Amount + (Amount x Construction Waste Factor)   Equation 4-1

Table 4-8 Corresponding materials in the database of the tool for each building material in the selected scenarios

Material	**Corresponding Material**	**Construction Waste Factor**	**Unit**
Concrete mixture	Concrete benchmark CAN	0.05	m^3
Steel reinforcement	Rebar, rod, light sections	0.01	Tonnes
Steel plates	Steel plate	0.01	Tonnes
Steel beams	Hollow structural steel	0.01	Tonnes
Mortar	Mortar	0.15	m^3
Timber formwork	Softwood plywood	0.05	m^2
	Nails	0.03	Tonnes
Dowels	Screws nuts and bolts	0.03	Tonnes
Asphalt	Roofing asphalt	0	kg
Paint	Water-based latex paint	0.02	L

The LCI database develops according to the regional market share's location for the product profiles and transportation profile (ATHENA, 2013). Assumptions also exist while using the tool to eliminate missing information as well as limitations in the LCI data. For example, materials take-offs, corresponding LCI data and transportation data have all been developed by the Athena Institute; however, they are not available for the public. Still, reports and publications that developed the database are available on the webpage (ASMI, 2019a). These data sources and assumptions are specific to the described scenarios as their BOM reflects the specific design and structural technique. In addition to the data and assumptions, the LCI and determined location create limitations for completing the analysis. For example, the LCI data and manufacturing materials are based on North America, and transport data for construction and demolition processes are estimated based on the selected area. All these parameters are generated according to recent technology and circumstances by the tool. Besides that, many parameters are difficult to determine and may not have standards or benchmarks to provide a process; these parameters are not involved in the LCA (ASMI, 2020a). This is because although new building materials and technologies are being developed, their life cycle impacts on the environment are often unclear. Therefore, further research is needed at the local level for local materials, construction techniques and technologies (Boyle, 2005). Currently, there is no available database in tools such as Athena (ASMI, 2019a), OpenLCA (OpenLCA, 2020) and GaBi (GaBi, 2020) on local construction materials and technologies in Turkey. However, very recently, TurComDat (Turkish Construction Materials Database), a database of scientifically compatible environmental performance of building materials produced in Turkey, has been published in accordance with national standards and norms (TurComDat, 2021).

Athena software database is proprietary, and it is not released to the public; therefore, it does not provide flexibility to create local data. Toronto was selected as a proxy location, as in a similar study on Turkey (Çakmaklı, 2007), because of the similarities of both locations' electricity profiles. **Appendix G** presents an example of environmental impact results from two different locations, considering for LCA stages of RC scenario. The results show that there is only a small difference between the environmental impacts due to transportation distances of the locations. It should be noted that this study does not design the best environmentally friendly option, presents a comparison between structural intervention scenarios that were selected and designed considering limitations related to structural performance. Also, both scenarios used roughly the same set of assumptions derived from the tool; therefore, there is no adverse effect for comparison of the scenarios. There cannot be exact results in the LCA because of a considerable number of assumptions and predictions about the uncertainties of the life cycle impacts and the building's modelling process (ASMI, 2011). These environmental impacts are evaluated according to building-related international standards such as the International Green Construction Code, ISO 21930 and ISO 21931 (ATHENA, 2013).

The impact estimator tool provides the classification and characterization of the LCI within the impact categories according to ISO 14040. The LCI includes five categories: energy consumption, air emissions, water emissions, land emissions and resource use. Then the program filters the LCI results based on mid-point impact assessment methodology since AIEB prefers mid-point assessment due to the uncertainties in the end-point (damage-oriented) indicators (ASMI, 2020a). Mid-point describes the environmental impacts from problem-oriented manner, such as global warming and ozone layer depletion. Indoor air quality and biodiversity are not included because of the limitations and lack of data of the tool (ASMI, 2020a). Figure 4-10 summarises the AIEB's working plan as a diagram from user input to results, which is derived from (ASMI, 2011; ATHENA, 2019b) and **Appendix F**.

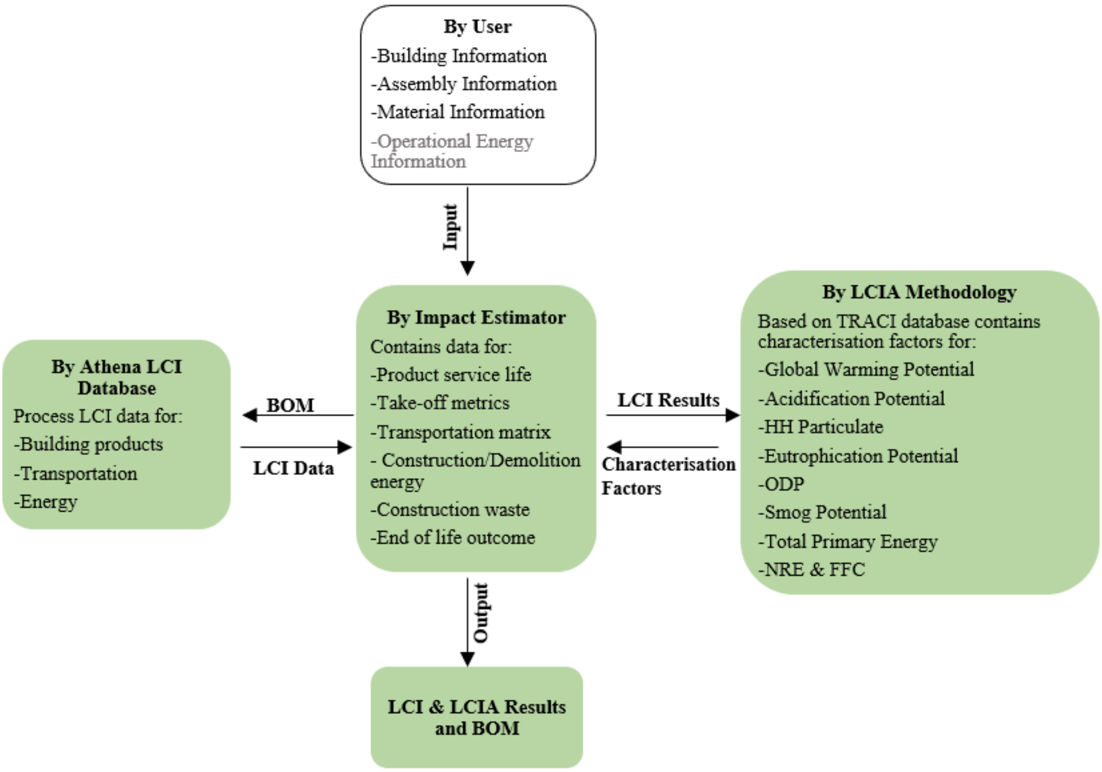


Figure 4-10 Baseline of the AIEB workflow

The input BOM consumed in the construction, use and site preparation (cleaning activities) is included in both scenarios from cradle-to-gate (see **Appendix H**). Since both scenarios have a different material inventory and techniques, it would be more accurate to compare these results according to resource use. Inventory analysis results for resource use are calculated from the A to D system boundary. According to the results, the significant impacts occurred during the manufacturing of the retrofit materials, the construction, and the transport. There are zero and neglectable impacts during the use and end-of-life stages. The extraction of resources causes high material and energy consumption levels from the manufacturing and construction stages for both scenarios, and the end-of-life stage includes energy during material transport but not for resource use. Table 4-9 provides the total LCI results for both scenarios' resource uses; and the results show that the RC scenario causes more resource consumption than the Steel scenario. The most significant depletion is observed for bauxite (83%), clay and shale (83%), coarse aggregate (90%), gypsum (natural) (82%) and wood fibre (96%), compared to the Steel scenario. Choosing the most sustainable scenario can minimise the resource use and related energy consumptions; these are reflected in the impacts on the environment and human health.

Table 4-9 LCI results for the resource uses of both scenarios from the manufacturing to the end-of-life stages (A to D)

Material	**Unit**	**Resource Use LCI Results (A to D)**	
		RC Scenario	**Steel Scenario**
Ash	kg	5.57E+01	2.25E+01
Bauxite	kg	2.64E+01	2.44E+00
Carbon dioxide, in air	kg	4.16E+02	1.72E+02
Clay and Shale	kg	1.18E+02	1.09E+01
Coal	kg	3.04E+03	2.85E+03
Coarse Aggregate	kg	5.40E+04	2.81E+03
Crude Oil	L	1.38E+03	5.93E+02
Crude Oil as feedstock	L	1.85E+02	1.31E+02
Dolomite	kg	3.95E+02	7.95E+02
Ferrous scrap	kg	6.09E+03	1.05E+04
Gypsum (Natural)	kg	3.91E+02	3.78E+01
Gypsum (Synthetic)	kg	4.79E+01	1.90E+01
Iron Ore	kg	2.70E+03	2.17E+03
Lignite	kg	6.73E+01	2.67E+02
Limestone	kg	1.14E+04	2.00E+03
Natural Gas	m3	7.71E+02	2.06E+03
Natural Gas as feedstock	m3	2.48E+02	1.55E+02
Other	kg	9.56E+02	2.89E+02
Peat	kg	6.55E-02	2.26E-02
Sand	kg	7.77E-04	2.84E-04
Tin ore	kg	2.66E-06	3.96E-07
Uranium	kg	2.35E-02	3.89E-02
Water	L	1.88E+05	1.50E+05
Wood Fiber	kg	9.89E+02	1.55E+01

4.3.3 Life cycle impact assessment (LCIA)

LCIA has calculated the impacts per unit of material (e.g., kilograms of CO_2 equivalents per m^3 of concrete) for understanding the burdens of structural interventions on the environment. The TRACI method is the selected as LCIA method, with its impact categories based on mid-point impact estimation methods. This characterisation model is used as the default, static LCI method.

The environmental impacts of each scenario were presented over the building's complete life cycle across eight impact categories. The AIEB follows international standards in the LCA reporting process, and the EBD is produced as a transparency report that provides these results and complies with the LCA procedures. These impact categories are included in the shortlist of globally accepted environmental themes (Schmidt and Sullivan, 2002). The presented environmental measures are used to summarise the LCA results based on AIEB version 5.4 (see **Appendix I** for definitions of these impact categories). Figure 3-8 in chapter 3 and **Appendix F** present the calculation process of the environmental impacts and working plan to help understand the background of the tool and related input parameters. Athena Sustainable Materials Institute develops program background data in cooperation with industry and institutions. The LCA process of each product includes a set of processes such as collection, validation, verification, evaluation and interpretation over their life cycle. For instance, one of the Athena Sustainable Materials Institute reports (2016) presents the LCA calculation process for a ready mixed concrete.

The AIEB mainly counts embodied emissions and energy of buildings. The operational energy and carbon impacts of retrofit materials on the façade, as an insulation material, are neglected, since there can be only a minor impact. Only the environmental impacts of the structural strengthening materials and works are allocated entirely to the cradle-to-grave life cycle. Therefore, the original building's use and demolition were kept outside the system boundary of both scenarios.

Regarding the sensitivity analysis, this LCA study is conducted on two actual and absolute structural strengthening techniques, since any change in material selection or design will affect the building's safety; any further sensitivity analysis was not selected. The sensitivity analysis is beneficial when approaching design alternatives during the design stage of buildings.

Normalisation is also not estimated because the building services, structural performance and the building area are the same for both scenarios and results equate on an equal functional unit to normalise the LCA results. The following sections interpret the LCIA results of the LCI analysis's characterisation by comparing the scenarios with details.

4.3.3.1 LCIA Results for Manufacturing and Construction Stages

In this study, the LCI data starts with the extraction of raw materials and follows with energy use and emissions during the extraction of materials. After that, the raw materials are transported to the plant. The construction stage includes onsite construction activities and energy use for transportation from the manufacturer to the distribution centre and from there to the building site and the installation of building elements. In addition to that, waste generation is also evaluated at this stage (ATHENA, 2013; ASMI, 2020a). In this case study, the assembly of the structural elements is included as only retrofit materials, and waste disposal caused by site preparation for the retrofit scenarios is also added to this stage. The AIEB determines transportation distances according to typical or average distances for the location, and extra basic materials assembly used without whole building modelling. In order to eliminate possible adverse effects that may arise from the results, the same location was chosen for both scenarios, and the results were given comparatively. The impacts of the RC and Steel scenarios are presented in Table 4-10 and Table 4-11. They are compared in a clustered column chart in Figure 4-11 that shows each value of the environmental impacts according to their varying units.

As seen in the tables, transportation has a minor impact and does not affect the comparison of the LCIA results. Therefore, Figure 4-11 was generated according to the total impacts. Each impact should be compared in its category because of the different units in every category. Since the non-renewable energy (NRE) and fossil fuel consumption (FFC) impacts are subtotals of the total primary energy (see **Appendix I**), these impacts are considered as one impact category during the comparison of the RC and Steel scenarios. The most significant change occurred for ozone depletion potential (ODP), where the RC scenario caused 88% more impact than Steel, and there was a slight increase in the RC scenario impacts compared to the Steel scenario. However, the Steel scenario had a notable impact on energy consumptions regarding the total primary energy, NRE and FFC; which was more than double the RC scenario energy consumptions. The Steel scenario constitutes only 45%, 34%, 11% and 42% of total emissions from the acidification potential, eutrophication potential, ODP and smog potential, respectively. Overall, the Steel scenario reduced emissions caused by the acidification potential, eutrophication potential, ODP, smog potential at nearly a 20%, 50%, 88%, and 30% reduction, respectively.

Table 4-10 The environmental impacts of the RC scenario in the manufacturing and construction stage

Impact Category	**Unit**	**Site Preparation for the RC Scenario**		**Manufacturing of the RC Scenario Materials**		**Construction Stage**			**Total**
		Disposal and Waste Processing	*Transport*	*Manufacturing*	*Transport*	*Construction Installation Process*	*Transport*	*Assembly of Retrofit*	
GWP[1]	Kg CO_2 eq	1.54E+01	1.13E+01	1.25E+04	1.03E+02	1.03E+03	4.81E+02	2.09E+00	1.42E+04
Acidification Potential	Kg SO_2 eq	2.21E-01	1.09E-01	5.40E+01	9.97E-01	8.79E+00	4.84E+00	5.13E-03	6.90E+01
HH Particulate[2]	Kg PM2.5 eq	5.42E-03	6.02E-03	3.24E+01	5.51E-02	9.57E-01	2.53E-01	4.31E-04	3.37E+01
Eutrophication Potential	Kg N eq	1.38E-02	6.75E-03	4.04E+00	6.20E-02	6.59E-01	3.00E-01	6.61E-04	5.08E+00
ODP[3]	Kg CFC-11 eq	6.74E-10	3.94E-10	8.35E-05	3.62E-09	6.14E-06	1.69E-08	2.58E-07	8.99E-05
Smog Potential	Kg O_3 eq	7.34E+00	3.43E+00	7.47E+02	3.15E+01	2.49E+02	1.53E+02	6.82E-02	1.19E+03
Total Primary Energy	MJ	2.30E+02	1.65E+02	1.59E+05	1.51E+03	1.19E+04	6.97E+03	2.76E+02	1.80E+05
NRE[4]	MJ	2.30E+02	1.65E+02	1.53E+05	1.51E+03	1.15E+04	6.97E+03	2.48E+02	1.74E+05
FFC[5]	MJ	2.30E+02	1.64E+02	1.05E+05	1.51E+03	1.07E+04	6.96E+03	2.85E+01	1.24E+05

[1]GWP, Global Warming Potential; [2]HH Particulate, Human Health Particulate; [3]ODP, Ozone Depletion Potential; [4]NRE, Non-Renewable Energy; [5]FFC, Fossil Fuel Consumption.

Table 4-11 The environmental impacts of the Steel scenario during the manufacturing and construction stage

Impact Category	**Unit**	**Site Preparation for the Steel Scenario**		**Manufacturing of the Steel Scenario Materials**		**Construction Stage**			**Total**
		Disposal and Waste Processing	*Transport*	*Manufacturing*	*Transport*	*Construction Installation Process*	*Transport*	*Assembly of Retrofit*	
GWP	Kg CO_2 eq	1.44E+01	1.10E+01	1.63E+04	7.36E-01	3.62E+02	1.63E+02	1.29E+01	1.69E+04
Acidification Potential	Kg SO_2 eq	2.07E-01	1.06E-01	5.11E+01	8.11E-03	2.41E+00	1.56E+00	3.16E-02	5.55E+01
HH Particulate	Kg PM2.5 eq	5.06E-03	5.85E-03	4.31E+01	4.08E-04	6.24E-01	8.66E-02	2.66E-03	4.38E+01
Eutrophication Potential	Kg N eq	1.29E-02	6.56E-03	2.32E+00	5.02E-04	1.67E-01	9.72E-02	4.07E-03	2.61E+00
ODP	Kg CFC-11 eq	6.30E-10	3.83E-10	8.52E-06	2.87E-11	1.20E-06	5.68E-09	1.59E-06	1.13E-05
Smog Potential	Kg O_3 eq	6.86E+00	3.33E+00	7.21E+02	2.58E-01	6.38E+01	4.94E+01	4.20E-01	8.45E+02
Total Primary Energy	MJ	2.15E+02	1.60E+02	2.64E+05	1.07E+01	5.02E+03	2.37E+03	1.70E+03	2.73E+05
NRE	MJ	2.15E+02	1.60E+02	2.63E+05	1.07E+01	4.95E+03	2.37E+03	1.52E+03	2.73E+05
FFC	MJ	2.15E+02	1.60E+02	1.90E+05	1.07E+01	4.13E+03	2.37E+03	1.76E+02	1.97E+05

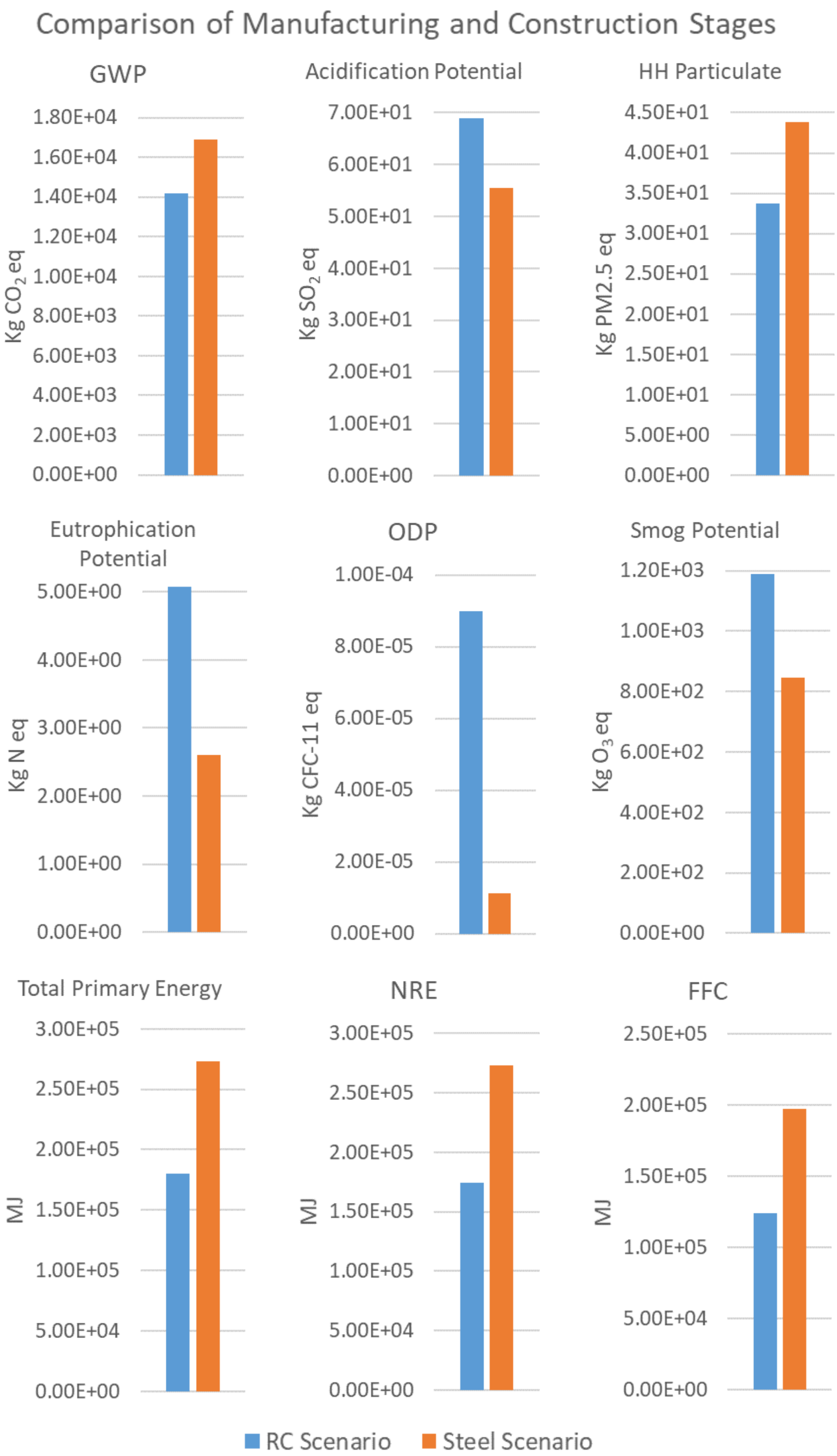


Figure 4-11 Comparison of the LCIA results of both scenarios for manufacturing and construction stages

4.3.3.2 LCIA Results for Usage Stages

Maintenance or replacement of materials is determined by using the BOM. The frequency of the maintenance activity is set according to the building's service life, the energy use for these activities, the transportation of the relevant materials, the generated waste, and final disposition. Then these inputs are assessed according to the building type in the software (ATHENA, 2013). The software also calculates the operating energy and its pre and direct combustion emissions (ASMI, 2020a); however, it was not used for this case study since both scenarios have the same service period, which is assumed to be 65 years.

The impacts of the RC and Steel scenarios during their use are shown in Table 4-12 and are compared in a clustered column chart in Figure 4-12 that shows each value of the impact factors. As seen in the table, transportation does not significantly differ in the comparison of the scenarios in the usage stage. The direct impact of the material quantities can be seen; where the painting material is used the most in the RC scenario because it has the most surface area. As a result of that, the RC scenario had the highest share of the environmental impacts, accounting for about a 60% increase in all categories.

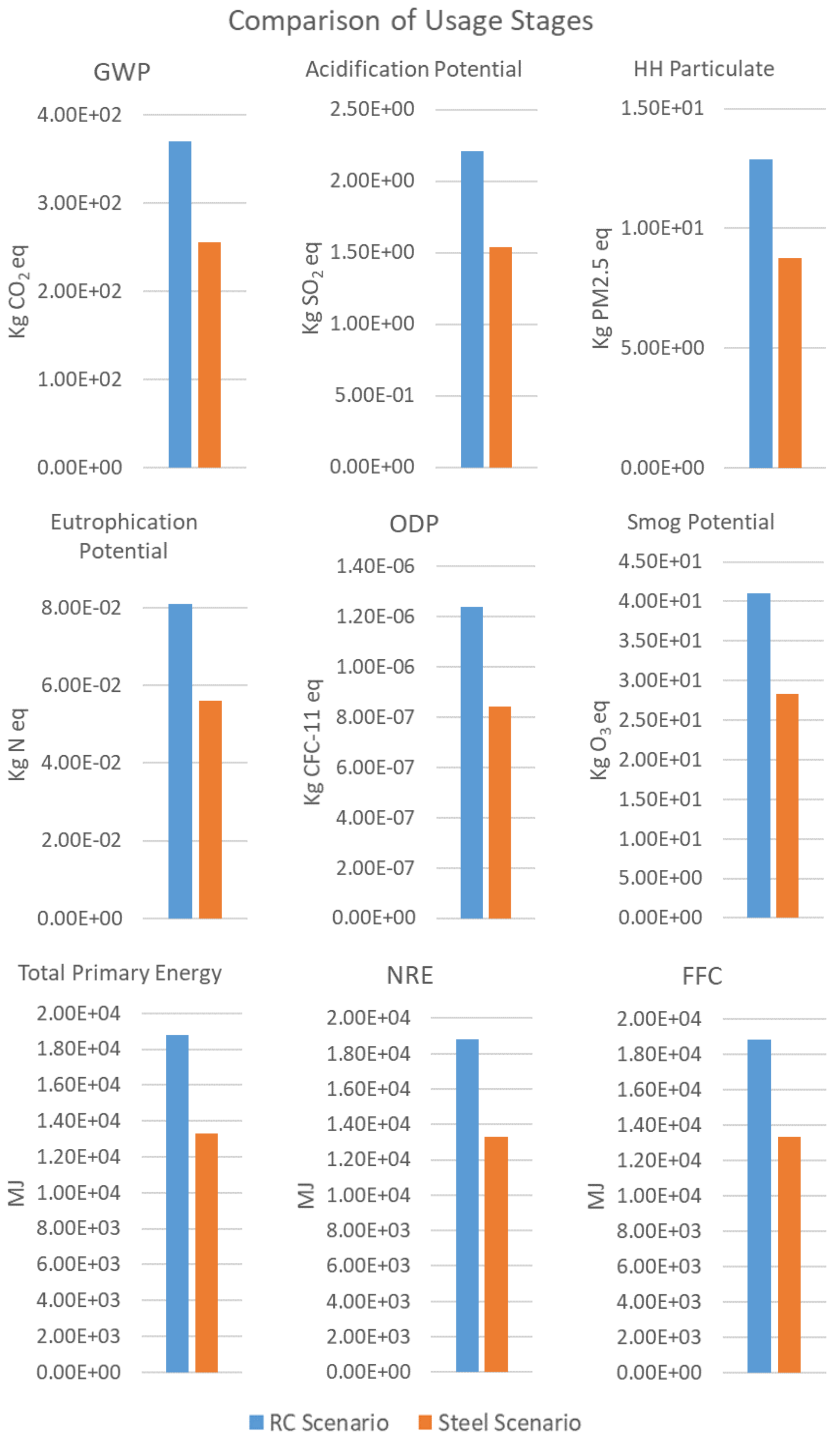


Figure 4-12 Comparison of the LCIA results of both scenarios for usage stages

Table 4-12 The environmental impacts of the RC and Steel scenarios in the usage stage

Impact Category	Unit	RC Scenario			Steel Scenario		
		Use		**Total**	**Use**		**Total**
		Maintenance Manufacturing	*Transport*		*Maintenance Manufacturing*	*Transport*	
GWP	Kg CO_2 eq	3.46E+02	2.37E+01	3.70E+02	2.40E+02	1.62E+01	2.56E+02
Acidification Potential	Kg SO_2 eq	1.97E+00	2.46E-01	2.21E+00	1.37E+00	1.68E-01	1.54E+00
HH Particulate	Kg PM2.5 eq	1.29E+01	1.29E-02	1.29E+01	8.77E+00	8.80E-03	8.78E+00
Eutrophication Potential	Kg N eq	6.59E-02	1.52E-02	8.11E-02	4.57E-02	1.04E-02	5.61E-02
ODP	Kg CFC-11 eq	1.24E-06	8.80E-10	1.24E-06	8.43E-07	6.01E-10	8.43E-07
Smog Potential	Kg O_3 eq	3.32E+01	7.80E+00	4.10E+01	2.30E+01	5.33E+00	2.83E+01
Total Primary Energy	MJ	1.85E+04	3.44E+02	1.88E+04	1.30E+04	2.35E+02	1.33E+04
NRE	MJ	1.85E+04	3.44E+02	1.88E+04	1.30E+04	2.35E+02	1.33E+04
FFC	MJ	1.85E+04	3.43E+02	1.88E+04	1.30E+04	2.35E+02	1.33E+04

4.3.3.3 LCIA Results for the End-of-life Stages

The AIEB reports and calculates the end-of-life effects in two ways; the first is the demolition and then the transportation of the landfill materials, which deals with current use. The second considers the future use of the materials and gives credit for recycling and reusing materials beyond the buildings' life (BBL) (ASMI, 2020a). Although the recycling or reuse potential of buildings is defined as an optional step in EN 15804:2012, it is important to include this factor in the LCA (Chastas, Theodosiou and Bikas, 2016). Each material is categorised as being landfilled, recycled, or reused with an estimated rate. Since all stages except the material production stage contain a high expectation of uncertainties, the BBL also contains forward-looking assumptions (ASMI, 2020b). The energy and materials are obtained from demolishing buildings and their transport to the destined area, and then calculated the landfill of waste materials (reported as Solid Waste to Landfill), disposal and recycling (ASMI, 2019a). The recycling or reused process follows an open-loop recycling scenario where the process leaves the system boundary with credits that are accounted for in the next use, demolition and waste. However, only metals follow closed-loop recycling and are accepted as "potentials" outside the system boundary. The process does not include the next use of recycled material and its disposal. Metals need to be subtracted from the LCI value of the steel scrap, and count as a credit (plus) given to the product system; the net amount of the scrap counts as a avoided burden (minus) which is the recycling of steel scrap to make new steel. Worldsteel database and methodology are used for the LCI profiles of cradle-to-grave in the software (ATHENA, 2013). The environmental impacts of the RC and Steel scenarios during their end-of-life stage are presented in Table 4-13 and Table 4-14, and are compared in a column chart in Figure 4-13 and Figure 4-14, for demolition and BBL processes, respectively. Land emissions' results of the

LCI are presented in Table 4-15 for disposal of waste materials in the end-of-life and compared in Figure 4-15.

The Steel scenario constitutes about 33%-38% of total impacts in each category, except the human health (HH) particulate which constitutes 67% of emissions from the Steel scenario. Therefore, a high reduction regarding the demolition process of between 40% and 52% was observed for the Steel scenario's environmental impacts. The highest reduction was seen in the smog potential with 52%; while the only increase was observed in the HH particulate, representing about 99%. Overall, the Steel scenario has the least effects in the demolition process. In supporting these results, each scenario's solid waste quantities were recorded, as seen in Table 4-15. For both scenarios, a high amount of material was used as landfill material at the end-of-life stage, and the most landfill material appeared in the RC scenario, which was approximately 93% more than for the Steel scenario. Solid waste materials are considered as landfill and that is suitable material for using as landfill, such as concrete waste.

The reason for the lower impact caused by the Steel scenario can be found in the BBL process. Figure 4-14 shows environmental impacts in negative values for the Steel scenario because of the higher recycling benefits caused by metal. In the LCA studies, these negative values include a positive contribution to the material's life cycle, so that avoided burdens are subtracted from positive environmental emission values. Here the negative values show the avoided burden of recycling steel. Therefore, compared to the RC scenario, the Steel scenario overperforms RC by 200% in its all impact categories. Only ODP does not have any impact on both scenarios in the BBL process.

Table 4-13 The environmental impacts of the RC scenario at the end-of-life stage

Impact Category	Unit	End of Life			Total
		Deconstruction, Demolition, Disposal and Waste Processing	*Transport*	*BBL Material*	
GWP	Kg CO_2 eq	5.54E+02	2.17E+02	2.46E+03	3.23E+03
Acidification Potential	Kg SO_2 eq	7.26E+00	2.08E+00	6.15E+00	1.55E+01
HH Particulate	Kg PM2.5 eq	6.03E-01	1.15E-01	2.70E+00	3.42E+00
Eutrophication Potential	Kg N eq	4.51E-01	1.29E-01	3.16E-01	8.97E-01
ODP	Kg CFC-11 eq	2.41E-08	7.56E-09	0.00E+00	3.17E-08
Smog Potential	Kg O_3 eq	2.39E+02	6.57E+01	6.22E+01	3.67E+02
Total Primary Energy	MJ	8.20E+03	3.16E+03	1.23E+04	2.37E+04
NRE	MJ	8.20E+03	3.16E+03	1.23E+04	2.37E+04
FFC	MJ	8.18E+03	3.15E+03	2.47E+04	3.60E+04

Table 4-14 The environmental impacts of the Steel scenario at the end-of-life stage

Impact Category	**Unit**	**End of Life**			**Total**
		Deconstruction, Demolition, Disposal and Waste Processing	*Transport*	*BBL Material*	
GWP	Kg CO_2 eq	4.54E+02	1.52E+01	-2.74E+03	-2.27E+03
Acidification Potential	Kg SO_2 eq	4.43E+00	1.46E-01	-6.29E+00	-1.71E+00
HH Particulate	Kg PM2.5 eq	1.42E+00	8.09E-03	-2.76E+00	-1.33E+00
Eutrophication Potential	Kg N eq	2.72E-01	9.08E-03	-3.23E-01	-4.24E-02
ODP	Kg CFC-11 eq	1.96E-08	5.30E-10	0.00E+00	2.01E-08
Smog Potential	Kg O_3 eq	1.41E+02	4.61E+00	-6.36E+01	8.18E+01
Total Primary Energy	MJ	6.61E+03	2.22E+02	-1.26E+04	-5.76E+03
NRE	MJ	6.61E+03	2.21E+02	-1.26E+04	-5.76E+03
FFC	MJ	6.60E+03	2.21E+02	-2.52E+04	-1.84E+04

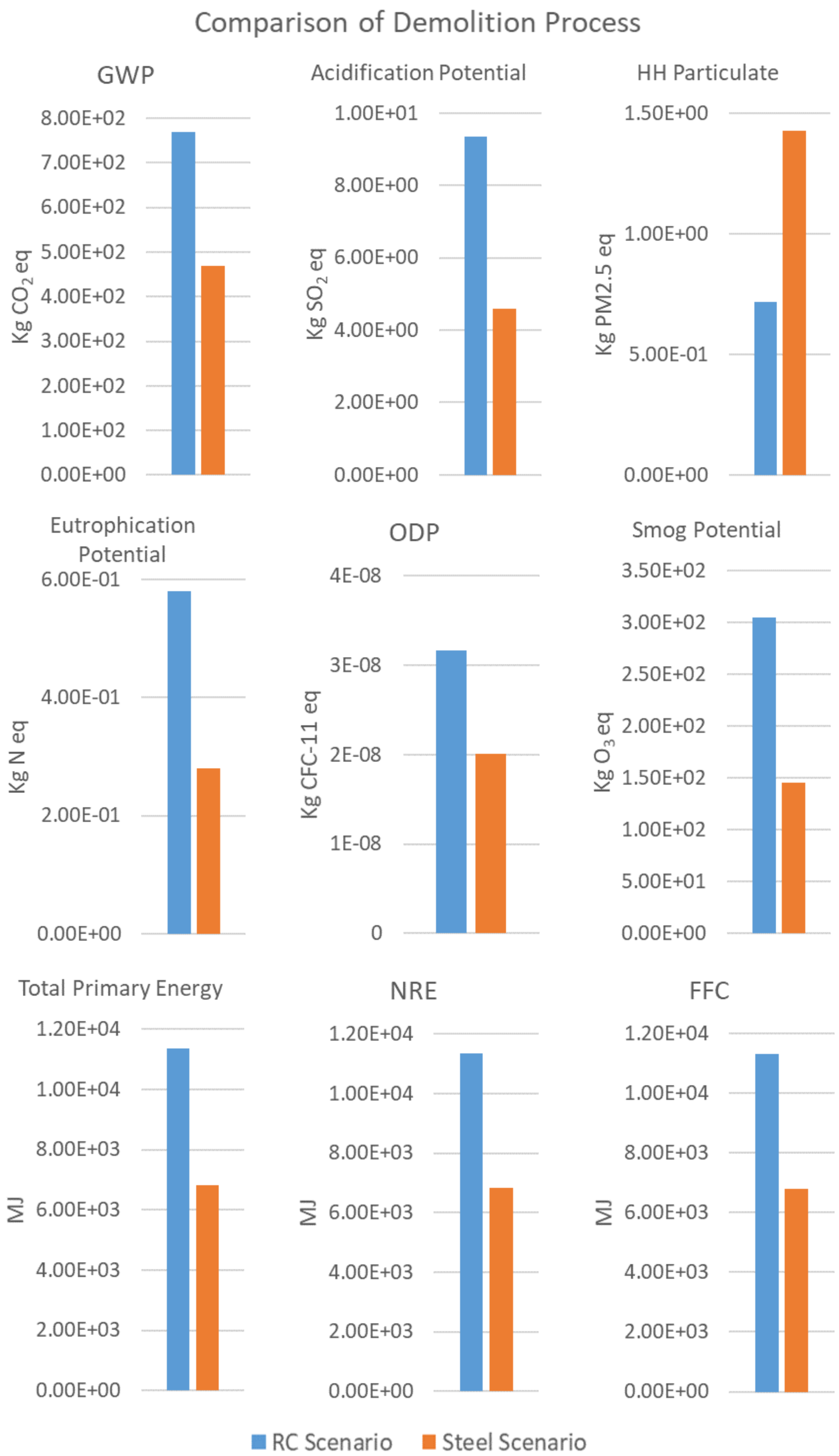


Figure 4-13 Comparison of the LCIA results of both scenarios for the demolition processes

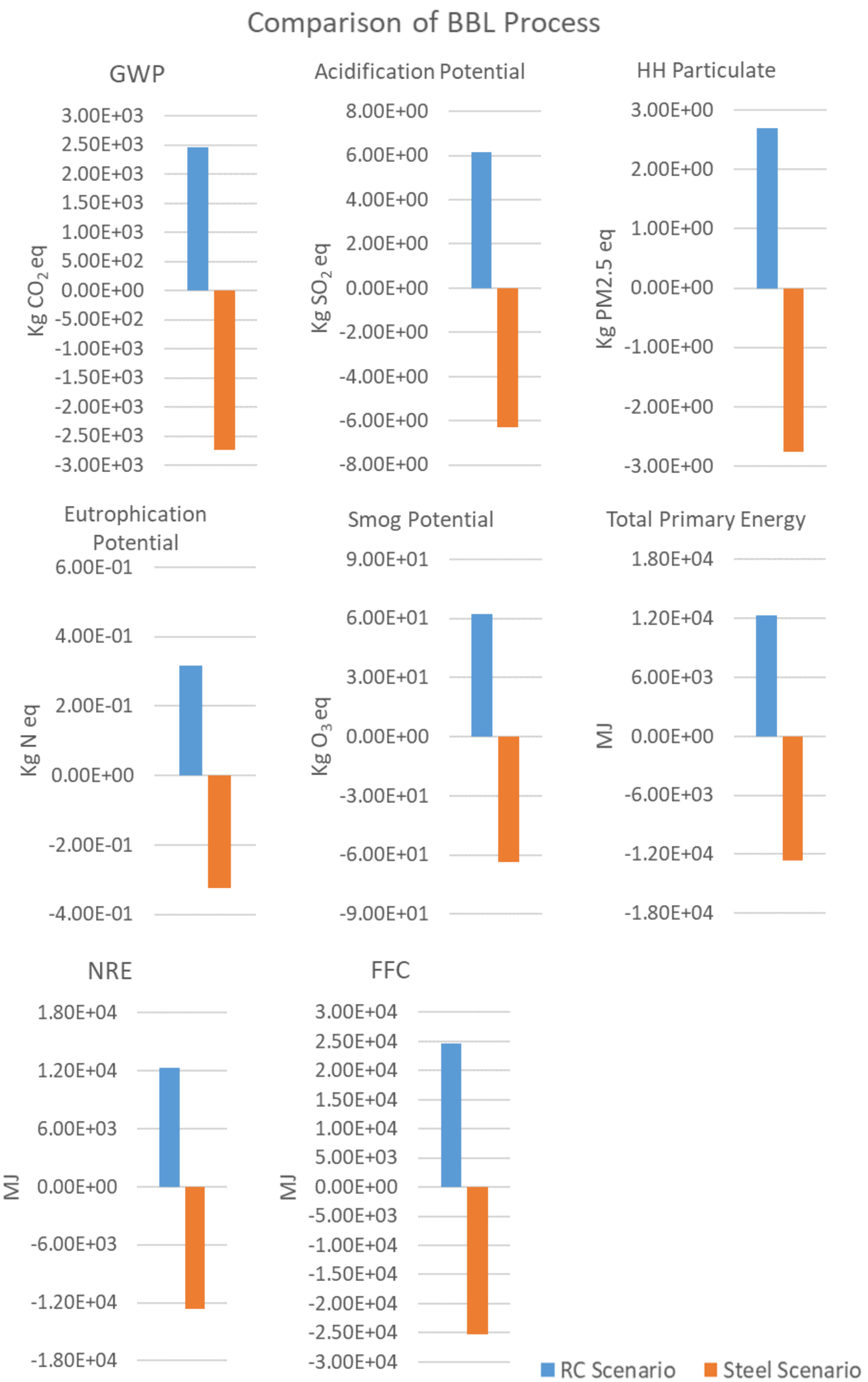


Figure 4-14 Comparison of the LCIA results of both scenarios for the BBL processes

Table 4-15 Life cycle inventory result of the RC and Steel scenarios for land emissions in the demolition process

Emission	Unit	RC Scenario		Total	Steel Scenario		Total
		Deconstruction, Demolition, Disposal and Waste Processing	*Transport*		*Deconstruction, Demolition, Disposal and Waste Processing*	*Transport*	
Solid Waste to Landfill	kg	2.68E+04	0.00E+00	2.68E+04	1.88E+03	0.00E+00	1.88E+03
Other Solid Waste	kg	5.66E+00	2.48E+00	8.14E+00	4.73E+00	1.74E-01	4.91E+00

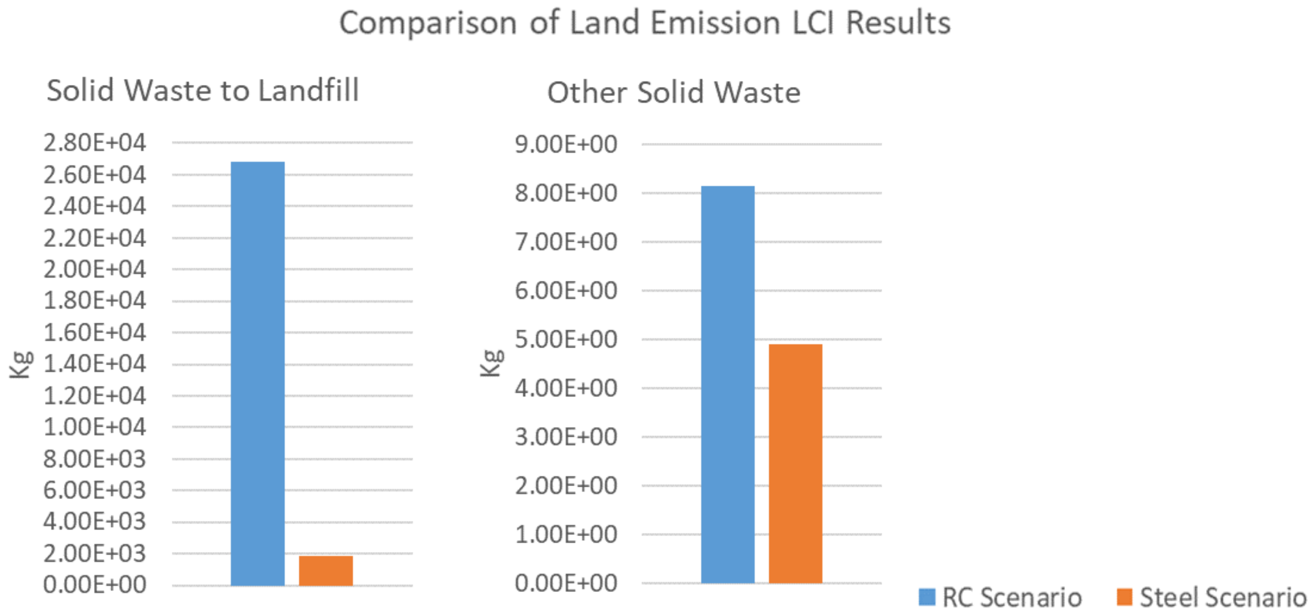


Figure 4-15 Comparison of land emissions of both scenarios in the demolition process

4.3.3.4 LCIA Results for Embodied Carbon and Energy during Service Lives

This section presents the embodied impacts and compares both scenarios' relative performances from cradle-to-grave. Table 4-16 gives the total embodied carbon and energy results of each stage; each impact factor's annual impact is displayed in Table 4-17 according to the 65-year service life. The data on embodied carbon and energy are taken from the GWP and total primary energy, respectively, according to the relevant stages. The primary energy is often used for the calculation procedure in LCA studies as this energy is a more suitable measure for environmental impacts, and conversion factors are proportional to CO_2 (Chastas, Theodosiou and Bikas, 2016). Figure 4-16 compares these embodied impacts of both scenarios, and Figure 4-17 displays the annual impacts and relevant emission reduction of each scenario.

The Steel scenario has the lowest embodied impacts during use and at the end of life; while the RC scenario gives better performance at the construction stage, as shown in Figure 4-16. The highest reduction was recorded at the end-of-life stage for the Steel scenario, which is 170% and 125% for embodied carbon and energy, respectively. Following that, there was a slight decrease in embodied energy in the construction stage of the RC scenario with a rate of about 35%. At the same time, the lowest reduction was observed in its embodied carbon, representing almost 16%. Nearly the same decline was recorded for energy and carbon in the Steel scenario compared to the RC, and accounts for approximately 30% during use. Apart from the life cycle stages, both scenarios' annual impacts were also calculated, as seen in Figure 4-17. Annual environmental impacts are calculated by dividing total impacts by extended service life. The highest increase was observed in the embodied energy; the Steel scenario was higher by 26% than the RC scenario. Conversely, a 16% decrease was recorded in embodied carbon emissions of the Steel Scenario compared to RC. Therefore, the building's LCA stages and service period have a meaningful impact on a building life cycle footprint.

Table 4-16 Embodied impacts of the scenarios throughout their life span

Scenarios	Impact Category	Unit	Cradle to Grave Boundary			Total
			Construction Stage	*Usage Stage*	*End of Life Stage*	
RC Scenario	**Embodied Carbon**	Kg CO_2 eq	1.42E+04	3.70E+02	3.23E+03	1.78E+04
	Embodied Energy	MJ	1.80E+05	1.88E+04	2.37E+04	2.23E+05
Steel Scenario	**Embodied Carbon**	Kg CO_2 eq	1.69E+04	2.56E+02	-2.27E+03	1.49E+04
	Embodied Energy	MJ	2.73E+05	1.33E+04	-5.76E+03	2.81E+05

Table 4-17 Total and annual embodied impacts of the scenarios

Scenarios	Impact Category	Unit	Total Impacts	Annual Impacts
RC Scenario	**Embodied Carbon**	Kg CO_2 eq	1.78E+04	2.74E+02
	Embodied Energy	MJ	2.23E+05	3.42E+03
Steel Scenario	**Embodied Carbon**	Kg CO_2 eq	1.49E+04	2.29E+02
	Embodied Energy	MJ	2.81E+05	4.32E+03

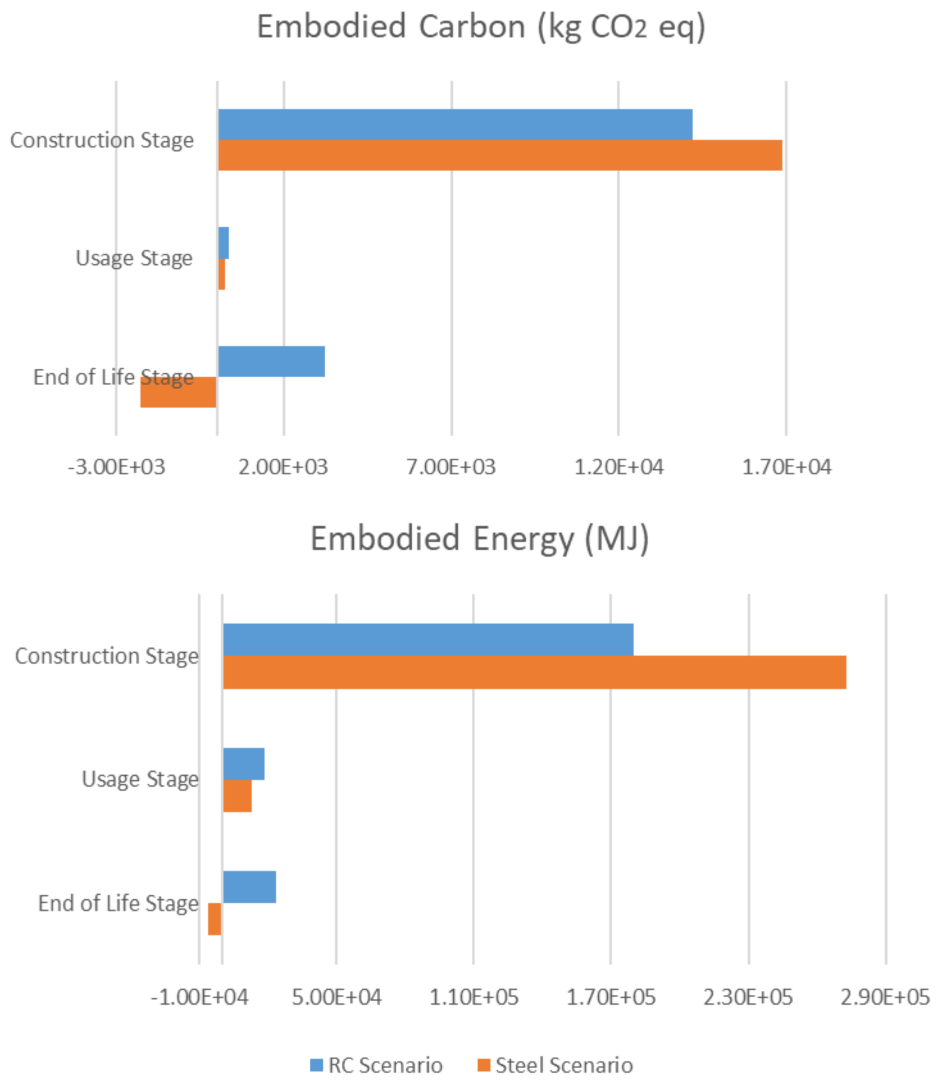


Figure 4-16 Embodied carbon and energy results of both scenarios

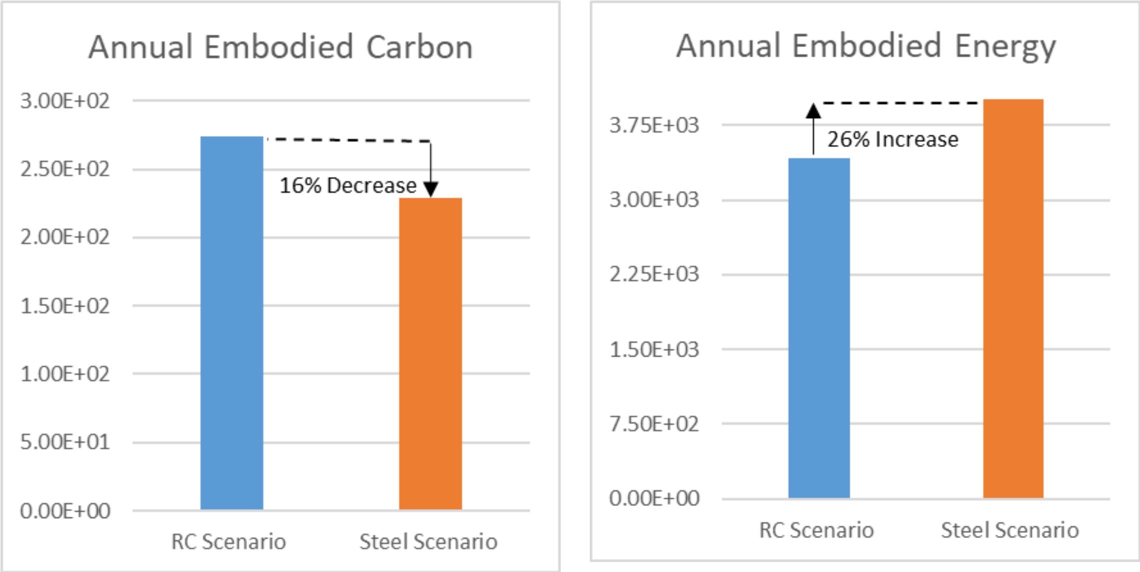


Figure 4-17 Annual embodied impacts

Table 4-18 lists the static embodied carbon emissions and energy over the building's life by dividing it into five-year sections for both scenarios, as seen in Figure 4-18. As the selected maintenance works take place every five years, the five-year sections have been chosen to represent the end of each five years and the usage stage of the distributed impacts that occur throughout the life cycle of the building. The impacts and changes for each five-year section were found by making calculations according to different service periods through the AIEB tool, and the future changes in technology and other changes were omitted due to the uncertainties in LCA studies. Since all stages of the LCA analyses except the manufacturing stage contain a high expectation of uncertainties (ASMI, 2020b). Therefore, these LCA analyses do not include dynamic aspects. The inclusion of these uncertainties in the LCA analysis of the vulnerable buildings, especially the variations that can occur for the usage and the end-of-life stages, will be possible with the development of the dynamic analysis. The table presents a 30% decrease in embodied impacts every five years during the Steel scenario use due to the maintenance. Embodied carbon due to maintenance every five years forms a minor part of the emissions compared to the construction and end-of-life stages, so it could be represented in Figure 4-18 with a special axis that can show the smaller numbers.

Table 4-18 Embodied carbon and energy every five years during the lifetime of the scenarios

Years	**Embodied Carbon**		**Years**	**Embodied Energy**	
	RC Scenario	Steel Scenario		RC Scenario	Steel Scenario
Retrofit Construction	1,42E+04	1,69E+04	Retrofit Construction	1,80E+05	2,73E+05
5	3,07E+01	2,13E+01	5	1,57E+03	1,12E+03
10	3,07E+01	2,13E+01	10	1,57E+03	1,12E+03
15	3,07E+01	2,13E+01	15	1,57E+03	1,12E+03
20	3,07E+01	2,13E+01	20	1,57E+03	1,12E+03
25	3,07E+01	2,13E+01	25	1,57E+03	1,12E+03
30	3,07E+01	2,13E+01	30	1,57E+03	1,12E+03
35	3,07E+01	2,13E+01	35	1,57E+03	1,12E+03
40	3,07E+01	2,13E+01	40	1,57E+03	1,12E+03
45	3,07E+01	2,13E+01	45	1,57E+03	1,12E+03
50	3,07E+01	2,13E+01	50	1,57E+03	1,12E+03
55	3,07E+01	2,13E+01	55	1,57E+03	1,12E+03
60	3,07E+01	2,13E+01	60	1,57E+03	1,12E+03
65	3,07E+01	2,13E+01	65	1,57E+03	1,12E+03
End of Life	3,23E+03	-2,27E+03	End of Life	2,37E+04	-5,76E+03

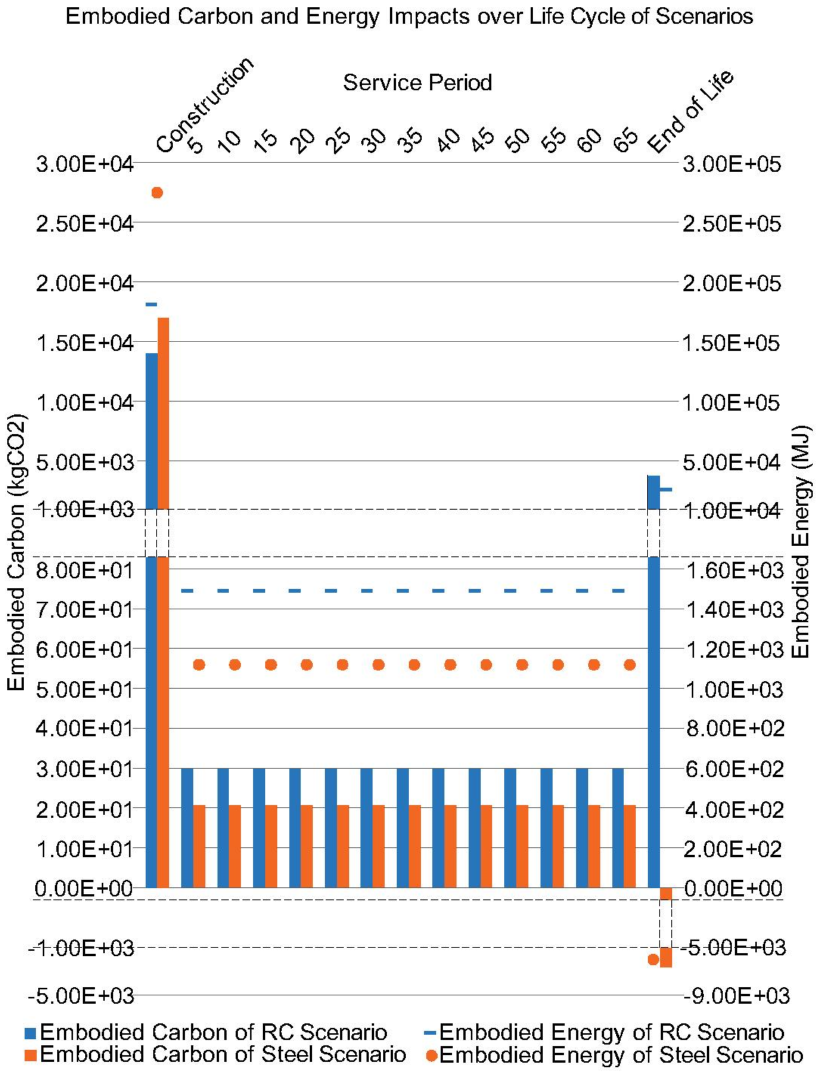


Figure 4-18 Embodied impacts of both scenarios during their life cycle

4.3.4 Interpretation

The previous sections presented the LCA of a retrofitted vulnerable building and the LCI and LCIA results. This section builds on these by critically interpreting and discussing the results of environmental impacts for a vulnerable building reinforced with concrete and steel strengthening techniques.

As with other LCA studies, this research has a few limitations. One of this research's limitations is that the focus is only on assessing environmental impacts based on the retrofitted scenarios and their technical features. The assumptions made in the LCI data are also inevitable limitations in LCA studies. Results of the analysis were interpreted for each stage in connection with LCI analysis and LCIA.

4.3.4.1 Interpreting the Results for Manufacturing and Construction Stage

The RC's manufacturing and construction stage had higher environmental impacts than the Steel scenario; which increased the ODP impacts by nearly 90% compared to the Steel scenario. For both scenarios, the manufacturing phase has the most significant environmental impacts; it constitutes an average of 84% (from smog potential- 63% to HH- 96%) of the total impacts during construction of the RC scenario. In comparison, it has exceeded 90% in the Steel scenario. Vitiello et al. (2016) also reported that during the construction of the RC jacketing, environmental impacts occur mostly during material manufacturing, and it has been found that this constitutes approximately 50% of the construction installation and preparation phases. These results in these two studies cannot be expected to be the same because many factors affect the results, for example, the RC scenario in this study also includes an RC beam application; at the same time there are different damage states and local buildings' practices, and the database and method used are also different. The Steel scenario's LCIA results had a significant impact on the manufacturing process, as there was more energy consumption caused by the steel fabrication. Transportation also causes energy consumption, but its impacts are minor and do not affect the comparison results.

4.3.4.2 Interpreting the Results for Usage Stage

It has been found that the environmental impacts arising from the usage stage are directly related to the surface area to be maintained. The final treatment to the surfaces was painting over mortar application; therefore, painting repeated every five years. Therefore, the Steel scenario reduced environmental impacts by 30% in all categories because of its smaller surface area than the RC scenario.

4.3.4.3 Interpreting the Results for End-of-life Stage

During the demolition process, resource demand is relatively less than in the construction stage because demolition needs energy for deconstruction and disposal transport. Therefore, the reduction in the environmental impacts caused by the Steel scenario becomes more apparent in the usage and the end-of-life stages (including demolition and BBL processes) than in the construction. While a 30% decrease is observed in all categories during the usage stage, it decreased by 50% on average during demolition, and a more than double decrease was observed for the BBL process. The reason for this high rate of decline is the reuse of steel materials that gives an advantage, and a high amount of landfill material caused by the RC scenario caused higher emissions in the BBL process. During the demolition process, a 52% reduction was observed in the smog potential of the Steel scenario compared to the RC; however, the destruction activities of steel doubled the amount of HH particulate impacts. Considering that the RC scenario produces a large amount of landfill material at the demolition process, the high HH impact should be due to the Steel scenario's demolition or waste processing.

4.3.4.4 Interpreting the Results for Embodied and Operating Impacts

Similar results to the impact categories were found in embodied carbon and energy. During the construction stage, the embodied energy and carbon of the RC scenario were lower by 35% and 16% compared to the Steel scenario; while these impacts of the Steel scenario decreased by almost three times compared to the RC at the end-of-life stage. The main reason for this reduction is an abundance of recyclable materials that help reduce environmental impacts. The benefit of reusing materials was also observed for the annual impacts, and 16% of the embodied carbon reduced in the case of implementing the Steel scenario. However, embodied energy increased by 26% because of the high energy use of the Steel scenario. The embodied energy results are similar to the study of Feese, Li and Bulleit (2015); where the repair energy was 270,924 MJ for the probability calculations of the pre-code design of a concrete building (low-rise office building with 60 years' service life) which experienced the Northridge earthquake. In this case study in Turkey, the total embodied energy was found as 222,500 MJ and 280,540 MJ for the RC and Steel scenarios' retrofits, respectively. Similarly, in the study of Feese, Li and Bulleit (2015), the annual energy consumption was 4,103 MJ for a moderately designed concrete building's repair; while in this study, it was found as 3,423 MJ and 4,316 MJ for the RC and Steel scenarios, respectively. The earthquake had a 6.7 magnitude and hit Los Angles in 1994, which was a lower magnitude than the scenarios in this study; however, the results were relatively similar for the concrete buildings.

4.3.4.5 Interpreting the Resource Use Results

According to the LCI results, the RC scenario causes higher resource consumption compared to the Steel scenario. Steel scenario performs quite well; for instance, about 33 kg of ash, 107 kg of clay and shale, 183 kg of coal, 51 tonnes of coarse aggregate, 790 L of crude oil, 353 kg of gypsum (natural), 537 kg of iron ore, 9 tonnes of limestone, 37,500 L of water and 973 kg of wood fibre can be avoided if the steel scenario is implemented. However, some resources such as dolomite, ferrous scrap, lignite, natural gas and uranium were used more in the Steel scenario compared to the RC.

4.3.4.6 Interpreting the Overall Results

The Figure 4-19 below provides the summary of the reduction and increase rates of each impact category representing total cradle to grave (including BBL) impacts in case the Steel scenario is applied. As a result, the benefit of the Steel scenario was considerably higher compared to the RC considering GWP, acidification potential, eutrophication potential, ODP and smog potential.

The corresponding values of the resulting impact rates are as follows:

- GWP – 3 tonne CO_2 (eq) less global warming emissions emitted,
- Acidification Potential – 31 kg SO_2 (eq) fewer acidifying substances released,
- HH Particulate – 1 kg PM 2.5 (eq) more substances affecting the human health system have been released,
- Eutrophication Potential – 3 kg N (eq) less substances affecting aquatic creatures have been released,
- ODP – 0.00008 kg CFC – 11 (eq) less emissions of ozone depleting substances emitted,
- Smog Potential – 643 kg O_3 (eq) less photochemical smog emissions emitted,
- Total Primary Energy –58,000 MJ more total primary energy consumed,
- NRE – 64,000 MJ more non-renewable energy consumed, and finally,
- FFC – 13,000 MJ more fossil fuels consumed.

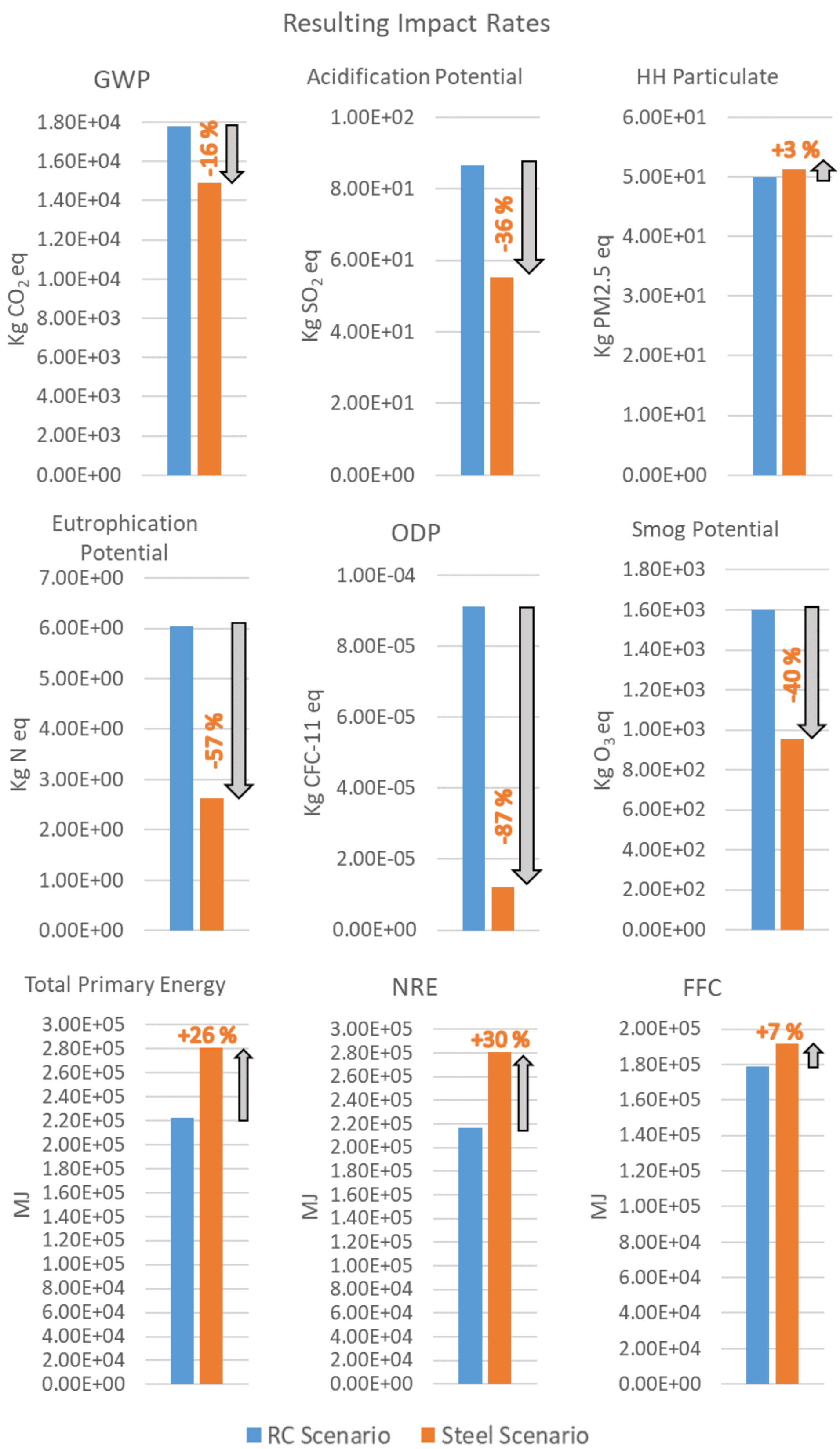


Figure 4-19 Resulting impacts in case the Steel scenario is applied

4.4 Summary

This chapter presented the results of the analysis of the low-damaged building. Firstly, two scenarios were generated; then their technical features were presented; following that, data collected for the LCA stages were incorporated into the LCA procedure. Finally, the LCIA analysis was carried out to assess the environmental impacts of the selected scenarios throughout their life span.

Overall, the Steel scenario had the least effects in the usage and end-of-life stages. However, its energy use during the fabrication of the steel materials increased the environmental impacts during the manufacturing process. On the other hand, the advantage of the reusability of steel materials and the lower deterioration of the resources reduced the Steel scenario's total impacts. The highest reduction in environmental burdens has been achieved with embodied carbon and energy during the end-of-life stage, which accounts for an average of three times the reduction compared to the RC scenario. Whereas, the high amount of energy consumption during the manufacturing and construction stage caused a 16% and a 35% increase in embodied carbon and energy for the Steel scenario, compared to the RC, respectively. During the use stage, the embodied impacts remained constant at a 30% reduction in the Steel scenario. Regarding the annual impacts, while the annual embodied carbon reduced by 16%, the embodied energy increased by 26% due to the high energy consumption of the Steel scenario.

Considering both strengthening techniques, it can be seen that these practices were not applied precisely the same. For instance, the Steel scenario has a steel plates' application to the beams and two more steel jacketing for additional steel beams; however, the RC scenario does not need such applications because of technical features. Therefore, the LCA of the strengthening techniques should not be considered from one aspect such as material; it should be considered project-based.

Overall, strengthening the vulnerable building with the Steel scenario instead of the RC scenario resulted in avoidance of the high amount of resources used and environmental impacts regarding GWP, acidification potential, eutrophication potential, ODP and smog potential.

5. THE ESSIM'S APPLICATION TO A MEDIUM-DAMAGED BUILDING

5.1 Foreword

In this chapter, the ESSIM described in Chapter 3 is applied to a medium-damaged hospital building in Mexico. The hospital, Centro Médico Nacional 20 de Noviembre started to operate in 1960.

There are several issues that arise in hospital buildings which lead to them not functioning well in regards to energy and emissions. One of the biggest challenges of these buildings is their high energy demand and emissions because of the 24-hour operation, the high-quality medical equipment, the air conditioning, ventilation, and operating the building's appliances (K-CEP, 2018). In addition to that, hospitals are facing an ageing problem. Their service period is designed for 50 years; however, it is generally expected that they will serve longer with renewal and retrofits. The reasons for these renewals can be varied, for example, the implementation of new advanced technologies or changes in the building regulations (Kolokotsa, Tsoutsos and Papantoniou, 2012). In Mexico, the national building code also includes energy performance standards for buildings. These standards have helped to achieve significant progress, resulting in 230,000 energy-efficient buildings in the last three years (IEA, 2018). More considerable gains can also be achieved by applying these standards to buildings that consume large amounts of energy, such as hospitals. Research has shown that each Mexican hospital can save approximately 50-60 tonnes of CO_2 equivalent and $8,500 each year with the implementation of renewed national standards, energy retrofitting and renewable systems (Robinson and Jensen, 2017). Disasters are also another problem that can be devastating for buildings. Mexico has been exposed to several disasters such as earthquakes, storms, floods and droughts between

1960 and 2020. Most deaths and economic losses were recorded for earthquakes: approximately 10791 and $ 14,436,000,000, respectively (EM-DAT, 2020).

Therefore, in this chapter, a medium-damaged building was investigated to understand the impact of interventions on a hospital building's environmental performance over its entire life cycle. The LCA procedure was used to compare and conclude on the relative performance of two scenarios. The flow chart in Figure 5-1 was followed for the sustainable design of these retrofitted versus non-retrofitted scenarios.

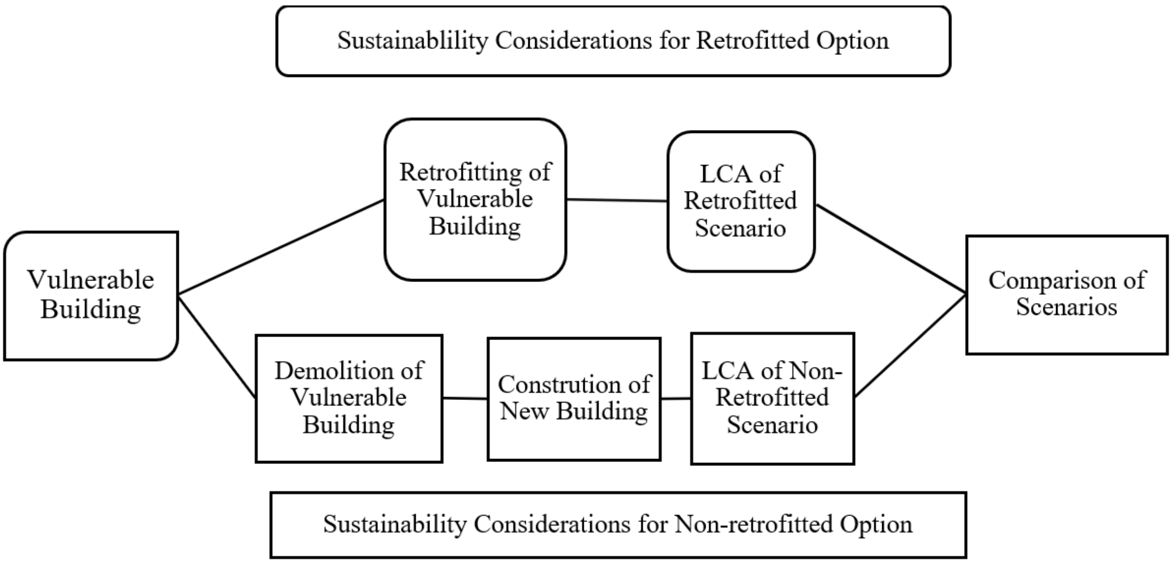


Figure 5-1 Flow-chart of the vulnerable building assessed considering retrofitted versus non-retrofitted scenarios for a medium-damaged building

The objectives set for this chapter:

- To describe and investigate the vulnerability conditions of the medium-damaged building.
- To incorporate the LCA stages according to the defined two intervention scenarios.

- To assess the environmental impacts of selected scenarios to minimise life cycle emissions.

5.2 Pre-LCA stages

Two feasible scenarios were generated based on the proposed methodology. The built-on scenarios are the strengthening of the vulnerable building and constructing a new building by demolishing the existing one. This section presents strengthening and reconstruction technique of these scenarios. Much information about the case study building was obtained from two Spanish theses: Martinez Vazquez (1995) and Almanza (1996); including retrofitting plans, field investigation, vulnerability condition of the building and structural analysis.

5.2.1 Obtaining as-built information

5.2.1.1 Location

The building is in Mexico City and subjected to the great 1957 and 1985 Mexico earthquakes (M_W=8.1). The building complex comprises five independent buildings, as seen in Figure 5-2 (Almanza, 1996). The original building A with its four sections was investigated in this thesis. The photograph of the building was taken in 1971, is shown in Figure 5-3 (REDALYC, 2011).

5.2.1.2 Original Drawings

The building does not have original drawings; however, plans were prepared in parallel with data obtained in the field investigation. Thus, the architectural blueprint of the hospital was created.

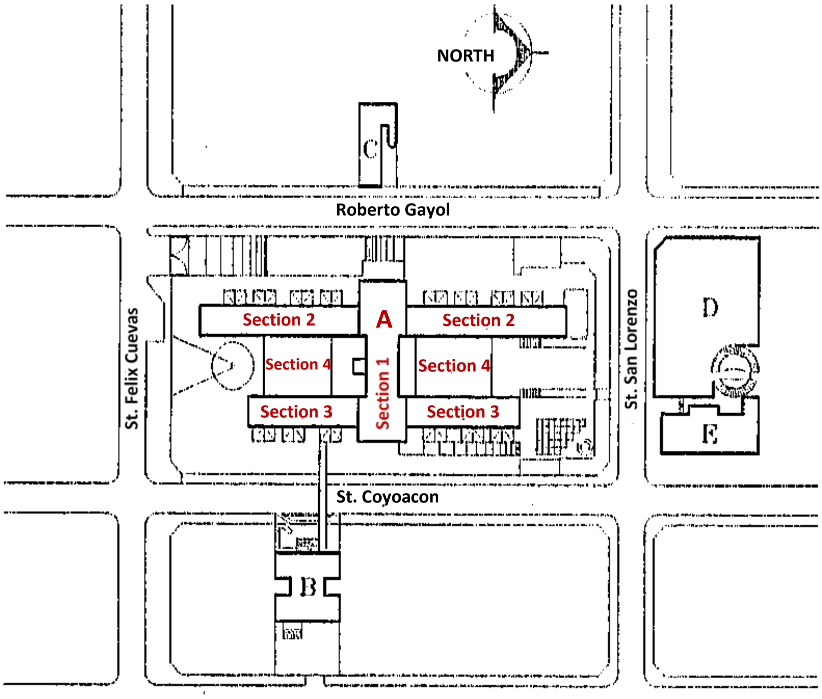


Figure 5-2 Location sketch of the building complex (Almanza, 1996)

Figure 5-3 A photograph of the hospital taking from 1971 (REDALYC, 2011)

5.2.1.3 Characteristics of the Building

The case study is a RC building. However, the division of the different rooms was built as masonry walls during its transformation to a hospital building. The structure was based on rigid frames formed by columns and beams with slabs. Table 5-1 shows the dimensions of each section of the building, and Table 5-2 gives dimensions of the building's elements that were estimated after investigation.

Table 5-1 Characteristics of each section

Section Body	Level	Dimensions
Section 1	9 + Basement	21.20 x 62.50 m^2
Section 2 (North)	8 + Basement	69.25 x 10.95 m^2
Section 2 (South)	8 + Basement	69.25 x 10.95 m^2
Section 3 (North)	7 + Basement	48.05 x 10.95 m^2
Section 3 (South)	7 + Basement	48.75 x 10.95 m^2
Section 4 (North)	2 + Basement	25.20 x 29.05 m^2
Section 4 (South)	2 + Basement	25.20 x 32.65 m^2
Foundation	1	5456.3 m^2

Table 5-2 Dimensions of the building's elements

Columns	
Levels	**Dimensions**
1	95 x 95 cm
2	85 x 85 cm
3	80 x 80 cm
4	80 x 80 cm
5	75 x 75 cm
6	70 x 70 cm
7	60 x 60 cm
8	60 x 60 cm
9	25 x 60 cm
Beams	
Directions	Sections
East	30 x 80 cm
North	25 x 60 cm
Slab	
Thickness	10 cm

5.2.1.4 Building Function

The building was built in 1949 as the Teachers Union Building. Later, the necessary changes were made in the design, and it turned into a hospital in 1960. Then it continued to be used as a hospital building after retrofitting in 1995. The selected retrofit needs to be applicable to the hospital to protect its functionality. In this case, the spaces inside the building must remain available.

5.2.1.5 Field Investigation

Several site visits were made for reviewing the existing condition of the building. It was observed that the beams' and columns' physical appearance, in general, were at an acceptable level. Destructive and non-destructive tests were conducted during the field investigation. Geotechnical revision of the foundations was carried out, and samples from the subsoil were taken. The subsoil exploration work consisted of the execution of two electric cone surveys, a standard penetration sounding and two mixed soundings. As part of the same exploration, five exterior coves (holes) were made in the building, in order to determine the type of the current foundation of the structure. The depth of the coves varied between 4.0 and 6.2 m. According to the test result of these coves, it was concluded that the buildings are based on a compensated foundation displaced 6.25 m deep. The bottom slab of this box rests on a uniform bed of cubic-shaped basalt blocks.

The samples obtained from the standard penetration probe and the selective mixed probe were subjected to different laboratory tests, which enabled the defining of the subsoil stratigraphy, its properties and characteristics. The work carried out consisted primarily of a macroscopic visual and tactile classification of the materials, for which characteristics such as texture, colour, odour and resistance were taken into account both in the natural state and in the dry state (toughness). Following the results of the properties, the samples were classified within the unified soil classification system. Another laboratory test was done for concrete strength by taking concrete samples from determined points in the building, and the concrete samples showed 250 kg/cm^2 resistance at compression.

Since the building does not have a foundation plan, excavation work was carried out, and a foundation was found at a depth of 2.5 m. It was discovered that the building is supported on foundations formed by slabs and countertops of RC. The superstructure was integrated with RC columns and columns forming flat frames. Masonry walls mostly built as a division of rooms, and reinforced concrete walls also exist in the interior design. These masonry walls did not connect to the original structure, but the concrete walls were connected. There are also constructive joints between intersecting bodies, and it is clear how each of these bodies works independently before the action of any type of load.

The non-destructive tests were done to determine the parameters of resistance and deformability of the materials; these tests were: simple, standard, and rebound compression, conventional and rebound U-U triaxial compression tests. Granulometric analysis of the soil particles retained in mesh No. 200 was also performed.

5.2.1.6 Vulnerability State

The existing condition of the building was assessed to determine what could have induced structural failure. Buildings had partially collapsed during the great 1985 earthquake; however, regarding this hospital building, it was observed that the physical appearance of the beams and columns in general was acceptable. In the hospital's structural elements, 27 failures were identified, as it is not designed for seismic actions (Morán-Rodríguez and Novelo-Casanova, 2018). For instance, this building has an elongated rectangle geometric form that can generate torsion forces and cause damage. Also, different heights and inconsistency of the joined building sections can create a pounding effect during an earthquake. The fact that the building was not seismic resistant and not built according to anti-seismic technology is one of the failures that triggered the damage (Morán-Rodríguez and Novelo-Casanova, 2018). It was not destroyed in the 8.1 Mw earthquake; however, it could be heavily-damaged or collapse by earthquakes that may occur in the future due to its vulnerability.

The general factors for the occurrence of damage in buildings are quality of materials, workmanship and ignoring building standards. The factor specific to Mexico was that earthquake movements changed over time with the effect of lake sediments and the ground motion frequency range increased. This situation later changed the earthquake design force in the building standards (Beck and Hall, 1989). Establishing seismic coefficients was considered acceptable for the design of structures of this magnitude when the building was constructed. Therefore, the case study building was designed following the old regulation existing at that time. However, the building deformed with lateral forces that were well above the limit state of the current regulation. This situation is a good example of possible changes in the earth with the impact of disasters and so changes are necessary in national regulations. Therefore, in 1985, when the most intense earthquake occurred in Mexico City, the analysis and design guidelines established in the Earthquake Design Standards were modified.

After its transformation to a hospital building, changes in the building also created a rigidity problem because of the masonry walls and fillings. This lack of rigidity placed the building in an unfavourable situation in the presence of significant earthquakes. Another issue encountered in Mexico's buildings after the earthquake was the deterioration and destruction of the upper floors. The reason for this is the narrowing of columns to the upper floors significantly (Beck and Hall, 1989), and this inaccurate design was also seen in this case study.

5.2.1.7 Service Life

Hospital buildings are designed for long-term use and generally operate longer than planned. The building was built in 1949, however, it was transformed into a hospital building in 1960. In 1985, after being damaged in a major earthquake, a complex and massive retrofit was applied in 1995. The building's age was 46 at the time of the retrofit. Classic buildings are designed for 50 years; however, it can be seen from this example, hospital buildings are designed for a service life of at least 60 years, and various reinforcement processes extend this period. This study assumed that the reinforcement would increase the building's service life by approximately 50% according to expert opinion, so serving for about another 40 years after retrofitting. If it is in use for longer (5 or 10 years more), some components of the building, such as the windows, will need replacement after 40 years. Therefore, the service period of this building, which has already been used for a long time, is kept within the 40-year limit to make more accurate calculations.

5.2.2 Assessment of the building's structural capacity

During the field investigation, samples were taken from eight different distances up to 25 m, and soil testing was carried out in the laboratory. From the ground surface to deep down, several types of soil were found, such as sandy clay, fine sand, gravels, sand, clay with gravels, and very high compact gravels with sand. Subsoil properties under buildings are predicted to have better properties due to overloading over time, which induces pre-consolidation of the subsoil. Also, there is a resistant layer 20 m deep. According to seismic and geotechnical zoning of the current construction regulations, the building is located within Zone II (transition).

Engineers modelled the real system's structural behaviour and applied the design loads (dead load, live load and accidental load) following the Mexican building codes. The structural elements were modelled in frames to perform static analysis to determine their displacements and rigidities. Then, the dynamic analysis was carried out considering seismic forces according to the Mexican Code (RCDF, 1987). The maximum displacement associated with critical load conditions and the structure's total load on the foundation was calculated according to the static and dynamic analysis. The analysis of these forces was made with the help of the computer program called M-STRUDL, which performs iterations and calculations based on the method of stiffness; this is considered an exact method that accepts elastic-linear hypotheses behaviour of the materials. Once the seismic forces were obtained in the static analysis, a structural analysis was run by using the SISCO program. Sections 1 and 2 were calculated individually, because there was no way for Section 1 to contribute to the rigidity of the building complex at the time of the seismic movement. According to national codes, the maximum allowable displacement is 0.006 times the height of the building. The maximum permissible displacement value was obtained as 19.32 cm when considering the masonry walls for Section 1. However, the original structure's static and dynamic analysis showed that the maximum displacement exceeded this limit. The maximum displacement was obtained as 32.3 cm and 38.2 cm for static and dynamic analysis, respectively, for Section 1. The maximum permissible displacement was determined as 17 cm for Section 2, and the total displacement (static, dynamic and rigidity) was calculated as 42 cm for the original structure without retrofit after analysis. Therefore, the rigidity of the structure needed to increase against lateral forces.

5.2.3 Selection and design of structural intervention

5.2.3.1 The First Scenario: Structural Retrofit

The corresponding authorities decided to carry out the total remodelling of the property leading to the need for a retrofit project. This project considered all the existing unfavourable conditions, the adaptation of the spaces to provide better hospital services, and was intended to make the structure comply with the current regulation.

According to the guidelines in the regulation, the reinforcement project needed to be met with permissible displacement and stiffness. During the alternative intervention design, maintaining the hospital's functionality conditions, providing free mobility and free spaces in the building, and the aesthetics were also considered. While many reinforcement designs were discussed, the small distance between the columns (4.7 m) and the building's small internal spaces caused the reinforced design to the façade of the building to be advantageous. Also, according to the seismic zoning of the building and the determined soil condition, six pillars under each structure in Sections 2 and 3 were proposed for behavioural compatibility with the existing foundation, both in the long term and during an earthquake.

The retrofitted structure's expected performance is mainly the stiffening of the existing building without deteriorating its ductility and resistance, as well as the improvement in its seismic performance. This performance was achieved by connecting metal elements using friction bolts capable of efficiently dissipating energy during seismic action and not damaging the building and its functionality. These metal elements were placed in the plane and longitudinal direction and adjusted to counterbalance. All the levels in Sections 1, 2, 3 and 4 were strengthened with internal diagonal steel elements linked to the original structure with connections designed with plates and fixing anchors. In addition, Sections 2 and 3 were strengthened with external three-dimensional (3D) steel bracings that were connected to each other with bolts and to the original structure with steel plates and anchors. Tubular diagonals as bracing elements were selected to achieve adequate stiffening of the structure without increasing its mass and weight considerably; these could be distributed mainly on the building facades to achieve larger spaces inside for optimum use. The objective of the retrofitting is to strengthen the building as a whole. Steel tubes were connected to high-strength steel plates, and anchors to the original structure's concrete structural elements. These metal plates with oval holes were connected to the concrete with bolts which allow the element to slide when the horizontal loads per earthquake exceed the value of the forces, and release some of the energy taken during the movement through friction between the metal plates. Then anchors transmit compression to the concrete element of the original structure. This system aims to transmit the tension and compression forces from the original structure during the earthquake to the columns and beams. This solution demonstrates the importance of preventing the increase of loads transmitted to the existing foundation.

The building was then analysed again by introducing the reinforced structure's data to the program. In Section 1, a total of 29 diagonal bracing groups of various dimensions were counterbalanced, of which 14 corresponded to the transverse direction, and 15 corresponded to the longitudinal direction. In Section 2, 18 diagonal bracing groups and eight trusses were located corresponding to Section 3 with 14 diagonal bracing groups and six trusses of various dimensions, as seen in Figure 5-4. The details of the structural analysis results and retrofits can be seen in the thesis of Martinez Vazquez (1995) and Almanza (1996). **Appendix J** also presents the retrofit project details.

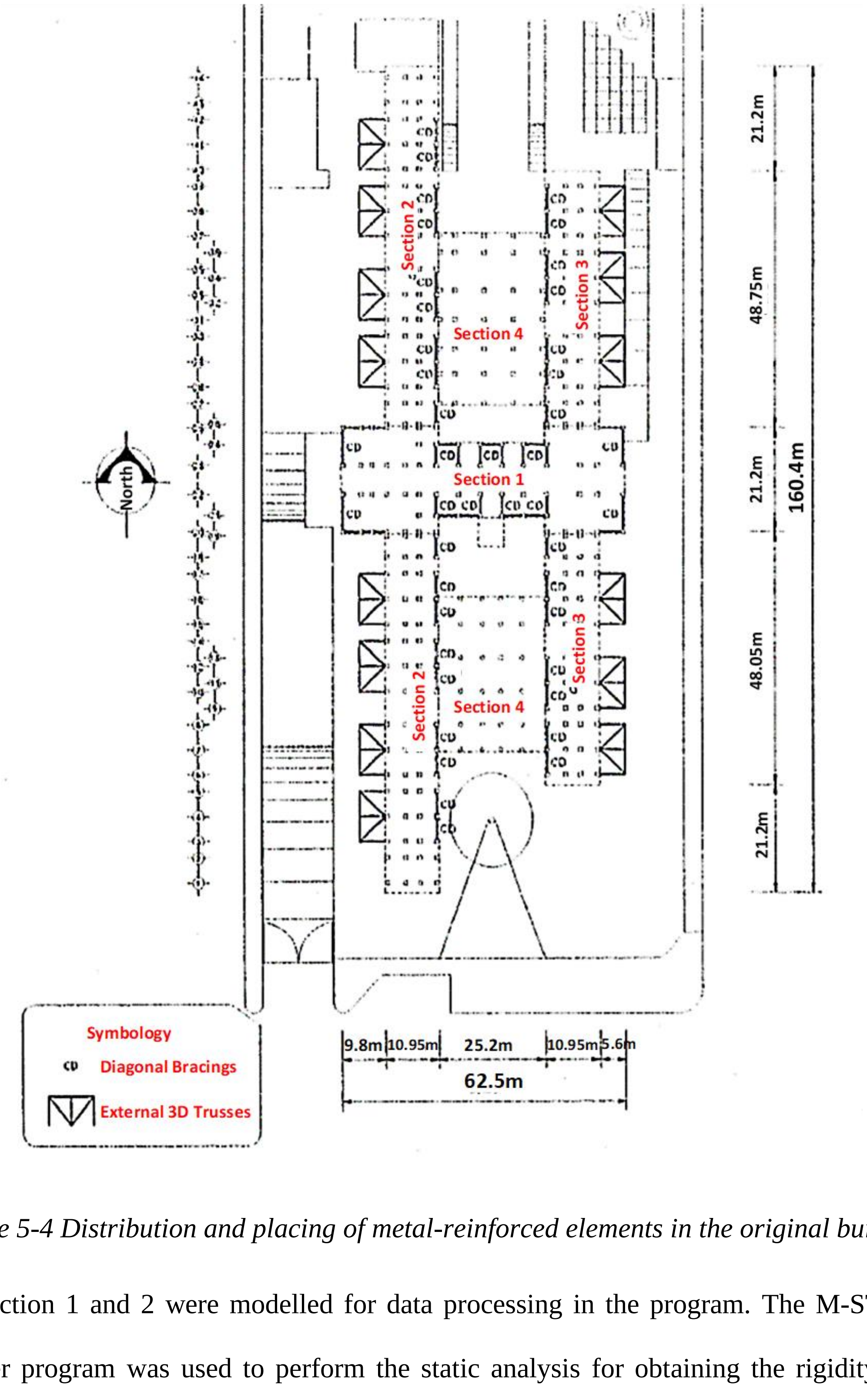


Figure 5-4 Distribution and placing of metal-reinforced elements in the original building

Only Section 1 and 2 were modelled for data processing in the program. The M-STRUDL computer program was used to perform the static analysis for obtaining the rigidity of the frames and stiffening of the new additions, and SISCO was used for performing dynamic analysis to obtain the structure's behaviour under seismic forces. Then, the displacements were obtained for each level and the total maximum displacement was determined. With the reinforcement the rigid reinforced concrete frames, together with the concrete walls, can withstand at least 80% of the total lateral forces acting on the structure. The maximum displacement was calculated as 13 cm for Section 2, which is within the permissible limit.

Regarding Section 1, maximum displacement in the X (longitudinal) direction was 2.9 cm, and in the Y (transversal) direction was 8 cm for the static analysis; and the total displacement was 7 cm for the dynamic analysis. Figure 5-5 shows the maximum total displacements (as mentioned above, Section 1 evaluated according to dynamic analysis results and Section 2 based on total analysis results) of the before and after strengthening and the permissible displacement. The strength of the building was evaluated by proportioning the total displacement of the Sections according to their vulnerable, permissible and strengthened state, and represented in Figure 5-6 as the rational values for the building's performance.

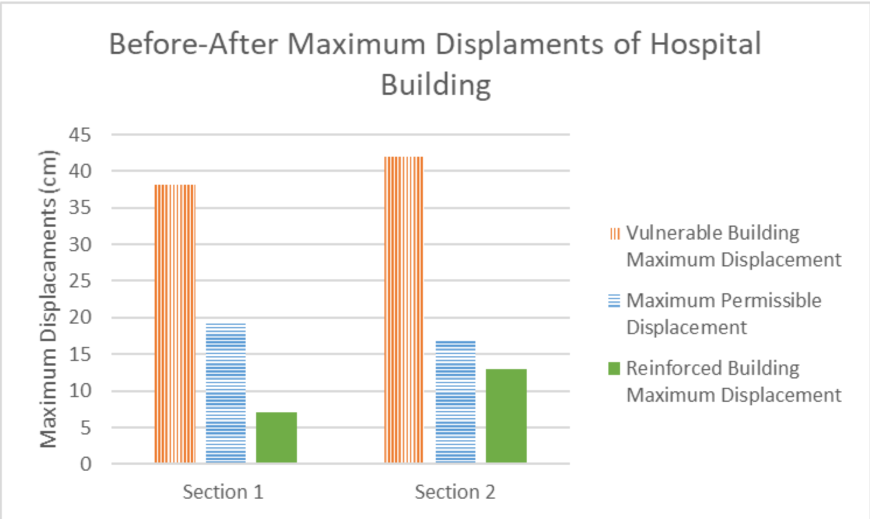


Figure 5-5 Measured maximum total displacements for the hospital building before and after strengthening

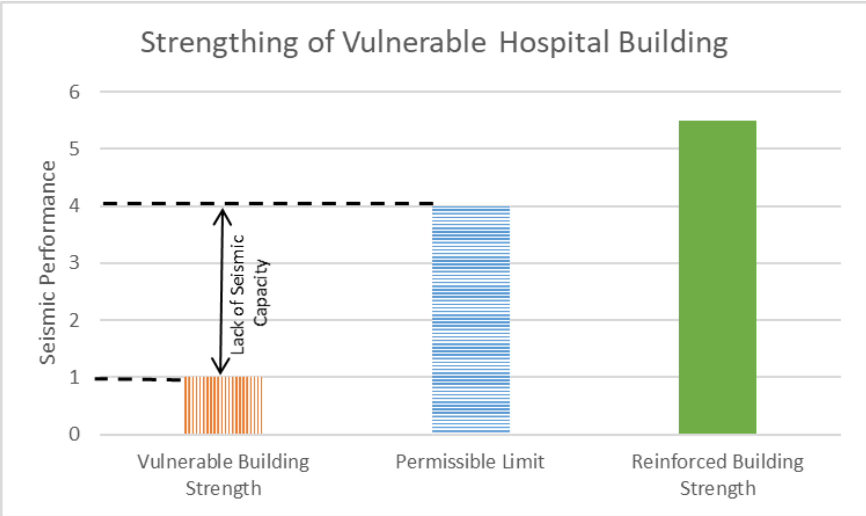


Figure 5-6 The contribution of potential reinforcement to the building's seismic performance

As a result, improvements reached after strengthening the vulnerable building:

- Seismic demand of the forces reduced.
- Permissible displacement and stiffness met.
- Resistance and ductility of the original structure protected.
- Huge mass load to the foundation of the original structure avoided.
- The functionality of the building preserved.

5.2.3.2 The Second Scenario: New Building

The second scenario includes processes for demolishing the vulnerable building and constructing a new one, referred to as a non-retrofitted scenario. In this thesis, there is no selection regarding the structural performance of the scenarios. The applied structural interventions have brought the vulnerable building to a sufficient level of structural performance.

It is known that demolition and reconstruction are preferred where strengthening/repair is not economical or feasible. However, the waste resulting from demolition and the use of the large amount of material required by a new construction should be considered. At the same time, these environmental and economic burdens must be evaluated through the building's life cycle. This section aims to present how to evaluate environmental impacts from a non-retrofitted vulnerable building over its lifetime. Construction and demolition stages include many parameters. In this case study, factors such as the material use and the demolition of the building that may affect the environmental issues more are considered. It is assumed that the new building has the same architectural design as the existing building, but is more durable and was built following recent regulations.

There are characteristic and design differences between old and modern structures. Structural deficiencies that affect the ductility of the building exist and make the structure vulnerable to seismic forces as in this example. The building's field investigation and damage level, as described above, show the vulnerable hospital building's high deformation capacity. The deformation that exceeds the limit levels is about two times higher than standard values. Besides, considering that it is a medium-damaged building, it is known that the damage percentage of the building can reach 20-50%. Also, according to Liel (2008), while economic losses for retrofitted vulnerable reinforced concrete frame structures are 0.65%, it is 0.3% for modern structures. These economic losses of up to two times more than for the modern structures can be based on reasons such as lack of adherence to the seismic building codes and material quality. The material and structure characteristics also influence the level of the damage. These deficiencies' insufficient design affects the building's strength and can be shown as in Figure 5-7.

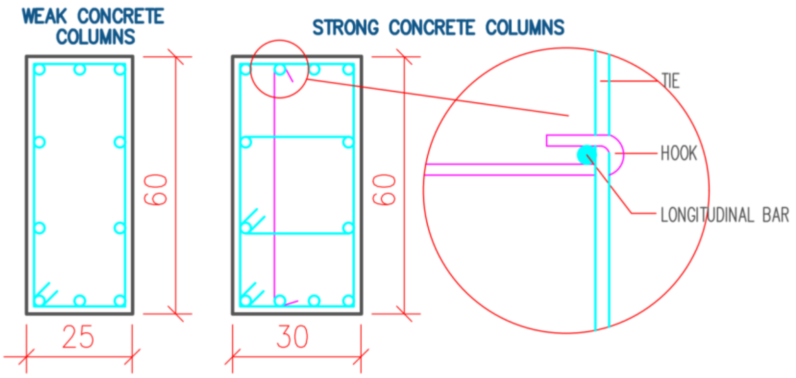


Figure 5-7 Design differences between vulnerable and strong buildings

Therefore, the characteristics of a vulnerable building differ from the new building; these differences are assumed during the calculations of demolishing the vulnerable building and building a new modern constructed building. Accordingly, hospital buildings are built as more durable due to their functions compared to a standard building, and this is also included in the calculations. In addition to that, the service life of the new hospital building is considered as 60 years, which is longer than for the retrofitted scenario (40 years). Building dimensions are assumed to be the same for demolished and reconstructed buildings. Below are the differences considered during the design of the demolished and new hospital building for the LCA calculations:

- Strength and stiffness of structural elements.
- Insufficient design of building components.
- Remaining service period of buildings.

5.3 LCA stages

This process includes the life cycle environmental assessment of the retrofitted scenario versus the non-retrofitted scenario of the damaged hospital building. Therefore, the LCA method is detailed and described in four steps.

5.3.1 Goal and scope

This case study's goal is a comparative sustainability performance for the two presented scenarios of the vulnerable hospital building. The scope of the analysis includes structural retrofitting and new building construction. The life cycle of the scenario is from material production to the end-of-life stage. The functional unit includes materials of retrofitted and non-retrofitted buildings.

5.3.2 Life cycle inventory analysis (LCI)

Data on structural retrofitting and reconstruction should be collected for environmental impact analysis. In this study, the LCI is quantifying the retrofit materials' flow, the construction works, transportation, maintenance, and the end of life of the materials for their embodied environmental impacts throughout the life cycle stages of the retrofit. How the material quantities are calculated for each stage and scenario is shown in the following sections. For assessing the environmental impacts, the AIEB tool and its database are used. A flow chart in Figure 5-8 is drawn to explain the case study's steps over its selected scenarios.

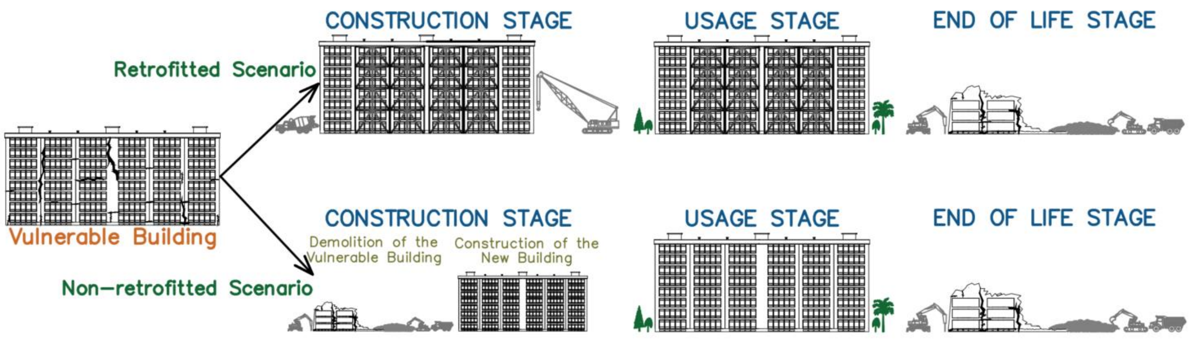


Figure 5-8 Schematic representation of a medium-damaged building's LCA stages over the two selected scenarios

5.3.2.1 LCI of the First (Retrofitted) Scenario

The LCA stages were customised for the structural retrofitting of the hospital building, as seen in Figure 5-9 which illustrates the organisation of the LCA with related modules.

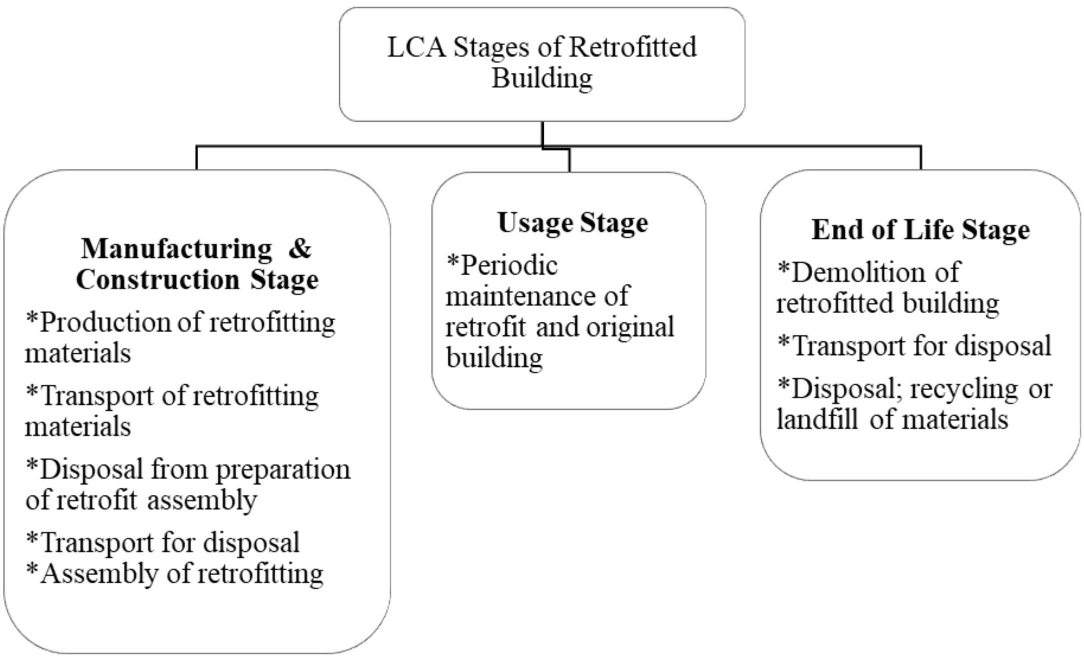


Figure 5-9 Specific parameters of the LCA stages for the first scenario using the unit process method

Manufacturing and Construction Stage

In this structural retrofitting example, two types of steel retrofit applied: 3D steel trusses as external reinforcement and tubular diagonal bracings as internal reinforcement. Each 3D truss consists of columns, beams and diagonals which have different characteristics according to the structural function they performed. Also, there are different ways of joining each of the connections, depending on the elements that are to be joined. To connect circular tubes to the connection, plates are inserted in the tubes by welding to provide a flat end to be able to make bolted joints. The connections have a different number of units as well as bolts. Each of the 3D trusses has its foundation which is built on six pillars made of RC confined with perimeter beams. These concrete pillars are 80 cm in diameter and about 18 m in depth. The 3D trusses and their foundation are linked with a base plate on which one tube column rises. Each base plate has eight studs that penetrate to concrete base footing, and anchors. Regarding the internal diagonals, the diameter and length of the circular tubes were designed differently depending on the changes in the building's design. The design of the retrofit elements, in general, is as follows: high-strength plates in two vertical and two horizontal directions; another plate for connection of diagonal tubes with bolts and anchors with plates to connect to the concrete structural element. The connection of the plates with columns, beams and tubes was welded. Also, anchor connections were strengthened with epoxy applications. Finally, blasting, prime and paint were applied by using an air compressor to the surface of all steel elements to protect from corrosion. Below, Figure 5-10 shows the connection design of the tubes and plates in the 3D trusses and diagonal bracing reinforcements. The retrofit plan is further detailed in **Appendix J**.

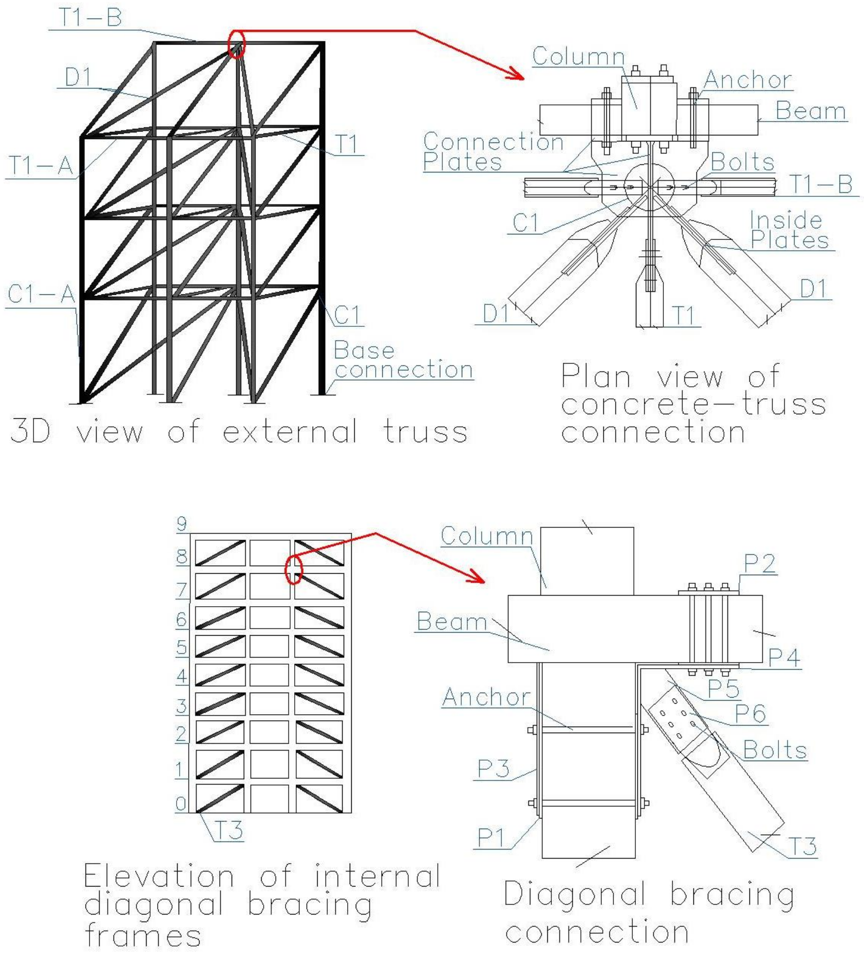


Figure 5-10 The 3D and diagonal joints of plates and tubes

Steps of steel reinforcement works that applied to the retrofit:

- Excavation of the foundation for the casting of concrete piles for 3D trusses includes drilling working hours (h) with a helical type drilling mechanism helical type. It excavates 20 cm per minute, excavating soil (m^3 - neglected) and its transport (km-neglected).
- Assembly of the concrete piles' steel reinforcement includes hydraulic crane use for steel assembly (h-neglected), steel reinforcement of concrete piles (kg) and its transport (km).

- Casting the concrete mixture into the well includes lowering the concrete (kg or m^3), disposing of concrete waste from cleaning (kg), its transport (km), breaking concrete with a breaker (h-neglected), and timber formworks (kg-neglected).
- Assembly of the footings and beams includes steel assembly for reinforcement foundation (kg) and casting concrete for reinforcement foundation (kg or m^3).
- Assembly of anchors and applying a grout layer includes assembling anchors (kg), concrete grout (kg or m^3), base plates (kg), clay filling (m^3 - neglected).
- Pre-assembly of some retrofit includes drilling works for the holes on plates with magnetic drilling (each hole less than 5 min (h)), cuts in tubular elements (h-neglected), manufacturing connection plates with a blowtorch for welding (h), steel tubes and plates (kg), trimming the plates to be installed (h-neglected), bolting plates with bolts (kg) and fixing with welding (h).
- Placement of 3D steel element with manual winch includes assembly of a manual winch with pulleys, ropes and hooks, placement of bolts, washers (neglected).
- Connection of reinforcement with a concrete structure includes connection of plates with anchors and nuts (kg) and welding with the electrode (h), drilling the beam and columns for anchors' placement (h), the concrete waste from drilling (kg), epoxy application (kg), placing caps in the cuts of tubes (neglected), placing washers (neglected), unifying concrete surface for proper placement (neglected).
- The treatment works for reinforcement includes sandblasting with silica sand (kg-neglected) by using an air compressor (h), then prime and painting (kg).

The analysis aims to consider all the materials and processes used included and actual take-offs from drawings and data sources used for retrofitting materials. In addition to that, some assumptions are made because of the limited knowledge about the case study building. Since the transport distance of the material is unknown, the available data used in the impact estimator tool assumes an average transport distance. The collected data from the foundation of the 3D trusses, the other construction works during the assembly of the reinforcements and their characteristics, and the retrofitting metal elements' features are presented in **Appendix K.**

Usage Stage

Various repair and maintenance operations occur in the original building during the building's usage stage after the structural retrofitting. Maintenance may be required in a hospital building for many reasons related to technical machinery or the operation of the building. It was foreseen that the building could serve for another 40 years. Besides, it was assumed that the RC structures would need major maintenance after 50 years. In this building, necessary maintenance was taken into account for the relevantly applied metal trusses and diagonal bracings. The other parameters were neglected in the usage stage because these 3D trusses and diagonals need painting during their service life and it needs to be repeated every five years to protect the steel elements from corrosion. Painting that will take place in the main building is also considered. Other replacement and maintenance works did not apply. Maintenance works and assumptions based on the service life of the applied works are presented in **Appendix K**. A photograph of the hospital building (Google Map, 2017) and (Tena-Colunga and Villegas-Jimenez, 2010) presents the recent condition of the building in Figure 5-11.

Retrofit of hospital complex with slotted-bolted-connections

3D Trusses

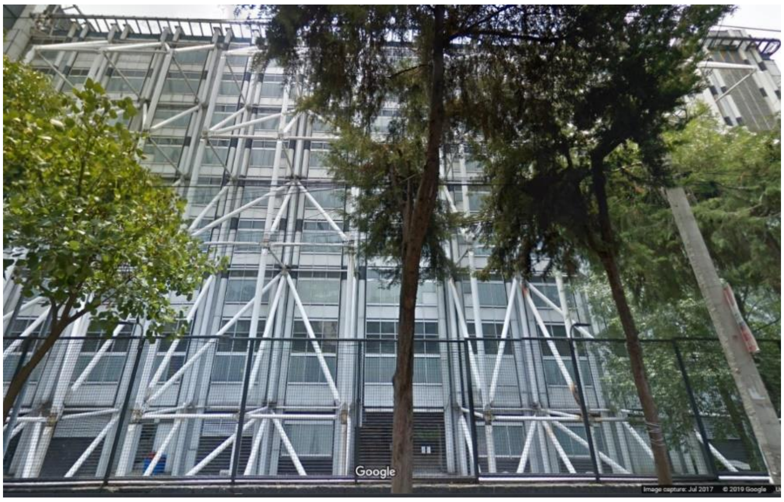


Figure 5-11 Reinforced hospital building during use (Tena-Colunga and Villegas-Jimenez, 2010; Google Map, 2017)

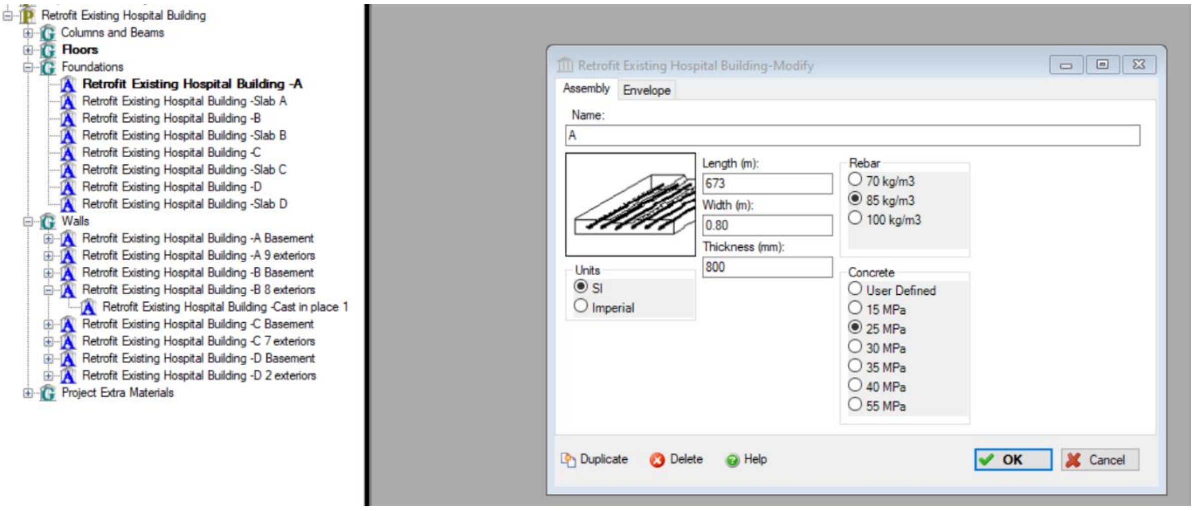
End-of-life Stage

This stage needs to be determined by including the demolition of the reinforcement elements along with the original building. Therefore, the original building was modelled in the AIEB tool to generate BOM for the end-of-life stage and the retrofitting materials was added as a building product. The building model was developed by creating a series of assemblies: walls, roofs, columns, foundation, and beams. Some of the building components, such as some non-structural components, interior design and finishes, were omitted, as there is no information about these features in the building. There can be some error margin (10%) between the BOM from the software, and manual take-offs from actual designs since the AIEB is not a design tool

(ATHENA, 2019b). After modelling the building by using the software's assembly feature, the retrofitting materials were calculated separately and included as extra material as one of the assemblies.

The screenshot from the tool shows the modelling of the assemblies, as shown in Figure 5-12. The assumptions taken during modelling for the original building are presented in **Appendix K**. These assumptions were determined according to the original building's weakness that can reflect on the durability of the building as described in section 5.3.2. Similarly, lower durability was reflected in the vulnerable building, compared to the new building designed according to structural features of hospital buildings in Mexico by Melendez (2014). A building demolition depends on many other criteria such as structural characteristics, safety and site conditions. This stage in this case study includes deconstruction, final disposition of the materials such as scrap collection, processing, and transport back to steel plants at the end of its 40 years' lifespan. During deconstruction, building materials have a demolition energy per physical unit of the major structural system of the building (concrete, steel, etc.) along with its transport energy. The BOM of the building also determines the final disposition of the building. Finally, the tool creates the building's demolition and disposal scenario, as per the building's height and area.

Modelling foundation of the original building



Modelling walls of the original building

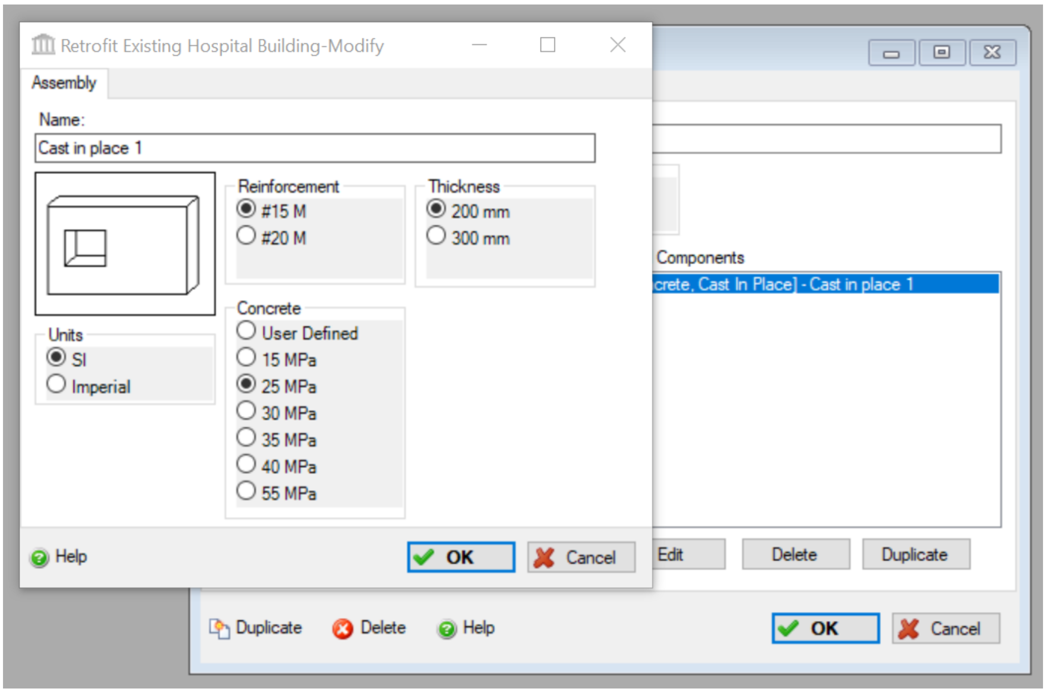


Figure 5-12 Modelling of assemblies in the AIEB for the original building

5.3.2.2 LCI of the Second (New Building) Scenario

Figure 5-13 illustrates the LCA of the non-retrofitted scenario for the vulnerable building, with related modules which represent specific parameters (consideration) under specific stages from cradle-to-grave.

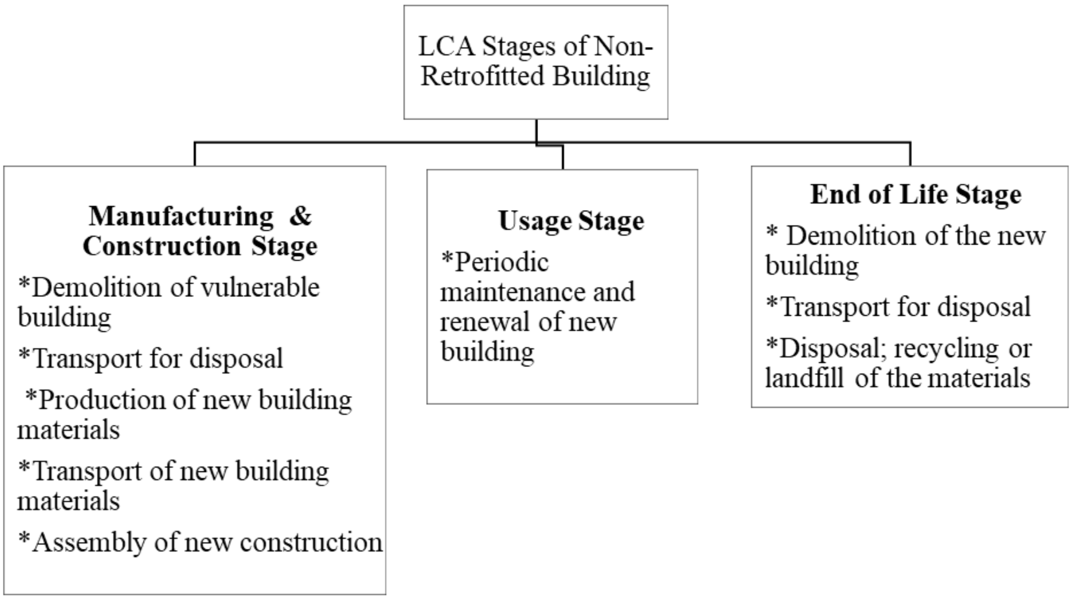


Figure 5-13 Specific parameters of the LCA stages for the second scenario using the unit process method

Manufacturing and Construction Stage

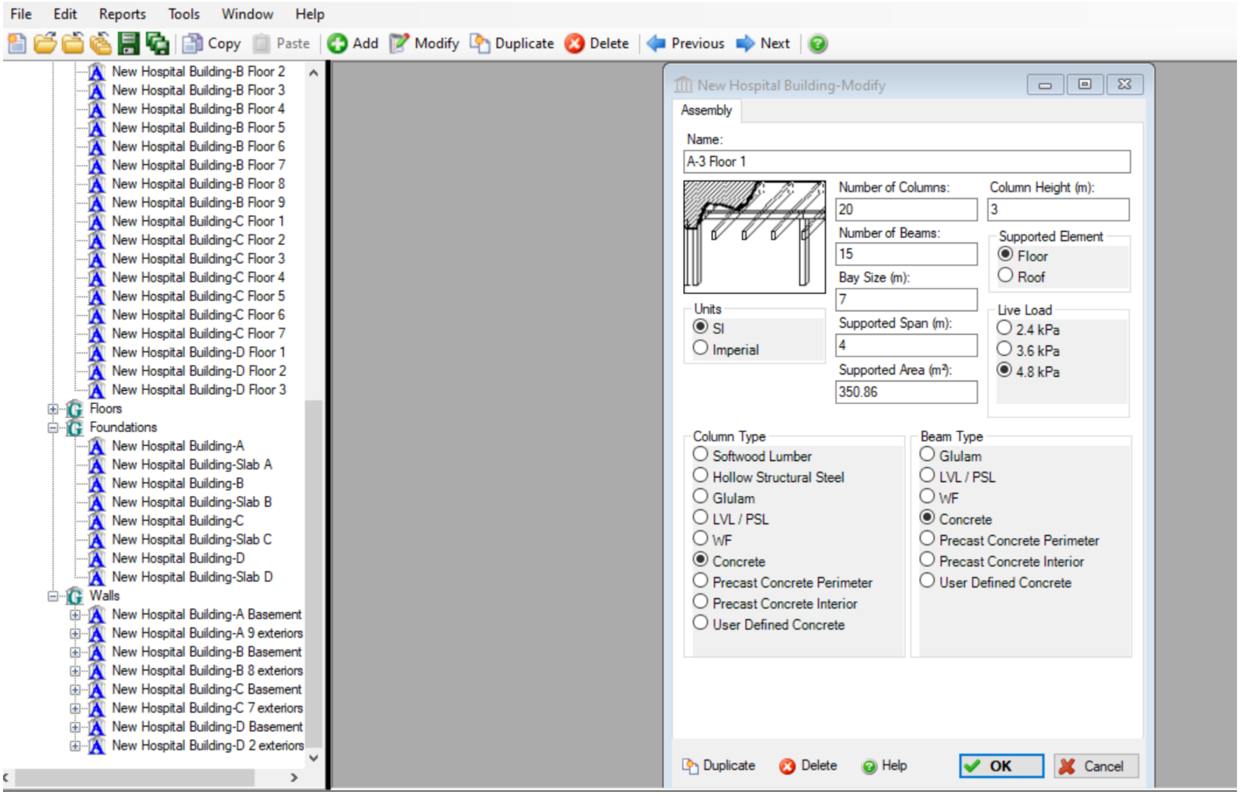
The proposed framework includes demolishing the vulnerable hospital building and building a new one. In this case study, the scenario was generated according to the original building and its vulnerability. Thus, the new building was assumed to have the same architectural and material features as the old building; however, it would be more robust than the original building.

The construction works applied at this stage are as follows. Firstly, the vulnerable building was demolished the same at the end-of-life stage of the first scenario (retrofit excluded) in section 5.4.1.3, and the disposal transported for landfill recycling. Finally, building materials were manufactured, transported and constructed for the new building.

The new building was also modelled similarly to the original building, and a series of assemblies created: walls, roofs, columns, foundation, and beams. However, the new building needed to perform better than the vulnerable building, so some assumptions were considered.

These assumptions were determined according to the robustness of the new building and the vulnerability of the original building—both buildings were relevantly designed according to structural features of hospital buildings in Mexico by Melendez (2014). Figure 5-14 shows a screenshot from the tool while modelling one of the new building's assemblies. The assumptions taken during modelling for the new building are presented in **Appendix L**.

Modelling foundation slab of the new building



Modelling floors of the new building

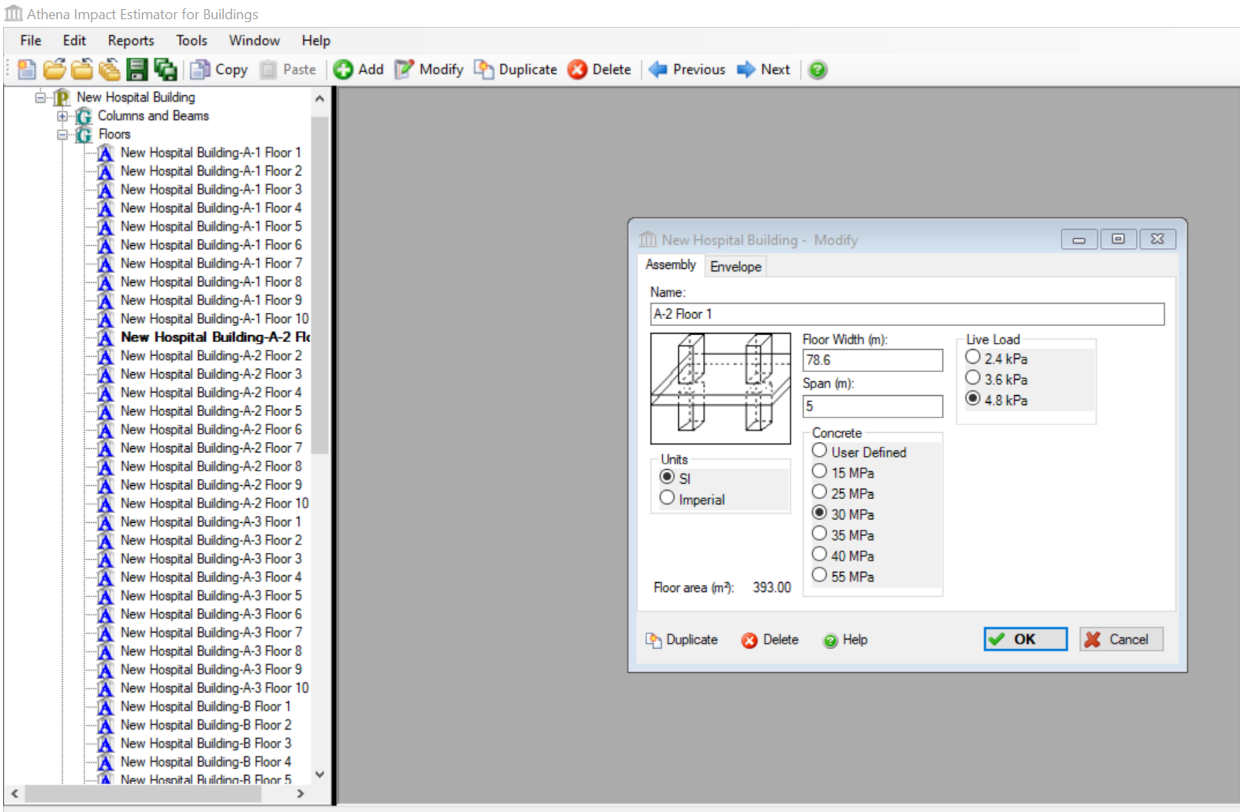


Figure 5-14 Modelling of assemblies in the AIEB for the new building

Usage Stage

The hospital buildings need various repairs and replacement works during use; however, the maintenance works are included only for the basic structure in this building. The other parameters could not be compared with the retrofitted building. Therefore, painting needs to be done during the usage stage also in the new building, and due to the more extended service period of the new building, some other building elements need to be replaced in the 60-year service time. Windows have a shorter service period than the life span of the building. Figure 5-15 shows one sample of the modelling of the windows in the tool. Maintenance works and assumptions based on the service life of the applied works and its unit used in LCA calculations are presented in **Appendix L**.

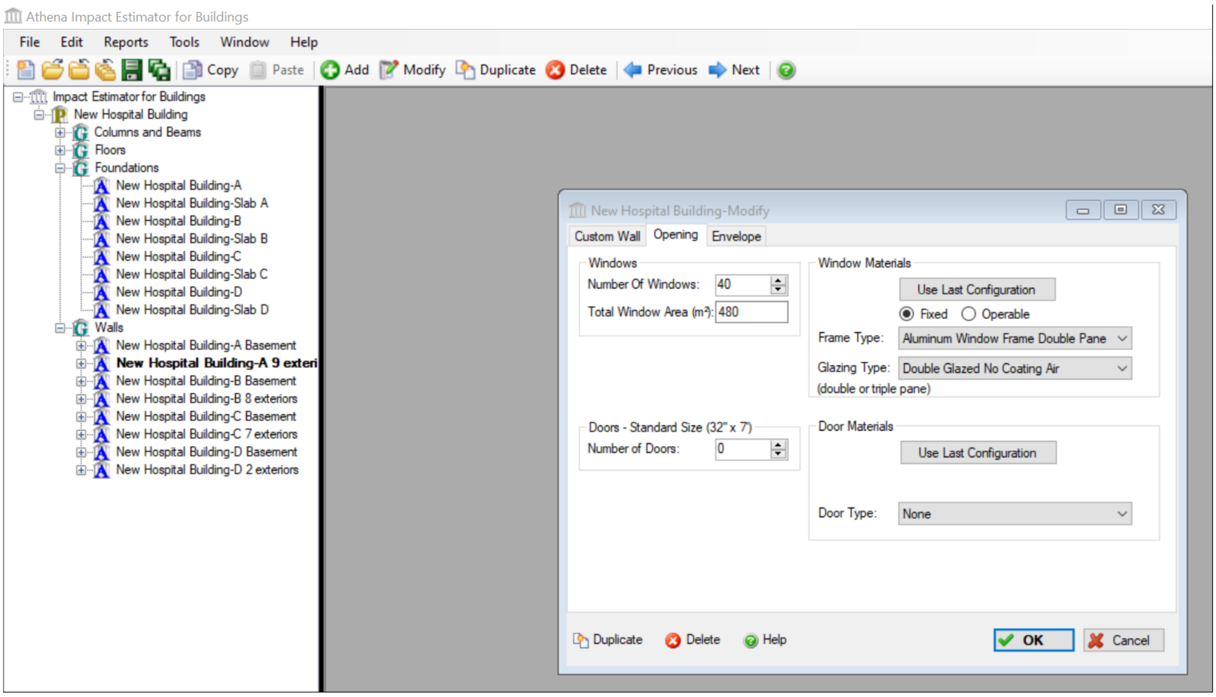


Figure 5-15 Modelling of assemblies in the AIEB tool for the new building

End-of-life Stage

The end-of-life stage of the new building includes demolition, disposal of materials, and transport at the end of its 60 years' lifespan. The new building was modelled in the AIEB tool and the building's demolition was estimated according to its total height and gross floor area.

5.3.2.3 LCI Results

The AIEB tool provided a summary of the LCI results for the retrofitted and non-retrofitted building. The tool conforms to the EN 15804 (2013) and EN 15978 (2011) system boundary and reporting format. Figure 5-16 shows the summary of the system boundary of both scenarios that was integrated with the AIEB system boundary.

Both scenarios were modelled in the software according to the relevant assemblies and characteristics of the buildings, and the same method was used as with the previous case study. The LCI data and manufacturing materials are based on North American standards and practice; hence transport data for the construction and demolition process can target specified regions provided in the AIEB. Los Angeles was selected as a proxy location recommended by the software company. As in the other case study (chapter 4), two selected intervention scenarios are compared in this study and these scenarios are limited in terms of structural performance priorities. Also, both scenarios used roughly the same set of assumptions derived from the tool. The results of the environmental impacts resulting from the selection of different locations are presented in the **Appendix G,** and the difference occurred as a minimal difference in the transportation process. Since it will compare the environmental impacts of the scenarios, it will not have an adverse impact on the final result evaluation. After modelling the buildings, the software applies a structural algorithm to calculate the BOM. Then results are generated in various categories and formats. Input data of the scenarios and the corresponding product in the tool are presented in Table 5-3 for the manufacturing stages, with the construction waste factor and converted units for each material (according to Equation 4-1).

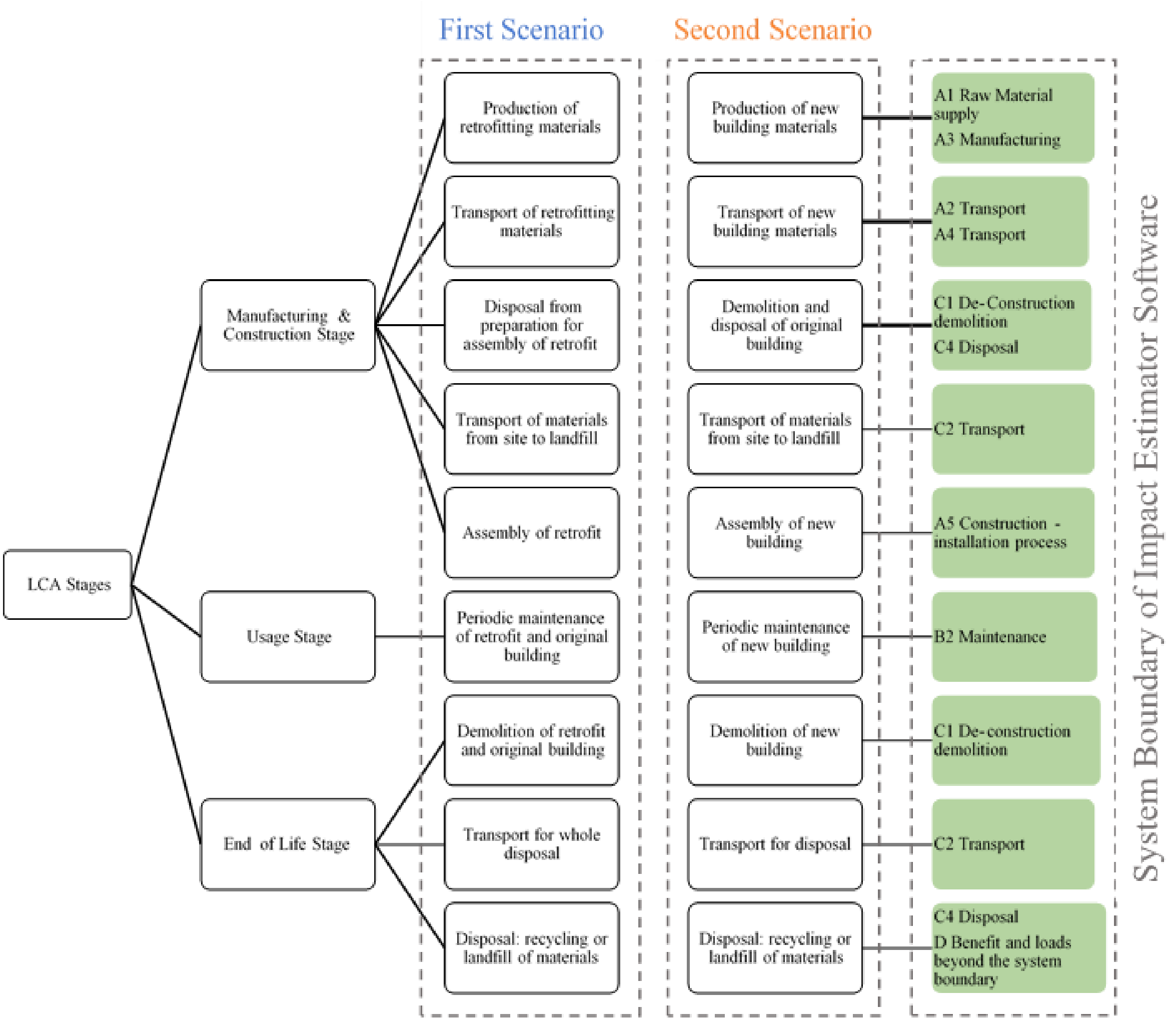


Figure 5-16 LCA stages of first (retrofit) and second (non-retrofit) scenarios and their corresponding modules in the AIEB tool

Table 5-3 Corresponding materials in the database of the tool for each material in the scenarios

Material	**Corresponding Material**	**Construction Waste Factor**	**Unit**
Steel tubes of retrofitting	Steel tubing	0.01	Tonnes
Steel plates of retrofitting	Steel plate	0.01	Tonnes
Bolts and anchors of retrofitting	Screws nuts and bolts	0.03	Tonnes
Steel rebar of retrofitting	Rebar, rod, light sections	0.01	Tonnes
Casting concrete mixture	Concrete benchmark USA	0.05	m^3
Epoxy and mortar	Mortar	0.15	m^3
Paint	Water-based latex paint	0.02	L
Window	Aluminium window frame	0	kg
	Double glazed no coating air	0	m^2
Foundation steel	Welded wire mesh / ladder wire	0.02	Tonnes

The BOM values of each scenario include site preparation of the first scenario versus demolishing the existing building of the second scenario and retrofit materials of the first scenario versus the new building construction. The life cycle inventory of the BOM results of both scenarios is presented from cradle-to-gate in **Appendix M**. Different inventories exist for two cases; therefore, LCI results for resource use are listed in Table 5-4 considering total use (A to D) and excluding operational energy, site preparation and assembly of the retrofit. While the positive values represent the resource consumption, the negative values represent avoided amount of materials when producing the new one. Therefore, the specified amount of materials will be re-use for new material production. While the most outstanding contribution to resource use came from the construction stages, the usage and the end-of-life stages had the lowest impact. There has been a significant change in total resource use between scenarios, and the highest difference occurred for ash use, as the ash was used only for the retrofit materials. However, the second scenario caused more resource consumption in all other sources, and the highest depletion was observed for clay and shale, coarse aggregate, gypsum (natural), gypsum (synthetic), limestone, peat, tin ore, uranium, water and wood fibre at 94%, 94%, 93%, 88%, 93%, 94%, 94%, 94%, 73%, and 94%, respectively. Also, the Second scenario has more reusable materials, e.g., lignite and sand; however, this makes a positive contribution. The environmental impacts of these highly used resources are shown below the LCIA results.

Table 5-4 LCI results for the resource use of first and second scenarios from the manufacturing to the end-of-life stages (A to D)

Material	**Unit**	**Resource Use LCI Results (A to D)**	
		First Scenario	**Second Scenario**
Aluminium scrap	kg	7.36E+03	2.47E+04
Ash	kg	3.63E+01	0
Bauxite	kg	-2.12E+04	-6.02E+04
Carbon dioxide, in air	kg	1.91E+04	6.24E+04
Clay and Shale	kg	1.50E+04	4.47E+05
Coal	kg	8.88E+05	3.04E+06
Coarse Aggregate	kg	2.13E+06	7.35E+07
Crude Oil	L	4.71E+05	2.08E+06
Crude Oil as feedstock	L	3.05E+04	4.73E+04
Dolomite	kg	9.77E+04	2.14E+05
Ferrous scrap	kg	9.54E+05	2.89E+06
Gypsum (Natural)	kg	1.57E+04	4.63E+05
Gypsum (Synthetic)	kg	6.67E+01	1.03E+03
Iron Ore	kg	1.30E+06	2.28E+06
Lignite	kg	-2.64E+04	-5.63E+04
Limestone	kg	5.52E+05	1.54E+07
Natural Gas	m3	1.53E+05	6.73E+05
Natural Gas as feedstock	m3	4.09E+04	6.34E+04
Other	kg	8.94E+04	8.31E+05
Peat	kg	3.83E+00	1.25E+02
Potash	kg	2.94E+02	1.12E+03
Sand	kg	-2.13E+02	-5.48E+02
Tin ore	kg	3.92E-04	1.19E-02
Uranium	kg	1.25E+00	1.41E+01
Water	L	2.70E+07	1.72E+08
Wood Fiber	kg	1.23E+04	3.65E+05

5.3.3 Life cycle impact assessment (LCIA)

In the next sections, the environmental impact results are categorised for each stage and the final results represented in the value of embodied carbon, representing indirect GHG emissions caused by the building. Thus, the stages are identified as causing the most significant embodied emissions; the inputs created the output, such as carbon footprints (weight of CO_2-eq) as embodied carbon and consumed MJ as embodied energy. Then the embodied impact results are compared with the operating impact results. It should be noted that the LCA analyses can only give estimated values, and this will be sufficient since the presented study is only for comparative purposes. A unit process method was utilised for the LCIA to increase the reliability of the analysis by evaluating available data and compensating for missing data with well-accepted assumptions. The represented results are fixed for a particular time, functional unit, and method. The environmental impacts of the scenarios are calculated by the same method and multiple impact categories with the previous case study.

5.3.3.1 LCIA Results for Manufacturing and Construction Stages

For the manufacturing and construction stages, the analysis is derived from: raw material extraction; manufacturing of construction materials; materials' transport; assembly of retrofit materials; construction materials of the vulnerable and new building; site preparation; waste disposal and transport for the two scenarios. The impacts of the first and second scenarios are presented in Table 5-5 and Table 5-6. They are compared in a clustered column chart in Figure 5-17 that shows each value of the environmental impacts according to their varying units.

Table 5-5 The environmental impacts of the first scenario in the manufacturing and construction stage

Impact Category	**Unit**	**Site Preparation for the Retrofit**		**Manufacturing of the Retrofit Materials**		**Construction Phase**			**Total**
		Disposal and Waste Processing	*Transport*	*Manufacturing*	*Transport*	*Construction Installation Process*	*Transport*	*Assembly of Retrofit*	
GWP[1]	Kg CO_2 eq	1.95E+02	8.17E+01	1.74E+06	2.87E+03	6.25E+04	2.30E+05	7.14E+03	2.04E+06
Acidification Potential	Kg SO_2 eq	2.79E+00	7.86E-01	5.56E+03	2.77E+01	4.92E+02	2.90E+03	1.54E+01	9.00E+03
HH Particulate[2]	Kg PM2.5 eq	6.85E-02	4.35E-02	4.18E+03	1.53E+00	7.09E+01	1.20E+02	1.50E+01	4.39E+03
Eutrophication Potential	Kg N eq	1.74E-01	4.88E-02	6.34E+02	1.72E+00	4.95E+01	1.79E+02	4.74E+00	8.69E+02
ODP[3]	Kg CFC-11 eq	8.52E-09	2.85E-09	1.04E-02	1.00E-07	5.20E-04	9.15E-06	3.91E-04	1.13E-02
Smog Potential	Kg O_3 eq	9.28E+01	2.48E+01	7.62E+04	8.73E+02	1.44E+04	9.34E+04	2.18E+02	1.85E+05
Total Primary Energy	MJ	2.91E+03	1.19E+03	2.49E+07	4.19E+04	7.80E+05	3.27E+06	1.23E+05	2.91E+07
NRE[4]	MJ	2.90E+03	1.19E+03	2.47E+07	4.18E+04	7.74E+05	3.27E+06	1.06E+05	2.89E+07
FFC[5]	MJ	2.90E+03	1.19E+03	1.79E+07	4.18E+04	6.87E+05	3.26E+06	9.41E+04	2.20E+07

[1]GWP, Global Warming Potential; [2]HH Particulate, Human Health Particulate; [3]ODP, Ozone Depletion Potential; [4]NRE, Non-Renewable Energy; [5]FFC, Fossil Fuel Consumption.

Table 5-6 The environmental impacts of the second scenario in the manufacturing and construction stage

Impact Category	Unit	Demolition of the Vulnerable Building			Manufacturing of the New Building		Construction Phase		Total
		Demolition, Disposal and Waste	*Transport*	*Beyond Building Life*	*Manufacturing*	*Transport*	*Construction Installation Process*	*Transport*	
GWP	Kg CO_2 eq	6.62E+05	2.63E+05	1.10E+06	1.49E+07	1.01E+05	1.28E+06	1.48E+06	1.98E+07
Acidification Potential	Kg SO_2 eq	9.10E+03	2.53E+03	2.39E+03	4.60E+04	9.73E+02	8.22E+03	1.56E+04	8.48E+04
HH Particulate	Kg PM2.5 eq	4.06E+02	1.40E+02	1.12E+03	2.08E+04	5.37E+01	6.18E+02	7.94E+02	2.39E+04
Eutrophication Potential	Kg N eq	5.66E+02	1.57E+02	1.30E+02	1.42E+04	6.05E+01	1.07E+03	9.65E+02	1.71E+04
ODP	Kg CFC-11 eq	2.94E-05	9.18E-06	-1.49E-06	3.19E-01	3.53E-06	1.52E-02	5.46E-05	3.34E-01
Smog Potential	Kg O_3 eq	3.01E+05	7.98E+04	2.46E+04	7.14E+05	3.07E+04	2.39E+05	4.95E+05	1.88E+06
Total Primary Energy	MJ	9.83E+06	3.83E+06	4.90E+06	1.23E+08	1.47E+06	1.37E+07	2.14E+07	1.78E+08
NRE	MJ	9.82E+06	3.83E+06	4.91E+06	1.20E+08	1.47E+06	1.36E+07	2.14E+07	1.75E+08
FFC	MJ	9.80E+06	3.83E+06	1.02E+07	9.43E+07	1.46E+06	1.31E+07	2.14E+07	1.54E+08

As seen in the tables, each impact category has different units; therefore, a comparison between the categories will not be accurate. Thus, the impact of each category for each scenario is shown in Figure 5-17, separately. There has been a significant fall in GWP, at nearly 90% in the case of applying the first scenario. The most major reduction occurred for ODP representing just over 95%, while the most minor decrease occurred at 82% for the HH particulate. The other impact categories: acidification potential, eutrophication potential, smog potential, total primary energy, NRE and FFC also had a notable reduction compared to the second scenario, representing 89%, 95%, 90%, 84%, 84% and 86% respectively. Overall, there was an almost 90% decline in the total of the impact categories. Since transportation did not change the results, it was not evaluated separately from the total result.

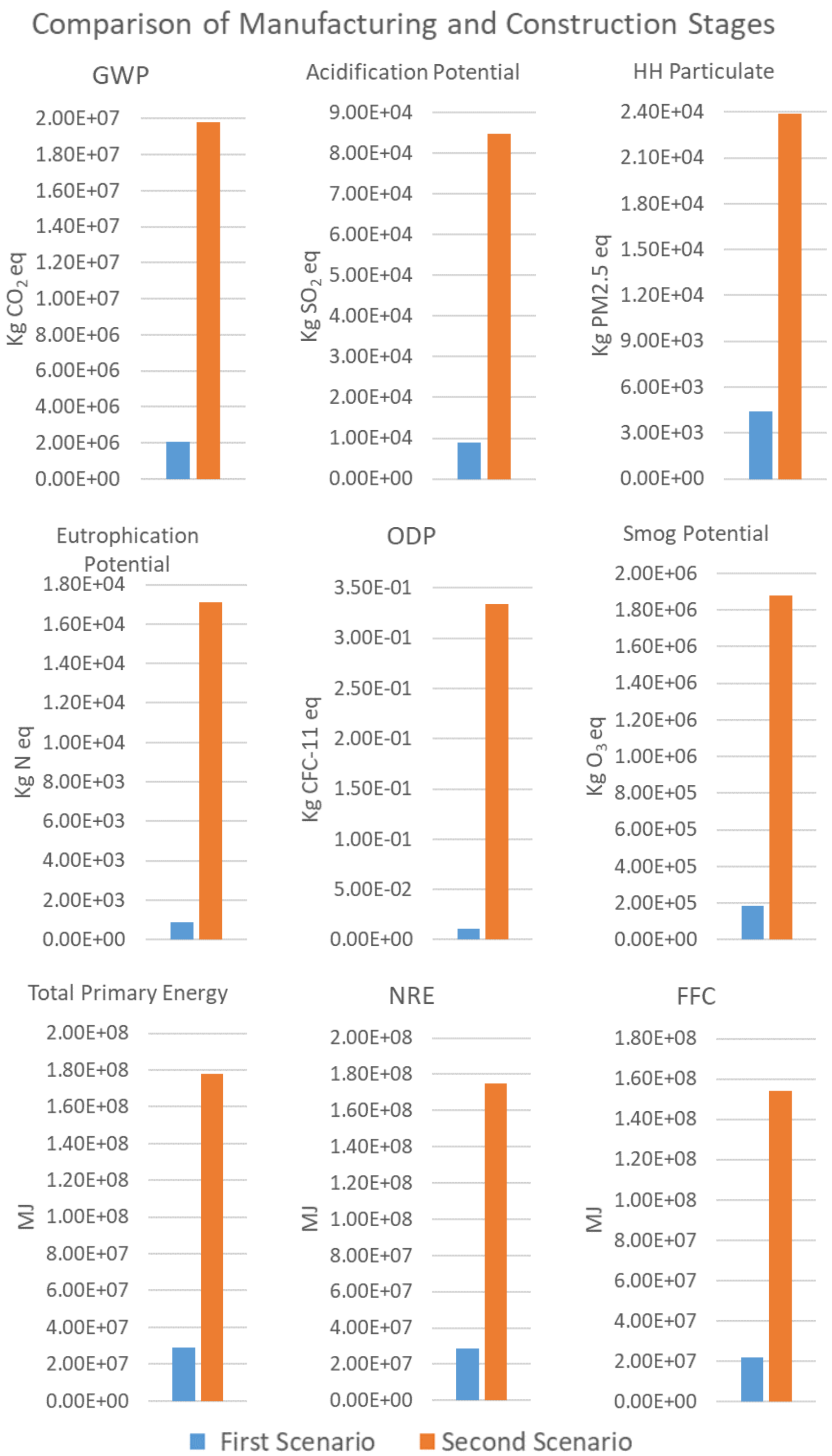


Figure 5-17 Comparison of the LCIA results of both scenarios for manufacturing and construction stages

The second scenario also includes the demolishing of the vulnerable building, which can affect the sole evaluation of the retrofit and new building impacts. Therefore, the contribution of each building factor to the construction stages is presented in Figure 5-18. As seen in the figure, the environmental impacts of demolishing the vulnerable building were the least overall. Retrofit construction had a higher impact on HH particulate, ODP, total primary energy, and NRE than the vulnerable building's demolition, with 6%, 3%, 14%, and 14% of the total share. Retrofit caused the lowest impact in acidification potential, smog potential and FFC representing 10%, 9% and 13% of the total share, respectively. The ODP of the original building was in neglectable values, and the new building had the highest increase, accounting for 97%. After ODP, eutrophication potential represented a higher increase for the new building's construction, which is almost 90%, and shared 5% with the vulnerable building's demolition and the retrofit. There has been a significant increase in the average at around 88% in the new building's construction, compared to the vulnerable building's demolition. The lowest increase recorded for smog potential occurred around 73%; while ODP and following that eutrophication potential had the most remarkable rise at nearly 100% and 95%, respectively. Finally, the new building's construction was found as the largest contributor, sharing the cause of environmental impacts at 80%, after that retrofit and the existing building's demolition which had nearly the same contribution, at approximately 10%.

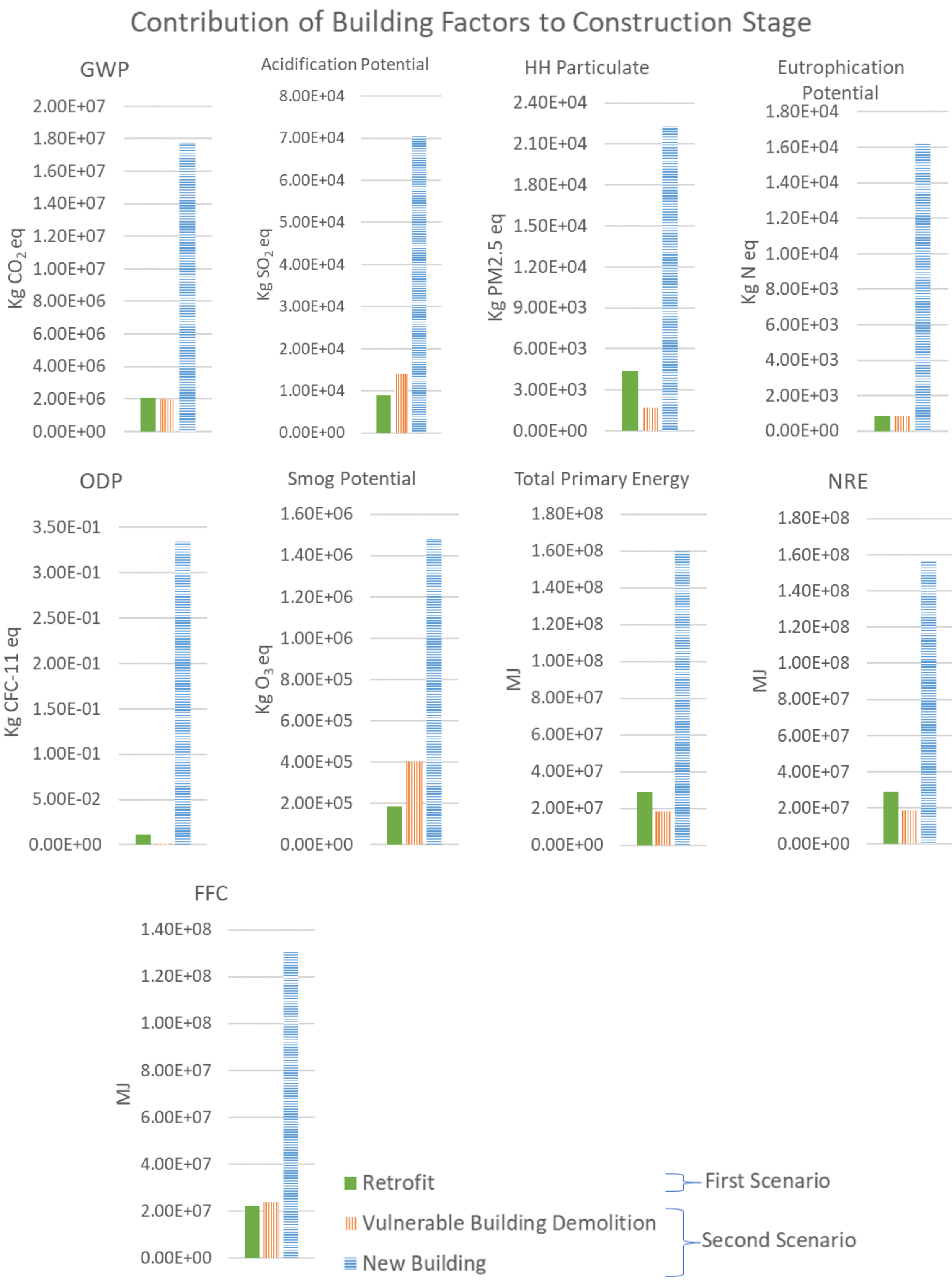


Figure 5-18 Contribution of retrofit construction, vulnerable building demolition and new building construction to the construction stage

5.3.3.2 LCIA Results for Usage Stages

For the usage stage, the environmental performance analysis is derived from maintenance and replacements' effects based on building type, material and assumed service period. This stage includes repeated surface painting, energy use for these activities, periodic replacement of existing materials, and their disposal and transport. There is no change in the type of replaced materials; the same material type is replaced. If the replaced material's service is longer than the remaining service life of the building, the difference is reflected in the environmental impact of the material. For example, the life of the existing windows is 40 years, and the remaining life of the new building will be 20 years in the period of change; in this case half of the window's environmental load is credited. The usage stage also includes operational impacts because of the different service periods of the scenarios, and the value is assumed as 350 kWh/m^2 per year as the annual energy consumption of a regular hospital building. The value was determined according to PEEB (2019) and the study of Ji and Qu (2019), considering bed number, floor area and climate zone. Better energy performance can be expected for the new building, as more efficient technologies can be applied. Besides that, energy retrofitting can be applied to the existing building. However, the target of this study is the environmental impacts of structural interventions, and that includes embodied impacts. On the other hand, as the first and second scenarios have different service periods, their operational impacts will also be different. Therefore, the same assumed annual energy consumptions have been assigned to both scenarios to reflect the impact of the different service periods on the results and show the difference between the embodied and operational impacts.

The software does not include operational energy simulation; however, it allows the inclusion of annual operational energy by fuel type per square floor area and location, that can be derived from another source or can be used a general assumption. The tool then estimates the primary operating energy, accounting pre-consumption energy and related emissions to the environment (ATHENA, 2013). Then it generates electricity grids and energy consumption during use according to TRACI methodology. The impacts of the first and second scenarios during their use are shown in Table 5-7 for 40 years and in Table 5-8 for 60 years; and compared in a column chart in Figure 5-19 according to the varying units of the impacts.

Nearly the same decline was observed in all categories in the first scenario. The first scenario shared 40% of the total impacts, because the impact of operational energy is very high compared to the embodied impacts, which makes embodied impacts nearly uncountable. Regarding transport, its impacts do not affect the comparison results, so they were included in the total results. Therefore, Figure 5-20 below compares the impacts apart from the operational energy of each building factor in the usage stage.

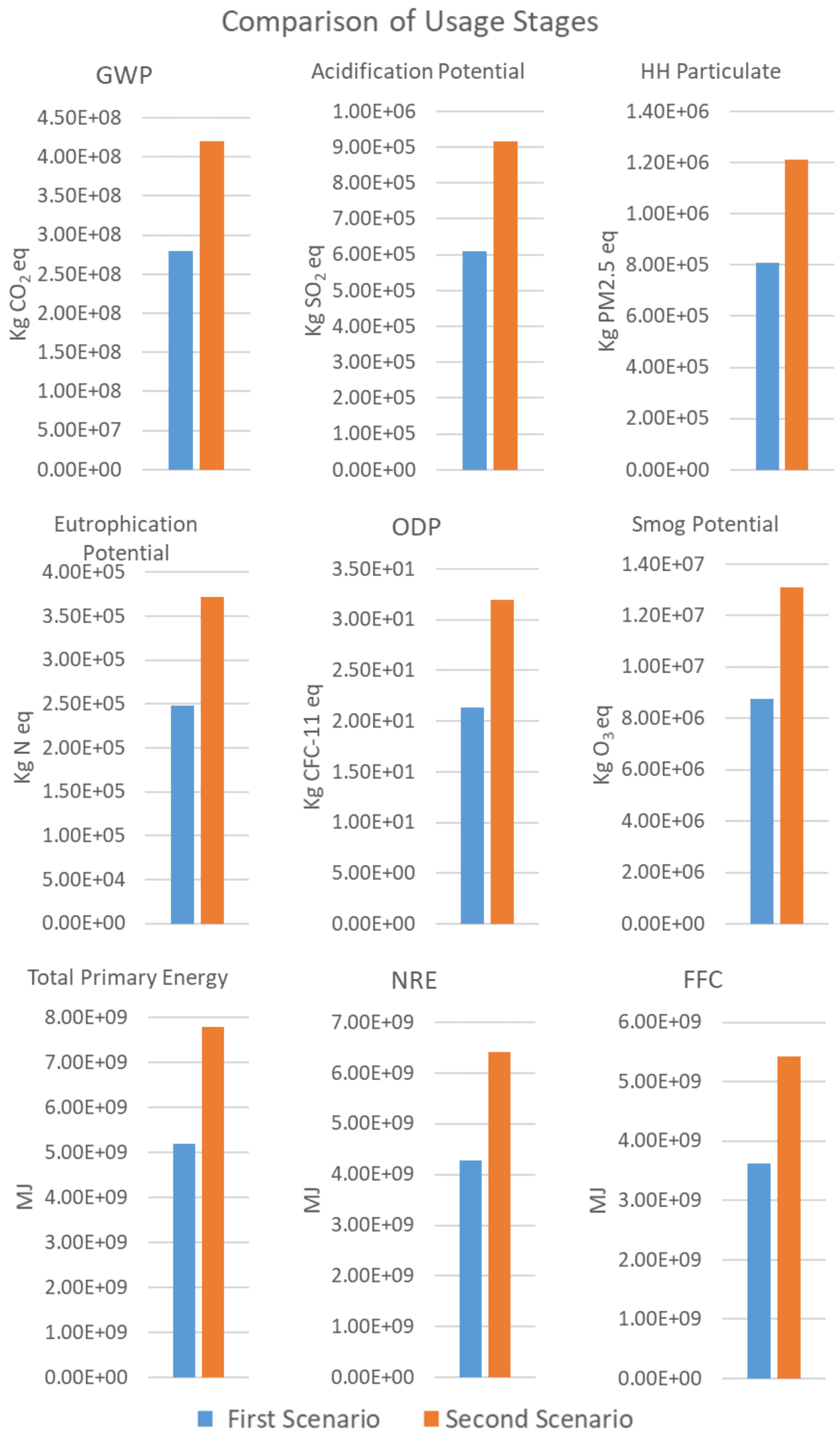


Figure 5-19 Comparison of the LCIA results of both scenarios for usage stages

Table 5-7 The environmental impacts of the first scenario in the usage stage

Impact Category	**Unit**	**Use**				**Total**
		Maintenance Manufacturing	*Transport*	*Maintenance Process*	*Operational Energy Use*	
GWP	Kg CO_2 eq	1.59E+05	2.81E+04	1.24E+03	2.80E+08	2.80E+08
Acidification Potential	Kg SO_2 eq	1.31E+03	3.09E+02	2.71E+00	6.09E+05	6.11E+05
HH Particulate	Kg PM2.5 eq	2.29E+03	1.58E+01	3.58E+00	8.05E+05	8.07E+05
Eutrophication Potential	Kg N eq	6.58E+01	1.91E+01	1.10E+00	2.48E+05	2.48E+05
ODP	Kg CFC-11 eq	2.19E-04	1.11E-06	9.48E-05	2.13E+01	2.13E+01
Smog Potential	Kg O_3 eq	3.67E+04	9.81E+03	3.86E+01	8.70E+06	8.75E+06
Total Primary Energy	MJ	4.72E+06	4.08E+05	2.30E+04	5.19E+09	5.20E+09
NRE	MJ	4.72E+06	4.08E+05	1.90E+04	4.27E+09	4.28E+09
FFC	MJ	4.72E+06	4.08E+05	1.60E+04	3.61E+09	3.62E+09

Table 5-8 The environmental impacts of the second scenario in the usage stage

Impact Category	**Unit**	**Use**			**Total**
		Maintenance and Replacement Manufacturing	*Transport*	*Operational Energy Use*	
GWP	Kg CO_2 eq	3.94E+05	5.68E+04	4.19E+08	4.20E+08
Acidification Potential	Kg SO_2 eq	3.25E+03	6.22E+02	9.14E+05	9.17E+05
HH Particulate	Kg PM2.5 eq	3.41E+03	3.19E+01	1.21E+06	1.21E+06
Eutrophication Potential	Kg N eq	1.16E+02	3.85E+01	3.72E+05	3.72E+05
ODP	Kg CFC-11 eq	8.37E-03	2.24E-06	3.20E+01	3.20E+01
Smog Potential	Kg O_3 eq	5.17E+04	1.98E+04	1.30E+07	1.31E+07
Total Primary Energy	MJ	8.40E+06	8.24E+05	7.78E+09	7.79E+09
NRE	MJ	8.40E+06	8.24E+05	6.41E+09	6.42E+09
FFC	MJ	8.38E+06	8.22E+05	5.41E+09	5.42E+09

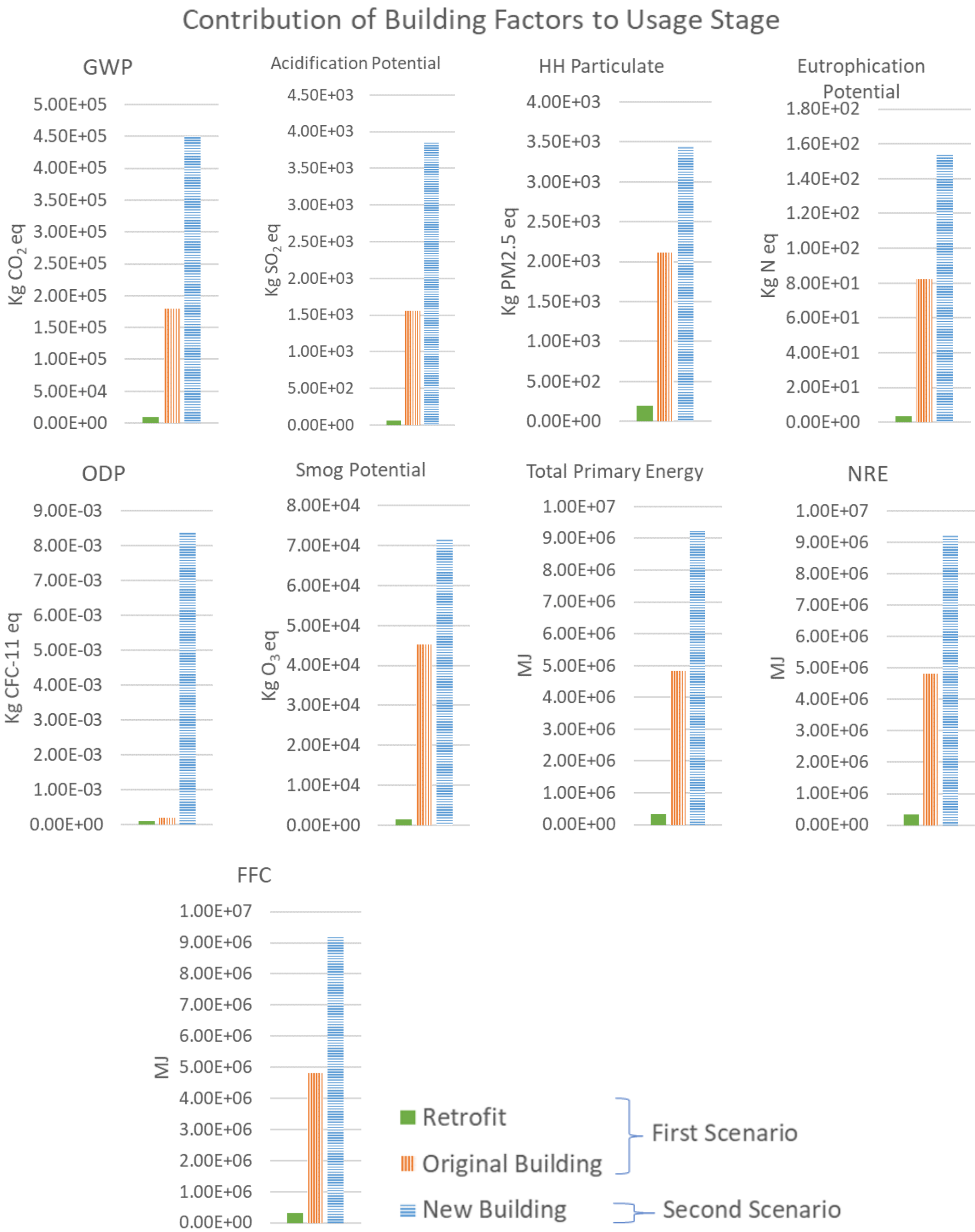


Figure 5-20 Contribution of retrofit, original and new building maintenance

It is apparent from Figure 5-20 that retrofitting has the lowest proportion of impacts during that stage ranging from 1% to 3.5%, representing acidification potential and HH particulate, respectively. The original building constitutes just under a third of the whole impacts. By contrast, the ODP of the original building shared just over 2% of the total impacts, the rest of the impact categories ranged from 28% to 38% for the original building. New building use had the highest proportion, which occurred at around 68% average. The ODP formed a major part of the emissions, at more than 95%, followed by GWP and acidification potential making up just over 70% of the total impacts. Turning now to the scenarios, the first scenario constituted a 32% average of all impact categories, including retrofit and original building impacts without operational impacts, and it constituted 40% with operational impacts. This result indicates that operational impacts make 8% difference when comparing the first and second scenario. Therefore, excluding operational energy makes a notable change when assessing the embodied impacts of retrofitted buildings. The rate of the first scenario share ranged from 4% to 40%, representing ODP and smog potential. Total primary energy, NRE and FFC came next at 36% of the total impacts. In general, in the case where the first scenario is implemented, approximately a 34% reduction is achieved in each impact categories during the usage stage. In summary, retrofitting had the lowest environmental impact in the usage stage; while the new building had the highest because of more maintenance, replacement activities and the extended service period.

5.3.3.3 LCIA Results for the End-of-life Stages

The end-of-life stage stimulates demolition equipment energy use, transport of waste materials for landfill, disposal and BBL. Their environmental impacts are derived from the building material, demolition energy per unit and an average ratio of waste discharge for recycling or landfill. The environmental impacts of the first and second scenarios during their end of life are presented in Table 5-9 and, Table 5-10 and compared in a column chart in Figure 5-21.

A small decrease of an average 4% was observed for the environmental impacts of the first scenario at the end-of-life stage. The highest reduction was seen in the GWP at about 9%, and the second highest decrease was recorded for FFC at 7%; while the only increase was observed in the ODP, representing almost 9%. These relative values between the scenarios may originate from the large and complex existing building demolition. In this context, Figure 5-22 presents each building factor's impacts in the demolition and BBL processes. The highest decline was seen in the HH particulate's impact of the original building, corresponding to nearly 9.5% compared to the new building demolition. The other impacts had just under a 9% decrease. Retrofit constituted only an average of 6% of the first scenario's total environmental impacts; apart from this, HH had the highest share with 18%. Overall, retrofitting has the least effect in the demolition process. Regarding BBL, the abundance of recyclable materials reduces the environmental impacts of retrofit as it's mainly made of metal elements. The retrofit materials' impacts dropped to negative values for avoided burdens that are recycling of steel for new steel and means a positive contribution to the material's life cycle. Approximately the same reduction rate has been observed for retrofit, corresponding to 110% compared to the original building. For the ODP, a zero impact was recorded in the retrofit. A significant credit in ODP was observed for the new building, which is just under 75% compared to the original building on the graph's negative side. Due to the more extended service period and the abundance of materials of the new building, recycling benefits were higher than the original building. On the positive side of the graph, a decrease of environmental impacts (acidification potential 15%, smog potential 8%, total primary energy 6% and NRE 6%) was also observed for the new building in comparison with the original building; while there was a slightly low increase (GWP 4%, HH particulate 6%, eutrophication potential 4%, FFC 4%) for the new building when compared to existing one. Land emissions' results of the LCI are presented in Table 5-11 for the end-of-life stage disposal of waste materials and are compared in Figure 5-23.

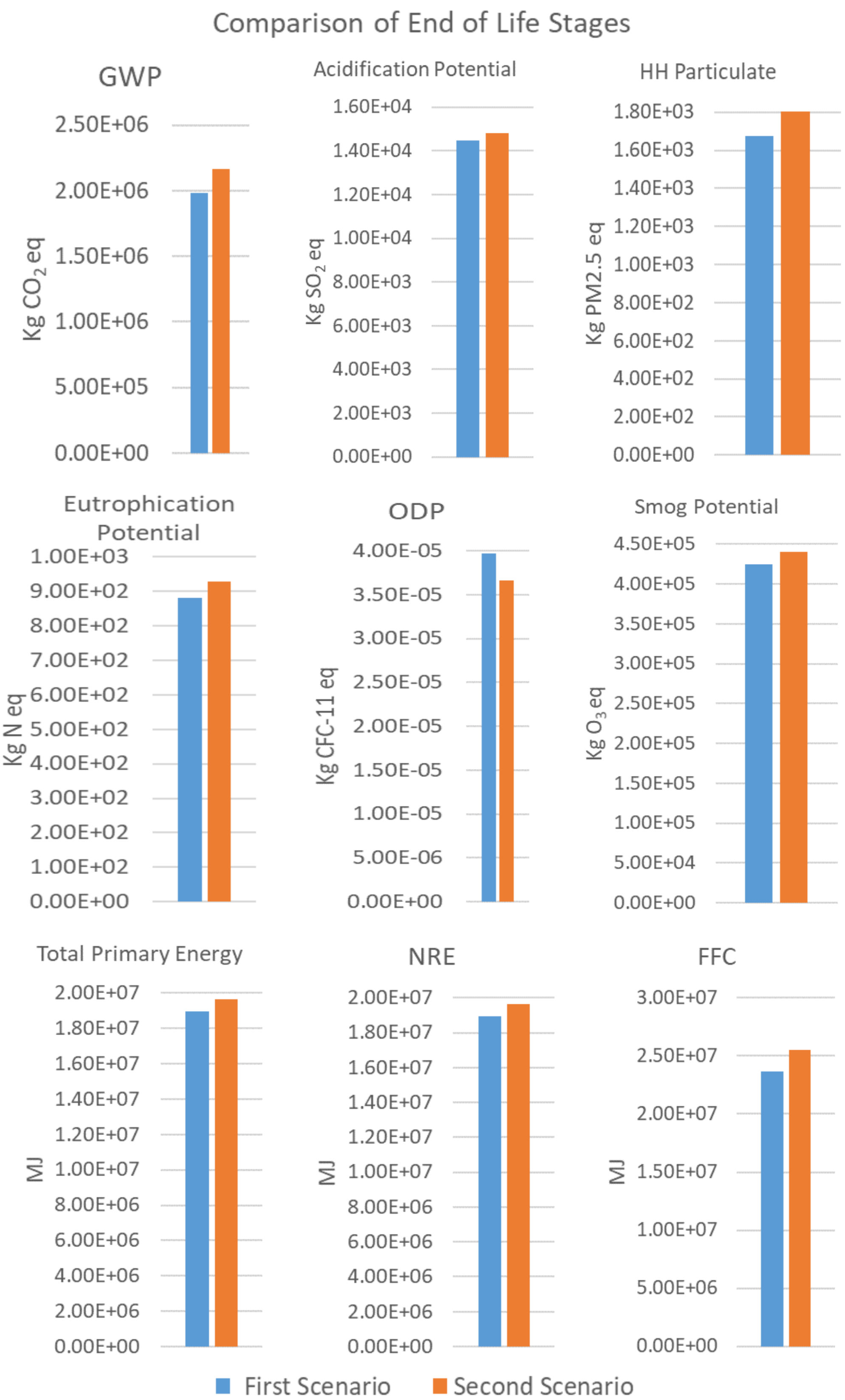


Figure 5-21 Comparison of the LCIA results of both scenarios for the end-of-life stages

Table 5-9 The environmental impacts of the first scenario at the end-of-life stage

Impact Category	**Unit**	**End of Life**			**Total**
		Deconstruction, Demolition, Disposal and Waste Processing	*Transport*	*BBL Material*	
GWP	Kg CO_2 eq	7.15E+05	2.72E+05	9.92E+05	1.98E+06
Acidification Potential	Kg SO_2 eq	9.71E+03	2.62E+03	2.13E+03	1.45E+04
HH Particulate	Kg PM2.5 eq	5.22E+02	1.45E+02	1.01E+03	1.68E+03
Eutrophication Potential	Kg N eq	6.03E+02	1.62E+02	1.17E+02	8.82E+02
ODP	Kg CFC-11 eq	3.17E-05	9.49E-06	-1.49E-06	3.97E-05
Smog Potential	Kg O_3 eq	3.20E+05	8.25E+04	2.20E+04	4.25E+05
Total Primary Energy	MJ	1.06E+07	3.96E+06	4.39E+06	1.90E+07
NRE	MJ	1.06E+07	3.96E+06	4.39E+06	1.90E+07
FFC	MJ	1.06E+07	3.96E+06	9.13E+06	2.37E+07

Table 5-10 The environmental impacts of the second scenario at the end-of-life stage

Impact Category	**Unit**	**End of Life**			**Total**
		Deconstruction, Demolition, Disposal and Waste Processing	*Transport*	*BBL Material*	
GWP	Kg CO_2 eq	7.26E+05	2.88E+05	1.15E+06	2.16E+06
Acidification Potential	Kg SO_2 eq	9.98E+03	2.77E+03	2.07E+03	1.48E+04
HH Particulate	Kg PM2.5 eq	4.49E+02	1.54E+02	1.20E+03	1.80E+03
Eutrophication Potential	Kg N eq	6.21E+02	1.72E+02	1.36E+02	9.29E+02
ODP	Kg CFC-11 eq	3.22E-05	1.01E-05	-5.71E-06	3.66E-05
Smog Potential	Kg O_3 eq	3.30E+05	8.75E+04	2.29E+04	4.40E+05
Total Primary Energy	MJ	1.08E+07	4.20E+06	4.63E+06	1.96E+07
NRE	MJ	1.08E+07	4.20E+06	4.64E+06	1.96E+07
FFC	MJ	1.07E+07	4.19E+06	1.06E+07	2.55E+07

Contribution of Building Factors to Demolition Process
GWP
Kg CO2 eq
Acidification Potential
Kg SO2 eq
HH Particulate
Kg PM2.5 eq
Eutrophication Potential
Kg N eq
ODP
Kg CFC-11 eq
Smog Potential
Kg O3 eq
Total Primary Energy
MJ
NRE
MJ
FFC
MJ
Retrofit
Original Building
New Building
First Scenario
Second Scenario

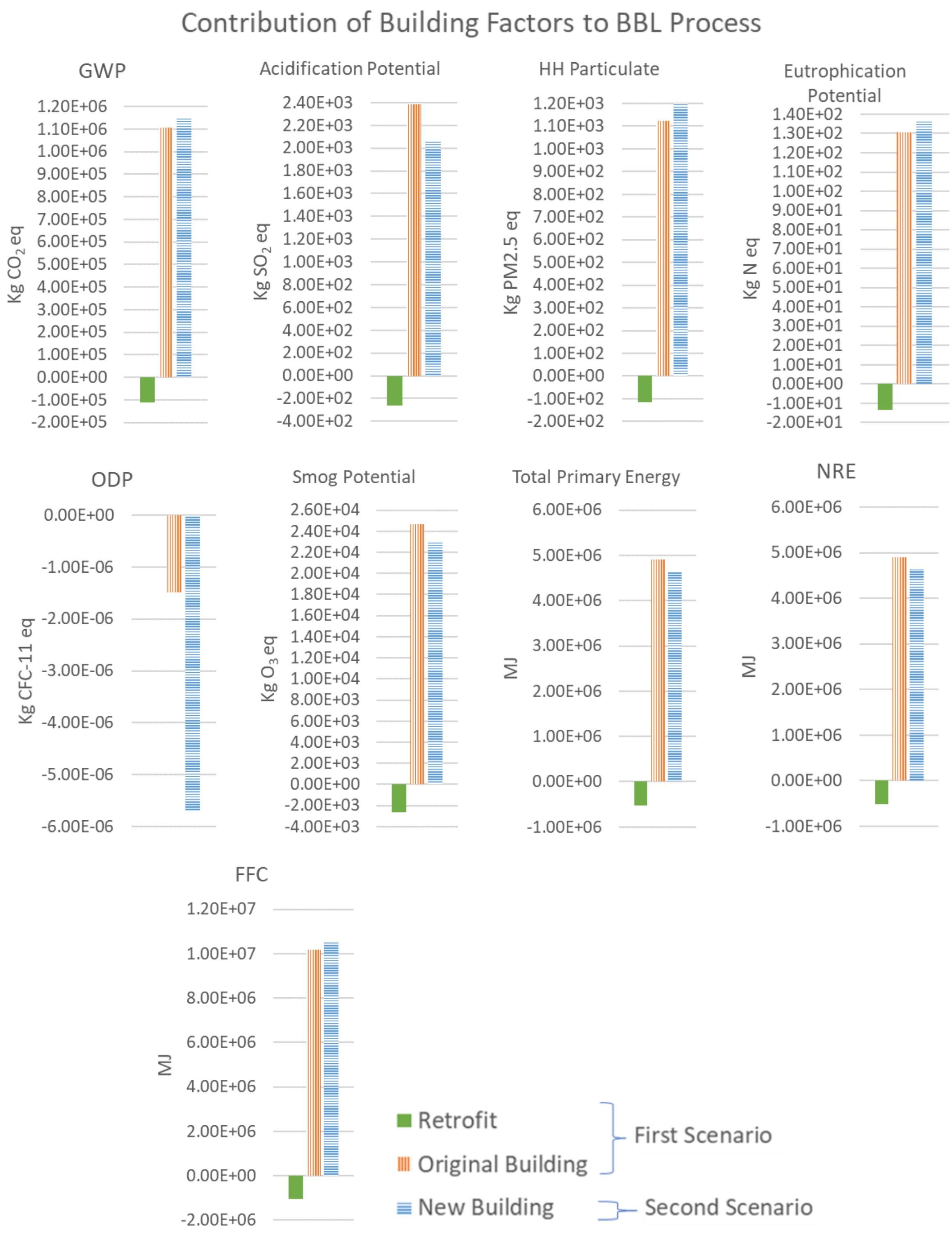


Figure 5-22 Contribution of retrofit, original building and new building demolitions and BBL at the end-of-life stage

Table 5-11 Life cycle inventory result of the first and second scenarios for land emissions in the demolition process

Emission	**Unit**	**First Scenario**		**Total**	**Second Scenario**		**Total**
		Deconstruction, Demolition, Disposal and Waste Processing	*Transport*		*Deconstruction, Demolition, Disposal and Waste Processing*	*Transport*	
Solid Waste to Landfill	kg	3.37E+07	0.00E+00	3.37E+07	3.57E+07	0.00E+00	3.57E+07
Other Solid Waste	kg	9.82E+03	3.11E+03	1.29E+04	9.91E+03	3.30E+03	1.32E+04

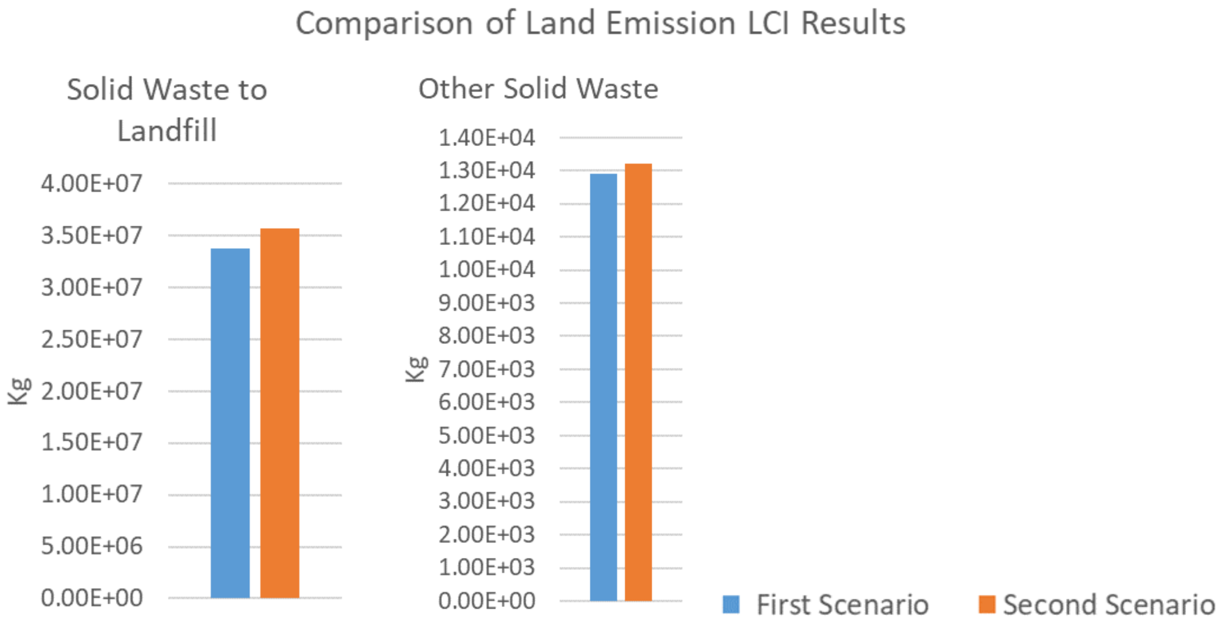


Figure 5-23 Comparison of land emissions of both scenarios in the demolition process

5.3.3.4 LCIA Results for Embodied versus Operating Impacts During Service Lives

The systems were designed to function for 40 years and 60 years for retrofitted and non-retrofitted scenarios, respectively. This section presents the embodied and operating impacts and compares both scenarios' relative performances from cradle-to-grave. The GWP gives the result for embodied carbon, and its unit is in equivalent tonnes of CO_2. The operational phase of the building is excluded since the applied structural retrofit may have a neglectable impact on the building's operation, such as heating and cooling. There is no direct intervention to the building's surface, such as an insulation material. However, a real zero carbon building requires a calculation of its embodied as well as operational carbon; a building's full environmental impacts include all of these GHG emissions. Also, the operating energy has a total impact on the scenarios because of the different services. Therefore, the operational carbon is also based on operating energy, which is taken as an average energy consumption of a hospital building and assumed as 350 kWh/m^2 per year. This value is converted to primary energy and calculates related environmental emissions. Table 5-12 gives the total embodied and operating impact results of each stage; the annual impact of each impact factor is displayed in Table 5-13. The data on embodied and operating impacts are taken from the GWP and total primary energy, respectively, according to the relevant stages. Figure 5-24 shows embodied and operational carbon impacts of both scenarios over the whole life, and embodied and operational energy impacts are presented in Figure 5-25. These impacts are calculated according to the total building lifetimes, and the total environmental annual impacts are shown in Figure 5-26.

Table 5-12 Embodied and operating impacts of the scenarios throughout their life span

Scenarios	Impact Category	Unit	Cradle to Grave Boundary			Total
			Construction Stage	*Usage Stage*	*End-of-life Stage*	
First Scenario	**Embodied Carbon**	Kg CO_2 eq	2.04E+06	1.88E+05	1.98E+06	4.21E+06
	Operational Carbon	Kg CO_2 eq	-	2.80E+08	-	2.80E+08
	Embodied Energy	MJ	2.91E+07	5.15E+06	1.90E+07	5.33E+07
	Operational Energy	MJ	-	5.19E+09	-	5.19E+09
Second Scenario	**Embodied Carbon**	Kg CO_2 eq	1.98E+07	4.51E+05	2.16E+06	2.24E+07
	Operational Carbon	Kg CO_2 eq	-	4.19E+08	-	4.19E+08
	Embodied Energy	MJ	1.78E+08	9.22E+06	1.96E+07	2.07E+08
	Operational Energy	MJ	-	7.78E+09	-	7.78E+09

Table 5-13 Total and annual embodied and operating impacts of the scenarios

Scenarios	Impact Category	Unit	Total Impacts	Annual Impacts
First Scenario	**Embodied Carbon**	Kg CO_2 eq	4.21E+06	1.05E+05
	Operational Carbon	Kg CO_2 eq	2.80E+08	7.00E+06
	Embodied Energy	MJ	5.33E+07	1.33E+06
	Operational Energy	MJ	5.19E+09	1.30E+08
Second Scenario	**Embodied Carbon**	Kg CO_2 eq	2.24E+07	3.73E+05
	Operational Carbon	Kg CO_2 eq	4.19E+08	6.98E+06
	Embodied Energy	MJ	2.07E+08	3.45E+06
	Operational Energy	MJ	7.78E+09	1.30E+08

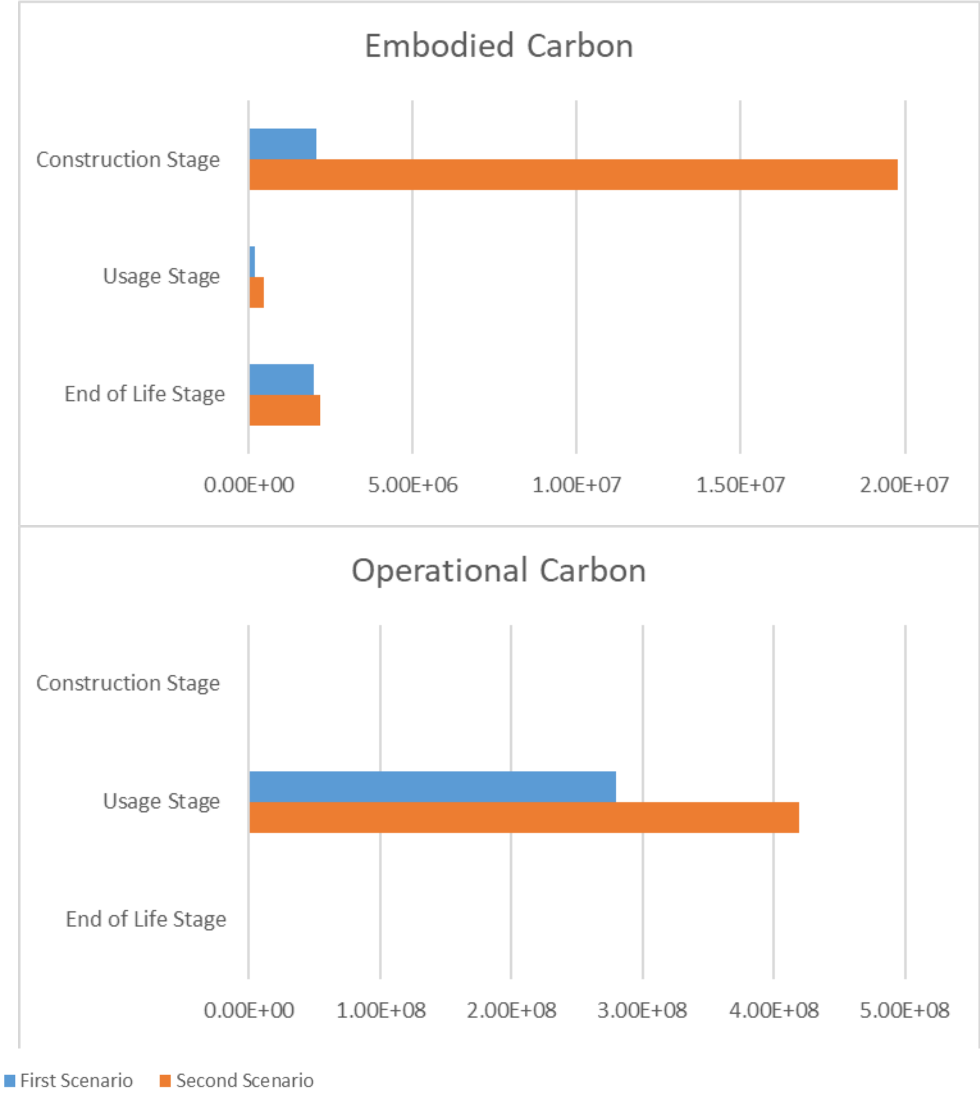


Figure 5-24 Embodied and operational carbon results of both scenarios

It is apparent from the above tables and figures that an average of 87% of the embodied impacts was caused by the manufacturing and construction stage of the second scenario, and 52% by the construction of the first scenario. Operational impacts caused more effects than embodied impacts according to the results. As shown in Figure 5-24, the embodied carbon reported a significant reduction at 90% for the first scenario compared to the second one, and the construction stage has the most reduction in the embodied impacts. The second largest reduction occurred during the usage stage and then the end-of-life stage, constituting 58% and 8%, respectively.

Figure 5-25 Embodied and operational energy results of both scenarios

Operational carbon only occurs during the usage stage, and there was a slight fall in the first scenario because of the short service period of the retrofit building, representing a 33% reduction. Embodied energy also significantly reduced in the construction stage by implementing retrofitting, as seen in Figure 5-25. There was an 84%, 44%, and a 3% decrease in embodied energy during the construction, usage, and end-of-life stages, respectively. There was also a slight reduction in operational energy, similarly at 33% due to the short service period.

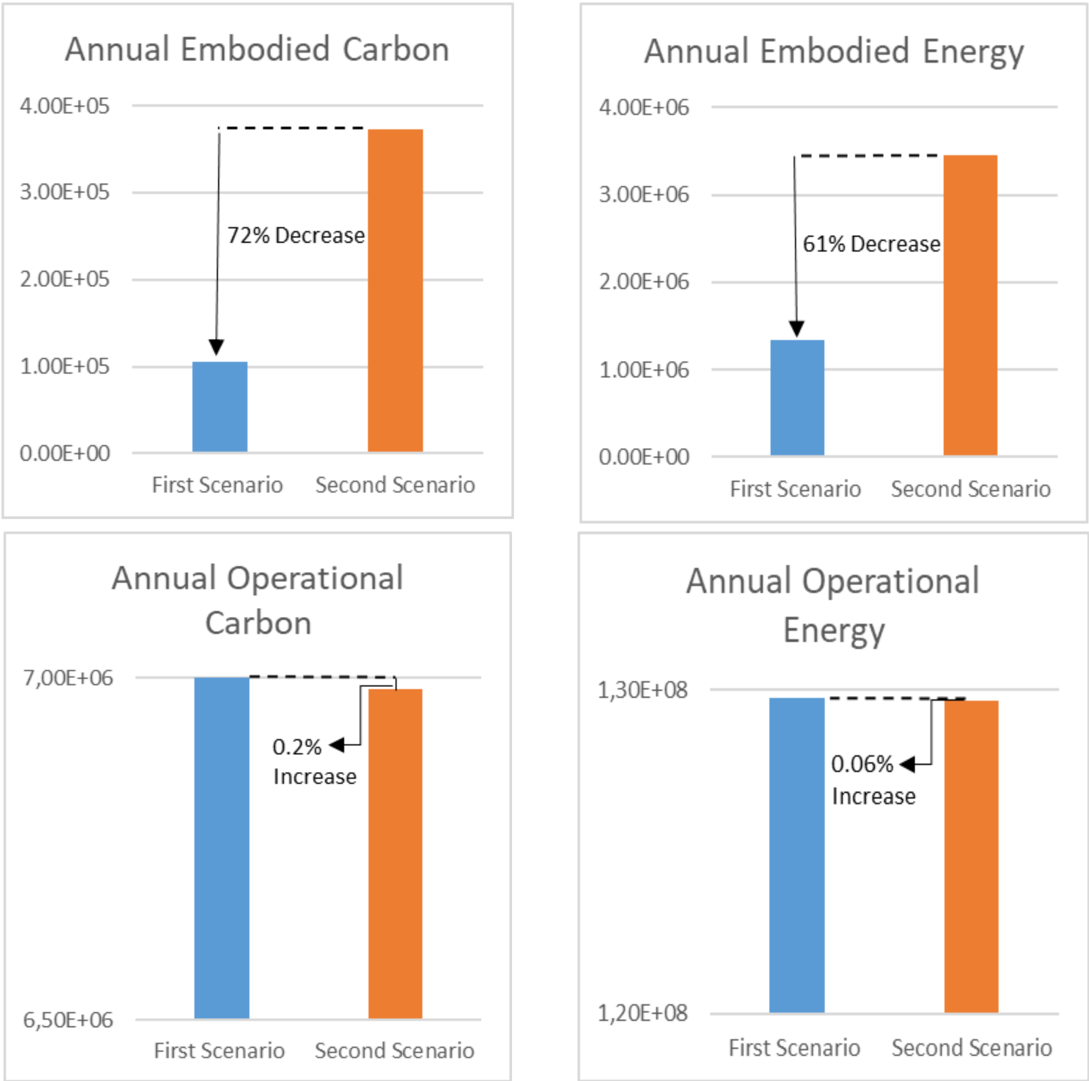


Figure 5-26 Annual embodied and operating impacts

Regarding the total environmental impacts, while the embodied carbon and energy of the first scenario constitutes 1% of the total impacts, the embodied carbon shares 5% and the embodied energy shares 3% in the second scenario. However, when the annual total environmental impacts of both scenarios are calculated, a different figure appears for annual operational energy consumption, as seen in Figure 5-26. The figure also reveals that there was a sharp drop in annual embodied carbon and energy, decreasing by 72% and 61%, respectively. In contrast, operational energy and carbon did not change significantly, with a 0.2% and 0.06% increase for the first scenario's annual impacts. Therefore, the building's service life and LCA stages have a meaningful impact on the building's life cycle footprint. Table 5-14 and Table 5-15 give embodied and operational carbon emissions and embodied and operational energy over the building's life, divided into five-year sections to present the lifetime impact of retrofit in the designed years. The five-year sections show the total impacts caused by operational and embodied impacts at the end of each five years during building use, and do not include future changes and energy efficiency measures.

Table 5-14 Embodied and operating carbon impacts every five years during the lifetime of the scenarios

Years	**First Scenario**		**Years**	**Second Scenario**	
	Embodied Carbon	Operational Carbon		Embodied Carbon	Operational Carbon
Retrofit Construction	2.04E+06	0	New Building Construction	1.98E+07	0
5	2.35E+04	3.50E+07	5	2.27E+04	3.49E+07
10	2.35E+04	3.50E+07	10	2.27E+04	3.49E+07
15	2.35E+04	3.50E+07	15	2.27E+04	3.49E+07
20	2.35E+04	3.50E+07	20	2.27E+04	3.49E+07
25	2.35E+04	3.50E+07	25	2.27E+04	3.49E+07
30	2.35E+04	3.50E+07	30	2.27E+04	3.49E+07
35	2.35E+04	3.50E+07	35	2.27E+04	3.49E+07
40	2.35E+04	3.50E+07	40	2.27E+04	3.49E+07
End of Life	1.98E+06	0	45	6.74E+04	3.49E+07
			50	6.74E+04	3.49E+07
			55	6.74E+04	3.49E+07
			60	6.74E+04	3.49E+07
			End of Life	2.16E+06	0

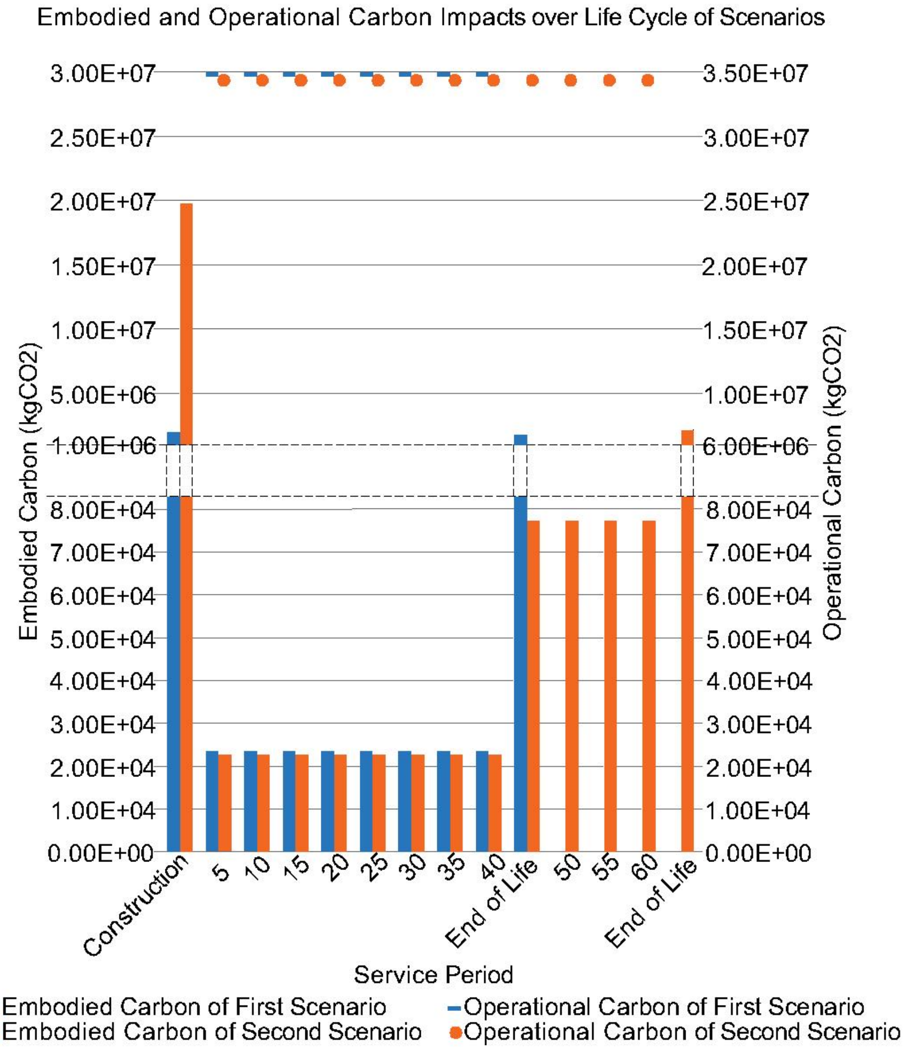
The results presented in Table 5-14 and Table 5-15 are static and neglect technological changes related to material replacement and maintenance. There has been an increase in the embodied impacts of the first scenario in the usage stage compared to the second one due to the maintenance activities of retrofit materials, apart from in the original building. Therefore, the first scenario had higher embodied impacts in the first 40 years, and this increase was 3% for embodied carbon every five years.

Table 5-15 Embodied and operating energy impacts every five years during the lifetime of the scenarios

Years	**First Scenario**		**Years**	**Second Scenario**	
	Embodied Energy	Operational Energy		Embodied Energy	Operational Energy
Retrofit Construction	2.91E+07	0	New Building Construction	1.78E+08	0
5	6.44E+05	6.49E+08	5	6.02E+05	6.48E+08
10	6.44E+05	6.49E+08	10	6.02E+05	6.48E+08
15	6.44E+05	6.49E+08	15	6.02E+05	6.48E+08
20	6.44E+05	6.49E+08	20	6.02E+05	6.48E+08
25	6.44E+05	6.49E+08	25	6.02E+05	6.48E+08
30	6.44E+05	6.49E+08	30	6.02E+05	6.48E+08
35	6.44E+05	6.49E+08	35	6.02E+05	6.48E+08
40	6.44E+05	6.49E+08	40	6.02E+05	6.48E+08
End of Life	1.90E+07	0	45	1.10E+06	6.48E+08
			50	1.10E+06	6.48E+08
			55	1.10E+06	6.48E+08
			60	1.10E+06	6.48E+08
			End of Life	1.96E+07	0

Operational energy and carbon and their improvement are not part of the case study, so remain the same at the end of each five years for both scenarios. However, there has been an increase also for operational carbon at 0.3% every five years because of the shorter service period of the first scenario compared to the second one during the operation. Similarly, embodied and operational energy of the first scenario was also slightly higher for the same period with a 6.5% and 0.2% increase, respectively. However, after 40 years, the embodied impacts increased, as the second scenario required the windows to be replaced due to the more extended service period. The environmental impacts caused by the replacement were credited to the remaining

20 years as a half load because the software calculates the impacts of products that have not completed their useful life during their usage. Figure 5-27 shows that embodied impacts form a minor part of the emissions compared to the operational impacts. The maintenance at the end of each five years also constitutes minor impacts, so it was represented with special axis that can show the smaller numbers. Embodied carbon formed 0.07% of the total carbon emissions, embodied energy constituted 0.1% of whole energy impacts during the same period of use.



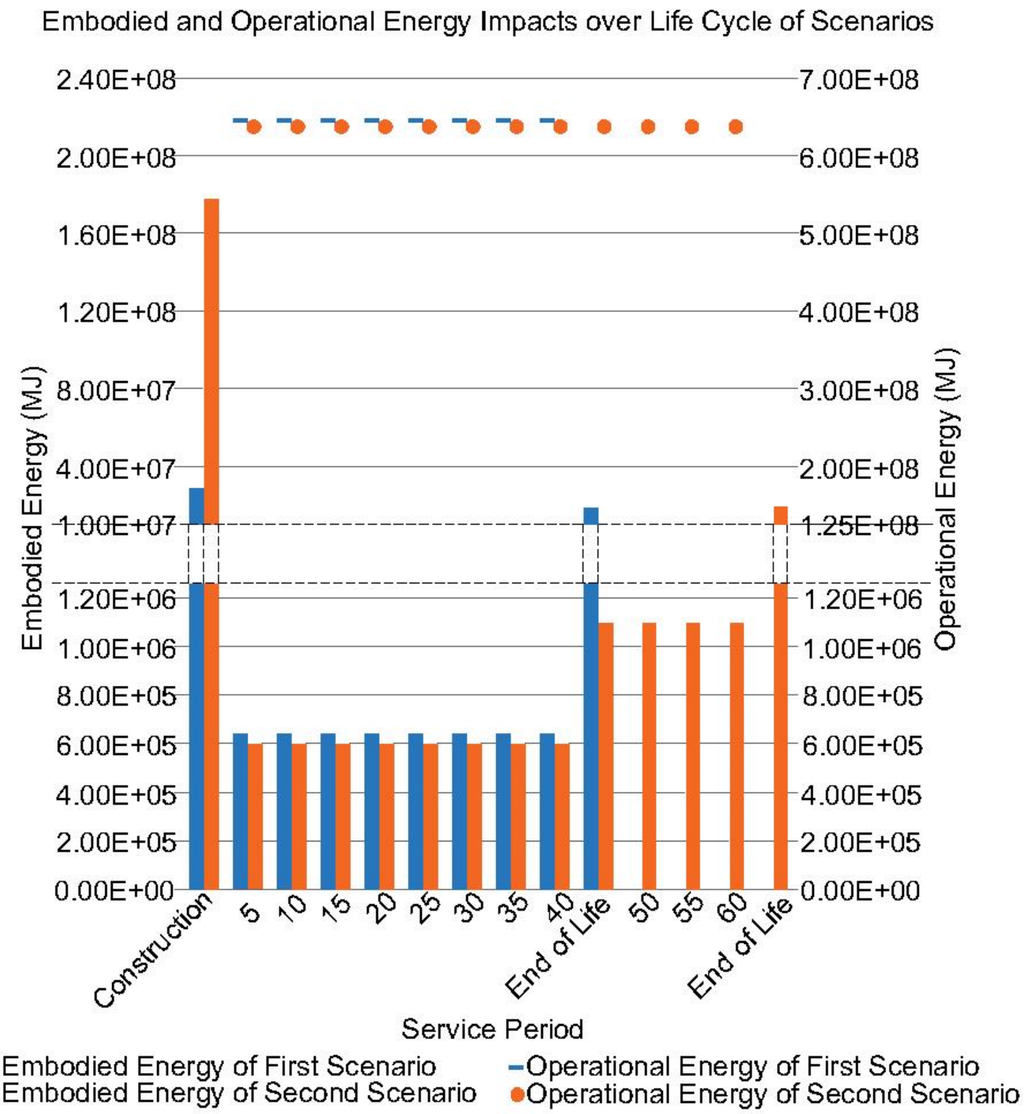


Figure 5-27 Embodied and operational impacts of both scenarios during life cycle

5.3.4 Interpretation

The previous sections presented the LCA of a retrofitted and non-retrofitted vulnerable building and the LCI and LCIA results. This section builds on these by critically interpreting and discussing the results of environmental impacts of strengthening the vulnerable hospital building by steel reinforcements, rather than building a new hospital building.

Similar to the other case study, there are limitations in this case study as well. The only focus of this study has been environmental sustainability based on the strengthening scenarios of the vulnerable building. Operational energy is included because of the different service lives of the scenarios; however, energy upgrading is beyond the study's system boundaries.

5.3.4.1 Interpreting the Results for Manufacturing and Construction Stage

The LCIA results were interpreted for each stage along with the LCI. During the construction and manufacturing stage, the greatest contribution to the overall impacts in the second scenario comes from the extensive manufacturing of new building materials. Following that, the construction phase causes increasing impacts for the second scenario because of the high amount of energy use and transportation activities during the new building construction. These environmental burdens cause a significant impact and account for a 90% increase compared to the first scenario. Only retrofitting activities constitute 10% of new building construction (including demolition of existing building).

In the study of Menna et al. (2013), they found that rehabilitation activities constitute 25% of initial construction, and 6% of total impacts of the whole building's life cycle (building construction to the end of life). Their study investigated the expected environmental impact of new buildings related to a building's seismic codes. In this study, by avoiding a new construction in the first scenario, retrofitting constituted approximately 50% of the existing building's total environmental impact throughout its life cycle, and retrofitting constituted only 9% of the new building's total CO_2 emissions. Likewise, in the study of Comber and Poland (2013), seismic upgrading of a medical building reduced its total emissions to around 9%; thus retrofitting an existing building can reduce 90% of emissions caused by the new building.

In the second scenario, the new building was considered as built with high standards. According to Simonen et al. (2015), CO_2 emissions can be reduced by implementing high-performance buildings; therefore, the reduction of seismic repair impacts is considerable (2- 24% of emissions from the manufacturing of the building). This shows that emissions from new building construction may increase even more when the probability of future damages are considered. In addition to that, retrofit designs cannot totally reduce damages from future disasters; however, these buildings would have been expected to be subject less to severe damage (Wei, Shohet, *et al.*, 2016). The impacts of retrofit can be various, depending on the retrofit technique, materials, and also the parameters included in the new construction, such as the demolition of the existing building or the structural performance of the building. Besides that, the effect of deconstruction of the original building on this increase is very small because it has slightly less impact overall than the retrofit construction stage. The energy use of retrofit construction mainly caused a considerable increase compared to the demolition of the original building. While manufacturing and construction of steel structures correspond to a high amount of energy consumptions due to fabrication and transportation, demolition of the original building mainly increased the smog and acidification potentials, representing around 55% and 36% compared to the first scenario, respectively.

Material manufacturing also causes a considerable amount of CO_2 emissions, and accounts for 85% of the total emissions of the first scenario during construction. This result is in accordance with Wei et al.'s (2016) findings that the manufacture of materials constitutes 84% of the total CO_2 emissions during retrofit construction.

The original building demolition also includes its BBL impacts since the reuse and recycling process of a completely demolished building should be included. The GWP and acidification potentials were the higher contributors to the BBL process when compared to demolition;

therefore, the increase in smog potential is mostly caused by demolition activities, which includes the demolishing device activities, disposal transportation and landfill. While demolition activities increase smog potential, manufacturing and construction activities mainly affect the ODP impacts which occurred the most in the new building construction, representing a 97% increase compared to retrofitting.

5.3.4.2 Interpreting the Results for Usage Stage

During the usage stage, including operational energy made a notable change; while the retrofitted building constituted 32% of the total impacts without operational impacts, it increased to 40% with operational impacts. In addition to that, with the five years distribution the 32% share of the embodied impacts over the building service life made the embodied impacts invisible because of the greater operational impacts. The reason for this increase is the longer service period and replacement activities in the second scenario are different from the first scenario. At this stage, the building's operational energy consumption with a long service period will be higher, which directly increases the environmental impacts. Therefore, although operational impacts are not the goal of this study, it was deemed necessary in terms of revealing the big difference between them and the embodied results. While embodied energy constituted 0.1% of embodied and operational energy impacts during the same period of usage of both scenarios, embodied carbon constituted only 0.07%. Apart from operational energy, a long service period also causes more periodic painting than for the original building. The period and type of maintenance or replacement activities will be variable during the building's use. In this study, these activities were included based on retrofit maintenance. Since similar maintenance made in the first 40 years will be eliminated during the comparison. However, after 40 years, the second scenario required replacement activities as well. As a result, embodied carbon and energy can be reduced at around 72% and 61% annually, respectively, by implementing the retrofitted scenario. Therefore, the annual impacts of each scenario give sensible results when comparing buildings with different service periods.

5.3.4.3 Interpreting the Results for End-of-life Stage

The end-of-life stage of the scenarios includes demolition and the BBL process. However, the demolition analyses' results showed a very small decrease of 4% on the impacts of the first scenario compared to the second one. This is because each scenario has the demolition of the whole building and that buildings have the same design; the only differences are strength and service period. These differences resulted in an average reduction of 9% in all impact categories of the original building. This result is a relative result because it will vary according to the design of the new and existing building, and the vulnerability of the original building will affect the results. In this study, an evaluation has been made based on the assumptions for both buildings.

Regarding retrofitting, it created only an average of 6% of the total environmental impacts of the first scenario; between the impact categories, the HH particulate caused the largest share at 18%. The HH particulate was also the highest contributor in other stages of the retrofit. While the factors affecting the usage stage of the retrofit are paint and its application, the demolition process factors are also the energy consumption caused by demolition. Similarly, the construction stage also has the same energy factor. However, it will be challenging to determine why HH particulate is slightly higher than the other categories, because of the different retrofit inputs and the whole building. A comparison of the two results reveals that the second scenario had a higher environmental impact than the first scenario and the main effects of the building demolition of the first scenario stemmed from the existing building.

BBL can be seen as a recycling benefit of the metal products and a potential outside of the system boundary. The benefit of retrofit resulted in a 110% decrease compared to the original building for all impact categories, except ODP. The new building has almost 75% higher ODP values than the existing building due to the higher amount of materials. However, the new building had slightly more credits than the original building with an average of 4% (from GWP, HH particulate, eutrophication potential, and FFC) and the original building has higher credits than the new building with an average of 9% (from acidification and smog potential, total primary energy and NRE) during the BBL. Therefore, the existing building had higher environmental impacts than the new building, contrary to other results. The resource use results show the higher re-use proportion of the second scenario as minus, and that decreases the credits of the new building as well. Also, when the retrofit's recycling benefit included the results, the first scenario had a lower impact on the environment than the second scenario.

5.3.4.4 Interpreting the Results for Embodied and Operating Impacts

Buildings have a high impact on the environment as it consumes many resources, and existing buildings are already partially free from embodied impacts of buildings. Structural retrofitting activities caused 48% of total embodied carbon impacts; this result is exactly the same as Hossain and Gencturk's (2016) case study for a low-cost low-performance building. They state that if the building is constructed as a high-cost high-performance building; it will cause two to four times fewer repair impacts than low performing buildings.

Regarding embodied energy, the demolition of retrofit is estimated to be equivalent to 2% of the first scenario's total embodied energy. According to Pan et al. (2014), in some cases, disposal from rehabilitation activities can reach about 42% of the total energy consumption. Demolition emissions caused by retrofitting are equal to 1.5% of the total emissions from the first scenario. The result is slightly less than Wei et al. (2016) found, which was equal to 2.4% total rehabilitation emissions.

The first scenario's total embodied carbon impacts are only 19% (5 times fewer) of the second scenario's total impacts, and the impact from the retrofit construction is only 1/10 of the new building's construction. In the results of Wei et al. (2016), new building construction corresponds to 117.8% of the construction stage of an existing building. Therefore, retrofitting of buildings provides a great advantage to reduce emissions from new building construction.

5.3.4.5 Interpreting the Resource Use Results

Considering the high amount of environmental impacts during construction and LCI resource use, the result shows that resource use is an important factor in increasing environmental impacts. It should be noted that operating energy and carbon occur from energy consuming activities, and so the depletion caused by them is limited to energy resources. However, embodied impacts are caused by the depletion of several natural resources. Therefore, the operating energy of the building is not included in the LCI in order to discover the effect of embodied impacts on resource use more clearly.

As a result, it has been observed that the embodied impacts have affected various natural resources. The second scenario's resource use turned out to be relatively high, and most of this amount was due to the construction stage. Hence, a high amount of resource consumption can be avoided if the retrofitted scenario is applied; for instance, about 71,370 tonnes of coarse aggregate, 14,848 tonnes of limestone, 520,000m^3 of natural gas, 353 tonnes of wood fibre and 145 million L of water usage can be saved.

5.3.4.6 Interpreting the Overall Results

Regarding the LCIA results, Figure 5-28 highlights the summary of the reduction rates of each impact category representing total A to D impacts in case the first scenario is applied. As a result, the overall advantage of retrofitting a vulnerable building rather than constructing a new one was an average of 36% of avoided impacts.

Corresponding values of the avoided impact rates are as follows:

- GWP-157,940 tonnes CO_2 (eq) less global warming emissions emitted;
- Acidification Potential-382 tonnes SO_2 (eq) fewer acidifying substances released;
- HH Particulate-423 tonnes PM2.5 (eq) less substances affecting the human health system have been released;
- Eutrophication Potential-140 tonnes N (eq) less substances affecting aquatic creatures have been released;
- ODP-11 kg CFC-11 (eq) less emissions of ozone depleting substances emitted;
- Smog Potential-6,060 tonnes O_3 (eq) less photochemical smog emissions emitted;
- Total Primary Energy-2,739,500,000 MJ less total primary energy consumed;
- NRE-2,286,700,000 MJ less non-renewable energy consumed; and finally,
- FFC-1,933,800,000 MJ fewer fossil fuels consumed.

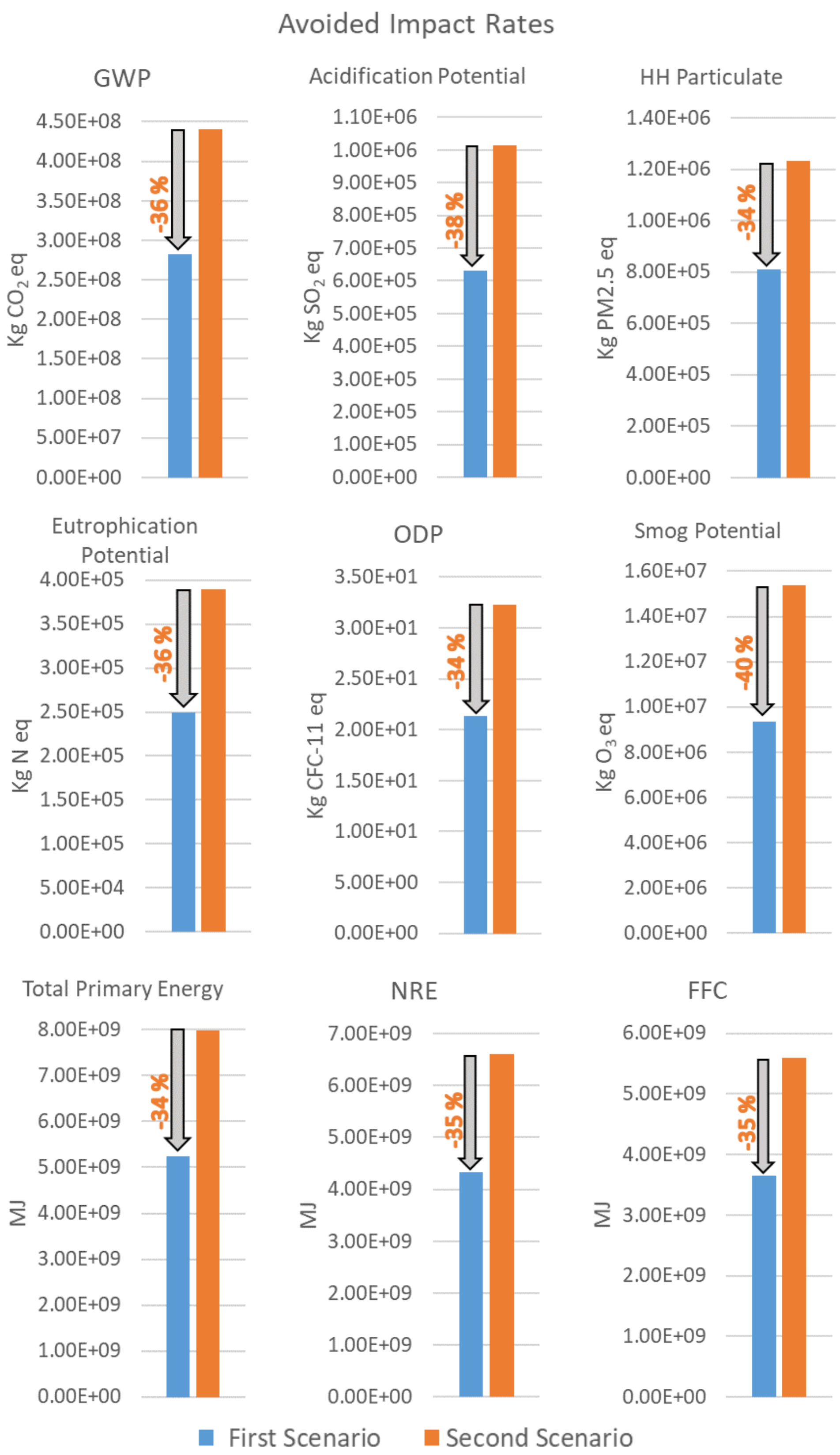


Figure 5-28 Avoided impacts in case the first scenario is applied

The new building scenario in this case study is a very optimistic sample of the current construction world, because it can be observed that growing cities have a destiny, where new buildings are built in place of old buildings. They are usually built with higher floors or cover more floor area. Thus, strengthening and preserving existing buildings will prevent the situation that increases the use of more materials, to some extent. As shown in the results, it requires less new construction or less material to reduce carbon emissions from buildings. In this respect, as long as they are not heavily damaged, post-disaster buildings can provide significant benefits in reducing embodied carbon emissions. However, this is still a case-by-case situation, project-based, and the entire life cycle of the building should be considered.

5.4 Summary

This chapter provided the analysed results of the medium-damaged building. Firstly, two possible scenarios were generated, and then their strengthening techniques and performances presented. After that, each scenario was integrated with the LCA procedure and data collected for each stage of the scenarios. Finally, the AIEB tool database has been used to assess the environmental impacts of both scenarios and an LCIA carried out using the TRACI method, which links midpoints impact estimation methods from cradle-to-grave.

Nine midpoint categories were selected to estimate the effects of both scenarios on the environment. Reduction in environmental burdens has been achieved by the implementation of the first scenario (retrofitted scenario) for all categories. The major contribution to the overall impacts in the manufacturing and construction stage comes from the new building construction. The maximum embodied carbon reduction is observed in the manufacturing and construction stage representing about 90%, and the least environmental impacts were caused during the usage stage if the operating impacts are neglected. As for the end-of-life stage, retrofitting also takes advantage of recyclable metal materials and contributes positively to the end of the first scenario. Embodied carbon and energy constitute 5% and 3% of total operational and embodied impacts in the second scenario, while they share only 1% in the first scenario. Apparently, including the building service period had an important impact on changes during the usage stage and total annual impact of environmental burdens; so 72% and 61% decreases in the annual impacts of embodied carbon and energy were recorded.

Overall, strengthening the vulnerable building instead of constructing the new building resulted in an average of 36% avoidance of environmental impacts across all impact categories and their damaging effects on the air, water, land and resources.

6. CONCLUSIONS

6.1 Foreword

This final chapter summarises the research findings. The chapter begins with a section that reflects on the research objectives. This is followed by the main findings and contributions of the research related to the aim and objectives. Finally, the chapter ends with recommendations for the sustainable strengthening of vulnerable buildings and ideas for future academic works.

6.2 Reflecting on the research objectives

In parallel with the aim determined in Chapter 1, the sustainability concept was evaluated for vulnerable buildings in structural strengthening scenarios from cradle-to-grave. How this aim is achieved and addressed in each objective is discussed below:

Objective 1: *State the importance of a sustainable structural intervention method.*

In Chapter 1 and 2, the importance of upgrading the environmental sustainability performance of vulnerable buildings was explored by investigating recent studies, trends, and developments. The increasing frequency of disasters and developments in sustainability literature was found to accelerate research on the sustainable function of vulnerable buildings. Therefore, gaps and barriers in existing literature were investigated to evaluate environmental sustainability for vulnerable buildings across their life cycle.

Objective 2: *Propose an integrated method for life cycle environmental impacts of structural interventions, considering different damage scales, local conditions, and service periods.*

This objective was addressed in Chapter 3. The concept of structural intervention in vulnerable buildings is further scrutinised and incorporated into key sustainability metrics. Therefore, an integrated sustainable structural intervention method was proposed to consider the life cycle environmental impacts of buildings, scales of damage and variability of local conditions regarding structural safety.

Objective 3: *Apply the proposed method for a low-damaged building to the entire life cycle of selected structural retrofits.*

This objective was met in Chapter 4 through a case study located in Turkey that was damaged during a massive earthquake. Two strengthening scenarios were defined for this low-damaged building, and its environmental impacts were assessed using the proposed methodology. LCI and LCIA analysis were utilised to select the optimal solution as the most sustainable design. Steel scenario was found as the most beneficial option since it leads to less resource use, embodied carbon emissions, acidifying substances, damage to aquatic creatures, ozone depletion and smog emissions compared to the RC scenario.

Objective 4: *Apply the proposed method for a medium-damaged building to the whole life cycle for both the retrofitted and new building when considering service life.*

This objective was achieved in Chapter 5 through a case study located in Mexico and damaged during a destructive earthquake. Two scenarios were determined as retrofitted and non-retrofitted options for this medium-damaged building, and its environmental impacts were assessed using the proposed method, based on the different service periods of scenarios. The retrofitted building has clearly upgraded its sustainable performance in both environmental impact and resource use when compared to the new building life cycle.

Objective 5: *Investigate the effects of the proposed method on building sustainable performance.*

The proposed method provided a practical and viable framework for improving vulnerable buildings' sustainable performance by using well-explained and defined steps of an integrated

LCA procedure. Selected sustainability measurements: structural safety, environmental impacts and resource use, provided more in-depth results by evaluating them according to service life and customised stages.

6.3 Key findings

In this research, reducing structural vulnerability and improving the sustainable assessment of existing buildings is responded to with the ESSIM (Environmentally Sustainable Structural Intervention Method) from a life cycle perspective. The study is unique, as it introduced a more comprehensive and systematic framework developed on Pre-LCA and LCA stages considering several design options of retrofit scenarios and retrofit-versus-non-retrofit scenarios of vulnerable buildings. It also addressed the resource use of selected scenarios beyond environmental impacts, including extended service lives of buildings after retrofitting. The results of this study can also contribute to the historical loss data of environmental impacts associated with the retrofitting of vulnerable buildings for selected regions as real case studies were used without using probabilistic loss estimation.

After current trends and developments in building sustainability, literature is examined in Chapter 1 and 2, which highlights that current vulnerable building stock and the possibility of future disasters cannot be neglected. The embodied impacts of buildings are also unavoidable in the realisation of genuinely zero-carbon buildings. Therefore, the study developed around these critical issues and proposed a method to address more in-depth details. The life cycle environmental analysis of vulnerable buildings led to the following main findings:

- Strengthening vulnerable buildings according to the proposed method provides an advantage through the avoidance of construction new buildings. Chapter 5 proved that new building construction contributes significantly towards increased environmental impacts and resource usage. It has also been found in Chapter 4 that obtaining the most sustainable solutions among the preferred structural retrofit scenarios provides a reduction in mainly embodied impacts and resource demand; however, this reduction is relatively small compared to the decreases achieved in Chapter 5. Therefore, following the proposed method provides an efficient way to reduce the environmental footprint and resource use caused by buildings over their life cycle.

- Service period was found to influence the annual environmental impacts significantly, making notable changes in life cycle assessments.
- The evaluation of each LCA stage provided detailed information and benefits on environmental performance throughout the buildings' service life. While less resource use helped to reduce environmental impacts during construction and use of vulnerable buildings, recyclable materials also provided an advantage in terms of re-use of resources at the end-of-life stage, and benefits in reducing environmental impacts.
- Embodied impacts are a minor part of the building life cycle environmental impacts; however, it has been observed that this impact can be further reduced with a sustainable method. In addition to that, reducing embodied impacts helps protect several resources in nature, while operational impacts affect a limited number of resources based on only energy sources.
- Each strengthening process is designed according to the weakness of buildings and includes specific criteria for safety and sustainability; safety takes precedence, limiting the design choices. Therefore, a general sustainability statement cannot be assigned to strengthening techniques; each project and scenario should be evaluated individually. It was also found that scenario planning is an appropriate method when choosing the most sustainable design for structural interventions of vulnerable buildings.

- Selected materials and their manufacturing footprint affect the environmental impacts the most. In this case, the manufacturing and supply of the selected material are also important concepts that should be considered by designers. Retrofit materials affect the creation of the most optimal solutions for the target building.

As with every study, there were limitations and challenges faced in this research. For instance, the whole LCA of vulnerable buildings is a very demanding task and this is mostly due to a lack of data. In this study, although different databases are integrated to obtain the life cycle flow of environmental impacts, uncertainties, and assumptions are indispensable for such analysis. Apart from that, whole building component, both structural and non-structural, can be damaged during a disaster; however, for this study, only a limited set of building components were included that are more likely to impact environmental impacts and others were left outside of the scope. Uncertainty analysis can be applied to determine the uncertainties in the data; also, using local databases will help to overcome the limitations of LCA studies.

The proposed method successfully integrated sustainability principles into the structural performance by adapting LCA modules for customised stages of vulnerable buildings. Comparative analysis with the presented method supports this research project's aim that the environmental impacts of vulnerable buildings can be significantly reduced through strengthening techniques. Therefore, the study acknowledges that LCA stands among new metrics to quantify sustainability in buildings with structural retrofits. LCA could be a beneficial tool in this ongoing process as the findings support these systems' changes with fewer impacts. On the other hand, the proposed method's flexibility led to applying it to varying local and national construction requirements. Also, including scenarios for different damage scales helped reach optimal sustainable solutions for vulnerable buildings' specific conditions. This method can help designers when they are following a sustainable method in vulnerable buildings and direct them on a process that is most likely to reduce the environmental impacts of the building. Therefore, the proposed method can be considered as an optimal solution for selecting the best sustainable design for structural strengthening of vulnerable buildings.

6.4 Recommendations and future research

The research findings can affect several other research areas and future research on sustainable improvement of buildings. This section outlines these possible future impacts of this research.

The results show that extending the service period of vulnerable buildings as much as possible ensures avoiding the new environmental impacts caused by replacement or demolition. Such an approach can help planners during the design of longer-lasting buildings through the longer-term service of existing buildings.

The method can be further expanded upon for national building codes and related disasters of the region. For instance, Japan and some EU countries have building codes integrated with building energy codes (Lucon and Ürge-Vorsatz, 2014; IEA, 2018; Keskin, Martinez-Vazquez and Baniotopoulos, 2020a). Similarly, national codes can be further improved with a sustainable structural intervention method for vulnerable buildings in disaster-prone areas like Mexico and Turkey. In addition to that, the combination of the method with energy retrofits can provide cost and energy-saving. For instance, in the study of Mora et al. (2018), while seismic retrofit increased the annualised global cost by 7%, this seismic energy retrofit resulted in 53% cost and 96% energy savings. This could steer countries towards better disaster risk governance and acting on climate change impacts and relevant GHG emissions. With such regional approaches, some uncertainties and barriers that are frequently seen in the LCA studies can be overcome. Moreover, this can also encourage investments and raise awareness for sustainable buildings, since several sectors play roles during sustainable development; from manufacturers to the real estate sector.

The results highlight high environmental impacts during the manufacturing of construction materials; for instance, high resource use for manufacturing of concrete materials and energy use for fabrication of steel. Therefore, including environmental assessment in the building design process will indirectly allow designers to consider other parameters such as resource use and energy during the design process. Solutions for sustainable buildings should also inquire about the industry, rather than only the designer. In this context, regarding developments in concrete, replacing the binders to reduce cement use is being researched and progress is being made. Therefore, it is beneficial to create incentives for these developments in the industry to have an impact on the market. As suggested above, improvements in building codes lead to incentives and therefore investments. Additionally, LCA, LCI and LCIA are still under research and development and any new progress in this area would be beneficial to the understanding of the topic.

Software used to estimate construction cost (especially nationally) can include add-ons to measure sustainability metrics. These tools help the user to calculate bill of materials used during construction and to approximate construction cost, but they do not analyse multiple impacts to buildings, such as sustainable performance. Bill of materials constitute a significant part of the LCA, as seen in the findings. Although the entire life cycle of the building might not be possible to analyse now, the environmental impacts that will occur during construction can be included as the construction stage causes the highest environmental impacts. LCA will be included as the demolition and maintenance cost of buildings are added to the tool in the future. Pursuing environmental impacts and cost after design will motivate the designer to create other designs and options. Therefore, integrated cost and environmental impacts of buildings in software tools, that construction companies use, would create the right investment system for them, and that can lead to a sustainable environment in cities.

Retrofitted buildings do not have straightforward stages; some inputs are not included in every stage. For instance, while the only available information on the use and demolition stages of the existing vulnerable building were included, the construction stage of the vulnerable building is not included, as seen in Chapter 5. Therefore, to facilitate the analysis of retrofitted buildings, an option in LCA tools should exist to input the stages that should be considered. The user should be allowed to choose the LCA stages they want to be included in the selected assembly or input.

Insurance companies can include building strengthening or maintenance costs in case of disasters. The framework of the method can be valuable for producing various disaster insurances according to strength, service period and location of the building. As it was found that different damage scales cause different measurements and scenarios based on buildings' durability, even the construction year of the building will be able to give information about whether it complies with the regulations and the level of damage to occur in the future. Additionally, the historical loss data related to disasters can provide data for insurance companies to produce more-in depth procedures.

The primary purpose of earthquake-resistant building design is that structures do not collapse and there is no loss of life even if damaged. In recent years, damages in buildings caused by severe and moderate earthquakes have increased, which aroused interest in the structural strengthening of existing buildings. Therefore, there have been significant developments in retrofitting techniques of vulnerable buildings and reconstructing heavily damaged buildings with urban regeneration projects. These urban transformations also create an excellent opportunity for increasing energy efficiency in buildings. Therefore, vulnerable buildings can provide an opportunity for reducing the embodied and operational impacts of cities. Unplanned urbanisation, lack of green spaces and other factors caused by today's urban sprawl have produced unavoidable results in global warming and the built environment. Considering the social impacts of this study, preserving existing buildings can help avoid new construction that ignores the traditional fabric of cities. This offers an alternative opportunity to preserve the traditional character and architecture. Also, considering advancing research and development has led to the creation of safer building, many new strengthening and renewal techniques will emerge as a by-product of increased instances of disasters, and such developments must be noted for evaluating sustainability criteria.

There are further points about integrating sustainability and safety of buildings due to the multiple deficiencies associated with post-disaster buildings. For instance, economic and social aspects are other aspects to consider over the entire lifespan of the post-disaster buildings. For example, green buildings are environmentally friendly; however, they can cause upfront costs, may require frequent maintenance or can cause a high amount of waste (Welsh-Huggins and Liel, 2017). Therefore, LCA is a necessary tool to make optimal decisions for sustainable buildings.

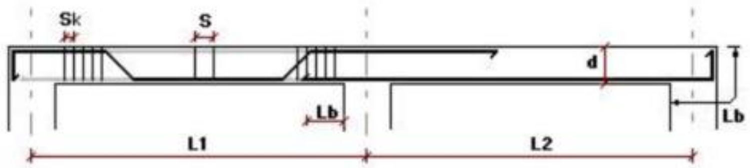
Current engineering practices are typically aimed at building's structural performance, hence mostly ignore interrelation of other building deficiencies. Also, such practices are increasing with the integration of energy retrofitting nowadays due to investments in zero energy buildings. However, as can be seen in this study, although the embodied impacts of buildings share a small percentage, it is still an issue that should not be ignored in reaching real zero buildings in terms of carbon and energy. Such targets should also consider local conditions by considering possible disasters, existing building stock, and sustainable performance of buildings. One of the most apparent trends in zero energy buildings is that a net gain can be obtained by reducing operational energy saving and the building can be certified with an energy certificate, as many governments require. Although zero embodied carbon has not yet been negotiated today, there would be a financial driver (for example, The Living Building Challenge requires to purchase a compensate for embodied carbon and CaGBC Zero Carbon program gives certification) or legal enforcement for carbon neutrality in the future as well. Since the formation of embodied carbon depends on many parameters, it is challenging to achieve zero embodied carbon in buildings. However, developing new technologies for capturing carbon in buildings or including carbonation in embodied carbon calculations can help to achieve zero carbon in buildings (O'Connor, 2020). Because, as Kibert (2016) pointed out, "It is clear that influencing energy consumption and climate change requires a comprehensive approach that addresses all forms of energy consumption, including operational energy, embodied energy, and commuting energy". For this reason, embodied energy and emissions reductions can be included in the building energy certificates, as well as the operational impacts. For example, existing buildings can provide an advantage by avoiding a new building, letting less embodied impacts and resource use. In addition, strategies and policies inevitably help countries achieve their sustainable building targets. Therefore, national authorises should put added effort into determining a carbon emissions reduction target for building stock by establishing long-term strategies.

Finally, the proposed method can be included in urban regeneration projects. This can provide insights for designers to develop projects that also cover sustainable improvement for the building stock. The further inclusion of single buildings, as well as expanding the study to more areas or a city scale, will help the sustainable transformation of cities.

Appendix A: Summary of the structural analysis of the RC scenario

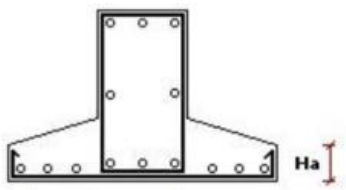
This appendix presents the summary of the relevant structural analysis results of the RC scenario.

BEAM DETAILING OPTIONS



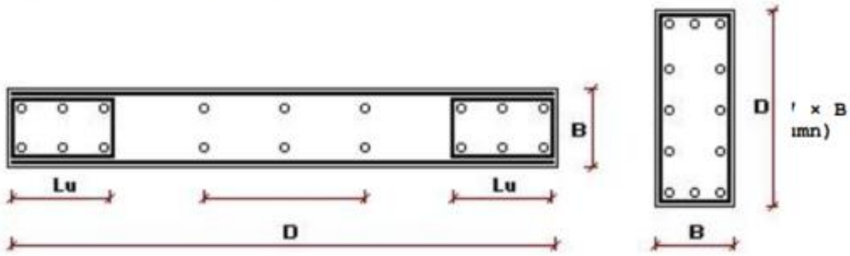

```
Etriye paspayi / Boyuna donati paspayi ..........cm.= 2 / 4
Min. longitudinal percentage .......................= .008
Arrangement Min. tension zone for TS500-2000........= 0.0026
     As min= 0.8 x fctd / fyd
Minimum straight and bent bar diameter............ø.= 12
Minimum montage reinforcement diameter............ø.= 12
Minimum web reinforcement diameter................ø.= 12
Minimum stirrup diameter .........................ø.= 8
Bent bar angle....................................°.= 45
Upper limit beam height for without web reinf....cm.= 59
Minimum top & bottom rebar spacing ..............cm.= 20
Concrete participation ratio for shear reinforcement= .8
Allowed column width for continuous beams........cm.= 200
Minimum montage reinforcement percentage..(% maxAs).= .25
Maximum stirrup spacing..S.......................cm.= 20
Minimum stirrup spacing..........................cm.= 10
Maximum stirrup spacing Sk.(1)...................cm.= 15
Maximum stirrup spacing Sk.(2)......................= d/4
Maximum stirrup spacing Sk.(3)......................= ø x 8
Maksimum side length for one single stirrup......cm.= 40
min.(bot As/top As) ................................= .5
min.top As=Fctd/Fyd ................................= No
min Lb =............................................= ø x 50
Bottom bar add to make longer L/4 side straight bar.= No
Top bar add to make longer L/4 side straight bar....= No
```

FOUNDATION DESIGN OPTIONS




```
Etriye paspayi / Boyuna donati paspayi ..............cm.= 5 / 7
Min. tension zone for TS500-2000(As min=0,8.fctd/fyd)= 0.0023
Min. gross cross section ............................= .005
Minimum pressure zone reinforcement ratio ...........= .333
Bent bar angle.......................................= 60
Minimum stirrup spacing ..........................cm.= 10
Maximum stirrups spacing..........................cm.= 20
Maximum stirrups spacing..........................cm.= 60
Minimum top & bottom rebar spacing ...............cm.= 20
Column dowel length for foundations ..............cm.= 50
Min stirrup dia. for continuous footing...........ø..= 8
Min. reinforcement dia for continuous footing ....ø..= 12
Min secondary reinf dia for continuous footing....ø..= 12
Min web reinf dia for continuous footing..........ø..= 12
Min reinf dia for footing slab....................ø..= 12
Base slab height          (Ha)....................cm.= 20
```

SHEARWALL DETAILING OPTIONS




```
COLUMNS AND SHEARWALLS detailing options              :
Etriye paspayi / Boyuna donati paspayi ..........cm.= 2 / 4
Min.column tension zone ..........................= .0025
Min. percentage for gross cross section............= .01
Column axial load eccentricity will be included ....= yes
Minimum stirrup spacing..........................cm.= 10
Maximum stirrup spacing(1).......................cm.= 20
Maximum stirrup spacing(2)......................min.= ø x 12
Minimum tie bar spacing.........................min.= ø x 25
Minimum reinforcement bar diameter.........ø........= 14
Minimum stirrup diameter .................ø........= 8
Shearwall/Column ratio (D/B).(transition limit).....= 7
Shearwall lateral reinforcement bar ends bent.......= Bent
Ribbed bar hook angle .................. (90ø,135ø)= 135
min.Hcr height ...................................<  D x 2
max.Hcr height ... ..............................>= D x 1
max.Hcr height ... ..............................>= Hw/6
Min.SWall end zone.(Hcr)..........................= .002
Min.percentage for the end area....................= .001
Min.percentage for the web area....................= .0025
Min.length for the wall with confining reinf.     Lu= 20 cm
Min.end zone size  (Hcr).........................Lu=B x 2
Min.end zone size  (Hcr).........................Lu=D x .2
Min.end zone size ...............................Lu=B x 1
Min.length for the wall with confining reinf.  ...Lu=D x .1
End zones min.reinf. bar dia....................ø..= 14
Min. reinforcement dia. for the web zones........ø..= 12
Shear Wall design moment considered  ..............= Yes
```

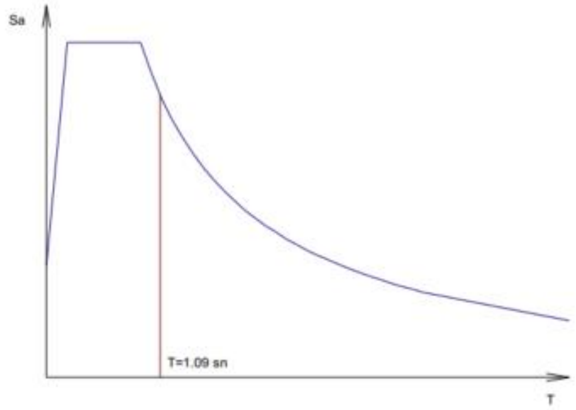
SEISMIC REPORT

```
SEISMIC CODE                                      : TDY2007 CODE
EARTHQUAKE ANALYSIS                               : MOD SUPERPOZISYONU YONTEMIYLE LINEER ANALIZ
SEISMIC ZONE COEFFICIENT                          : 0.40
STRUCTURAL BEHAVIOUR FACTOR                       : 4.00
SEISMIC IMPORTANCE FACTOR                         : 1.00
Seismic Analysis min. forces load ratio β         : 0.9
Seismic loading eccentricity                      : 0.000
BODRUM KAT DEPREM OPSIYONLARI                     :
Esdeger deprem analizi davranis katsayisi Rb      : 1.5
Modal Analiz davranis katsayisi           Rb      : 4.00
DIAPHRAGM NUMBER                                  :  8
Diaphragm definition : STORY(diaphragm no)
```

MODAL ANALYSIS DATA

TASARIM SPECTURUM BİLGİSİ (TDY2007 SPECTRUM)

T (s)	Sa (m/s²) Ao.I.S(t)
0.00	4.000
0.20	10.000
0.90	10.000
1.00	9.192
1.10	8.516
1.20	7.944
1.30	7.452
1.40	7.024
1.50	6.644
1.60	6.312
1.70	6.012
1.80	5.744
1.90	5.500
2.00	5.280
2.10	5.076
2.20	4.892
2.30	4.720
2.40	4.564
2.50	4.416
2.60	4.280
2.70	4.152
2.80	4.032
2.90	3.920
3.00	3.816
3.10	3.716
3.20	3.624
3.30	3.536
3.40	3.452
3.50	3.372
3.60	3.300
5.00	2.536



Ta> T   Sa=1+1.5 T/Ta

Ta< T < Tb   Sa=2.5

T > Tb $Sa=2.5\ (Tb\ /\ T)^{0.8}$

Ra(T)x= 4.000   Ra(T)y= 4.000   T<Ta => Ra(T) = 1.5 + (R - 1.5) * T / Ta

MODAL ANALYSIS - STRUCTURAL PERIODS and VECTORS

Mod w T yön	1.mod 5.78 1.0877 x	2.mod 7.56 0.8312 y	3.mod 8.67 0.7251 b	4.mod 19.83 0.3169 x	5.mod 28.83 0.2179 b	6.mod 33.15 0.1896 y	7.mod 44.75 0.1404 x	8.mod 66.51 0.0945 b	9.mod 80.96 0.0776 y
1/1x	0.00069	0.00004	-0.00029	0.00283	-0.00261	0.00056	0.00658	-0.01050	0.00737
2/2x	0.00686	0.00024	-0.00221	0.02201	-0.01642	0.00326	0.03706	-0.04581	0.02748
3/3x	0.01772	0.00019	-0.00246	0.04970	-0.02192	0.00438	0.06122	-0.03923	0.02407
4/4x	0.03112	0.00019	-0.00323	0.06953	-0.02057	0.00363	0.04475	0.00326	-0.01340
5/5x	0.04819	0.00029	-0.00404	0.06884	-0.01503	0.00112	-0.02388	0.03651	-0.03791
6/6x	0.06693	0.00009	-0.00187	0.03588	-0.00366	-0.00151	-0.07708	0.02123	0.01284
7/7x	0.08492	-0.00003	0.00007	-0.02153	0.00877	-0.00189	-0.03882	-0.00617	0.03989
8/8x	0.10094	0.00018	-0.00063	-0.08433	0.02334	-0.00130	0.06719	-0.01573	-0.02734
1/1y	-0.00001	0.00106	0.00025	0.00011	0.00124	0.00601	-0.00004	0.00124	0.01445
2/2y	-0.00004	0.00724	0.00186	0.00077	0.00701	0.02972	0.00017	0.00555	0.05059
3/3y	-0.00009	0.01802	0.00493	0.00207	0.01475	0.05695	0.00067	0.00729	0.06053
4/4y	-0.00009	0.03131	0.00795	0.00297	0.01788	0.07202	-0.00037	0.00079	0.02257
5/5y	0.00009	0.04824	0.00536	-0.00022	0.00636	0.06624	-0.00414	-0.00672	-0.03775
6/6y	0.00008	0.06581	0.00738	-0.00027	0.00194	0.03104	-0.00221	-0.00583	-0.06466
7/7y	0.00008	0.08356	0.00947	-0.00015	-0.00412	-0.02353	0.00040	-0.00127	-0.02454
8/8y	0.00015	0.10060	0.01345	-0.00045	-0.01220	-0.08420	0.00342	0.00595	0.05758
1/1b	-0.00001	-0.00001	0.00005	0.00000	0.00024	-0.00006	0.00008	0.00055	0.00012
2/2b	-0.00006	-0.00009	0.00072	0.00041	0.00254	-0.00041	0.00120	0.00398	0.00141
3/3b	-0.00011	-0.00027	0.00196	0.00132	0.00569	-0.00098	0.00274	0.00599	0.00181
4/4b	-0.00014	-0.00049	0.00347	0.00235	0.00778	-0.00142	0.00311	0.00366	-0.00020
5/5b	-0.00003	-0.00076	0.00545	0.00277	0.00722	-0.00156	-0.00023	-0.00340	-0.00301
6/6b	0.00017	-0.00102	0.00762	0.00171	0.00332	-0.00099	-0.00373	-0.00843	-0.00070
7/7b	0.00033	-0.00125	0.00966	-0.00044	-0.00277	0.00024	-0.00231	-0.00401	0.00174
8/8b	0.00041	-0.00145	0.01145	-0.00277	-0.00936	0.00171	0.00301	0.00786	-0.00067
Mxr%	58.699	0.001	0.122	15.388	1.852	0.055	5.097	2.436	0.826
Myr%	0.000	58.324	1.261	0.018	0.854	18.166	0.003	0.042	5.192
Mbr%	0.006	1.021	57.902	1.665	14.708	0.707	1.209	3.153	0.048

Mod w T yön	10.mod 82.95 0.0758 b	11.mod 113.67 0.0553 x	12.mod 126.81 0.0496 b	13.mod 141.24 0.0445 y	14.mod 157.35 0.0399 x	15.mod 176.28 0.0356 b	16.mod 200.38 0.0314 x	17.mod 203.36 0.0309 y	18.mod 240.89 0.0261 x	
1/1x	0.00996	0.02866	0.00999	-0.00145	0.04408	-0.01846	0.07458	-0.02034	0.05519	
2/2x	0.03673	0.07358	0.02065	-0.00266	0.05520	-0.01452	0.01283	-0.00224	-0.03754	
3/3x	0.03349	0.00556	0.00804	-0.00079	-0.04271	0.02820	-0.05584	0.01374	0.02203	
4/4x	-0.01940	-0.06185	-0.03065	0.00470	-0.01916	-0.02054	0.06266	-0.01586	-0.00359	
5/5x	-0.05580	0.00913	0.02594	-0.00378	0.07609	0.02196	-0.03918	0.00732	-0.02036	
6/6x	0.02090	0.04813	0.03332	-0.00979	-0.06578	-0.04792	0.00197	0.00589	0.03495	
7/7x	0.06197	-0.02457	-0.07031	0.01749	0.02696	0.05141	0.01321	-0.00914	-0.02729	
8/8x	-0.04370	0.00153	0.03443	-0.00821	-0.00471	-0.02067	-0.00664	0.00377	0.00929	
1/1y	-0.00909	-0.00113	0.00689	0.03447	-0.00031	0.00045	0.01469	0.05334	0.00475	
2/2y	-0.03055	-0.00353	0.01820	0.07486	-0.00045	0.00147	0.01667	0.05630	0.00208	
3/3y	-0.03629	-0.00095	0.00702	0.02656	0.00044	-0.00447	-0.01180	-0.03812	-0.00936	
4/4y	-0.01723	0.00476	-0.01892	-0.05682	-0.00058	-0.00236	-0.01212	-0.03873	0.01165	
5/5y	0.02284	-0.00108	-0.00470	-0.05091	0.00012	0.01331	0.02304	0.06668	-0.00628	
6/6y	0.04199	-0.00242	0.01081	0.04643	0.00116	-0.00268	0.00335	0.01880	-0.00459	
7/7y	0.01608	-0.00047	0.01068	0.06152	-0.00144	-0.01224	-0.02212	-0.07242	0.00813	
8/8y	-0.03669	0.00132	-0.01020	-0.04969	0.00058	0.00756	0.01139	0.03579	-0.00348	
1/1b	0.00041	-0.00072	0.00137	-0.00034	-0.00022	0.00213	0.00050	-0.00040	0.00301	
2/2b	0.00309	-0.00325	0.00733	-0.00133	0.00002	0.00716	0.00262	-0.00145	0.00633	
3/3b	0.00467	-0.00194	0.00529	-0.00137	0.00122	0.00012	0.00017	-0.00033	-0.00524	
4/4b	0.00161	0.00204	-0.00548	0.00068	0.00026	-0.00661	-0.00173	0.00197	0.00114	
5/5b	-0.00410	0.00519	-0.00391	0.00199	-0.00034	0.00820	0.00029	-0.00018	0.00438	
6/6b	-0.00208	-0.00175	0.00515	-0.00094	-0.00413	-0.00014	0.00415	-0.00180	-0.00747	
7/7b	0.00200	-0.00742	0.00122	-0.00082	0.00641	-0.00489	-0.00500	0.00201	0.00588	
8/8b	-0.00001	0.00511	-0.00186	0.00073	-0.00293	0.00254	0.00198	-0.00085	-0.00199	
Mxr%	1.494	3.369	0.437	0.007	2.872	0.270	3.860	0.281	1.283	∑= 98.3
Myr%	2.023	0.006	0.226	4.802	0.000	0.000	0.272	3.553	0.012	∑= 94.8
Mbr%	2.257	0.359	3.310	0.115	0.033	1.743	0.224	0.011	1.163	

$Mr = \sum(mi \cdot \Phi xir^2 + mi \cdot \Phi yir^2 + m\theta i \cdot \Phi\theta ir^2)$

$Mxr = \sum[(\sum m \cdot \Phi)^2/Mr]$ = %98.35 > %90.00 mode number OK. ✓

$Myr = \sum[(\sum m \cdot \Phi)^2/Mr]$ = %94.75 > %90.00 mode number OK. ✓

SEISMIC ANALYSIS 1.PERIOD CHECK

N= 7.00 < 13

Story Seismic displacement

Story	9. combination		10. combination		11. combination		12. combination	
(dyf)	δx (m)	θz (rad)	δx (m)	θz (rad)	δy (m)	θz (rad)	δy (m)	θz (rad)
8	0.1200438	0.0003399	0.1200438	0.0003399	-0.081517	0.0002421	-0.081517	0.0002421
7	0.1007311	0.0002639	0.1007311	0.0002639	-0.067439	0.0002217	-0.067439	0.0002217
6	0.0793347	0.0000982	0.0793347	0.0000982	-0.053025	0.0001955	-0.053025	0.0001955
5	0.0571705	-0.000099	0.0571705	-0.000099	-0.038832	0.0001600	-0.038832	0.0001600
4	0.0369894	-0.000197	0.0369894	-0.000197	-0.025724	0.0001110	-0.025724	0.0001110
3	0.0210595	-0.000146	0.0210595	-0.000146	-0.014854	0.0000535	-0.014854	0.0000535
2	0.0080145	-0.000082	0.0080145	-0.000082	-0.005961	0.0000136	-0.005961	0.0000136
1	0.0008165	-0.000013	0.0008165	-0.000013	-0.000872	0.0000031	-0.000872	0.0000031

Seismic amplitude : x= 0.00538 y= 0.00366

IRREGULARITY CHECK UNDER SEISMIC ACTION

A1,B2 type irregularities

```
max(di/hi)=0.02  CATLAMIS KESITLI P-DELTA ANALIZ YAPILMISTIR. KAT DEPLASMANLARI, 0.4 ILE CARPILMISTIR.
1. sto X dtop = -.0003266 + .0000052 × (1.05 - 14.92=.0009964  (PB01)
1. sto X dbot = -.0003266 + .0000052 × (25.52 - 14.92)=.0006788  (PB17)
2. sto X dtop = -.0032058 + .0000332 × (2.4 - 15.27) - .0009789 = .0081024  (SZ03)
2. sto X dbot = -.0032058 + .0000332 × (25.15 - 15.27) - .0006837 = .0065117  (SZ25)
```

X DIR. (+)

Story	ΔX dtop(m)	ΔX dbot(m)	ΔX ort	nbi	nki	R·Δx/h	θi	story type
8	0.0074296	0.0081200	0.0077748	1.04	0.00	0.01160	0.00633	Normal sto
7	0.0078695	0.0093743	0.0086219	1.09	1.11	0.01339	0.00822	Normal sto
6	0.0080011	0.0097981	0.0088996	1.10	1.03	0.01400	0.00975	Normal sto
5	0.0076036	0.0084885	0.0080461	1.05	0.90	0.01213	0.01002	Normal sto
4	0.0065792	0.0061137	0.0063465	1.04	0.82	0.00975	0.00941	Normal sto
3	0.0054960	0.0049216	0.0052088	1.06	0.79	0.00785	0.00851	Normal sto
2	0.0032410	0.0026047	0.0029228	1.11	0.56	0.00463	0.00542	Normal sto
1	0.0003986	0.0002715	0.0003350	1.19	0.00	0.00057	0.00000	Basement

X DIR. (-)

Story	ΔX dtop(m)	ΔX dbot(m)	ΔX ort	nbi	nki	R·Δx/h	θi	story type
8	0.0074296	0.0081200	0.0077748	1.04	0.00	0.01160	0.00633	Normal sto
7	0.0078695	0.0093743	0.0086219	1.09	1.11	0.01339	0.00822	Normal sto
6	0.0080011	0.0097981	0.0088996	1.10	1.03	0.01400	0.00975	Normal sto
5	0.0076036	0.0084885	0.0080461	1.05	0.90	0.01213	0.01002	Normal sto
4	0.0065792	0.0061137	0.0063465	1.04	0.82	0.00975	0.00941	Normal sto
3	0.0054960	0.0049216	0.0052088	1.06	0.79	0.00785	0.00851	Normal sto
2	0.0032410	0.0026047	0.0029228	1.11	0.56	0.00463	0.00542	Normal sto
1	0.0003986	0.0002715	0.0003350	1.19	0.00	0.00057	0.00000	Basement

Y DIR. (+)

Story	ΔY dlft(m)	ΔY drgt(m)	ΔY ort	nbi	nki	R·Δy/h	θi	story type
8	0.0056833	0.0055743	0.0056288	1.01	0.00	0.00812	0.00400	Normal sto
7	0.0058347	0.0056939	0.0057643	1.01	1.02	0.00834	0.00476	Normal sto
6	0.0057741	0.0055838	0.0056790	1.02	0.99	0.00825	0.00536	Normal sto
5	0.0053825	0.0051200	0.0052513	1.02	0.92	0.00769	0.00563	Normal sto
4	0.0045127	0.0041317	0.0043222	1.04	0.85	0.00669	0.00552	Normal sto
3	0.0036703	0.0034066	0.0035384	1.04	0.79	0.00524	0.00498	Normal sto
2	0.0020637	0.0019939	0.0020288	1.02	0.57	0.00295	0.00323	Normal sto
1	0.0003591	0.0003385	0.0003488	1.03	0.00	0.00051	0.00000	Basement

Y DIR. (-)

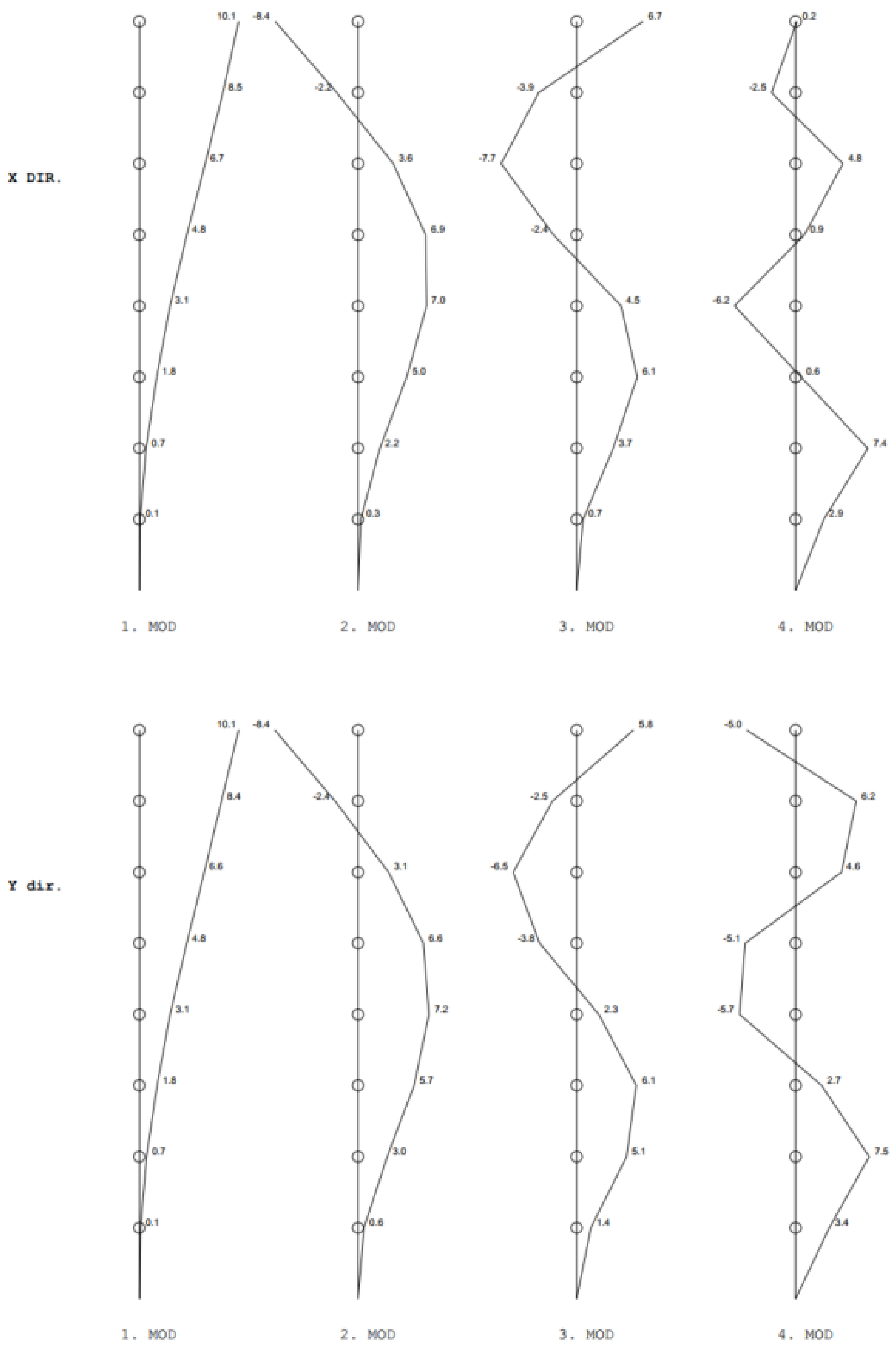
Story	ΔY dlft(m)	ΔY drgt(m)	ΔY ort	nbi	nki	R·Δy/h	θi	story type
8	0.0056833	0.0055743	0.0056288	1.01	0.00	0.00812	0.00400	Normal sto
7	0.0058347	0.0056939	0.0057643	1.01	1.02	0.00834	0.00476	Normal sto
6	0.0057741	0.0055838	0.0056790	1.02	0.99	0.00825	0.00536	Normal sto
5	0.0053825	0.0051200	0.0052513	1.02	0.92	0.00769	0.00563	Normal sto
4	0.0045127	0.0041317	0.0043222	1.04	0.85	0.00669	0.00552	Normal sto
3	0.0036703	0.0034066	0.0035384	1.04	0.79	0.00524	0.00498	Normal sto
2	0.0020637	0.0019939	0.0020288	1.02	0.57	0.00295	0.00323	Normal sto
1	0.0003591	0.0003385	0.0003488	1.03	0.00	0.00051	0.00000	Basement

B1-Vertical irregularity check

Story	Aw	Agx	Agy	Akx	Aky	Σ Aex	Σ Aey	ncix	nciy	EXPLANATION
8	9.24	1.39	3.39	0.00	4.47	10.63	13.30	1.00	1.00	top sto ✓
7	9.24	1.39	3.39	0.00	4.47	10.63	13.30	1.00	1.00	Regular ✓
6	9.24	1.39	3.39	0.00	4.47	10.63	13.30	1.00	1.00	Regular ✓
5	11.45	1.39	3.39	0.00	4.47	12.84	15.51	1.21	1.17	Regular ✓
4	13.10	1.39	6.04	0.00	8.95	14.49	20.48	1.13	1.32	Regular ✓
3	13.10	1.39	6.04	0.00	8.95	14.49	20.48	1.00	1.00	Regular ✓
2	13.10	1.39	6.04	0.00	8.95	14.49	20.48	1.00	1.00	Regular ✓
1	12.59	9.08	15.84	0.00	0.00	21.67	28.42	1.50	1.39	bodrum kat

Ba=Bax+0.3×Bay, Ba=0.3×Bax+Bay :
Kirişlerde, Kolonlarda; (Ba=Bax+0.3×Bay, Ba=0.3×Bax+Bay) düzeltmesi yapılmıştır.

MODAL ANALYSIS MODE SHAPE (1000 x Dis. vector)



SEISMIC TURN OVER CHECK

Story seismic moment (tm)

Story	H (m)	Fx	Fx . H	H (m)	Fy	Fy . H
8	22.30	162.20	3617.06	22.30	185.84	4144.31
7	19.50	124.75	2432.63	19.50	145.72	2841.62
6	16.70	92.40	1543.05	16.70	108.34	1809.24
5	13.90	72.58	1008.87	13.90	84.91	1180.27
4	11.10	65.92	731.69	11.10	76.42	848.31
3	8.40	47.25	396.88	8.40	54.92	461.32
2	5.60	19.59	109.72	5.60	24.18	135.41
1	2.80	3.80	10.63	2.80	5.51	15.42
		588.49	9850.54		685.85	11435.90

Story vertical load moment (tm) **X=0.0m** **Y=26.2m** **moment noktasi**

Kat	Wg+0.3·Wq	Xg-X	(Xg-X)·(Wg+0.3·Wq)	Yg-Y	(Yg-Y)·(Wg+0.3·Wq)
8	368.31	7.550	2780.78	12.670	4666.45
7	394.63	7.389	2915.92	12.571	4961.05
6	396.14	7.395	2929.57	12.604	4993.12
5	411.39	7.401	3044.64	12.616	5190.17
4	495.61	8.673	4298.69	12.205	6049.21
3	510.08	8.826	4502.03	12.170	6207.86
2	447.57	8.658	3875.09	13.278	5942.76
1	555.38	8.834	4906.29	12.452	6915.33
	967.70	9.274	8974.74	12.763	12350.83
			38227.76		57276.77

X yönü devrilme kontrolu=38227.758/9850.539=3.881 > 1.5 ✓
Y yönü devrilme kontrolu=57276.767/11435.897=5.009 > 1.5 ✓

Appendix B: Summary of the structural analysis of the Steel scenario

This appendix presents the summary of the relevant structural analysis results of the Steel scenario.

SEISMIC REPORT

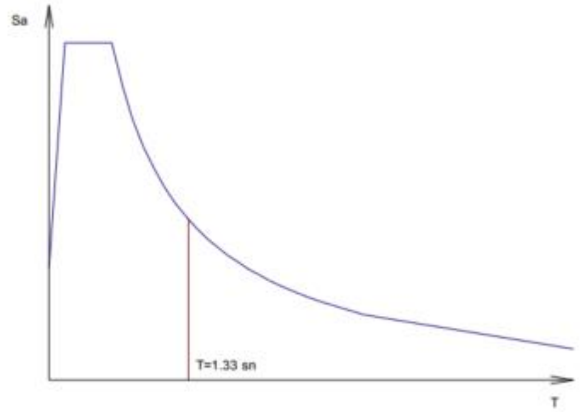
SEISMIC CODE	: TDY2007 CODE
EARTHQUAKE ANALYSIS	: MOD SUPERPOZISYONU YONTEMIYLE NONLINEER ANALIZ
SEISMIC ZONE COEFFICIENT	: 0.40
STRUCTURAL BEHAVIOUR FACTOR	: 4.00
SEISMIC IMPORTANCE FACTOR	: 1.00
Seismic Analysis min. forces load ratio β	: 0.9
Seismic loading eccentricity	: 0.000
BODRUM KAT DEPREM OPSIYONLARI	:
Esdeger deprem analizi davranis katsayisi Rb	: 1.5
Modal Analiz davranis katsayisi Rb	: 1.5
DIAPHRAGM NUMBER	: 8

Diaphragm definition : STORY(diaphragm no)

MODAL ANALYSIS DATA

TASARIM SPECTURUM BİLGİSİ (TDY2007 SPECTRUM)

T (s)	Sa (m/s²) Ao.I.S(t)
0.00	4.000
0.15	10.000
0.60	10.000
0.70	8.840
0.80	7.944
0.90	7.228
1.00	6.644
1.10	6.156
1.20	5.744
1.30	5.388
1.40	5.076
1.50	4.804
1.60	4.564
1.70	4.348
1.80	4.152
1.90	3.976
2.00	3.816
2.10	3.672
2.20	3.536
2.30	3.412
2.40	3.300
2.50	3.192
2.60	3.096
2.70	3.004
2.80	2.916
2.90	2.836
3.00	2.760
5.00	1.832

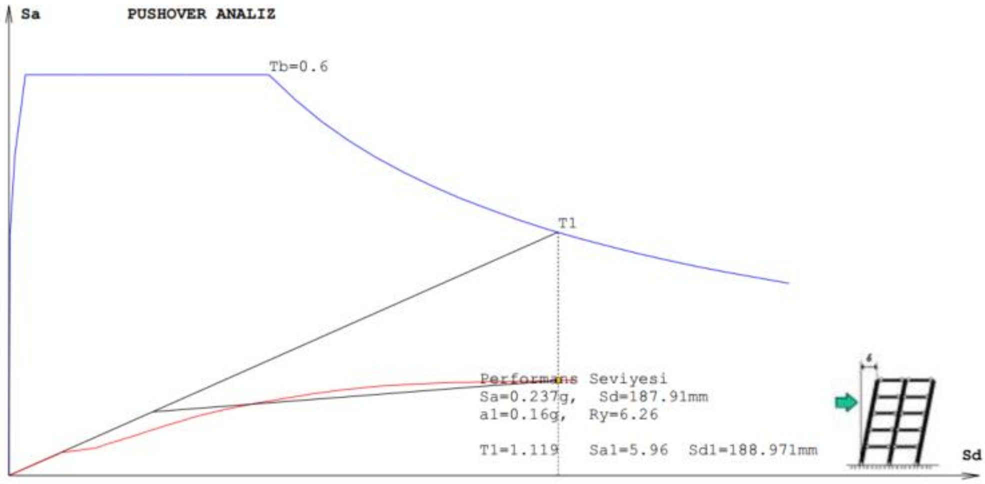


Ta> T Sa=1+1.5 T/Ta

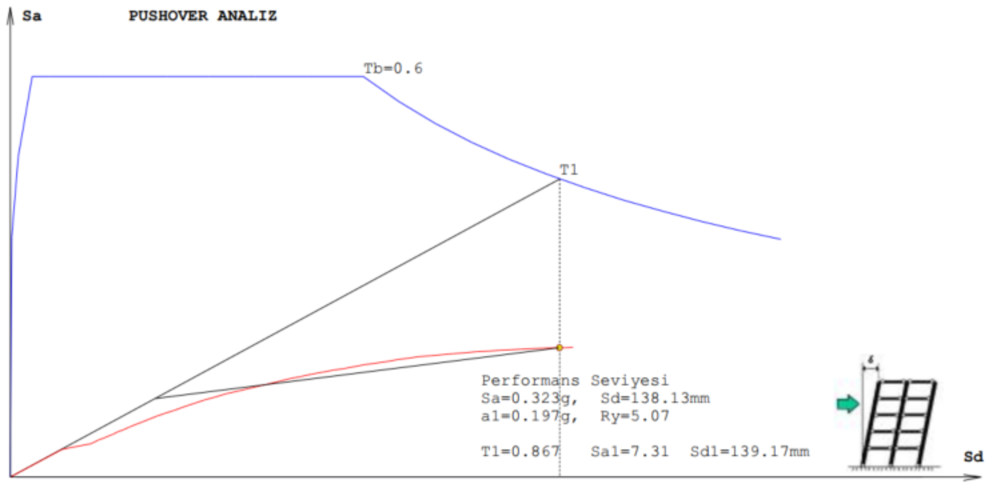
Ta< T < Tb Sa=2.5

T > Tb $Sa=2.5\ (Tb\ /\ T)^{0.8}$

Ra(T)x= 4.000 Ra(T)y= 4.000 T<Ta => Ra(T) = 1.5 + (R - 1.5) * T / Ta



X yonu NONLINEER ITERASYONU (t,m)



Y yonu NONLINEER ITERASYONU (t,m)

MODAL ANALYSIS - STRUCTURAL PERIODS and VECTORS

Mod	1.mod	2.mod	3.mod	4.mod	5.mod	6.mod	7.mod	8.mod	9.mod
w	4.72	6.24	7.00	16.65	25.04	30.04	36.94	59.00	69.36
T	1.3324	1.0073	0.8979	0.3773	0.2509	0.2092	0.1701	0.1065	0.0906
yön	x	y	b	x	b	y	x	x	b
1/1x	0.00051	0.00004	-0.00024	0.00213	-0.00217	0.00050	0.00435	0.00917	0.00692
2/2x	0.00691	0.00041	-0.00280	0.02373	-0.01871	0.00394	0.03671	0.05341	0.03966
3/3x	0.01803	0.00038	-0.00292	0.05566	-0.02259	0.00470	0.06690	0.04122	0.04223
4/4x	0.03189	0.00039	-0.00395	0.07292	-0.02297	0.00367	0.03625	-0.00673	-0.04204
5/5x	0.04898	0.00031	-0.00354	0.06531	-0.01572	0.00004	-0.03647	-0.03495	-0.05886
6/6x	0.06661	0.00035	-0.00303	0.03008	-0.00469	-0.00239	-0.07370	-0.01874	0.03883
7/7x	0.08313	0.00049	-0.00312	-0.02291	0.00834	-0.00189	-0.02980	0.00585	0.06701
8/8x	0.09790	0.00071	-0.00398	-0.07956	0.02233	0.00026	0.06635	0.01399	-0.05232
1/1y	0.00000	0.00096	0.00022	0.00014	0.00106	0.00582	-0.00006	-0.00114	0.00231
2/2y	0.00002	0.00699	0.00203	0.00130	0.00765	0.03081	0.00079	-0.00681	0.01113
3/3y	0.00004	0.01759	0.00484	0.00270	0.01463	0.05974	0.00051	-0.00758	0.01177
4/4y	0.00011	0.03069	0.00822	0.00375	0.01858	0.07384	-0.00153	-0.00165	-0.00023
5/5y	-0.00001	0.04749	0.00559	0.00016	0.00667	0.06585	-0.00495	0.00684	-0.00674
6/6y	-0.00003	0.06471	0.00777	-0.00008	0.00231	0.03081	-0.00305	0.00678	-0.00844
7/7y	-0.00006	0.08223	0.00999	-0.00037	-0.00376	-0.02174	0.00029	0.00190	-0.00260
8/8y	0.00001	0.09926	0.01401	-0.00108	-0.01182	-0.08053	0.00463	-0.00671	0.00765
1/1b	-0.00001	-0.00001	0.00003	0.00000	0.00017	-0.00005	0.00005	-0.00042	0.00025
2/2b	-0.00001	-0.00009	0.00069	0.00065	0.00253	-0.00041	0.00170	-0.00373	0.00366
3/3b	0.00000	-0.00028	0.00194	0.00179	0.00583	-0.00103	0.00369	-0.00609	0.00544
4/4b	0.00007	-0.00053	0.00350	0.00265	0.00790	-0.00146	0.00283	-0.00380	-0.00013
5/5b	0.00024	-0.00080	0.00545	0.00258	0.00719	-0.00159	-0.00109	0.00347	-0.00484
6/6b	0.00042	-0.00105	0.00744	0.00135	0.00341	-0.00104	-0.00361	0.00830	-0.00123
7/7b	0.00054	-0.00127	0.00928	-0.00058	-0.00239	0.00018	-0.00187	0.00409	0.00233
8/8b	0.00058	-0.00146	0.01091	-0.00256	-0.00874	0.00166	0.00273	-0.00710	-0.00023
Mxr%	60.083	0.005	0.287	14.658	2.100	0.053	3.759	2.543	1.111
Myr%	0.000	58.670	1.389	0.029	0.853	18.104	0.007	0.050	0.149
Mbr%	0.124	1.183	60.092	1.752	13.238	0.678	1.381	2.288	1.417

Mod	10.mod	11.mod	12.mod	13.mod	14.mod	15.mod	16.mod	17.mod	18.mod	
w	76.49	99.59	112.20	135.17	139.32	157.62	175.81	194.31	206.01	
T	0.0821	0.0631	0.0560	0.0465	0.0451	0.0399	0.0357	0.0323	0.0305	
yön	y	x	b	y	x	x	x	y	x	
1/1x	0.00015	0.02409	-0.00358	0.00759	0.04175	0.02759	0.04325	-0.01400	0.11080	
2/2x	0.00002	0.08425	-0.00717	0.01365	0.07096	0.02578	0.01585	0.00327	-0.06654	
3/3x	-0.00367	0.00271	0.01302	-0.01211	-0.05664	-0.03799	-0.03873	0.00277	0.03504	
4/4x	0.00396	-0.06628	-0.03067	0.00618	0.00239	0.04216	0.05260	-0.00487	-0.01848	
5/5x	0.00591	0.02644	0.03870	0.00474	0.05710	-0.05418	-0.03833	0.00022	0.00802	
6/6x	-0.00502	0.03977	0.02253	-0.01811	-0.05315	0.06724	-0.00529	0.00732	0.00003	
7/7x	-0.00815	-0.03455	-0.07045	0.01989	0.01798	-0.05526	0.02490	-0.00821	-0.00244	
8/8x	0.00685	0.00829	0.03581	-0.00792	-0.00114	0.01970	-0.01160	0.00313	0.00108	
1/1y	0.01603	-0.00085	0.00548	0.03435	-0.00578	0.00179	0.00411	0.06005	0.00560	
2/2y	0.05930	-0.00331	0.01873	0.07824	-0.01161	0.00190	0.00870	0.06224	0.00362	
3/3y	0.07251	-0.00130	0.00634	0.02640	-0.00458	0.00330	-0.00981	-0.04674	-0.00140	
4/4y	0.02677	0.00346	-0.01903	-0.06140	0.00895	-0.00045	-0.00469	-0.02998	-0.00407	
5/5y	-0.04540	0.00005	-0.00217	-0.04653	0.00731	-0.01082	0.01971	0.06881	0.00512	
6/6y	-0.07471	-0.00155	0.01003	0.04638	-0.00651	0.00390	-0.00191	0.01044	0.00181	
7/7y	-0.02782	-0.00123	0.00792	0.05754	-0.00861	0.00991	-0.01771	-0.06802	-0.00568	
8/8y	0.06632	0.00140	-0.00847	-0.04708	0.00679	-0.00656	0.01013	0.03431	0.00267	
1/1b	-0.00012	-0.00042	0.00093	-0.00011	0.00007	-0.00077	0.00162	-0.00004	-0.00080	
2/2b	-0.00093	-0.00176	0.00717	-0.00037	0.00201	-0.00358	0.00808	-0.00054	-0.00353	
3/3b	-0.00187	-0.00142	0.00568	-0.00114	0.00197	-0.00039	0.00073	-0.00089	0.00036	
4/4b	-0.00105	0.00155	-0.00657	0.00075	0.00064	0.00481	-0.00492	0.00210	0.00004	
5/5b	0.00043	0.00504	-0.00323	0.00165	-0.00304	-0.00722	0.00347	-0.00044	0.00055	
6/6b	0.00079	-0.00183	0.00500	-0.00126	-0.00272	0.00267	0.00440	-0.00138	-0.00120	
7/7b	0.00012	-0.00696	0.00171	-0.00004	0.00688	0.00131	-0.00709	0.00170	0.00106	
8/8b	-0.00059	0.00432	-0.00205	0.00032	-0.00306	-0.00094	0.00272	-0.00067	-0.00035	
Mxr%	0.000	3.194	0.023	0.111	3.187	0.870	1.669	0.121	6.167	∑= 99.9
Myr%	6.297	0.005	0.177	4.530	0.120	0.010	0.020	4.369	0.035	∑= 94.8
Mbr%	0.570	0.039	1.875	0.003	0.324	0.192	1.575	0.002	0.366	

$Mr = \sum(mi \cdot \Phi xir^2 + mi \cdot \Phi yir^2 + m\theta i \cdot \Phi\theta ir^2)$

$Mxr = \sum[(\sum m \cdot \Phi)^2 / Mr] = \%99.94 > \%90.00$ mode number OK. ✓

$Myr = \sum[(\sum m \cdot \Phi)^2 / Mr] = \%94.82 > \%90.00$ mode number OK. ✓

SEISMIC ANALYSIS 1.PERIOD CHECK

N= 7.00 < 13

Story Seismic displacement

Story	9. combination		10. combination		11. combination		12. combination	
(dyf)	δx (m)	θz (rad)	δx (m)	θz (rad)	δy (m)	θz (rad)	δy (m)	θz (rad)
8	0.1034446	0.0003335	0.1034446	0.0003335	-0.075994	0.0001739	-0.075994	0.0001739
7	0.0873372	0.0003192	0.0873372	0.0003192	-0.062690	0.0001643	-0.062690	0.0001643
6	0.0697172	0.0002350	0.0697172	0.0002350	-0.049256	0.0001527	-0.049256	0.0001527
5	0.0513562	0.0001023	0.0513562	0.0001023	-0.036136	0.0001328	-0.036136	0.0001328
4	0.0336903	-0.000019	0.0336903	-0.000019	-0.023944	0.0000952	-0.023944	0.0000952
3	0.0192560	-0.000047	0.0192560	-0.000047	-0.013799	0.0000414	-0.013799	0.0000414
2	0.0074616	-0.000027	0.0074616	-0.000027	-0.005548	0.0000088	-0.005548	0.0000088
1	0.0006204	-0.000009	0.0006204	-0.000009	-0.000802	0.0000021	-0.000802	0.0000021

Seismic amplitude : x= 0.00464 y= 0.00341

IRREGULARITY CHECK UNDER SEISMIC ACTION

A1,B2 type irregularities

max(di/hi)=0.02 CATLAMIS KESITLI P-DELTA ANALIZ YAPILMISTIR. KAT DEPLASMANLARI, 0.4 ILE CARPILMISTIR.
1. sto X dtop = -.0002481 + .0000036 × (1.05 - 14.46=.0007405 (PB22)
1. sto X dbot = -.0002481 + .0000036 × (25.52 - 14.46)=.0005212 (PB26)
2. sto X dtop = -.0029846 + .000011 × (2.4 - 12.93) - .0007284 = .0070232 (SZ03)
2. sto X dbot = -.0029846 + .000011 × (25.1 - 12.93) - .000525 = .0066012 (SZ19)

X DIR. (+)

Story	ΔX dtop(m)	ΔX dbot(m)	ΔX ort	nbi	nki	R·Δx/h	θi	story type
8	0.0063758	0.0065062	0.0064410	1.01	0.00	0.00929	0.00827	Normal sto
7	0.0066927	0.0074570	0.0070748	1.05	1.10	0.01065	0.01128	Normal sto
6	0.0068019	0.0080065	0.0074042	1.08	1.05	0.01144	0.01415	Normal sto
5	0.0065625	0.0076706	0.0071166	1.08	0.96	0.01096	0.01559	Normal sto
4	0.0056625	0.0059130	0.0057877	1.02	0.84	0.00876	0.01478	Normal sto
3	0.0047950	0.0046156	0.0047053	1.02	0.78	0.00685	0.01280	Normal sto
2	0.0028093	0.0026405	0.0027249	1.03	0.58	0.00401	0.00819	Normal sto
1	0.0002962	0.0002085	0.0002523	1.17	0.00	0.00042	0.00000	Basement

X DIR. (-)

Story	ΔX dtop(m)	ΔX dbot(m)	ΔX ort	nbi	nki	R·Δx/h	θi	story type
8	0.0063758	0.0065062	0.0064410	1.01	0.00	0.00929	0.00827	Normal sto
7	0.0066927	0.0074570	0.0070748	1.05	1.10	0.01065	0.01128	Normal sto
6	0.0068019	0.0080065	0.0074042	1.08	1.05	0.01144	0.01415	Normal sto
5	0.0065625	0.0076706	0.0071166	1.08	0.96	0.01096	0.01559	Normal sto
4	0.0056625	0.0059130	0.0057877	1.02	0.84	0.00876	0.01478	Normal sto
3	0.0047950	0.0046156	0.0047053	1.02	0.78	0.00685	0.01280	Normal sto
2	0.0028093	0.0026405	0.0027249	1.03	0.58	0.00401	0.00819	Normal sto
1	0.0002962	0.0002085	0.0002523	1.17	0.00	0.00042	0.00000	Basement

Y DIR. (+)

Story	ΔY dlft(m)	ΔY drgt(m)	ΔY ort	nbi	nki	R·Δy/h	θi	story type
8	0.0053456	0.0052943	0.0053199	1.00	0.00	0.00764	0.00552	Normal sto
7	0.0054039	0.0053417	0.0053728	1.01	1.01	0.00772	0.00685	Normal sto
6	0.0053027	0.0051960	0.0052493	1.01	0.98	0.00758	0.00796	Normal sto
5	0.0049852	0.0047836	0.0048844	1.02	0.93	0.00712	0.00849	Normal sto
4	0.0042135	0.0038575	0.0040355	1.04	0.86	0.00624	0.00820	Normal sto
3	0.0033942	0.0031781	0.0032861	1.03	0.79	0.00485	0.00715	Normal sto
2	0.0019170	0.0018725	0.0018948	1.01	0.58	0.00274	0.00455	Normal sto
1	0.0003277	0.0003137	0.0003207	1.02	0.00	0.00047	0.00000	Basement

Y DIR. (-)

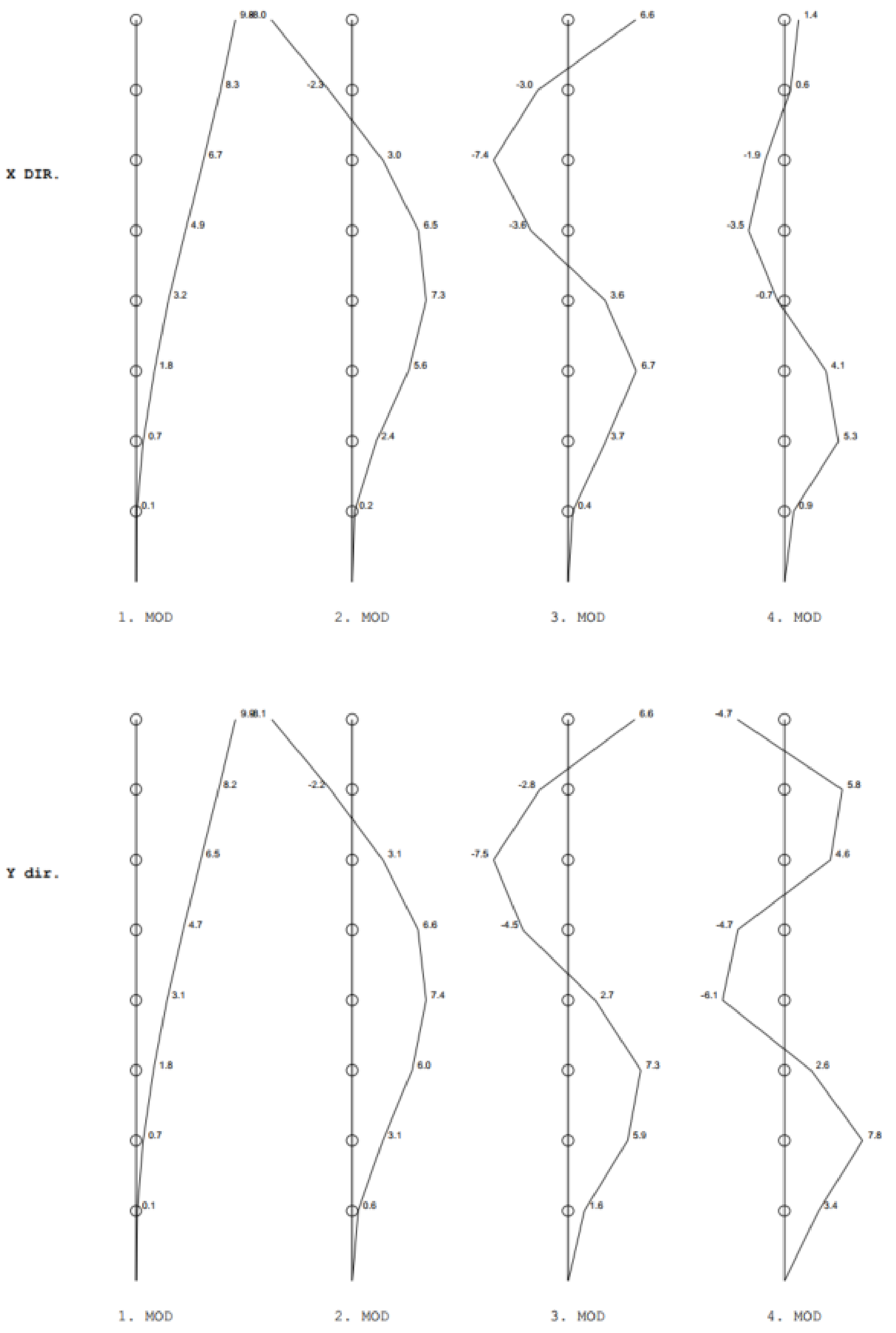
Story	ΔY dlft(m)	ΔY drgt(m)	ΔY ort	nbi	nki	R·Δy/h	θi	story type
8	0.0053456	0.0052943	0.0053199	1.00	0.00	0.00764	0.00552	Normal sto
7	0.0054039	0.0053417	0.0053728	1.01	1.01	0.00772	0.00685	Normal sto
6	0.0053027	0.0051960	0.0052493	1.01	0.98	0.00758	0.00796	Normal sto
5	0.0049852	0.0047836	0.0048844	1.02	0.93	0.00712	0.00849	Normal sto
4	0.0042135	0.0038575	0.0040355	1.04	0.86	0.00624	0.00820	Normal sto
3	0.0033942	0.0031781	0.0032861	1.03	0.79	0.00485	0.00715	Normal sto
2	0.0019170	0.0018725	0.0018948	1.01	0.58	0.00274	0.00455	Normal sto
1	0.0003277	0.0003137	0.0003207	1.02	0.00	0.00047	0.00000	Basement

B1-Vertical irregularity check

Story	Aw	Agx	Agy	Akx	Aky	∑ Aex	∑ Aey	ncix	nciy	EXPLANATION
8	9.24	1.13	3.13	0.28	10.81	10.41	13.99	1.00	1.00	top sto ✓
7	9.24	1.13	3.13	0.28	10.81	10.41	13.99	1.00	1.00	Regular ✓
6	9.24	1.13	3.13	0.28	10.81	10.41	13.99	1.00	1.00	Regular ✓
5	9.24	1.13	3.13	0.28	10.81	10.41	13.99	1.00	1.00	Regular ✓
4	10.89	1.13	3.13	0.33	10.73	12.07	15.63	1.16	1.12	Regular ✓
3	11.05	1.13	3.13	0.33	10.19	12.23	15.71	1.01	1.00	Regular ✓
2	11.05	1.13	3.13	0.33	8.95	12.23	15.52	1.00	0.99	Regular ✓
1	11.05	8.60	12.28	0.00	0.00	19.65	23.33	1.61	1.50	bodrum kat

Ba=Bax+0.3×Bay, Ba=0.3×Bax+Bay :
Kirişlerde, Kolonlarda; (Ba=Bax+0.3×Bay, Ba=0.3×Bax+Bay) düzeltmesi yapılmıştır.

MODAL ANALYSIS MODE SHAPE (1000 x Dis. vector)



SEISMIC TURN OVER CHECK

Story seismic moment (tm)

Story	H (m)	Fx	Fx . H	H (m)	Fy	Fy . H
8	22.30	107.54	2398.20	22.30	133.01	2966.17
7	19.50	70.13	1367.53	19.50	89.20	1739.49
6	16.70	46.86	782.55	16.70	60.80	1015.29
5	13.90	37.82	525.74	13.90	47.85	665.16
4	11.10	40.15	445.63	11.10	49.41	548.42
3	8.40	36.77	308.88	8.40	43.76	367.60
2	5.60	16.11	90.22	5.60	20.49	114.76
1	2.80	120.15	336.41	2.80	120.15	336.41
		475.53	6255.16		564.67	7753.30

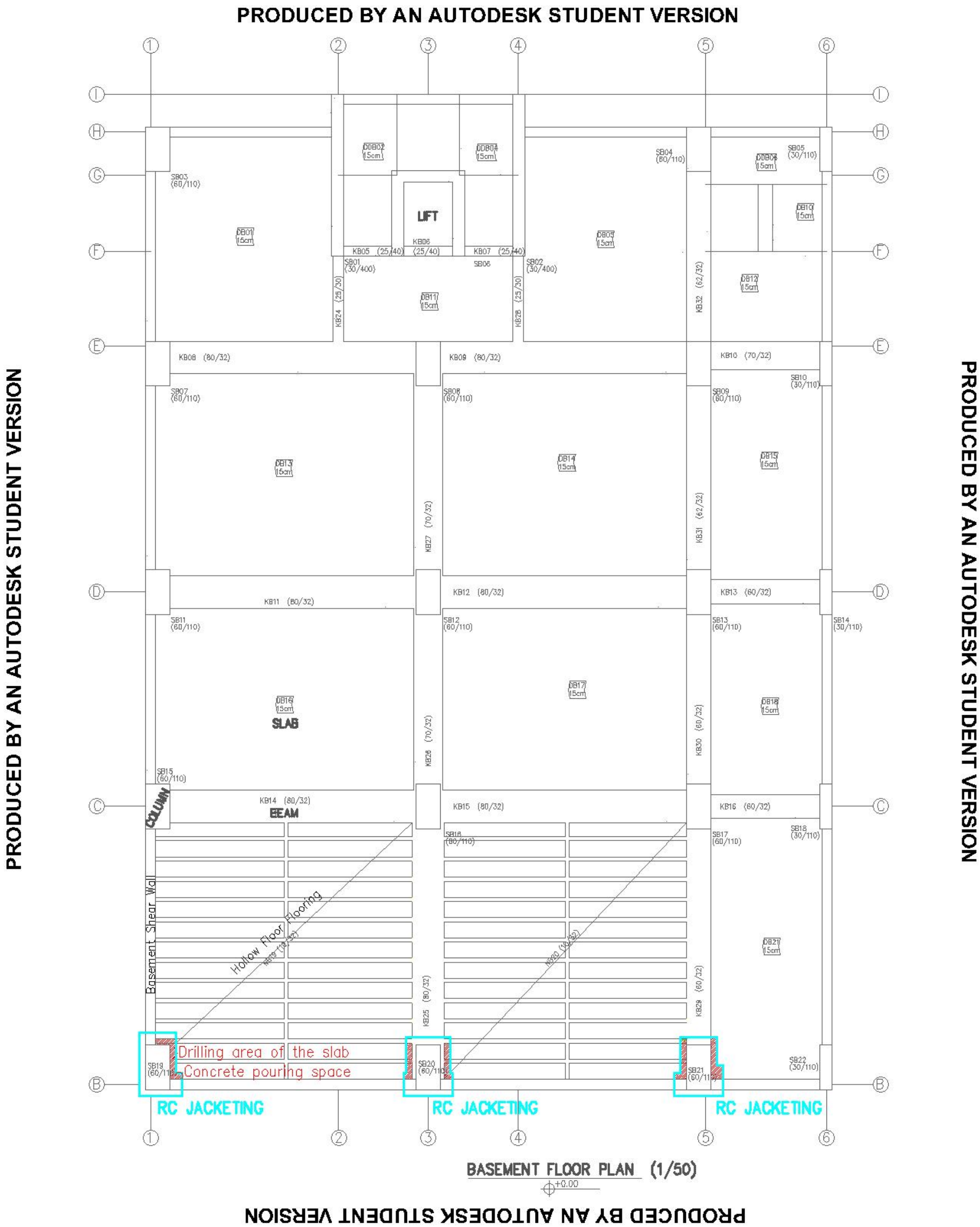
Story vertical load moment (tm) **X=0.0m** **Y=0.5m** **moment noktasi**

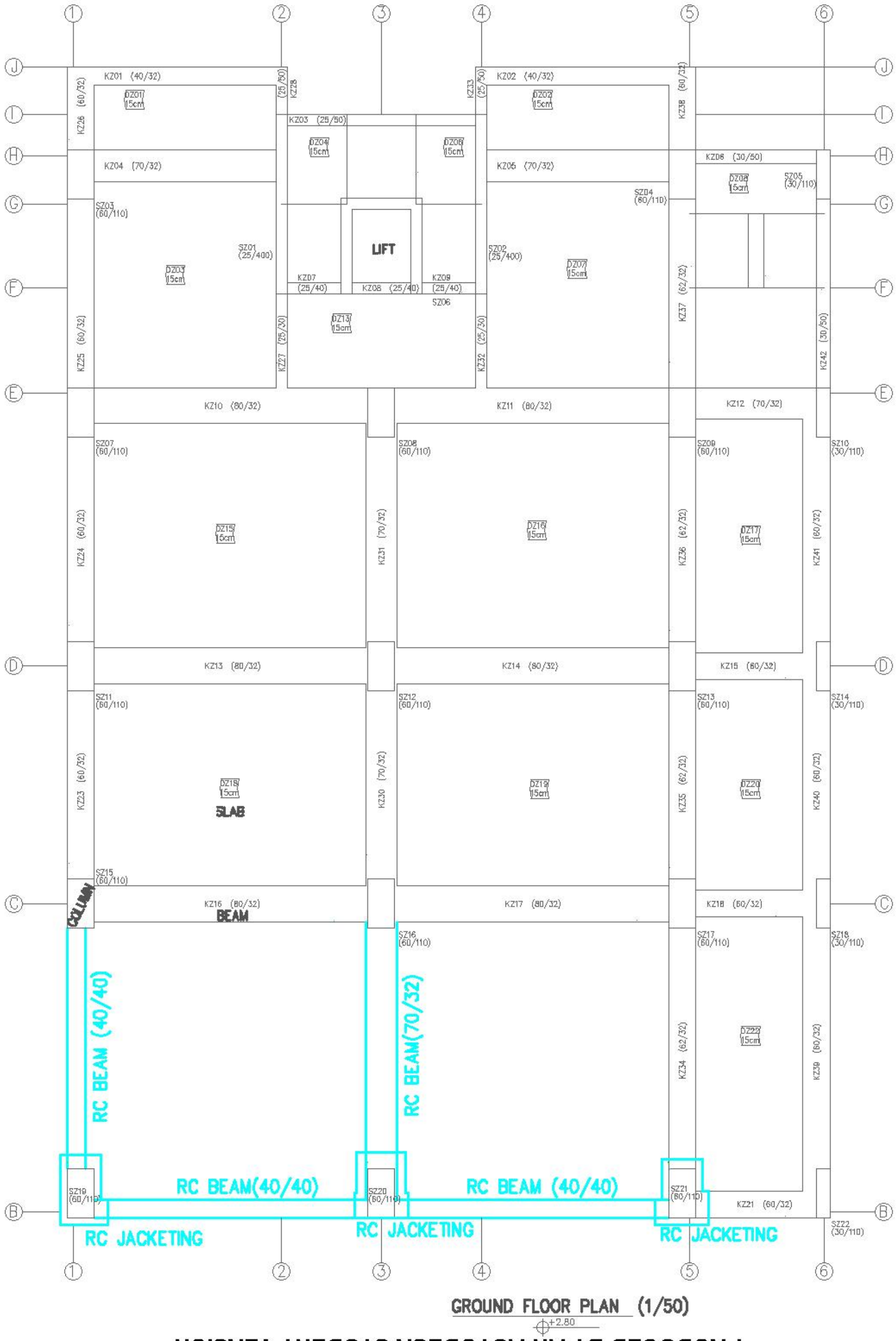
Kat	Wg+0.3·Wq	Xg-X	(Xg-X)·(Wg+0.3·Wq)	Yg-Y	(Yg-Y)·(Wg+0.3·Wq)
8	386.72	7.708	2980.88	13.099	5065.76
7	406.71	7.544	3068.33	13.056	5309.97
6	408.14	7.550	3081.36	13.026	5316.59
5	408.14	7.550	3081.36	13.026	5316.59
4	476.30	8.854	4216.93	13.046	6213.90
3	498.85	8.909	4444.40	13.135	6552.25
2	405.43	9.087	3684.09	11.106	4502.53
1	563.19	8.926	5027.03	13.076	7364.19
	980.09	9.267	9082.04	12.839	12583.78
			38666.41		58225.56

X yönü devrilme kontrolu=38666.413/6255.164=6.182 > 1.5 ✓
Y yönü devrilme kontrolu=58225.559/7753.297=7.51 > 1.5 ✓

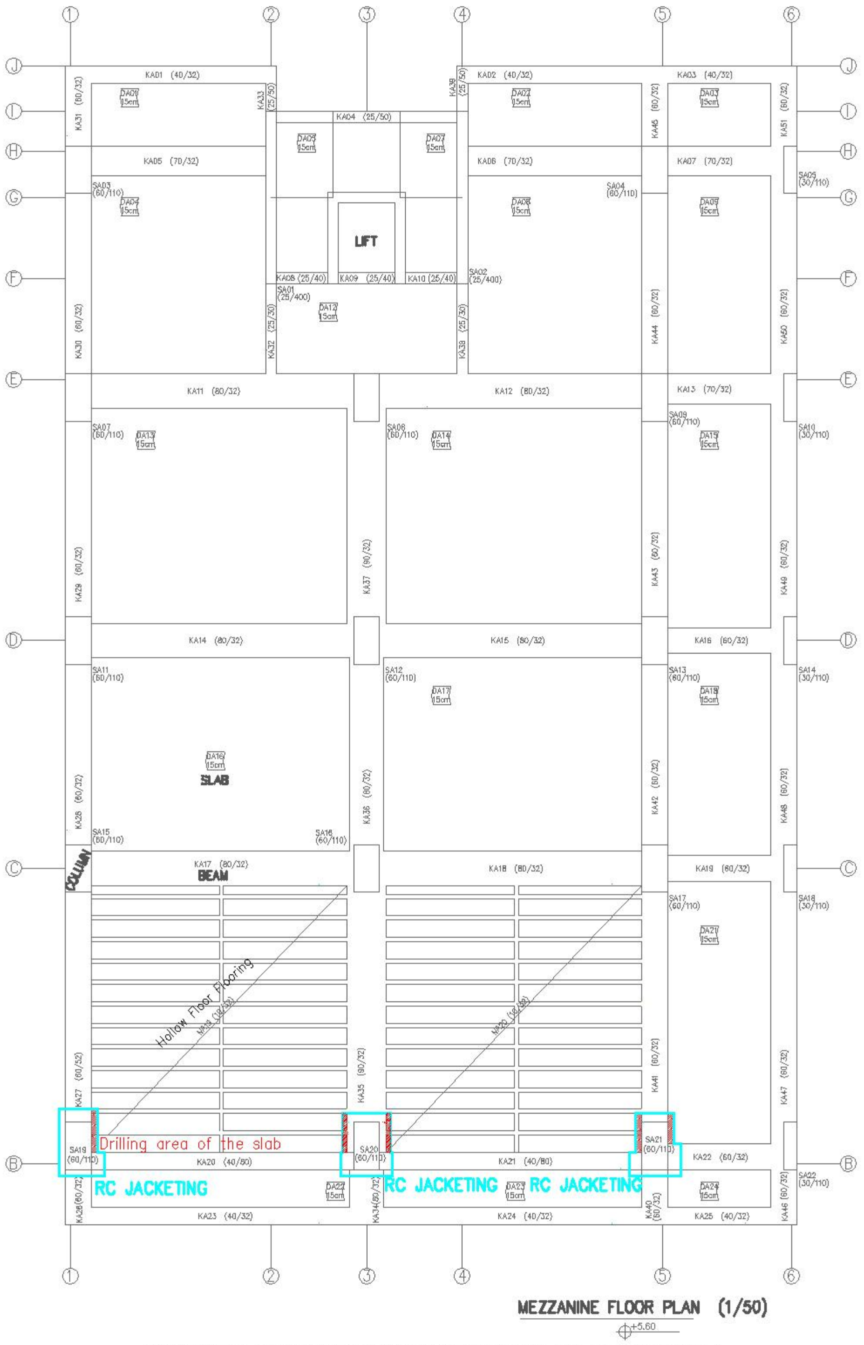
Appendix C: Retrofit plan of the RC scenario

The floor plans show the RC jacketing and beam addition on the basement, ground, and mezzanine floors.



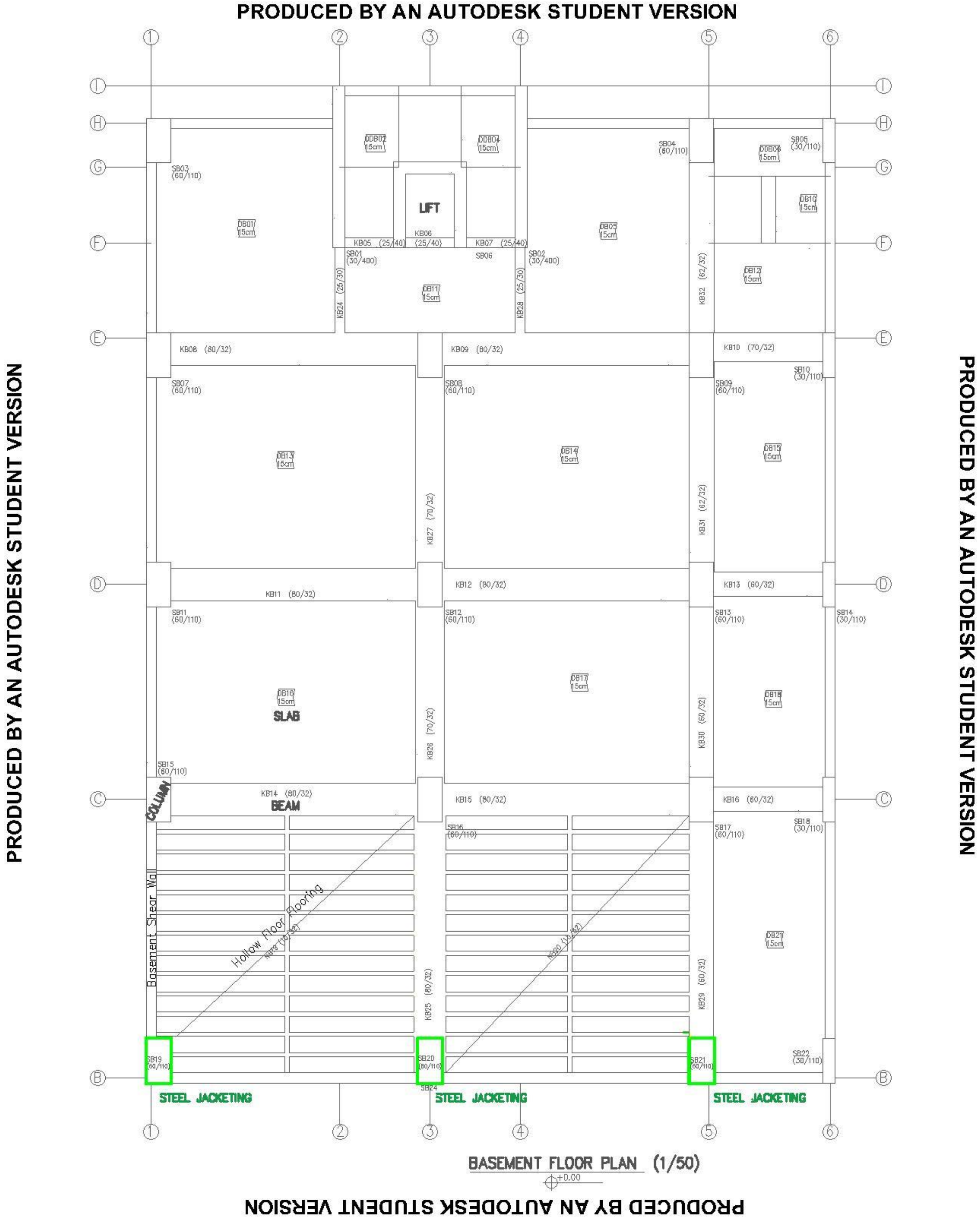


GROUND FLOOR PLAN (1/50)

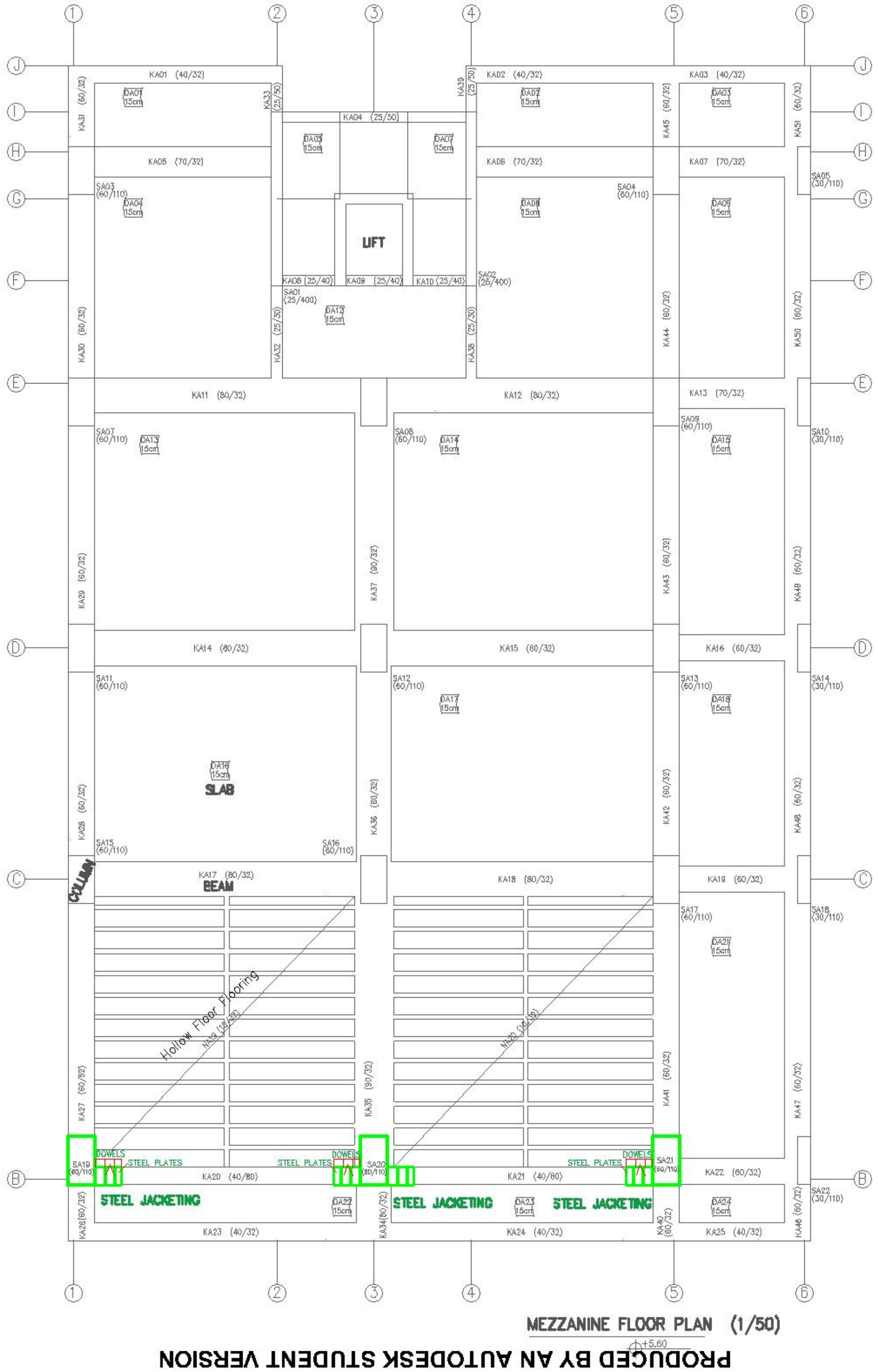

LIFT
SLAB
BEAM
COLUMN
Hollow Floor Flooring
Drilling area of the slab
RC JACKETING
RC JACKETING
RC JACKETING
MEZZANINE FLOOR PLAN (1/50)
+5.60

Appendix D: Retrofit plan of the Steel scenario

The floor plans show the steel jacketing and beam addition on the basement, ground, and mezzanine floors.




LIFT
SLAB
BEAM
COLUMN
STEEL JACKETING (H=60 CM)
STEEL JACKETING (H=60 CM)
STEEL BEAM 20 X 30 CM
STEEL BEAM 20 X 30 CM
STEEL BEAM 20 X 30 CM
STEEL BEAM 20 X 30 CM
STEEL JACKETING
STEEL JACKETING
STEEL JACKETING
GROUND FLOOR PLAN (1/50)


LIFT
SLAB
BEAM
COLUMN
Hollow Floor Flooring
DOWELS
STEEL PLATES
STEEL JACKETING
MEZZANINE FLOOR PLAN (1/50)
+5.60

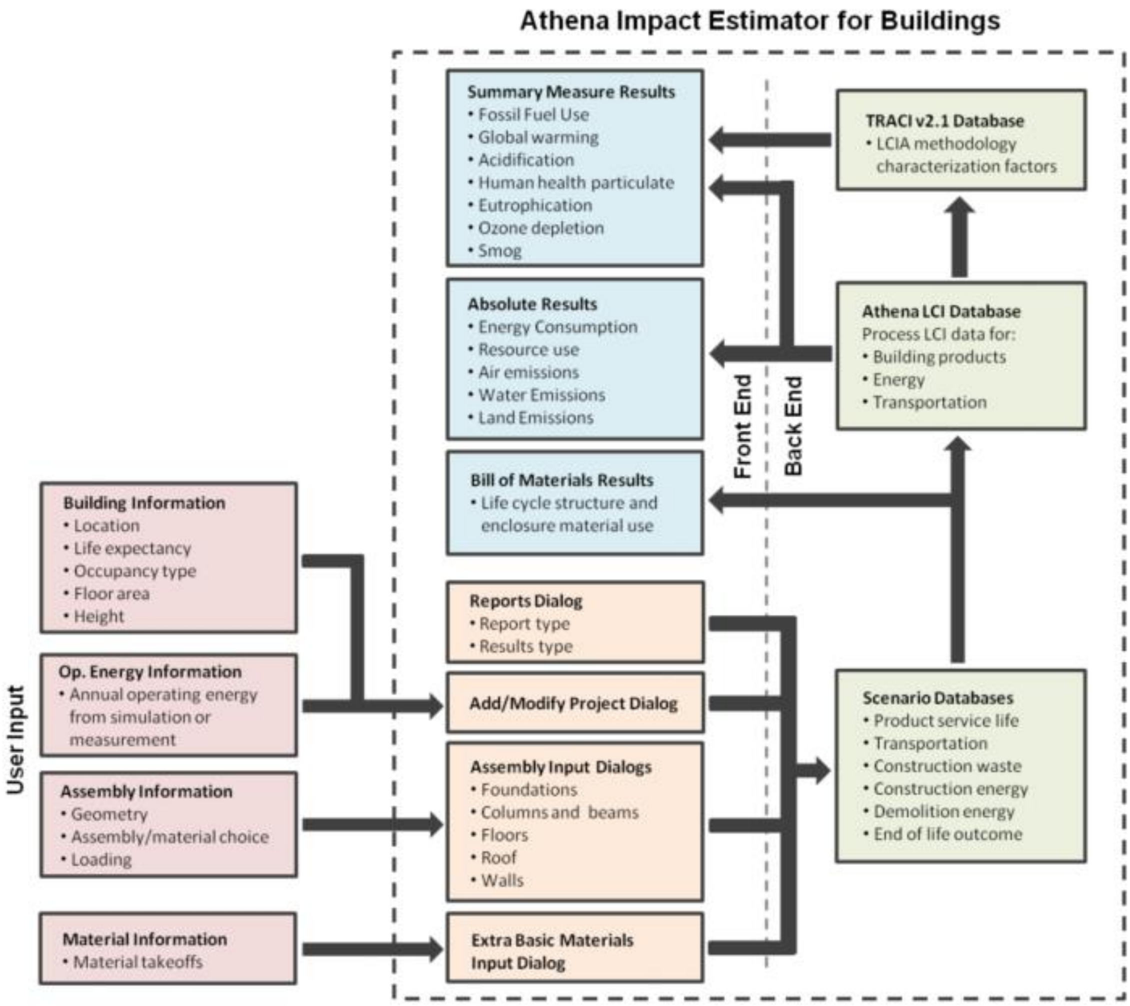
Appendix E: The system boundary of the software program

The table presents Athena Impact Estimator for Buildings (AIEB) software program's system boundary capacity. Source: User Manual and Transparency Document May 2019

Information Module	Supports?	Processes Included
A1 Raw material supply	Y	Primary resource harvesting and mining
A2 Transport	Y	All transportation of materials up to manufacturing plant gate
A3 Manufacturing	Y	Manufacture of raw materials into products
A4 Transport	Y	Transportation of materials from manufacturing plant to site.
A5 Construction-installation process	Y	Construction equipment energy use, and A1-A4, C1, C2, C4 effects of construction waste
B1 Installed product in use	N	n/a (currently insufficient consensus in methodology and data for this module to be addressed)
B2 Maintenance	Partial	Painted surfaces are maintained (i.e. repainted), but no annual maintenance aspects are included
B3 Repair	N	n/a (not currently well-supported with data)
B4 Replacement	Y	A1-A5 effects of replacement materials, and C1, C2, C4 effects of replaced materials
B5 Refurbishment	N	n/a (this module applies to known future refurbishment and needs to be addressed on a case-by-case basis if applicable)
B6 Operational energy use	Y	Energy primary extraction, production, delivery, and use
B7 Operational water use	N	n/a
C1 De-construction demolition	Y	Demolition equipment energy use
C2 Transport	Y	Transportation of materials from site to landfill
C3 Waste Processing	N	Most material data does not include waste processing effects, however, the newer metals "avoided burden" methodology data does include waste processing effects, but it is not separated into its own C3 module (see Metal Recycling on page 28)
C4 Disposal	Y	Disposal facility equipment energy use and landfill site effects
D Benefits and loads beyond the system boundary	Y	Carbon sequestration and metals recycling

Appendix F: The working plan of the software program

The diagram presents the AIEB software program's inputs, outputs, and processes. Source: User Manual and Transparency Document May 2019



Appendix G: A comparison of environmental impacts by different locations

The table presents a comparison of the environmental impacts of the RC scenario for different locations.

Location	**LCA Stage**	**Impact Category**	
		Global Warming Potential (Kg CO_2 eq)	**Total Primary Energy** (MJ)
Toronto	**Manufacturing**	1.25E+04	1.59E+05
	Transport	1.03E+02	1.51E+03
Vancouver	**Manufacturing**	1.25E+04	1.59E+05
	Transport	1.04E+02	1.51E+03
Toronto	**Construction**	1.03E+03	1.19E+04
	Transport	4.81E+02	6.97E+03
Vancouver	**Construction**	1.03E+03	1.19E+04
	Transport	4.56E+02	6.66E+03
Toronto	**Use**	3.46E+02	1.85E+04
	Transport	2.37E+01	3.44E+02
Vancouver	**Use**	3.46E+02	1.85E+04
	Transport	2.32E+01	3.37E+02
Toronto	**Demolition**	5.54E+02	8.20E+03
	Transport	2.17E+02	3.16E+03
Vancouver	**Demolition**	5.54E+02	8.20E+03
	Transport	2.17E+02	3.16E+03

Appendix H: BOM occurring in the RC and Steel scenarios

BOM was presented for the RC and Steel Scenarios from cradle-to-gate.

Material	**Unit**	**Total Quantity from the Construction and Use**		**Total Quality from the Site Preparation**	
		RC Scenario	**Steel Scenario**	**RC Scenario**	**Steel Scenario**
Concrete Benchmark CAN 25 MPa	m^3	23.6250	-	0.0777	-
Rebar, Rod, Light Sections	Tonnes	5.5247	-	-	-
Steel Plate	Tonnes	-	10.3692	-	-
Hollow Structural Steel	Tonnes	-	1.7584	-	-
Mortar	m^3	5.9800	2.4150	2.0240	2.0700
Softwood plywood	m^2	65.8560	-	-	-
Nails	Tonnes	0.0063	-	-	-
Screws Nuts and Bolts	Tonnes	-	0.0618	-	-
Roofing Asphalt	kg	-	13.5909	-	-
Water-Based Latex Paint	L	827.4240	560.8980	-	-

Appendix I: LCA measures

As output, the Impact Estimator produces a detailed life cycle inventory for an entered design. It also generates a set of summary impact indicators in graphical and tabular form based on US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (the US Environmental Protection Agency's TRACI - Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) life cycle impact indicator methodology (version 2.1). The software supports characterization measures based on mid-point impact estimation methods, including the following:

Acidification Potential (AP): Acidification is a more regional rather than global impact affecting human health when high concentrations of NO_x and SO_2 are attained. The AP of an air or water emission is calculated based on its SO_2 equivalence effect on a mass basis.

Aquatic Eutrophication Potential: Eutrophication is the fertilization of surface waters by nutrients that were previously scarce. When a previously scarce or limiting nutrient is added to a water body, it leads to the proliferation of aquatic photosynthetic plant life. This may lead to a chain of further consequences ranging from foul odours to the death of fish. The calculated result is expressed on an equivalent mass of nitrogen (N) basis.

Global Warming Potential (GWP): Global warming potential is a reference measure. The methodology and science behind the GWP calculation can be considered one of the most accepted LCIA categories. GWP will be expressed on an equivalency basis relative to CO_2 – in kg or tonnes CO_2 equivalent.

Carbon dioxide is the common reference standard for global warming or greenhouse gas effects. All other greenhouse gases are referred to as having a "CO_2 equivalence effect" which is simply a multiple of the greenhouse potential (heat-trapping capability) of carbon dioxide. This effect has a time horizon due to the atmospheric reactivity or stability of the various contributing gases over time.

As yet, no consensus has been reached among policymakers about the most appropriate time horizon for greenhouse gas calculations. The International Panel on Climate Change100-year time horizon figures have been used here as a basis for the equivalence index:

CO_2 Equivalent kg = CO_2 kg + (CH_4 kg x 28) + (N_2O kg x 265)

A recent IPCC report, "CLIMATE CHANGE 2013 The Physical Science Basis" provided an updated list of GWP equivalence factors, that have not as yet been updated (June 2014) in TRACI. However, the Impact Estimator includes updated values for nine of the most common GWP contributors (Methane, Nitrous Oxide (N_2O), CFC-11, CFC-12, HCFC-22, HCFC-141b, HCFC-142b, HFC-134a and Sulphur Hexafluoride). When the EPA publishes an updated list of TRACI characterization factors, the Impact Estimator will be updated with all the new factors.

While greenhouse gas emissions are largely a function of energy combustion, some products also emit greenhouse gases during the processing of raw materials. Process emissions often go unaccounted for due to the complexity associated with modelling manufacturing process stages. One example where process CO_2 emissions are significant is in the production of cement (calcination of limestone). Because the Impact Estimator uses data developed by a detailed lifecycle modelling approach, all relevant process emissions of greenhouse gases are included in the resultant global warming potential index.

Human Health (HH) Criteria Air Mobile: Particulate matter of various sizes (PM_{10} and $PM_{2.5}$) have a considerable impact on human health. The EPA has identified "particulates" (from diesel fuel combustion) as the number one cause of human health deterioration due to its impact on the human respiratory system – asthma, bronchitis, acute pulmonary disease, etc. It should be mentioned that particulates are an important environmental output of plywood product production and need to be traced and addressed. The Institute used TRACI's "Human Health Particulates from Mobile Sources" characterization factor, on an equivalent $PM_{2.5}$ basis, in our final set of impact indicators.

Ozone Depletion Potential (ODP): Stratospheric ozone depletion potential accounts for impacts related to the reduction of the protective ozone layer within the stratosphere caused by emissions of ozone-depleting substances (CFCs, HFCs, and halons). The ozone depletion potential of each of the contributing substances is characterized relative to CFC-11, with the final impact indicator indicating mass (e.g., kg) of equivalent CFC-11.

Photochemical Ozone Formation Potential (Smog): Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level where, in the presence of sunlight, they produce photochemical smog, a symptom of photochemical ozone creation potential (POCP). While ozone is not emitted directly, it is a product of interactions of volatile organic compounds (VOCs) and nitrogen oxides (NOx). The "smog" indicator is expressed on a mass of equivalent O_3 basis.

Total Primary Energy: Total Primary Energy Consumption is reported in mega-joules (MJ) at the bottom of the Energy Consumption absolute value table as well as the Detailed and Condensed Summary Measure tables. Embodied primary energy includes all energy, direct and indirect, used to transform or transport raw materials into products and buildings, including inherent energy contained in raw or feedstock materials that are also used as common energy sources. (For example, natural gas used as a raw material in the production of various plastic (polymer) resins.) In addition, the Impact Estimator captures the indirect energy use associated with processing, transporting, converting and delivering fuel and energy. If the user inputs Operating Energy Consumption, it will also be included in Total Primary Energy.

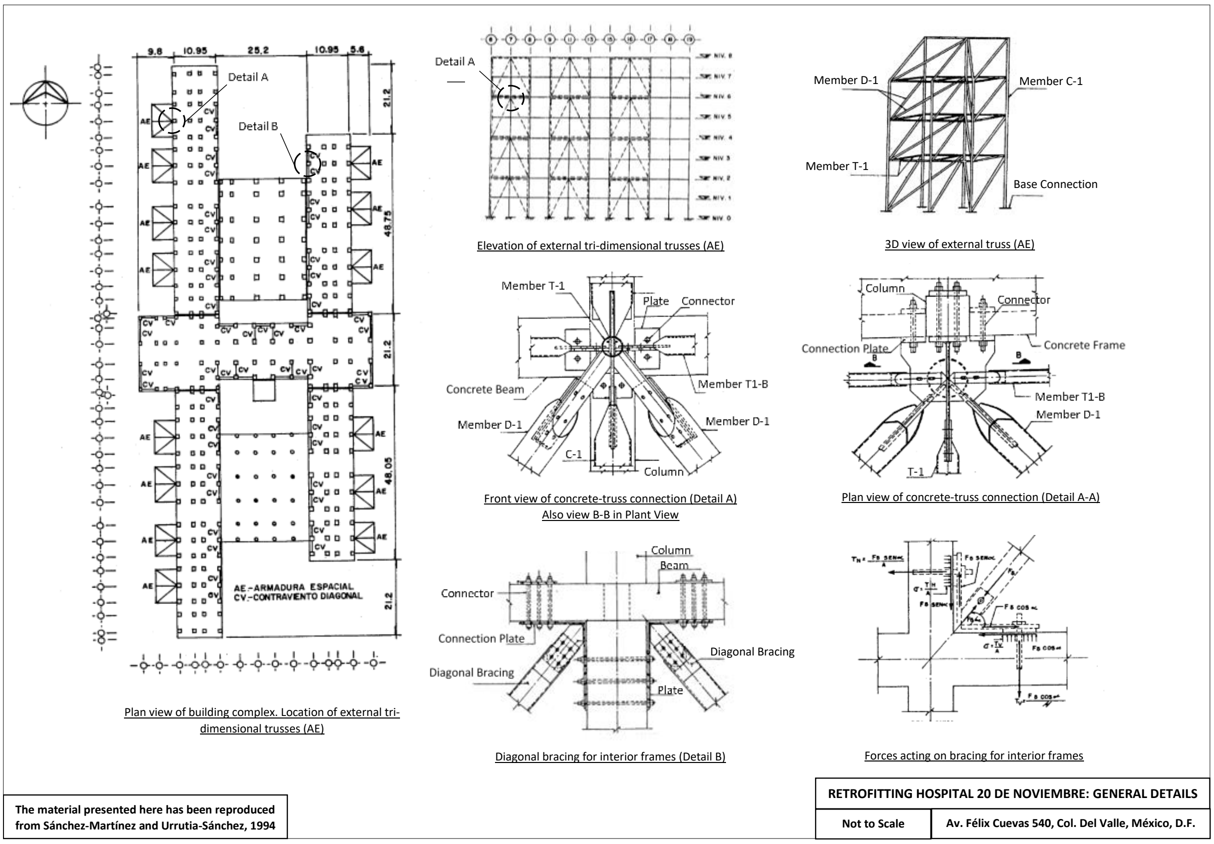
Non-Renewable Energy: Non-Renewable Energy is a subtotal of Total Primary Energy, by energy type, that includes all fossil fuel energies and nuclear energy.

Fossil Fuel Consumption: Fossil Fuel Consumption is a subtotal of Total Primary Energy, by energy type, that includes all fossil fuel energies.

https://calculatelca.com/software/impact-estimator/help-files/

Appendix J: Retrofitting details of the first scenario

This appendix presents the details of the 3D trusses and diagonal bracing retrofits.



Appendix K: Life cycle inventory of the first scenario

This appendix presents the collected data from the first scenario for 3D trusses and internal diagonal bracings.

Collected data from each foundation of 3D trusses for LCA calculations

Work	Characteristics	Unit	Amount
Drilling of soil for wells of the one 3D truss	Drilling mechanism with helical type excavates 20 cm per minute and has 40 kW motor power. The excavation of each well is 2 hours.	h	12 hours
Steel reinforcement of each pile	Steel density is 7850 kg/m^3.	kg	785 kg
Casting concrete mixture of piles for one truss	Concrete is f'c=250 kg/cm3.	m^3	53.4 m^3
Cleaning the upper part of the piles	The breaker was used for cleaning the concrete to prepare for foundation assembly. The concrete density for disposal is 2400 kg/m^3.	kg	1.35 m^3
Steel reinforcement of perimeters beam and concrete base footing	Base footing and beams were assembled. Steel density is 7850 kg/m^3.	kg	2,115 kg
Casting concrete of one truss' foundation	Concrete is f'c=250 kg/cm^3.	m3	26.7 m^3
Grout for one foundation of the truss	The surface of the concrete was uniformised by applying a grout layer. Size is 60x60, and the thickness is 5 cm.	m^3	0.108 m^3
Assembly of anchors for one foundation	Each base footing has eight anchors, and each anchor reaches a depth of 1.75 m. Diameter is 1 ½= 38.1 mm, and weight is 8.94 kg/m.	kg	751 kg

Work	Characteristics	Unit	Amount
Steel base plate for one foundation	Base plates are A-36 type, and steel density is 7850 kg/m^3. Dimension of each plate is 50x50 and the thickness is 3.8 cm.	kg	448 kg

The construction works during assembly of the retrofit

Work	Characteristics	Unit	Amount
Drilling of holes	The holes in the plates were made with magnetic drills for the bolts. In total, 47830 holes exist. Each drilling takes less than 5 min. The magnetic drill is 120-volt 375 RPM 1500 watt.	h	3588 h
Welding	Plates were fixed by welding depend on the connection type. The fillet of the weld is varying in each beam, column, and tubes. This welding chose as long weld (>250mm) and 8mm continuous fillet with 0.5 h/m for the structural purpose from (Watson *et al.*, 1996). A total of 1802.5 m welding made. The welding machine has 230 V and 2200 watts.	h	901 h
Drilling for anchors	Concrete beam and columns were drilled for anchors. Each drilling took approximately 10 minutes. A total of 8118 holes were drilled. The magnetic drill device has 120-volt, 6.25 amp and 750 watts.	h	1353 h
Concrete waste from drilling	9.67 m^3 concrete was wasted from drilling for anchors. Concrete density is 2400 kg/m^3.	kg	23208 kg
Air compressor for blasting, prime and painting of reinforcement	Air compressor was used for the cleaning of the tubes (blasting), prime and paint. Silica sand used for blasting, which can clean 0.73 m^2 surface of a metal in 2.5 min (Hansink, 1998). Prime and paint can be done in 0.8 min and 1.25 min for 1 m^2, respectively. The air compressor machine has 2200 watt and 10 Bar.	h	866 h
Silica sand	Sand size is 0.1-2 mm, and 50 kg of sand consumes in 2.5 min for the cleaning of metal surfaces (Hansink, 1998). Blasting was applied to 7755 m^2 surface area.	kg	531182 kg

Work	Characteristics	Unit	Amount
Prime of Reinforcement	Prime is applied to one layer, and its application is 0.126 kg/m^2. The reinforcement surface area for paint prime is 7755 m^2.	m^2	7755 m^2
Paint of Reinforcement	Paint is applied two layers over the metal surfaces. Two layers of paint are 0.252 kg/m^2, and the total area of the paint surface is 7755m^2.	kg	1954 kg
Epoxy	Epoxy was applied for the connection of anchors to concrete holes, which fills 5mm gap between anchors and concrete. Application of volume of 0.025 m^3 corresponds to the use of 6 kg of epoxy. In total, 3.5 m^3 epoxy was applied.	kg	842 kg

Characteristics of the metal elements used in the reinforcement of the building

Metal Element	**Characteristics**			
Steel Tubes	The 3D truss and diagonal bracings have different thickness and heights according to the placement. All diagonals have different heights, decreasing diameter and various thickness towards to upper floors. Steel tube A500 was selected from “Aceromex Product Catalog” (Aceromex, 2018) (“=inch)			
One 3D Truss in East Façade x 6 pieces	**Height**	**Diameter**	**Thickness**	**Weight**
T1-A x 6 pieces	4.7 m	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T1 x 9 pieces	5 m	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T1-B x 8 pieces	4.7 m	4.5”=114 mm	0.24”=6.02 mm	20.35 kg/m
C1 x 12 pieces	7.2 m	12”=324 mm	0.33”=8.38 mm	65.21 kg/m
C1-A x 9 pieces	7.1 m	12”=324 mm	0.33”=8.38 mm	65.21 kg/m
D1 x 20 pieces	9 m (avg)	10”=273 mm	0.307”=7.80 mm	51.01 kg/m
One 3D Truss in West Façade x 8 pieces	**Height**	**Diameter**	**Thickness**	**Weight**

T1-A x 6 pieces	4.7 m	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T1 x 9 pieces	5 m	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T1-B x 8 pieces	4.7 m	4.5”=114 mm	0.24”=6.02 mm	20.35 kg/m
C1 x 12 pieces	7.1 m	12”=324 mm	0.33”=8.38 mm	65.21 kg/m
C1-A x 9 pieces	7.3 m	12”=324 mm	0.33”=8.38 mm	65.21 kg/m
D1 x 20 pieces	9.2 m (avg)	10”= 273 mm	0.307”=7.80 mm	51.01 kg/m
Diagonals in Section 1	**Height**	**Diameter**	**Thickness**	**Weight**
T3 x 4 pieces	8 m x 2 7.7 m x 4	10”= 273 mm	0.307”=7.80 mm	51.01 kg/m
	7.7 m 8 m x 2	8”=203 mm	0.354”=9 mm	45 kg/m
T4x 4 pieces	5.8 m x 2 5.3 m	10”= 273 mm	0.307”=7.80 mm	51.01 kg/m
	5.3 m x 3	8”=203 mm	0.354”=9 mm	45 kg/m
	5.3 m 5.7 m x 2	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T5 x 4 pieces	5.8 m x 2 5.3 m	10”= 273 mm	0.307”=7.80 mm	51.01 kg/m
	5.3 m x 3 5.3 m	8”=203 mm	0.354”=9 mm	45 kg/m
	5.7 m x 2	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T6 x 2 pieces	5.8 m x 2 5.3 m x 4	8”=203 mm	0.354”=9 mm	45 kg/m
	5.3 m 5.7 m x 2	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T7 x 2 pieces	5.8 m x 2 5.3 m x 4	8”=203 mm	0.354”=9 mm	45 kg/m
	5.3 m 5.7 m x 2	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T8 x 2 pieces	4.66 m x 2 4 m x 4	8”=203 mm	0.354”=9 mm	45 kg/m
	4 m 4.5 m x 2	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T9 x 2 pieces	5 m x 2 4.6 m x 4	8”=203 mm	0.354”=9 mm	45 kg/m
	4.6 m 5 m x 2	6”=168 mm	0.28”=7.11 mm	28.26 kg/m

T10 x 4 pieces	6.48 m x 2	8”=203 mm	0.354”=9 mm	45 kg/m
	6 m x 4			
	6 m	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
	6.39 m x 2			
T11 South	6.88 m x 2	8”=203 mm	0.354”=9 mm	45 kg/m
	6.5 m x 4			
	6.5 m	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
	6.79 m x 2			
T11 North	6.88 m x 2	8”=203 mm	0.354”=9 mm	45 kg/m
	6.5 m x 5			
	6.79 m x 2			
T12 x 3 pieces	6.48 m x 2	8”=203 mm	0.354”=9 mm	45 kg/m
	6 m x 5			
	6.39 m x 2			
Diagonals in Section 2 and 3	**Height**	**Diameter**	**Thickness**	**Weight**
T2 x 32 pieces	5.8 m x 2	10”= 273 mm	0.307”=7.80 mm	51.01 kg/m
T2 x 32 pieces	5.3 m			
T2 x 32 pieces	5.3 m x 3	8”=203 mm	0.354”=9 mm	45 kg/m
T2 x 32 pieces	5.3 m	6”=168 mm	0.28”=7.11 mm	28.26 kg/m
T2 x 18 pieces	5.7 m			
Steel Plates	Plates had different sizes and thicknesses, A-36 steel plates were selected from “Aceromex Product Catalog” (Aceromex, 2018)			
Steel plates in one 3D truss x 14 Pieces	**Pieces**	**Dimensions**	**Thickness**	**Weight**
Connection Plates	37	20x30 cm	25.4 mm	7850 kg/m^3
	19	40x70 cm	38.1 mm	7850 kg/m^3
	3	80x20 cm	25.4 mm	7850 kg/m^3
	9	30x20 cm	25.4 mm	7850 kg/m^3
	8	20x40 cm	25.4 mm	7850 kg/m^3
	6	80x25 cm	25.4 mm	7850 kg/m^3
	5	60x45 cm	25.4 mm	7850 kg/m^3
	30	80x40 cm	25.4 mm	7850 kg/m^3
Inside plates	25	40x20 cm	25.4 mm	7850 kg/m^3
	20	80x20 cm	25.4 mm	7850 kg/m^3
	21	40x20 cm	25.4 mm	7850 kg/m^3
	24	40x60 cm	25.4 mm	7850 kg/m^3
	9	50x40 cm	25.4 mm	7850 kg/m^3

Steel plates in Section 1	Pieces	Dimensions	Thickness	Weight
P1 x 2 pieces	56	25x70 cm	15.88 mm	124.62 kg/m^2
	112	25x70 cm	19.05 mm	149.54 kg/m^2
	168	25x55 cm	19.05 mm	149.54 kg/m^2
	112	25x35 cm	19.05 mm	149.54 kg/m^2
	56	25x35 cm	12.70 mm	99.70 kg/m^2
P2 x 2 pieces	56	25x95 cm	34.93 mm	274.16 kg/m^2
	168	25x95 cm	44.45 mm	348.93 kg/m^2
	112	25x95 cm	38.10 mm	299.09 kg/m^2
	56	25x55 cm	44.45 mm	348.93 kg/m^2
	56	25x55 cm	38.10 mm	299.09 kg/m^2
	56	25x55 cm	25.40 mm	199.39 kg/m^2
P3	280	23x50 cm	9.53 mm	74.77 kg/m^2
	56	23x50 cm	12.70 mm	99.7 kg/m^2
	112	23x50 cm	6.35 mm	49.85 kg/m^2
	56	23x50 cm	3.18 mm	24.925 kg/m^2
P4	56	23x50 cm	12.70 mm	99.7 kg/m^2
	168	23x50 cm	22.23 mm	174.47 kg/m^2
	56	23x50 cm	19.05 mm	149.54 kg/m^2
	168	23x50 cm	15.88 mm	124.62 kg/m^2
	56	23x50 cm	6.35 mm	49.85 kg/m^2
P5 x 2 (for P6)	56	24.3x60 cm	28.58 mm	224.32 kg/m^2
	56	24.3x60 cm	47.63 mm	373.86 kg/m^2
	112	24.3x60 cm	44.45 mm	348.93 kg/m^2
	56	24.3x60 cm	38.10 mm	299.09 kg/m^2
	56	24.3x60 cm	31.75 mm	249.24 kg/m^2
	56	19.4x55 cm	44.45 mm	348.93 kg/m^2
	56	19.4x55 cm	31.75 mm	249.24 kg/m^2
	56	19.4x55 cm	15.88 mm	124.62 kg/m^2
Steel plates in section 2 and 3	**Pieces**	**Dimensions**	**Thickness**	**Weight**
P1 x 2 Pieces	64	25x70 cm	15.88 mm	124.62 kg/m^2
	128	25x70 cm	19.05 mm	149.54 kg/m^2
	192	25x55 cm	19.05 mm	149.54 kg/m^2
	100	25x35 cm	19.05 mm	149.54 kg/m^2
P2 x 2 Pieces	64	25x95 cm	34.93 mm	274.16 kg/m^2
	192	25x95 cm	44.45 mm	348.93 kg/m^2
	128	25x95 cm	38.10 mm	299.09 kg/m^2
	64	25x55 cm	44.45 mm	348.93 kg/m^2

	36	25x55 cm	38.10 mm	299.09 kg/m^2
P3	320	23x50 cm	9.53 mm	74.77 kg/m^2
	64	23x50 cm	12.70 mm	99.7 kg/m^2
	100	23x50 cm	6.35 mm	49.85 kg/m^2
P4	64	23x50 cm	12.70 mm	99.7 kg/m^2
	192	23x50 cm	22.23 mm	174.47 kg/m^2
	64	23x50 cm	19.05 mm	149.54 kg/m^2
	164	23x50 cm	15.88 mm	124.62 kg/m^2
P5 x 2 (for P6)	64	24.3x60 cm	28.58 mm	224.32 kg/m^2
	64	24.3x60 cm	47.63 mm	373.86 kg/m^2
	128	24.3x60 cm	44.45 mm	348.93 kg/m^2
	64	24.3x60 cm	38.10 mm	299.09 kg/m^2
	64	24.3x60 cm	31.75 mm	249.24 kg/m^2
	64	19.4x55 cm	44.45 mm	348.93 kg/m^2
	36	19.4x55 cm	31.75 mm	249.24 kg/m^2
Other Connection Elements	Anchors features were selected from "Aceromex Product Catalog" (Aceromex, 2018). Bolts are A325 and various according to tube and connection plate. DIN 7990-M12 was selected from the catalogue (Karaca, 2020).			
One 3D truss x 14 pieces	**Pieces**	**Height**	**Size**	**Weight**
Anchors	32	750 mm	33 mm	7.74 kg/m
	42	850 mm	33 mm	7.74 kg/m
Bolts	152	90 mm	19 mm	0.07 kg each
	300	90 mm	31.7 mm	0.12 kg each
Section 1	**Pieces**	**Height**	**Size**	**Weight**
Anchors (Column)	224	1.09 m	1=25.40 mm	3.97 kg/m
	224	0.90 m	1 3/8=34.93 mm	7.51 kg/m
	448	0.94 m	1 1/8=28.58 mm	5.03 kg/m
	224	0.89 m	1 1/8=28.58 mm	5.03 kg/m
	224	0.84 m	1=25.40 mm	3.97 kg/m
	224	0.65 m	1=25.40 mm	3.97 kg/m
	224	0.65 m	7/8=22.23 mm	3.04 kg/m
	224	0.64 m	1=25.40 mm	3.97 kg/m
Anchors (Beam)	84	0.68 m	1 ½=38.10 mm	8.94 kg/m
	90	0.88 m	1 ½=38.10 mm	8.94 kg/m
	84	0.70 m	2=50.80 mm	15.90 kg/m
	90	0.90 m	2=50.80 mm	15.90 kg/m
	168	0.70 m	1 7/8=47.63 mm	13.97 kg/m
	180	0.90 m	1 7/8=47.63 mm	13.97 kg/m
	168	0.70 m	1 ¾=44.45 mm	12.17 kg/m

	180	0.90 m	1 ¾=44.45 mm	12.17 kg/m
	84	0.70 m	1 ½=38.10 mm	8.94 kg/m
	90	0.90 m	1 ½=38.10 mm	8.94 kg/m
	84	0.70 m	1 3/8=34.93 mm	7.51 kg/m
	90	0.90 m	1 3/8=34.93 mm	7.51 kg/m
	84	0.62 m	7/8=22.23 mm	3.04 kg/m
	90	0.82 m	7/8=22.23 mm	3.04 kg/m
Bolts	336	90 mm	1 1/8=28.58 mm	0.11 kg each
	2352	90 mm	1 3/8=34.93 mm	0.13 kg each
	336	90 mm	5/8=15.88 mm	0.06 kg each
Section 2 and 3	**Pieces**	**Height**	**Size**	**Weight**
Anchors (Column)	256	1.09 m	1=25.40 mm	3.97 kg/m
	256	0.90 m	1 3/8=34.93 mm	7.51 kg/m
	512	0.94 m	1 1/8=28.58 mm	5.03 kg/m
	256	0.89 m	1 1/8=28.58 mm	5.03 kg/m
	256	0.84 m	1=25.40 mm	3.97 kg/m
	256	0.65 m	1=25.40 mm	3.97 kg/m
	144	0.65 m	7/8=22.23 mm	3.04 kg/m
Anchors (Beam)	192	0.68 m	1 ½=38.10 mm	8.94 kg/m
	192	0.70 m	2=50.80 mm	15.90 kg/m
	384	0.70 m	1 7/8=47.63 mm	13.97 kg/m
	384	0.70 m	1 ¾=44.45 mm	12.17 kg/m
	192	0.70 m	1 ½=38.10 mm	8.94 kg/m
	108	0.70 m	1 3/8=34.93 mm	7.51 kg/m
Bolts	384	90mm	1 1/8=28.58mm	0.11 kg each
	2520	90mm	1 3/8=34.93mm	0.13 kg each

The maintenance activities in the building during the usage stage of the first scenario

Works	**Description**	**Service Life**	**Unit**
Painting of the retrofit	Paint application to retrofit is 0.252 kg/m^2 for two layers. The total area of application is 7755 m^2.	5 years	kg
Air compressor for the painting of the retrofit	Painting can be done in 1.25 min for 1m^2 with the air compressor machine. It has 2200 watt and 10 Bar.	5 years	h
Original building painting	Painting is applied 8 times during its lifetime.	5 years	kg

The assumptions taken during the modelling of the original vulnerable building at the end-of-life stage

Assembly	Description	Assumptions	Unit
Foundation	The building's foundation was modelled separately for each section (A, B, C and D). The foundation type was selected as a concrete base footing with a slap.	Foundation width	0.80 m
		Foundation thickness	800 mm
		Slap thickness	100 mm
		Concrete Type	25 MPa
		Rebar Type	85 kg/m^3
Walls	The building walls were only modelled for the exterior, and basement walls, since the interior design of the building is unknown, and they made of cast in place concrete. The exterior walls have fixed aluminium windows. Only wall painting was included, without any insulation system.	Thickness	200 mm
		Concrete Type	25 MPa
		Reinforcement Type	16 mm
Columns and Beams	The columns and beams of the building were modelled for each section and the level of the building. Therefore, the number of column/beams, bay size, supported span and supported area were calculated according to the area of the sections and available floor plan of the building.	Column Height	3 m
		Live Load	3.6 kPa
Floors	The floor widths and span were modelled according to the dimensions of each floor in each section.	Concrete Type	25 MPa
		Live Load	3.6 kPa

Appendix L: Life cycle inventory of the second scenario

This appendix presents the collected data for the second scenario.

The assumptions taken during modelling for the new building's manufacturing and construction stage

Assembly	Description	Assumptions	Unit
Foundation	The building's foundation was modelled separately for each section (A, B, C and D). The foundation type was selected as a concrete base footing with a slab.	Foundation width	1.1 m
		Foundation thickness	1000 mm
		Slab thickness	200 mm
		Concrete Type	30 MPa
		Rebar Type	100 kg/m^3
Walls	The building walls were only modelled for the exterior and basement walls since the interior design of the building is unknown, and they made of cast in place concrete. The exterior walls have fixed aluminium windows. Only wall painting was included, without any insulation system.	Thickness	300 mm
		Concrete Type	30 MPa
		Reinforcement Type	20 mm
Columns and Beams	The columns and beams were modelled for each section and the level of the building. Therefore, the number of column/beams, bay size, supported span and supported area were calculated according to the area of the sections and available floor plan of the building.	Column Height	3 m
		Live Load	4.8 kPa
Floors	The floor widths and span were modelled according to the dimensions of each floor in each section.	Concrete Type	30 MPa
		Live Load	4.8 kPa

The maintenance activities in the building during the usage stage of the second scenario

Replacement Works	Description	Service Life	Unit
Paint	Paint for the building was applied 8 times in the building lifetime.	5 years	kg
Window	Windows were replaced once in the building lifetime.	40 years	kg

Appendix M: BOM occurring in the first and second scenarios

BOM was presented for both scenarios from cradle-to-gate.

Material	**Unit**	**Total Quantity from Construction and Use**		**Total Quality from Site Preparation**	
		Retrofit	**New Building**	**Disposal from Assembly of Retrofit**	**Demolition of Existing Building**
Concrete Benchmark USA 3000 psi	m^3	-	24,166.9	10.2	32,286.8
Concrete Benchmark USA 4000 psi	m^3	1,179.10	15,487.9	1.4	3,954.7
Rebar, Rod, Light Sections	Tonnes	96.5	2,620.7	-	2,341.2
Steel Plate	Tonnes	390.2	-	-	-
Steel Tubing	Tonnes	436.0	-	-	-
Mortar	m^3	4	-	-	-
Screws Nuts and Bolts	Tonnes	61.8	-	-	-
Welded Wire Mesh / Ladder Wire	Tonnes	-	4.8	-	4.8
Aluminium Window Frame	kg	-	11,874.9	-	7,916.6
Double Glazed No Coating Air	m^2	-	14,926.2	-	9,950.8
Water-Based Latex Paint	L	13,042.9	211,244.6	-	140,829.8

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