EMBODIED LIFE CYCLE ASSESSMENT AND POTENTIAL ENVIRONMENTAL IMPACTS OF IMPROVEMENT OPTIONS FOR DETACHED SINGLE-FAMILY HOUSES IN ATLANTA

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EMBODIED LIFE CYCLE ASSESSMENT AND POTENTIAL ENVIRONMENTAL IMPACTS OF IMPROVEMENT OPTIONS FOR DETACHED SINGLE-FAMILY HOUSES IN ATLANTA

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To my beloved parents, my brother, Pooya and my love, Ali!

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Air Conditioner
ACH	Air Changes per Hour
ACS	American Community Survey
AEE	Annualized Embodied Energy
ANSI	American Nation Standards Institute
AP	Acidification Potential
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BOM	Bill of Material
BTU	British Thermal Unit
CFC	ChloroFluoroCarbon
CICE	Construction Industry Cost Effectiveness
DEQO	Database for Embodied Quantity Outputs
DHW	Domestic Hot Water
DOE	Department of Energy
EEM	Energy Efficiency Measure
EIA	Energy Information Administration
EIO-LCA	Economic Input-Output Life Cycle Assessment
EP	Eutrophication Potential
EPA	Environmental Protection Agency
IEA	International Energy Agency
GBI	Green Building Initiative
GDP	Gross Domestic Product

GHG	Greenhouse Gas
GWP	Global Warming Potential
HCFC	HydroChloroFluoroCarbon
HFC	HydroChloroCarbon
HH Particulate	Human Health Respiratory Effects Potential
HVAC	Heating, Ventilation and Air Conditioning
IECC	International Energy Conservation Code
IEE	Initial Embodied Energy
IRC	International Residential Code
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCEA	Life Cycle Energy Analysis
LCEE	Life-Cycle Embodied Energy
LCI	Life Cycle Inventory
LC-ZEB	Life Cycle Zero Energy Buildings
LEED	Leadership in Energy and Environmental Design
NAHB	National Association of Home Builders
ODP	Ozone Depletion Potential
ORNL	Oak Ridge National Laboratory
RECS	Residential Energy Consumption Survey
SDG	Sustainable Development Goal
SEER	Seasonal Energy Efficiency Ratio
SERC	Southeast Electric Reliability Grid
SP	Photochemical Smog Potential
SQFT	Square Footage

TPE	Total Primary Energy
TRACI	Tool for the Reduction and Assessment of Chemical Impacts
UNEP	United Nations Environment Program
ZEB	Zero Energy Building

SUMMARY

20% of US energy consumption and the consequential environmental impacts are associated with the building sector. Previous studies showed that approximately 30% of a building's life cycle energy is attributed to its embodied energy. The residential housing market alone has a significant impact on US emissions. According to a recent report from the Washington Post, detached single-family houses represent the most common style of housing in major US cities and it is close to 40% for Atlanta.

This study focuses on residential buildings in the Atlanta metropolitan area. The overarching objective of this research is to include the changes of building construction methods and building energy codes into an embodied Life Cycle Assessment (LCA) model to evaluate the long-term impacts of improvement options for the residential buildings in the region. The primary contributions of this research are: (1) benchmarking the generic characteristics of existing residential buildings considering building codes and construction changes in the region; (2) investigating the trend of embodied energy and emissions of benchmarked buildings considering the 1970s transition in the construction industry; and (3) identifying potential improvement options for benchmarked buildings and comparing the embodied energy and environmental impacts of identified options.

The main findings of this research showed: (1) lower embodied energy and environmental impacts per unit area for houses built before 1970s; (2) lower embodied energy and impacts per unit area for 2-story houses; (3) a range of 1.8 to 3.9 Gj/m2 embodied energy for residential buildings in the region; (4) highest environmental impacts for attic/knee insulation and heating, ventilation and air conditioning (HVAC) units

replacement through retrofitting residential buildings; and (5) significant environmental impacts for foundation wall insulation and window upgrading through retrofitting dwellings built before the 1970s.

The results of this research highlight the role of the life cycle approach for selecting low emission options during the design and implementation of construction and retrofit actions for residential dwellings. The results could further be used to investigate the potential improvement options for an optimum energy usage while reducing life cycle emissions by renovating existing residential buildings in a region.

CHAPTER 1. INTRODUCTION

1.1 Research Motivation

On January 1, 2016, the 17 Sustainable Development Goals (SDGs) of the 2030 agenda for sustainable development, officially came into force [1]. One of the goals that it encouraged the world to take urgent action on was to combat climate change. One of the most important contributors to climate change and global warming is Greenhouse Gas (GHG) emissions [2]. The International Energy Agency (IEA) reported a large share of energy-related carbon emissions from the building sector [3]. Residential housing market alone has a significant impact on U.S. emissions. An analysis of 1997 data revealed that the new single-unit residential sector accounted for 5% of the U.S. Global Warming Potential (GWP) [4]. Although a study from 2017 showed that this number is decreasing by around 10 million metric tons of CO_2 in Atlanta, but Atlanta is still ranked 5^{th} in producing GHG emissions in the nation and residential sector is the 3^{rd} contributor among all the sectors in the region [5]. Additionally, a study in 2004 showed that the average single-family home adds more than twice as much GHG emissions to the atmosphere as the average passenger vehicle [6].

One of the other goals identified in the 17 SDGs plan was to consume and produce responsibly by reducing resource use and pollution along the whole life cycle, while increasing quality of life. Affordable and clean energy was another important goal, which is achievable by increasing access to clean fuel and technology and more progress on integrating renewable energy into end-use applications in buildings, transport and industry. Sustainable cities and communities is among other identified goals that can be overcome in ways that allow communities to continue to thrive and grow, while improving resource use and reducing pollution and poverty [1].

A pressing question in the building construction field nowadays is whether to raze old buildings or retrofit and reuse them in urban areas. One engineer has noted that, if the embodied energy of construction is taken into account, the economic benefits of retrofitting, even if you are assuming the new building has significantly better energy efficiency, is still much better than constructing a new building. However, he also cautioned that there are exceptions to the rule [7].

This report, along with the significant emphasis on emission reduction, resource reuse and energy efficiency in cities and communities in the 17 SDGs plan, was the underlying motivation for this research to further investigate the hidden energy and emissions in building construction industry. Therefore, this research aimed to feel this gap in the residential construction industry by studying the embodied energy and consequential environmental impacts of existing residential buildings and the possible options to improve the embodied emissions and impacts through the building's life cycle. Moreover, a recent study which have calculated the contribution of residential construction to climate change by including the temporal allocation of the emissions [8], stimulate the further distinction between different types of residential buildings built over years and the effects of construction transitions and building codes and standards on the outcome.

1.2 Building's Embodied Energy and Emissions

Buildings' share of the total worldwide energy consumption is approximately one third [9]. According to a study in India, in a worldwide scale, 30–40% of all primary energy is used for buildings and they are held responsible for 40–50% of GHG emissions. [10]. Most of the studies indicated that the use phase of buildings accounts for the majority of life cycle energy consumption and environmental impacts [11]. However, recent studies showed that there are indications that materials may play a large role, particularly in energy efficient homes. A research center in Spain revealed that embodied energy can represent more than 30% of the primary energy requirement during the life span of a single house with a garage for one car [12]. A recent study shows that with a restricted functional unit and accounting for technological progress, approximately 30% of a building's life cycle energy is attributed to its embodied energy [13]. A similar study on the multi-family dwellings also showed that with the new definition of the functional unit, the share of materials and construction of total life cycle energy doubles to around 26% [14]. Researchers even showed that the production phase of an energy efficient passive house may account for more than a half of the building's total life cycle primary energy use [15]. Another study in Finland discussed that this amount is even higher in terms of consequential embodied carbon specially when the temporal allocation of the GHG emissions is taken into account, meaning that carbon emission released today should have higher impacts than carbon emission released tomorrow [16]. Therefore, regional building codes and standards as well as the building designers must be aware of materials embodied impacts in order to meet long and short-term emission reduction goals of the region and nation.

On the other hand, the United Nations Environment Program (UNEP) predicted that 87% of the US population will be living in urban areas by 2030 [17]. This means that a lot of new construction will take place during the next couple of decades. However, the emissions of the construction phase occur at the beginning of the building's life cycle and in a very short time horizon. Thus, the environmental trade-off between construction methods and materials as well as potential reuse of older buildings should also be considered when the temporal allocation of the emissions, is taken into account [18].

For a systematic energy and carbon assessment of buildings, it is critical to use a whole life cycle approach. Life Cycle Energy Analysis (LCEA) of buildings and Life Cycle Assessment (LCA) are two well-known tools to systematically analyze a building through its entire lifetime. These tools enable the practitioners to formulate achievable strategies to reduce primary energy use of the buildings and control emissions. LCEA studies the total energy use during the life cycle of a building, including, embodied (initial + recurring), operational, demolition, etc. On the other hand, LCA is a process whereby the material and energy flows of a system are quantified and evaluated. Subsequently, global and/or regional environmental impacts are calculated.

1.3 Energy Standards and Green Buildings

Building energy standards in the U.S. have recently moved towards more energy efficient and sustainable buildings. Green Building Initiative (GBI) [19] and Leadership in Energy and Environmental Design (LEED™) [20] are among several criteria-based assessment methods developed to improve buildings' energy consumption in the U.S. However, the focus of the building codes is still on the use phase of the building, ignoring other life cycle stages such as embodied phase, which is related to the construction and delivery of the building and its components and can account for a significant portion of life cycle emissions. A review of 90 Life Cycle Energy Analysis (LCEA) case studies of conventional, passive, low energy and nearly Zero Energy residential Buildings (nZEB), highlighted an increasing share of embodied energy in the transaction from conventional to energy efficient buildings, despite the reduction in the total life cycle energy that could reach up to 50% [21]. Researchers even defined Annualized Embodied Energy (AEE) to investigate the annualized life cycle share of embodied energy of different materials and compare it to the annualized operational energy usage in generic buildings to optimize for the Life Cycle Zero Energy Buildings (LC-ZEB) [22]. Additionally, as green building requirements grow, practitioners will need to provide environmental impact data such as carbon emissions to the local governments. A recent study evaluated the current construction industry practice and identified barriers and omissions of implementing the effective measurement of embodied CO_2 of buildings. This study recommended that governments support the development of a simplified, applicable embodied CO_2 eq. assessment approach with reliable datasets [23]. For instance, the residential building industry could make a significant positive impact on the environment if they consider the material production and construction phase in their life cycle analysis to provide better and more efficient system choices and less energy and carbon intensive designs based on all life cycle stages of a building [24].

1.4 Research Need and Objective

Whereas the energy consumption and environmental impacts during the operating phase of a building is tangible for people, not everyone can think of the embodied phase of the building and the associated hidden impacts. Additionally, lack of a complete and consistent construction material-specific embodied energy database hampers industrywide application of embodied energy analyses [25]. A number of LCEA and LCA methods exist to calculate energy usage in different phases of a building's life cycle [26]. However, there currently are few LCA frameworks available that describes the lifecycle impacts of residential sectors at a regional scale. The overall goal of previous regional scale LCA studies was to compare energy consumption and GHG emission rates for different urban density neighborhoods [27–29]. Therefore, they all used a simplified method to roughly estimate the embodied energy and emissions of the infrastructures including buildings and none of them conducted detailed embodied LCA analysis on building sectors separately. Additionally, among those, no one considered the effect of construction evolution through the energy crisis of the 1970s [30] and following changes in the material quality, construction methods, and building codes over the years. Therefore, there is a great need of a systematic methodology to identify major changes in building construction over the past decades and examine their effects on trends of embodied energy and environmental impacts in order to improve the regional and national building codes and energy standards.

Considering the importance of embodied energy and consequential embodied emissions of buildings, this study investigates the building codes and building construction industry within the Atlanta metropolitan area. State of Georgia implemented the very first residential building code in 1978 [31] and eventually improved the code towards energy efficient buildings and sustainable construction [32]. The major objective of this work is to evaluate and compare the magnitude of embodied energy and environmental impacts of detached single-family houses of Atlanta considering the changes in building codes and construction in 1970s and investigate the potential environmental impacts of improvement options for the existing buildings.

The results of this research highlight the role of the life cycle approach for selecting low emission options during the design and implementation of construction and retrofit actions for residential dwellings. The results could further be used to investigate the potential improvement options for an optimum energy usage while reducing life cycle emissions by renovating existing residential buildings in a region.

1.5 Why Atlanta?

City of Atlanta and its nearby regions are one of the biggest and most populous metropolitan areas all over the US. Hence, the increasing number of people in this growing urban area and the consequential increase in building construction and residential buildings, lead to an urgent need for city-level action on correctly monitoring the building construction trends, energy consumption of buildings and evaluating their environmental emissions. To achieve this goals it is required to adopt a multi-disciplinary approach covering a number of features such as energy saving, improved use of materials and emissions control.

Based on new 2014 American Community Survey (ACS) data on the characteristics of occupied housing, almost 40% of the homes in Atlanta are single family detached houses [33]. A recent study showed that Atlanta ranked 5th in producing GHG emissions among 100 US metropolitan areas and residential buildings sector is ranked 4th among other contributing sectors [5]. Moreover, Atlanta recently named as one of the top 10 U.S. cities for innovation and the practitioners are willing to implement research outcomes into city development plans [34].

1.6 Research Questions and Organization of the Dissertation

To attain the research objective, this study proposed and answered the following research questions through this dissertation:

1. What are the generic characteristics (structural, construction, etc.) of existing residential buildings of Atlanta considering the building codes and construction changes in the region over years? Develop a building benchmark model for identified scenarios.
2. What are the embodied energy and environmental impacts of benchmarked residential buildings? What are the differences between scenarios and why?
3. What are the potential energy improvement options in the region? What are the embodied energy and environmental impacts of identified options? Which improvement option has the lowest embodied energy and environmental impacts for different building vintages?

To answer the mentioned research questions, the following chapters of this dissertation are shaped around the concepts, details, and implementation of the research questions listed above. This dissertation is divided into six chapters. In particular:

- Chapter 1: Introduction – This chapter started with a preliminary background study and identified gaps that motivated this research, a brief narrative of the buildings' embodied energy and emissions as well as the existing energy standards and green building protocols in the US. The chapter then discussed the research need and objective and the justification of choosing Atlanta as the case study. Finally, the chapter concluded with the description of the research questions and the tasks that defined and accomplished in order to answer the identified research questions.

- Chapter 2: Literature Review – This chapter presents a review of previous related research and studies in the realm of the LCA of buildings and embodied LCA of residential buildings in various regions. The chapter concluded with the identified gaps in the existing literature.
- Chapter 3: Longitudinal Study of Existing Residential Dwellings of Atlanta – This chapter identified the generic characteristics of existing residential buildings of Atlanta and benchmarked four residential building models. The chapter also estimated the residential building's energy consumption rates based on the vintages.
- Chapter 4: Embodied LCA Comparison of Single-Family Residential Houses Considering the 1970s Transition of Construction Industry in Atlanta – This chapter presented the process-based LCA model utilized to estimate and compare the embodied life cycle energy and environmental impacts of the benchmarked residential buildings and discussed the differences between scenarios and the associated reasons.
- Chapter 5: Embodied LCA Comparison of Single-Family Residential Improvement Options: Atlanta Case Study – This Chapter discussed the potential improvement options for the region and the embodied energy and environmental impacts of the identified options for the benchmarked buildings. The chapter ends with a discussion about the best options from the energy conservation and environmental impacts perspectives.

- Chapter 6: Conclusions, Limitations and Future Works – A discussion about the identified gaps in knowledge and the developed methodology for addressing these gaps is presented in this chapter, limitations of the study and possible future research for further development of the presented LCA framework is described.

CHAPTER 2. LITERATURE REVIEW

2.1 Life Cycle Assessment (LCA)

As described in the introduction chapter, LCEA studies the total energy use during the life cycle of a system. On the other hand, LCA is a set of methods, tools, and data designed to estimate material flows and assess environmental impacts over the life cycle of a product or a service. The International Organization for Standardization (ISO) has developed international standards that describe how to conduct an LCA [35]. LCA can be conceptually divided into four phases: (1) scope and boundaries, (2) Life Cycle Inventory (LCI), (3) impact assessment and (4) interpretation [36]. In the first phase, the purpose of the study, the functional unit, the boundary condition, the assumption and omissions are defined. The second phase is the data collection and data preparation. Through this phase the materials and energy use, and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges, etc.) are quantified over the life cycle of the system. In the third phase, the impacts to human health and environment are measured and inventoried. Finally, in the fourth phase the results are interpreted and combined to estimate impacts on one or more environmental issues [37].

The three main methods for estimating LCI of material and energy used are (1) process-based, (2) economic input-output, and their combination, known as (3) hybrid analysis. Additionally, the researchers in Georgia Institute of Technology have recently proposed a forth method, called (4) parametric LCA [38]. Process-based LCA is the most common approach that practically quantifies the energy and materials' flows and the resulting environmental impacts for a product or system within the system boundary. The sources of data are usually facility-based; however, industry or even nationally averaged data are also used in case of data limitations. Many different software and databases have also been developed over years for various products and services in different regions of the world. The second method which is called the Economic Input-Output LCA (EIO-LCA) method, is based on economic transactions between sectors of the economy [39] rather than using physical quantities of energy and materials' flows. This data is normally aggregated by a government agency in a country. In the U.S., researchers at Carnegie Mellon University have developed and maintained a public use model based on the 428-sector benchmark U.S. input-output tables [40]. Furthermore, to reduce both methods' disadvantages and take the advantage of both approaches, a hybrid LCA method was proposed [41]. The inevitable goal of the hybrid method is to combine the best features of process-based and EIO-based approaches. In general, hybrid approach use either a process-based LCA or EIO-LCA as the core model, but then use elements of the other approach to extend the utility of the overall model. The hybrid method has been particularly used for a long time by practitioners to evaluate building's embodied energy [42]. Finally, the parametric LCA involves investigating governing equations and identifying overall relationships between input and output variables to develop a parametric form of LCA models [38].

2.2 LCA of Buildings

There is a growing body of literature on embodied and operational energy and emission analysis over different life stages of buildings all around the world. Many researchers studied one stand-alone building and conducted a detailed LCEA or LCA analysis for it. As an example, researchers in Australia have conducted an LCEA of a local residential building to optimize the building's energy consumption using alternative design strategies [43]. In another study, life cycle environmental effects of a new high-end office building in Finland was analyzed [44]. A new university building, located in Michigan, was also studied for its energy usage and environmental impact assessment over its 75 years of life span [45].

2.2.1 Embodied versus Operational Trade-offs

Most of the mentioned studies indicated that the life cycle emissions of the materials and construction phase only cause around one tenth of building's total life cycle emissions and the energy consumption of the use phase overwhelmingly dominates the embodied energy of the buildings. However, due to the advent of energy efficient Heating, Ventilation and Air Conditioning (HVAC) systems, advanced insulation materials, green building codes and requirements [46] along with increasing renewable energy generation in power plants, the emphasis has eventually been shifted to the share of embodied energy of buildings over their life time energy usage portfolio [47,48]. A review report from India also studied 73 cases across 13 countries and concluded that building's life cycle energy demand can be reduced by reducing its operating energy significantly through use of passive and active technologies [10].

One study showed that the primary energy use and the CO_2 emission depend strongly on the energy supply, for both conventional and low-energy buildings [49]. A recent case study compared the life cycle environmental impacts of two typical single-family homes in similar climates built in accordance with different regional construction practices and electricity sources (New Jersey, US versus Chur, Switzerland). The results showed that the

Swiss building performed better mainly due to the geothermal heat pump and the Swiss electricity mix. This study also substituted the New Jersey electricity mix with Swiss electricity mix and confirmed that the US building performed on a per heated area basis as well as or better than the basic Swiss case study building [50].

2.3 Embodied LCA of Residential Buildings

According to a recent report from Washington Post, the detached, single-family houses are by far the most common style of housing in major American cities. The percentage is varying in a range between 20-60% among cities and it is close to 40% for Atlanta [33]. Several studies investigated the energy usage and environmental impacts of various materials or components in a residential building in different regions [51,52]. A comprehensive survey of material quantities and embodied carbon in building structures were collected in the Database for Embodied Quantity Outputs (deQo), developed at MIT. The MIT researchers then analyzed and quantified the embodied carbon of over 200 existing buildings with deQo and identified the range of 250 – 750 CO_2/m^2 for embodied carbon in buildings [53].

An embodied carbon benchmark study has been conducted by the carbon leadership forum at the University of Washington. This study identified a wide range of 32 – 1004 kg CO_2/m^2 initial embodied carbon for residential buildings, based on 222 residential case studies [54]. The amount of variation in the embodied energy of residential buildings within and across international geographic regions is also examined in the literature [55]. The results showed a range of 2.8-6.6 GJ/m^2 Initial Embodied Energy (IEE) and a range of 46.6-138.6 MJ/m2/year Life-Cycle Embodied Energy (LCEE) for American wood-construction residential buildings.

A contemporary residential home in Ann Arbor, Michigan was studied and the primary life-cycle energy consumption and the corresponding release of GHG were compared to the energy efficient modeled version of the same building. The results of this study showed the embodied energy of 6.29 Gj/m2 for a standard home. Additionally, this study showed that walls have the highest contribution to embodied energy, followed by floors and foundation respectively. Moreover, concrete, timber, gravel and steel identified as the four largest contributors to GHG emissions [56].

2.3.1 Embodied LCA Comparison of Residential Building Components

A group of researchers studied environmental impacts of different exterior wall systems in six single-story residential buildings in various US climate regions. The results of this study indicated the importance of a holistic approach, such as LCA, to properly assess the negative environmental impact of different technologies [57]. Various exterior window shadings in residential buildings were compared in five climate zones of the U.S. including Atlanta. The results showed that the wood shadings are the most environmentally friendly materials. Additionally, this study concluded that using the solar shading systems are noticeably beneficial in mixed-humid (e.g., Atlanta) climate zones [58].

Another study examined the embodied impacts of traditional clay versus modern concrete houses in Indonesia. The results of this study revealed that although the traditional clay-based houses have an operational impact advantage (692 GJ for the 40-years life of the buildings compared to 733 GJ for cement-based houses), they do not display an advantage in the embodied impacts of the materials. This study also identified the material production processes as the highest contributor to the embodied environmental and emissions impacts of buildings [59]. Detailed embodied energy analysis of two typical 40-story residential buildings in Hong Kong had also been undertaken. This study showed that the embodied energy intensity for manufacturing and transporting building materials is within the range of 6.96-7.15 GJ/m2 when using the virgin steel and aluminum. Further sensitivity analysis in this study also revealed that the use of recycled steel and aluminum will confer savings of more than 50% in embodied energy [60].

Another research team analyzed virtual residential houses in Atlanta, Georgia, and Minneapolis, Minnesota, to determine energy consumption and GHG emission during the use, maintenance, and demolition phases of the building's lifetime. This study estimated the energy consumption over a 75-year life to be 4,575 GJ for the Atlanta wood frame and 4,725 GJ for the Atlanta concrete block structure. In this study, energy consumption related to structural/exterior maintenance was estimated at 110.5 GJ for the Atlanta location and 73.3 GJ for Minneapolis, only 1–2% as large as used for heating and cooling. However, there is a lack of calculating production and construction energy consumption rates in this case study [61]. A recent study shows that the energy and carbon embodied in buildings are not the same when different methods of construction are used [62]. Therefore, it is vital to distinguish between different constructions methods of residential buildings before conducting LCEA and LCA analysis on buildings of a region.

2.3.2 Embodied LCA of Buildings in Different Cities

Cities and their building stocks result in huge energy consumption and environmental impacts that are critical to reduce. Although the focus is more on the operational phase of the building, studies showed that materials and construction might also play a large role, particularly in energy efficient homes. Therefore, there is an urgent need for an urban-level action on correctly monitoring the building construction trends, trade-offs between embodied and operational energy consumption rates and evaluating the life cycle energy and emissions of future development plans. To date, very few studies have quantified embodied environmental requirements of building stocks and spatialized them in cities [63].

One of the very first urban level LCA analysis was a study conducted on the city of Toronto. The goal of this study was to compare two different high and low residential density regions of the city of Toronto from their energy usage and GHG emissions perspective. For this purpose, building materials, infrastructures (roads), utilities, and transportation data were collected, analyzed and compared. The paper finally concluded that the GHG emissions are highest for transportation and the energy usage is highest for building operations in both functional units (per person and per square meter). It also showed that the total energy usage is higher within the low density area in comparison to the high density regions [27]. Another urban level LCA analysis available in the literature, studied four different regions of central city and suburban, with both high-density and low-density structured neighborhoods in Phoenix, AZ. The goal of this study was to analyze the impact of different urban forms on infrastructures' energy demand. The final results of this paper indicated that suburban-high density, is the most densely developed, and the most energy and GHG intensive area among the four case study areas [29].

2.4 Gap in the Literature

Various number of LCEA and LCA methods exist to calculate energy usage in different phases of a building's life cycle. However, there currently are few LCA frameworks available that describes the lifecycle impacts of residential sectors at a regional scale. The overall goal of previous regional scale LCA studies was to compare energy consumption and GHG emission rates for different urban density neighborhoods. Therefore, they all used a simplified method to roughly estimate the energy and emissions of the infrastructures including buildings and none of them conducted detailed embodied LCA analysis on building sectors separately. Specifically, as the residential units where built in various periods, there are differences in the material quality, construction quality, and technologies used. However, all of the regional LCA studies simply assumed that all the buildings were built at the same time and were all of equivalent quality and none of them included the longitudinal perspective such as the effect of construction evolution through the energy crisis of the 1970s in their analysis.

A review report from MIT studied 65 cases taken from 16 studies on LCA of residential buildings. The results indicated that as municipalities and regulations move to adopt energy efficiency policies, it is necessary to correctly recognize the most suitable energy efficiency measures and materials in different regions and for different structures. Furthermore, this report showed that there is limited research on the renovation of existing housing and thus, understanding the threshold where the impacts of new construction or renovation exceed the benefits of keeping the existing houses is of high importance to distinguish what measures are most beneficial in which cases [64]. Based on the MIT report, there is limited research on the renovation of existing housing and thus, understanding the threshold where the impacts of new construction or renovation exceed the benefits of keeping the existing houses is of high importance to distinguish what measures are most beneficial in which cases.

The gaps in the literature motivated the author to identify the existing condition of residential buildings in Atlanta metropolitan region considering the 1970s transition in building construction industry and conduct a systematic calculation and comparison on the changes in the embodied energy usage and consequential environmental impacts of them from the system level, assembly group and life cycle stage perspectives. Moreover, this research investigate the potential improvement options for the existing buildings of the region and their effects on energy consumption rates and the consequential environmental impacts.

CHAPTER 3. LONGITIDUNAL STUDY OF EXISTING RESIDENTIAL DWELLINGS OF ATLANTA

Residential units in Atlanta metropolitan area were built in a period spanning from the early 1900s to 2010 and the development in the region continues to grow. During this period, the biggest change in the construction industry happened in the 70's, following several national circumstances including the national energy crisis [30,65] and changes in the building codes. The first building code was implemented in the state of Georgia in 1978 [31]. However, the energy efficiency and sustainable construction did not implement until late 2008 and minimum residential green building standard is still only an optional code for one- and two-family dwellings, adopted in 2011 [32]. This chapter attempts to identify existing buildings of the region and benchmark the typical building scenarios considering both structural changes and energy consumption rates over years of building construction industry in the region.

3.1 Benchmark Building Structures and Components

As stated earlier, various changes occurred in the U.S. construction industry over the 70s. Additionally, our interview with building construction experts in the region confirmed that there has been a transition in building construction strategies in the 1970s, due to the energy crisis and implementation of building codes in the US. Researchers showed that State of Georgia, began to implement building restrictions on the residential construction to save energy starting from 1970s [31]. Therefore, based on the history of U.S.

construction and interview with regional experts, 1970s was chosen as the transition decade from older to recent construction techniques in this study.

To consider the effects of this change, I have categorized residential buildings into two groups of buildings built before 1970s and built after 1970s. Figure 1 shows the distribution of single-family residential buildings built before 1970s and after 1970s in the city of Atlanta. There are 110,247 properties built before 1970s and 131,315 properties built after 1970s. In addition, the circles represent the directional distribution of properties within the area. This figure shows that the two categories of buildings are almost evenly distributed in the city. The similar trend is also observed for the rest of the Atlanta metropolitan area with a lower density.

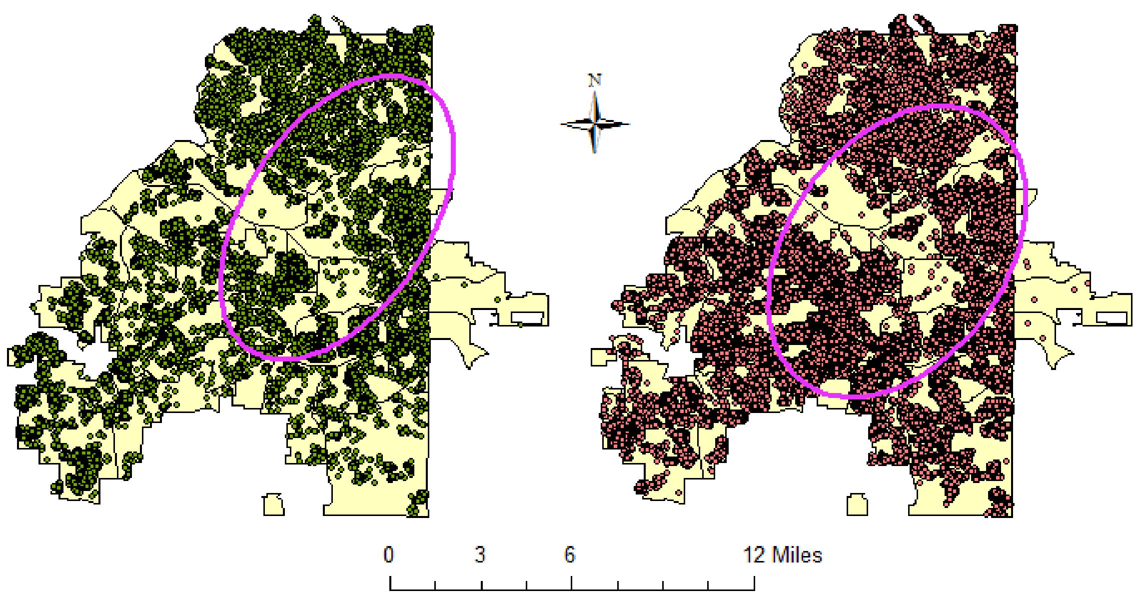


Figure 1 – Single-family residential buildings distribution in City of Atlanta – Built before 1970s on the right and after 1970s on the left.

In addition, a recent study showed that the energy and GHG emission embedded in the material and in the construction processes for the single-family residential units is correlated with the size of the building after controlling for the number of stories [66]. Hence, this study also distinguished the 1-story and 2-story buildings to control for this factor and have a more precise classification of single-family residential building types for further analysis. The final classification of buildings is presented in Figure 2 . In this figure and throughout the manuscript, “1S or 2S” shows the number of stories and “-B/A” represents whether the building is constructed “before” or “after” 1970s, respectively.

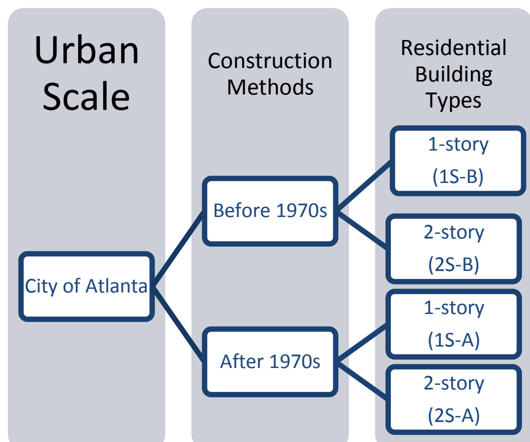
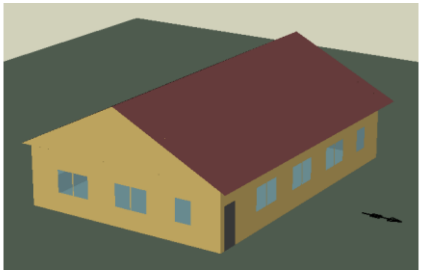
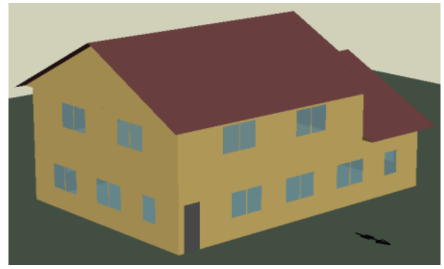


Figure 2 – Single-family residential buildings’ classification scenarios and their acronyms

The history of building codes in Georgia [67–70], national residential building provisions and protocols [71–73] as well as existing case studies of the regional residential buildings [74,75] were utilized to define the baseline of four building scenarios. It is understood that there is more than a dozen of different architectural styles in the study area. However, since the objective of this study is to assess and compare the effect of major construction changes on the residential buildings industry and not individual structures, all building classifications are assumed to be of average construction quality, with no basement and no garage. The schematic design views of the 1-story and 2-story building scenarios are presented in Figure 3.





Gross Living Area (m^2) = 163

Average Height (m) = 3.05

Gross Living Area (m^2) = 330

Average Height (m) = 5.48

Figure 3 – Schematic views of the 1-story and 2-story building scenarios

Additionally, detailed information about all the exact materials and processes used in each of the residence in the study is not available nor would such a detailed analysis be feasible. Thus, the modeling process is simplified by making some generic assumptions, which are presented in Table 1 .

Table 1 – General assumptions used for modeling before and after 1970s buildings.

	Before 1970s	After 1970s
Foundation	Foundation wall Concrete Masonry	Slab on grade vapor barrier
Building Envelope (Wall Systems)	Fiberglass Batt No sheathing	Gypsum Board & Polyethylene vapor and air barrier
Siding	Wood	Brick
Roofing	Asphalt shingle (organic felt)	Asphalt shingle (fiberglass-based)
Flooring	Wood Joist	Wood Joist
Windows	Unclad wood frame single pane	Vinyl clad wood frame double pane
Doors	solid wood door	solid wood door

Based on the generic assumptions, the final list of building characteristics for all four building scenarios are presented in Table 2, Table 3, Table 4 and Table 5 separated by the number of stories and whether the building was built before or after 1970s. The created building characteristics have been reviewed and verified by subject matter experts in the Atlanta homebuilding industry.

Table 2 – 1-Story built before 1970s building characteristics

Building Characteristics	Before 1970s
Base house foundation	Concrete strip footing length: 79.25m, width: 0.457m, thickness: 203mm, rebar #15 M, concrete 20 MPa, no envelope
Foundation	Concrete masonry foundation wall length: 51.82m, height: 1.8m, thickness: 200mm, concrete 20 MPa, no envelope
Exterior walls	height = 2.6m, length = 68.58m, 38*184 mm wood studs, load bearing, 400mm o.c. (stud spacing), no sheathing, stud type: kiln-dried, wood bevel siding – pine, 88.8mm Fiberglass Batt R11, Alkyd Solvent based paint
Interior walls	height = 2.59m, length = 27.43m, 38*184 mm wood studs, non-load bearing, 400mm o.c. (stud spacing), no sheathing, stud type: kiln-dried, 11.15 m^2 opening area
Windows	12 windows (32.5 m^2 opening), unclad wood window frame single pane, no glazing.
Exterior doors	2 standard size solid wood door
Interior doors	5 Hollow core wood interior doors
Roofing	Wood joist - span 4.42m and total area = 163 m^2, Live load = 2.4 kPa, Decking type = 12mm plywood. Asphalt shingle (organic felt)
Flooring	Wood joist flooring - span 4.27m and total area = 163 m^2. Live load = 2.4 kPa, Decking type = 15mm plywood. No insulation

Table 3 – 1-Story built after 1970s building characteristics

Building Characteristics	After 1970s
Base house foundation	Concrete strip footing length: 79.25m, width: 0.457m, thickness: 203mm, rebar #15 M, concrete 20 MPa, no envelope
Foundation	Slab on grade - length: 15.24m, width: 10.67m, thickness: 100mm, concrete 20 MPa, Polyethylene 6 mil vapor barrier
Exterior walls	height = 2.6m, length = 68.58m, 38*89 mm wood studs, load bearing, 400mm o.c. (stud spacing), sheathing type: plywood, stud type: kiln-dried, Gypsum Board (Gypsum Moisture Resistant 12.7mm), brick cladding, 3 mil Polyethylene vapor and air barrier, 12.7mm layer of expanded Polystyrene insulation
Interior walls	height = 2.59m, length = 27.43m, 38*89 mm wood studs, non-load bearing, 400mm o.c. (stud spacing), sheathing type: plywood, stud type: kiln-dried, 12.7mm regular gypsum board, 11.15 m^2 opening area
Windows	12 windows (32.5 m^2 opening), vinyl clad wood window frame double pane, double glazed no coating air
Exterior doors	2 standard size solid wood door
Interior doors	5 Hollow core wood interior doors
Roofing	Light frame wood truss – span 14.3m and total area = 163 m^2. Live load = 2.4 kPa, Truss type = pitched. Decking type = 12mm plywood, R11 fiber-glass based asphalt shingle
Flooring	Wood joist flooring - span 4.27m and total area = 163 m^2. Live load = 2.4 kPa, Decking type = 15mm plywood.

Table 4 – 2-Story built before 1970s building characteristics

Building Characteristics	Before 1970s
Base house foundation	Concrete strip footing length: 79.25m, width: 0.457m, thickness: 305mm, rebar #15 M, concrete 20 MPa, no envelope
Foundation	Concrete masonry foundation wall length: 51.82m, height: 3m, thickness: 200mm, concrete 20 MPa, no envelope
Exterior walls 1st floor	height = 2.7m, length = 70m, 38*184 mm wood studs, load bearing, 400mm o.c. (stud spacing), no sheathing, stud type: kiln-dried, wood bevel siding – cedar, 88.8mm Fiberglass Batt R11, Alkyd Solvent based paint
Exterior walls 2nd floor	height = 2.4m, length = 45.7m, other things same as 1st floor
Interior walls 1st floor	height = 2.7m, length = 27.43m, 38*184 mm wood studs, non-load bearing, 400mm o.c. (stud spacing), no sheathing, stud type: kiln-dried, 47 m2 opening area
Interior walls 2nd floor	height = 2.4m, length = 67m, other things same as 1st floor
Windows	18 windows (47 m2 opening), unclad wood window frame single pane, no glazing.
Exterior doors	4 standard size solid wood door
Interior doors	10 Hollow core wood interior doors
Roofing	Wood truss - span 14.6m and total area = 163 m2, Live load = 2.4 kPa, Decking type = 12mm plywood. Asphalt shingle (organic felt)
Flooring 1st floor	Wood joist flooring - span 4.27m and total area = 163 m2. Live load = 2.4 kPa, Decking type = 15mm plywood. No insulation
Flooring 2nd floor	Wood joist flooring - span 3.35m and total area = 120 m2 other things same as 1st floor

Table 5 – 2-Story built after 1970s building characteristics

Building Characteristics	After 1970s
Base house foundation	Concrete strip footing length: 79.25m, width: 0.457m, thickness: 305mm, rebar #15 M, concrete 20 MPa, Polyethylene 6 mil vapor barrier
Foundation	Slab on grade - length: 15.24m, width: 10.8m, thickness: 200mm, concrete 20 MPa, Polyethylene 6 mil vapor barrier
Exterior walls 1st floor	height = 2.7m, length = 70m, 38*89 mm wood studs, load bearing, 400mm o.c. (stud spacing), sheathing type: plywood, stud type: kiln-dried, Gypsum Board (Gypsum Moisture Resistant 12.7mm), brick cladding, 3 mil Polyethylene vapor and air barrier, 12.7mm layer of expanded Polystyrene insulation
Exterior walls 2nd floor	height = 2.4m, length = 45.7m, other things same as 1st floor
Interior walls 1st floor	height = 2.59m, length = 27.43m, 38*89 mm wood studs, non-load bearing, 400mm o.c. (stud spacing), sheathing type: plywood, stud type: kiln-dried, 12.7mm regular gypsum board, 47 m2 opening area
Interior walls 2nd floor	height = 2.4m, length = 67m, other things same as 1st floor
Windows	18 windows (47 m2 opening), vinyl clad wood window frame double pane, triple glazed no coating air
Exterior doors	4 standard size solid wood door
Interior doors	10 Hollow core wood interior doors
Roofing	Light frame wood truss – span 14.3m and total area = 163 m2. Live load = 2.4 kPa, Truss type = pitched. Decking type = 12mm plywood, R11 fiber-glass based asphalt shingle
Flooring 1st floor	Wood joist flooring - span 4.27m and total area = 163 m2. Live load = 2.4 kPa, Decking type = 15mm plywood with Regular 12mm gypsum board
Flooring 2nd floor	Wood joist flooring - span 3.35m and total area = 120 m2 other things same as 1st floor

3.2 Estimate Buildings' Energy Consumption Rates

To estimate the energy consumption rates, the publicly available Residential Energy Consumption Survey (RECS) microdata from Energy Information Administration (EIA) was utilized. The RECS survey represents national household energy consumption and expenditures based on a national area-probability weighted sample of households [76]. In order to observe the trend of energy consumption rates over years, all the available RECS microdata releases spanning from 1987 to 2015 were utilized. The data sets were then narrowed down to observations with the following characteristics to better represent the designated buildings of the region. The reason of adding "not fully insulated windows and walls" to the separation criteria is to make sure the selected data is not associated with already upgraded dwellings and the energy consumption rates better represent an average house in the region.

- South Atlantic US Division
- Census Metropolitan Area / Urban Area
- Single Family Detached Residential Buildings
- Only 1 or 2 stories
- Windows and walls not fully insulated

The data availability of each RECS release is presented in Table 6. From this table, we can see that the only two missing variables among selected features are "census metropolitan" variable that is also observed by the "urban area" variable in all the releases except 1987 and the "single pane glass window" variable that is missing in four versions of releases.

Table 6 – RECS releases and data availabilities

Data Release Year	Division South Atlantic	Census Metropolitan	Urban Area	1 or 2 stories	Single family detached	Single-pane glass window	Wall not/poorly insulated
1987	√	-	-	√	√	-	√
1990	√	-	√	√	√	-	√
1993	√	-	√	√	√	√	√
1997	√	-	√	√	√	-	√
2001	√	-	√	√	√	-	√
2005	√	-	√	√	√	√	√
2009	√	√	√	√	√	√	√
2015	√	√	√	√	√	√	√

A recent report from National Association of Home Builders (NAHB) claimed that on a per square foot basis, the newer the home is, the less energy it uses. This report concluded that for a correct building energy efficiency evaluation, the analyzes should be controlled for the part of the energy consumption which is not related to building structure [77]. Therefore, after selecting the designated datasets, I have calculated the climate-related energy usage (space heating, space cooling and water heating) per square footages from the extracted data and averaged for buildings of each vintage separately for 1-story and 2-story buildings. In occasions with high uncertainty, the median was replaced with average to lower the effect of data spread. The results of the analysis are presented in Table 7 and Table 8. The general trend of numbers confirm the outcome of the NAHB report claiming that on a per square foot basis, the newer home consumes less energy [77]. Furthermore, to realize the trend of energy consumption rates over decades as buildings get older, the calculated numbers were then presented in Figure 4 and Figure 5.

Table 7 – Longitudinal trend of energy consumption (Thousand BTU/Sqft) over RECS releases for 1-story buildings.

RECS Release Year	1940s	1950s	1960s	1970s	1980s	1990s	>1999
1987	18.4	17.7	26.1	17.3	23.5	-	-
1990	51.1	36.7	31.9	18	-	-	-
1993	74.6	38.5	32.7	-	17.9	22.7	-
1997	53.6	61.6	48.3	18.5	-	25.9	-
2001	34.3	27.9	34.5	20.8	18	19	-
2005	19.6	18.4	16.5	27.9	32.6	-	11.8
2009	34.6	28.9	28.1	17.8	19.1	20.8	16.1
2015	45.2	35	25.5	22.5	22.7	32.6	19.5

Table 8 – Longitudinal trend of energy consumption (Thousand BTU/Sqft) over RECS releases for 2-story buildings.

RECS Release Year	1940s	1950s	1960s	1970s	1980s	1990s	>1999
1987	60.9	61.9	30.4	18.5	-	-	-
1990	-	45.7	76.5	-	11.3	-	-
1993	44.6	31.4	48.4	-	-	-	-
1997	62.7	76.7	-	-	-	-	-
2001	46.4	-	-	-	-	-	-
2005	25.9	27.5	80.4	-	-	-	8.7
2009	28.8	28	32.9	28.4	17	23.4	18.4
2015	6.6	28.4	26.7	21.7	17	-	16.6

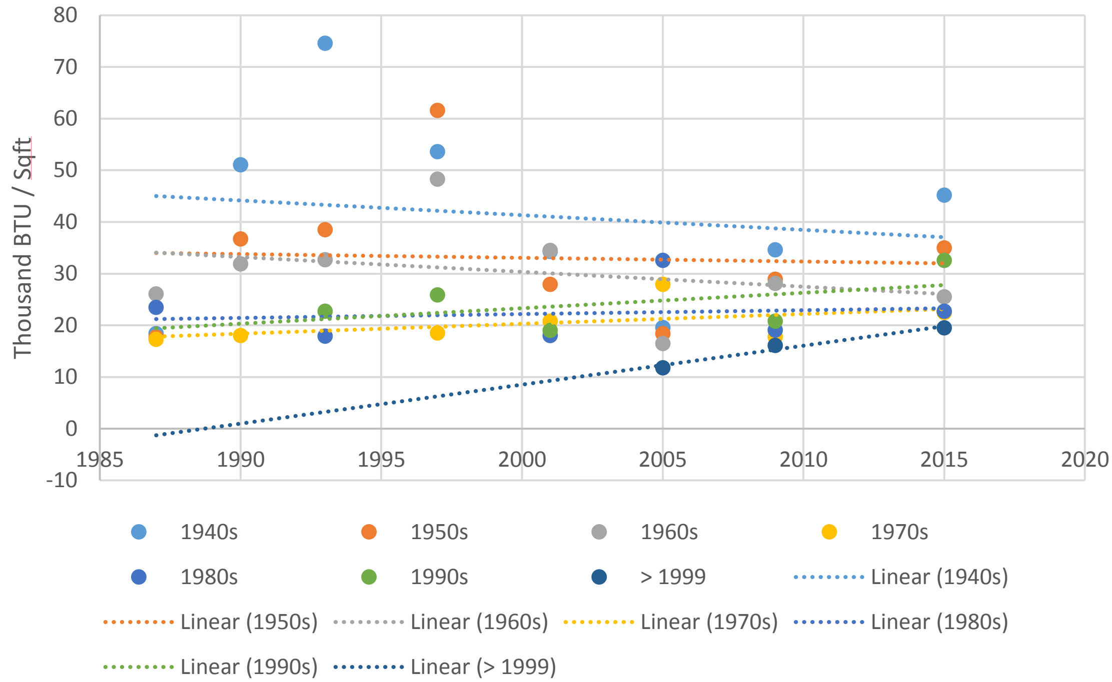


Figure 4 – Longitudinal trend of energy consumption: 1-story buildings built over decades.

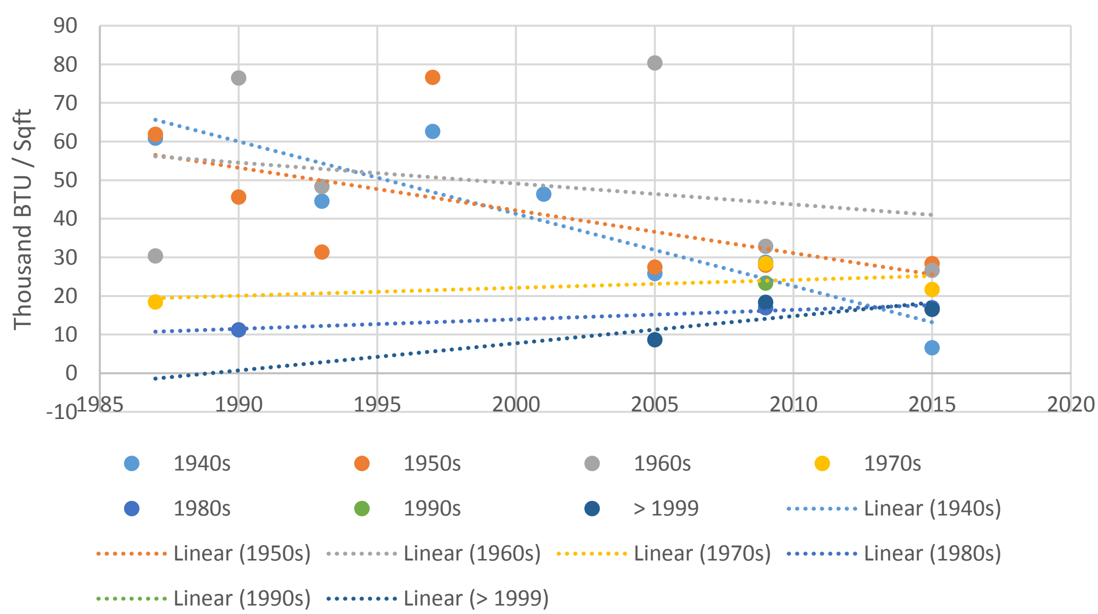


Figure 5 – Longitudinal trend of energy consumption: 2-story buildings built over decades.

In Figure 4 and Figure 5, each color represent the vintage of the building, and the dashed lines represent the linear energy consumption trend of the same color vintage over years as the buildings aged. Both figures show a decreasing trend for buildings built before 1970s. However, this trend is reversed when it comes to buildings built in 1970s and afterward, meaning that the energy consumption rate per unit area increases as time passes in newer buildings. One important fact to notice is that although the general trend is decreasing for older buildings and increasing for newer ones, the rates at each time frame (e.g. 2015) are still lower for newer buildings in comparison to older ones as mentioned previously in the NAHB report.

A recent study investigated the durable airtightness in single-family dwellings [78]. The results of this work showed that the increase in air leakage with age is the highest for homes that were built between 2001 and 2010 and were lower for homes that were built between 1991 and 2000, and were even lower for homes built between 1981 and 1990. Additionally, no effect of aging was observed for homes that were built before 1980, where majority of the homes were at least 30 years old when tested. Hence, this study concluded that aging might be occurring initially and not indefinitely. This phenomenon could potentially justify the difference in trends observed in Figure 4 and Figure 5. In this case, older buildings that were built before 1970s already aged and the consumption rates are already calibrated in them. On the other hand, the newer buildings built from 1970s and afterwards are still going through their calibration process which results in an increase in their energy consumption rates over the next three or four decades after their construction.

CHAPTER 4. EMBODIED LCA COMPARISON OF SINGLE FAMILY RESIDENTIAL HOUSES CONSIDERING THE 1970S TRANSITION OF CONSTRUCTION INDUSTRY IN ATLANTA

As stated in previous chapters, LCA is a set of methods, tools, and data designed to estimate material flows and assess environmental impacts over the life cycle of a product or a service [37]. This chapter aims to closely apply the ISO14040 standard [35] procedure to conduct an embodied LCA analysis on the residential buildings in Atlanta. For this purpose, I have used the four benchmarked buildings defined in previous chapter as the baseline of the analysis.

The scope of this chapter is to systematically compare the embodied energy and subsequent environmental emissions in typical residential buildings through their material production, construction, maintenance and replacements as well as the end of life phases. The following sections describe the four LCA steps conducted including the system under consideration, the procedures undertaken to obtain the required data, the impacts assessment and the following interpretation of the outcomes.

4.1 Scope and Boundaries

4.1.1 Goal and Scope

The goal of this study is to estimate and assess the comparative embodied energy and environmental impacts of residential buildings in Atlanta region considering the 1970s transition in building construction industry. This is accomplished by mapping the life cycle embedded energy and environmental measures of a variety of single-family detached residential buildings in the region, through 75 years of maintenance and replacements. The results will provide quantifiable and comparable energy and environmental impacts of single-family detached units built either before or after 1970s in Atlanta metropolitan area.

4.1.2 Functional Unit

In this study, the product system is one typical stand-alone single-family detached residential building. The functional unit is the embodied energy and associated environmental impacts per one square footage gross living area of the building. However, the embodied energy and associated environmental impacts are also calculated per person in order to compare people footprints as well.

4.1.3 System Boundary

In this study, the product system is one building. The process flows for this system include the embodied primary energy and environmental impacts associated with material manufacturing, including resource extraction and recycled content, related transportation, on-site construction, maintenance and replacement required over life cycle of the building as well as demolition, disposal and material reuse. Figure 6 shows the detailed system boundary of this study separated by life stages of the building.

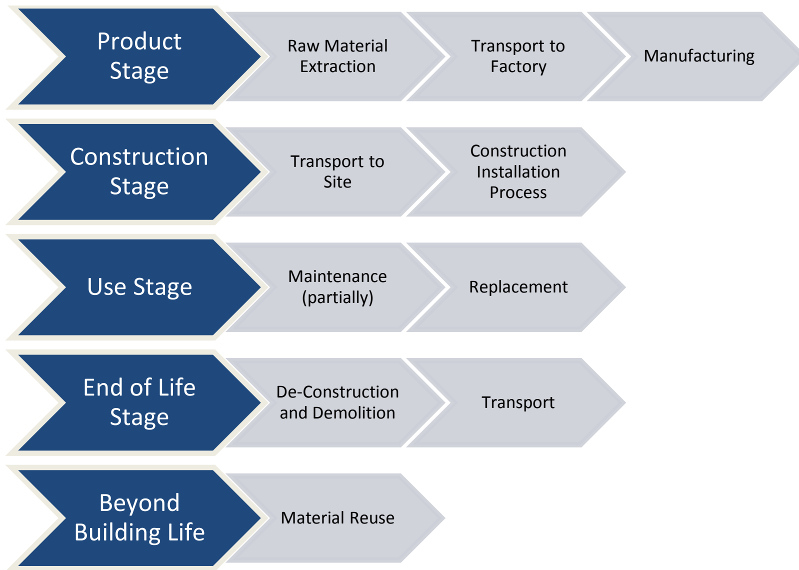


Figure 6 – System boundaries for the embodied LCA of residential buildings

4.2 Life Cycle Inventory (LCI)

In this study, the process-based LCA method was used to calculate embodied energy and associated environmental impacts of the buildings. For this purpose, the Athena Impact Estimator for Buildings 5.2 [79] was utilized to model the four baseline classification of buildings as defined in Figure 2. The advantage of using Athena impact estimator over other available LCA tools is that it is the only North American process-based LCA tool which not only covers the cradle to cradle systems boundary, but also is particularly designed for building product systems [23]. Moreover, this tool has the "Atlanta" regional data in its database which makes it an even more exceptional LCA tool for the purpose of our analysis in this study. The Athena LCI database is comprised of ISO 14040/14044-compliant unit process LCI data related to basic materials, building products and components, fuel use, and transportation.

Previous study on embodied energy analysis of buildings showed that the foundation and floors, walls and roofs dominate the impact in the embodied phase. Floor and wall finishes can make up to 30% of the embodied phase impact over a 100-year life time due to their relatively shorter lifetime [80]. In this study, all building structural and envelope components (including walls, windows, foundation, roof, and floors, etc.) of the previously benchmarked buildings were modeled within the Athena software. Table 9, Table 10, Table 11 and Table 12 show the breakdown of Bill of Material (BOM) quantities with the materials contribution to each building element for four building scenarios. In all tables, the "year 1" columns represent the amount of material required up until the construction of the structure, and the following columns represent additional amount of same material needed over the 75 years of building's life span.

The calculated quantities were extracted from Athena impact estimator, after designing the models presented in chapter 3. Although the details of background calculations for each phase of the system boundary is available within the software's manual [79], specific methodologies used in calculating construction, replacement and maintenance of the building scenarios as well as the regional specifications is provided in the following paragraphs:

On-site construction: This phase includes the energy used to transport materials or components from the manufacturer to a national distribution center and from the distribution center to the building site. The transportation distances are based on regional surveys. The impact estimator also calculates the energy used to construct the structural elements of the building and the environmental emissions associated with it.

Table 9 – BOM to construct 1-story building built before 1970 and after 75 years of its life span

Material	Unit	Year 1				Additional in 75 years			
		Floors	Foundations	Roofs	Walls	Floors	Foundations	Roofs	Walls
#15 Organic Felt	m2	0.0000	0.0000	185.8242	0.0000	0.0000	0.0000	511.0167	0.0000
Concrete Benchmark 3000 psi	m3	0.0000	27.5551	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FG Batt R11-15	m2 (25mm)	0.0000	0.0000	0.0000	511.6012	0.0000	0.0000	0.0000	0.0000
Galvanized Sheet	Tonnes	0.0271	0.0000	0.1250	0.0000	0.0000	0.0000	0.0000	0.0000
Large Dimension Softwood Lumber, kiln-dried	m3	4.0469	0.0000	4.2023	0.0000	0.0000	0.0000	0.0000	0.0000
Nails	Tonnes	0.0234	0.0000	0.0348	0.0496	0.0000	0.0000	0.0000	0.0205
Organic Felt shingles 20yr	m2	0.0000	0.0000	171.1539	0.0000	0.0000	0.0000	684.6156	0.0000
Pine Wood Bevel Siding	m2	0.0000	0.0000	0.0000	155.8619	0.0000	0.0000	0.0000	311.7238
Rebar, Rod, Light Sections	Tonnes	0.0000	0.4398	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Small Dimension Softwood Lumber, kiln-dried	m3	0.0000	0.0000	0.0000	7.1635	0.0000	0.0000	0.0000	0.3254
Softwood Plywood	m2 (9mm)	269.5433	0.0000	216.1891	0.0000	0.0000	0.0000	0.0000	0.0000
Solvent Based Alkyd Paint	L	0.0000	0.0000	0.0000	14.7417	0.0000	0.0000	0.0000	206.3838
Unclad Wood Window Frame	kg	0.0000	0.0000	0.0000	143.2334	0.0000	0.0000	0.0000	214.8500
Water Based Latex Paint	L	0.0000	0.0000	0.0000	25.3940	0.0000	0.0000	0.0000	247.6544
Welded Wire Mesh / Ladder Wire	Tonnes	0.0000	0.0856	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 10 – BOM to construct 2-story building built before 1970 and after 75 years of its life span

Material	Unit	Year 1				Additional in 75 years			
		Floors	Foundations	Roofs	Walls	Floors	Foundations	Roofs	Walls
#15 Organic Felt	m2	0.0000	0.0000	193.1852	0.0000	0.0000	0.0000	531.2593	0.0000
Cedar Wood Bevel Siding	m2	0.0000	0.0000	0.0000	272.5156	0.0000	0.0000	0.0000	545.0312
Concrete Benchmark 3000 psi	m3	0.0000	44.6765	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
FG Batt R11-15	m2 (25mm)	0.0000	0.0000	0.0000	894.5054	0.0000	0.0000	0.0000	0.0000
Galvanized Sheet	Tonnes	0.0513	0.0000	0.1883	0.0000	0.0000	0.0000	0.0000	0.0000
Large Dimension Softwood Lumber, kiln-dried	m3	6.3103	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nails	Tonnes	0.0400	0.0000	0.0291	0.1023	0.0000	0.0000	0.0000	0.0440
Organic Felt shingles 20yr	m2	0.0000	0.0000	177.9337	0.0000	0.0000	0.0000	711.7349	0.0000
Rebar, Rod, Light Sections	Tonnes	0.0000	0.4398	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Small Dimension Softwood Lumber, kiln-dried	m3	0.0000	0.0000	4.7343	15.2082	0.0000	0.0000	0.0000	0.4727
Softwood Plywood	m2 (9mm)	460.2259	0.0000	224.7529	0.0000	0.0000	0.0000	0.0000	0.0000
Solvent Based Alkyd Paint	L	0.0000	0.0000	0.0000	25.7750	0.0000	0.0000	0.0000	360.8503
Unclad Wood Window Frame	kg	0.0000	0.0000	0.0000	210.5010	0.0000	0.0000	0.0000	315.7515
Water Based Latex Paint	L	0.0000	0.0000	0.0000	45.2955	0.0000	0.0000	0.0000	434.3529
Welded Wire Mesh / Ladder Wire	Tonnes	0.0000	0.1427	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 11 – BOM to construct 1-story building built after 1970 and after 75 years of its life span

Material	Unit	Year 1				Additional in 75 years			
		Floors	Foundations	Roofs	Walls	Floors	Foundations	Roofs	Walls
1/2" Moisture Resistant Gypsum Board	m2	0.0000	0.0000	0.0000	155.8619	0.0000	0.0000	0.0000	0.0000
1/2" Regular Gypsum Board	m2	0.0000	0.0000	0.0000	56.3767	0.0000	0.0000	0.0000	0.0000
3 mil Polyethylene	m2	0.0000	0.0000	0.0000	150.3075	0.0000	0.0000	0.0000	0.0000
6 mil Polyethylene	m2	0.0000	172.4652	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cold Rolled Sheet	Tonnes	0.0000	0.0000	0.0000	0.0286	0.0000	0.0000	0.0000	0.0000
Concrete Benchmark 3000 psi	m3	0.0000	24.7181	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Double Glazed No Coating Air	m2	0.0000	0.0000	0.0000	30.3786	0.0000	0.0000	0.0000	45.5679
Expanded Polystyrene	m2 (25mm)	0.0000	0.0000	0.0000	146.8485	0.0000	0.0000	0.0000	0.0000
FG Batt R11-15	m2 (25mm)	0.0000	0.0000	174.8119	0.0000	0.0000	0.0000	0.0000	0.0000
Galvanized Sheet	Tonnes	0.0271	0.0000	0.0856	0.0000	0.0000	0.0000	0.0000	0.0000
Joint Compound	Tonnes	0.0000	0.0000	0.0000	0.2118	0.0000	0.0000	0.0000	0.0000
Large Dimension Softwood Lumber, kiln-dried	m3	4.0469	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Metric Modular (Modular) Brick	m2	0.0000	0.0000	0.0000	148.7772	0.0000	0.0000	0.0000	0.0000
Mortar	m3	0.0000	0.0000	0.0000	3.9082	0.0000	0.0000	0.0000	0.0000
Nails	Tonnes	0.0234	0.0000	0.0279	0.0479	0.0000	0.0000	0.0000	0.0205
Paper Tape	Tonnes	0.0000	0.0000	0.0000	0.0024	0.0000	0.0000	0.0000	0.0000
Rebar, Rod, Light Sections	Tonnes	0.0000	0.4398	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Roofing Asphalt	kg	0.0000	0.0000	1389.9335	0.0000	0.0000	0.0000	3574.1147	0.0000
Small Dimension Softwood Lumber, kiln-dried	m3	0.0000	0.0000	4.7343	3.5770	0.0000	0.0000	0.0000	0.3254

Table 11 continued

Softwood Plywood	m2 (9mm)	269.5433	0.0000	224.7529	269.4487	0.0000	0.0000	0.0000	0.0000
Vinyl Clad Wood Window Frame	kg	0.0000	0.0000	0.0000	157.2723	0.0000	0.0000	0.0000	235.9085
Water Based Latex Paint	L	0.0000	0.0000	0.0000	4.9038	0.0000	0.0000	0.0000	7.3556
Welded Wire Mesh / Ladder Wire	Tonnes	0.0000	0.1469	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 12 – BOM to construct 2-story building built after 1970 and after 75 years of its life span

Material	Unit	Year 1				Additional in 75 years			
		Floors	Foundations	Roofs	Walls	Floors	Foundations	Roofs	Walls
1/2" Moisture Resistant Gypsum Board	m2	0.0000	0.0000	0.0000	272.5156	0.0000	0.0000	0.0000	0.0000
1/2" Regular Gypsum Board	m2	305.3537	0.0000	0.0000	186.8435	0.0000	0.0000	0.0000	0.0000
3 mil Polyethylene	m2	0.0000	0.0000	0.0000	262.8041	0.0000	0.0000	0.0000	0.0000
6 mil Polyethylene	m2	0.0000	213.3641	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cold Rolled Sheet	Tonnes	0.0000	0.0000	0.0000	0.0500	0.0000	0.0000	0.0000	0.0000
Concrete Benchmark 3000 psi	m3	0.0000	46.1389	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Expanded Polystyrene	m2 (25mm)	0.0000	0.0000	0.0000	256.7562	0.0000	0.0000	0.0000	0.0000
FG Batt R11-15	m2 (25mm)	0.0000	0.0000	174.8119	0.0000	0.0000	0.0000	0.0000	0.0000
Galvanized Sheet	Tonnes	0.0513	0.0000	0.0856	0.0000	0.0000	0.0000	0.0000	0.0000

Table 12 continued

Joint Compound	Tonnes	0.3047	0.0000	0.0000	0.4584	0.0000	0.0000	0.0000	0.0000
Large Dimension Softwood Lumber, kiln-dried	m3	6.3103	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Metric Modular (Modular) Brick	m2	0.0000	0.0000	0.0000	260.1285	0.0000	0.0000	0.0000	0.0000
Mortar	m3	0.0000	0.0000	0.0000	6.8332	0.0000	0.0000	0.0000	0.0000
Nails	Tonnes	0.0429	0.0000	0.0279	0.0998	0.0000	0.0000	0.0000	0.0440
Paper Tape	Tonnes	0.0035	0.0000	0.0000	0.0053	0.0000	0.0000	0.0000	0.0000
Rebar, Rod, Light Sections	Tonnes	0.0000	0.4398	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Roofing Asphalt	kg	0.0000	0.0000	1389.9335	0.0000	0.0000	0.0000	3574.1147	0.0000
Small Dimension Softwood Lumber, kiln-dried	m3	0.0000	0.0000	4.7343	7.4795	0.0000	0.0000	0.0000	0.4727
Softwood Plywood	m2 (9mm)	460.2259	0.0000	224.7529	583.1821	0.0000	0.0000	0.0000	0.0000
Triple Glazed No Coating Air	m2	0.0000	0.0000	0.0000	44.2406	0.0000	0.0000	0.0000	66.3609
Vinyl Clad Wood Window Frame	kg	0.0000	0.0000	0.0000	231.1332	0.0000	0.0000	0.0000	346.6997
Water Based Latex Paint	L	0.0000	0.0000	0.0000	10.5080	0.0000	0.0000	0.0000	15.7621
Welded Wire Mesh / Ladder Wire	Tonnes	0.0000	0.1490	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

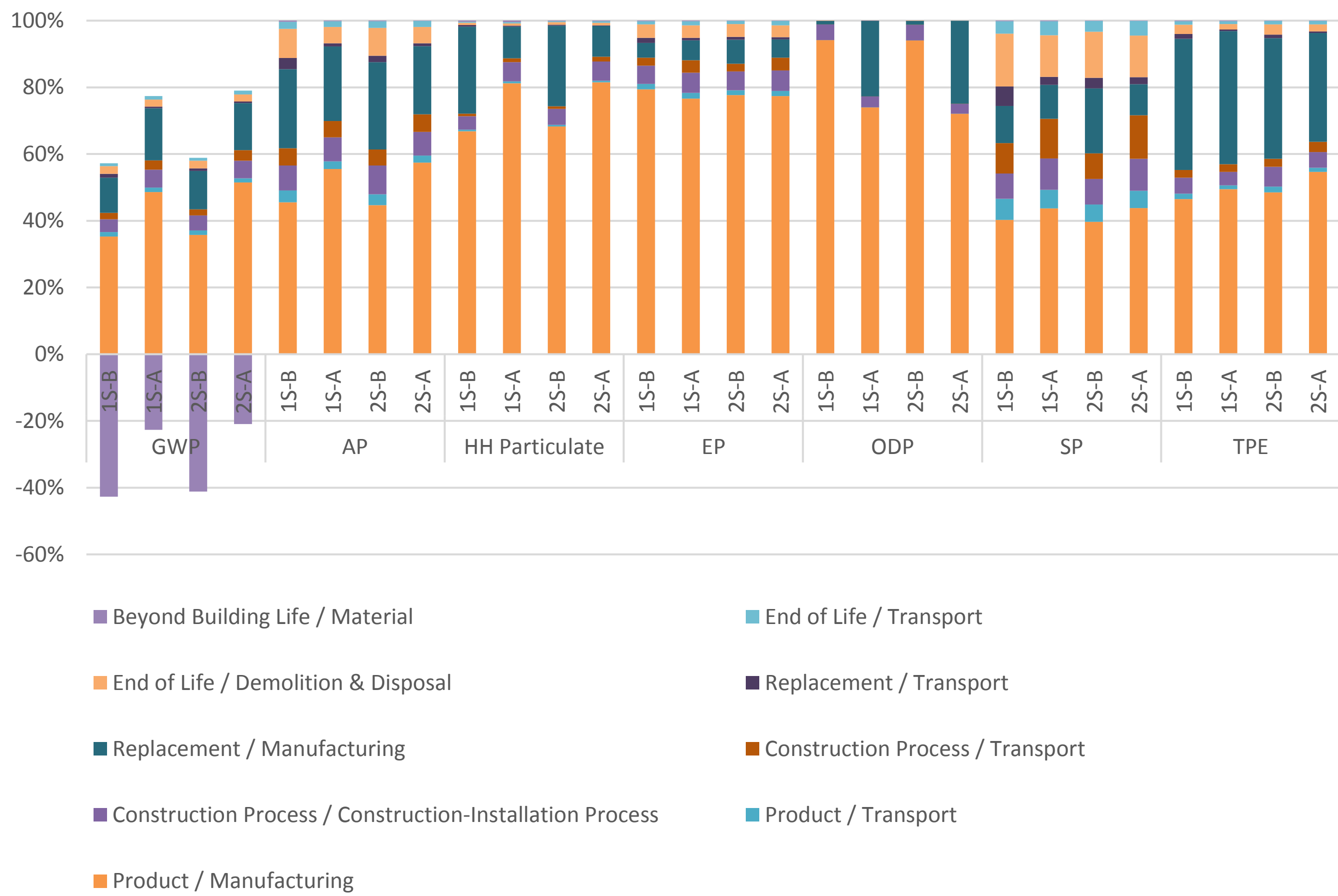


Figure 7 – LCA measures by life cycle stages for four building scenarios

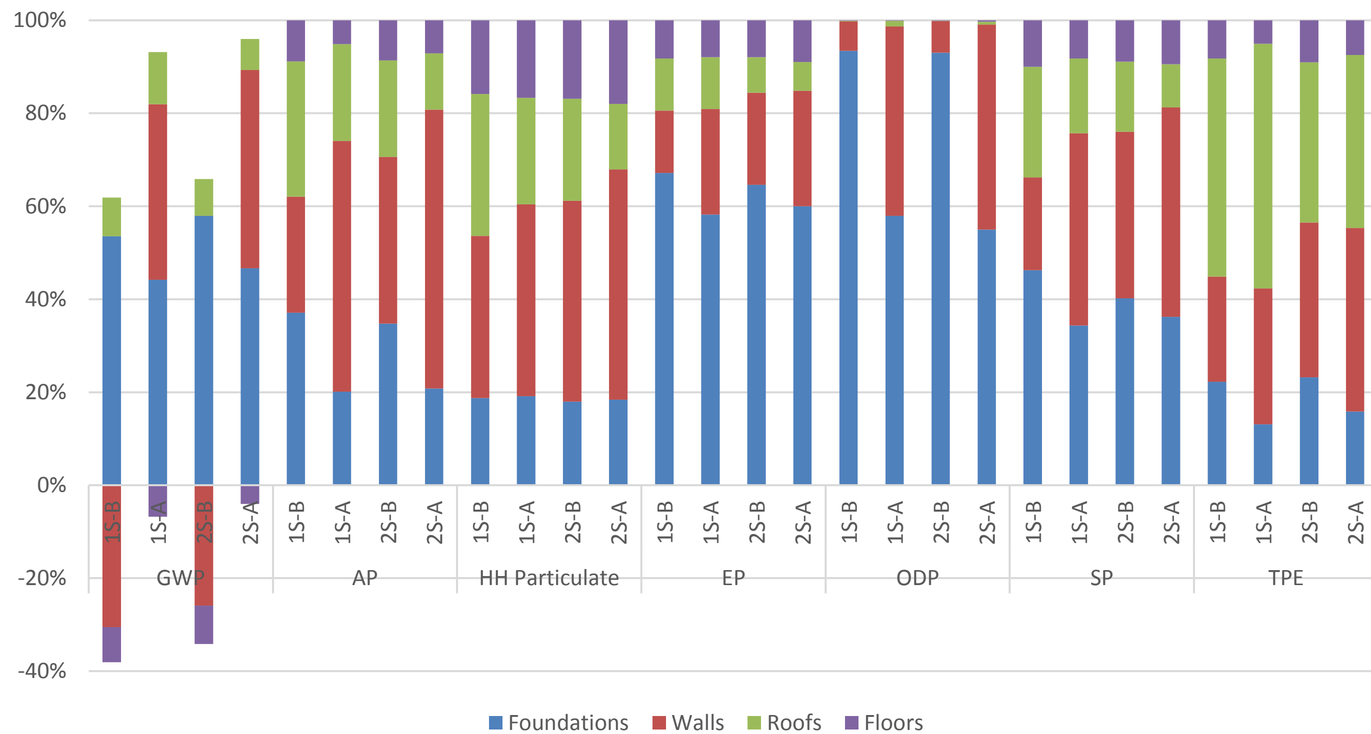


Figure 8 – LCA measures by assembly groups for four building scenarios

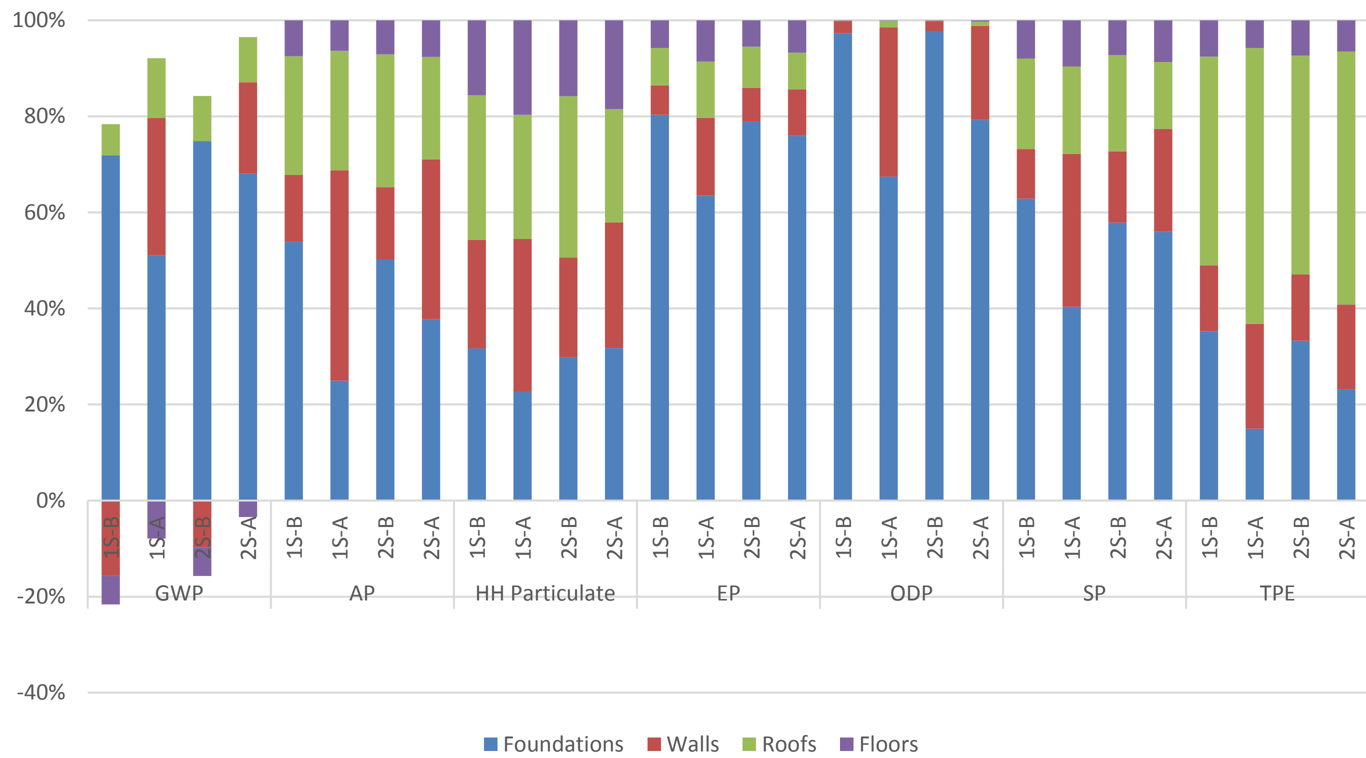


Figure 9 – LCA measures per square meter of assembly area for four building scenarios

Table 13 – The list of six TRACI environmental impact categories with their acronyms, descriptions and measurement metrics

Impact Categories	Acronym	Description	Measurement Basis
Global Warming Potential	GWP	Heat trapping in the atmosphere	CO2 equivalence
Acidification Potential	AP	High concentrations of NOx and SO2 in air or water	SO2 equivalence
Human Health Respiratory	HH Particulate	Particulate of various sizes (PM10 and PM2.5)	PM2.5 equivalent
Ozone Depletion Potential	ODP	Reduction of the protective ozone layer within the stratosphere	CFC-11 equivalent
Photochemical Smog Potential	SP	Interactions of volatile organic compounds (VOCs) and nitrogen oxides at the presence of sunlight in the atmosphere	O3 equivalent
Eutrophication Potential	EP	Fertilization of surface waters by nutrients that were previously scarce	Nitrogen (N) equivalent

Table 14 – Embodied LCA measures per gross living area for four building scenarios

Number stories	Year built	GWP (kg CO2/ m2)	AP (kg SO2/ m2)	HH Particulate (kg PM2.5/ m2)	EP (kg N/ m2)	ODP (kg CFC-11/ m2)	SP (kg O3/ m2)
1	Before 70s	2.94E+01	7.49E-01	3.02E-01	1.01E-01	1.43E-06	1.36E+01
	After 70s	1.19E+02	1.29E+00	2.86E-01	1.05E-01	2.08E-06	1.66E+01
2	Before 70s	2.83E+01	6.26E-01	2.27E-01	8.37E-02	1.15E-06	1.24E+01
	After 70s	1.06E+02	1.10E+00	2.29E-01	9.31E-02	2.01E-06	1.42E+01

Table 15 – Embodied LCA measures per person for four building scenarios

Number stories	Year built	GWP (kg CO2/ person)	AP (kg SO2/ person)	HH Particulate (kg PM2.5/ person)	EP (kg N/ person)	ODP (kg CFC-11/ person)	SP (kg O3/ person)
1	Before 70s	1.85E+03	4.72E+01	1.90E+01	6.37E+00	9.04E-05	8.57E+02
	After 70s	7.52E+03	8.14E+01	1.80E+01	6.62E+00	1.31E-04	1.05E+03
2	Before 70s	3.62E+03	8.00E+01	2.90E+01	1.07E+01	1.47E-04	1.58E+03
	After 70s	1.35E+04	1.40E+02	2.93E+01	1.19E+01	2.57E-04	1.82E+03

Maintenance and replacement: The Athena database assumes that replacement materials and components will be the same as those used in original construction. In situations where the service life of a replacement material or component exceeds the remaining user specified service life of the building, the difference is credited. General information about the reference service life and replacement schedule of the main materials are presented in Table 16, based on reported Athena database [81]. However, due to limitations in the publicly available maintenance and replacement schedules and their LCI of the Athena Impact Estimator tool, detailed information is not presented in this table. Additionally, the maintenance of small components such as doors are negligible and therefore, not considered in this study.

Table 16 – Maintenance and replacement schedule for buildings' main materials (All numbers are extracted from Athena manual for residential single-family buildings in Atlanta)

Activity Description	Maintenance and Repair Cycle after (# years)
Re-painting wood siding	5
Replacement of 100% of the wood siding	25
Repainting of wood windows	6
Replacement of failed glazing units	1
Removal and replacement of window system	16
Window re-caulking (replacement of sealant)	8
Annual replacement of failed glazing units of windows	1
Replacement of 100% of organic-based asphalt shingled roof	16
Replacement of 100% of fiberglass-based asphalt shingled roof	20

Regional specification: Based on the selected region ("Atlanta" in this study), appropriate electricity grid, transportation modes and distances as well as product-manufacturing technologies are used to calculate the material and energy quantities.

Regional product market share analysts have generated the background assumptions by developing weighted average life cycle inventory profiles for the products as well as weighted average transportation profiles based on distance and modal split. In terms of electricity supply, Atlanta belongs to the Southeast Electric Reliability Grid (SERC). Consequently, a composite of the Georgia grid and Eastern North America grid intertie are proportionally combined and used by the model to represent the electricity use in the region. This approach to electrical grids is taken when calculating electricity-related environmental burdens associated with the manufacturing of basic materials, products and components used in a building, as well as electricity used in the construction and maintenance of a building.

By modeling the baselines in Athena Impact Estimator, and choosing "Atlanta" as the project location, appropriate electricity grids, transportation modes and distances, and product manufacturing technologies applicable to the product mix for the selected region is automatically included in the analysis. However, since neither Athena Impact Estimator nor any other process-based LCA tool covers historical LCI databases, it was not practicable to utilize a dynamic temporal LCI analysis in this study. Hence, I have assumed that the construction transition only affect the structural and building envelope changes and did not take into account other changes such as material manufacturing and electricity mixes over the years.

4.3 Impact Assessment

The LCI is characterized based on mid-point impact estimation methods developed by the US Environmental Protection Agency (EPA) and reported in their Tool for the

Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) [82]. Through this method, six environmental impacts as described in Table 13 plus the Total Primary Energy (TPE) were calculated over building's life cycle. TPE 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. This is also known as "embodied energy" of the building [83].

The results are shown in Figure 7 (separated by life cycle stages) and Figure 8 (separated by assembly groups). Figure 7 indicates that material manufacturing dominates the embodied environmental impacts followed by the material replacement as the second largest contributor, which is aligned with the results of a previous study on residential houses in Indonesia [59]. On the other hand, end of life stage seems to have the lowest impacts of all the stages. This is aligned with previous study on typical US residences in 1997 which identified disposal phase as the smallest environmental impact contributor to US residential building's environmental impacts [84].

Comparing the buildings built before 1970s and after 1970s, it can be observed that after 1970s, product manufacturing, construction and end of life phases contributes more in all environmental measurements. However, maintenance and material replacement contributes more in terms of SP and HH Particulate for buildings built before 1970s. From Figure 8 and Table 16, we can see that this is mostly because of roof assembly effect and shorter maintenance and repair cycles (16 years) for before 1970s roof assembly materials. Additionally, Figure 7 shows that material replacement contributes more in terms of ODP for buildings built after 1970s. Previous study showed that the high share of pre-use phase in ODP has to do with the use of CFCs or HCFCs in insulating manufacturing [85].

Additionally, investigating the replacement materials from Table 9, Table 10, Table 11 and Table 12 reveals that the use of "vinyl" in window frames for building built after 1970s could be one of the reasons. This statement is based on a previous study which indicated that production and installation of vinyl-based materials have a high environmental impacts in the ODP category [86].

Figure 7 also shows that by recycling and reusing the building materials after the 75 years of building service life, we can save carbon emission by up to 40% for buildings built before 1970s and up to 20% for buildings built after 1970s. It can be seen in Figure 8 that this carbon emission savings is mostly because of recycling walls and floors in buildings built before 1970s and some floor materials in buildings built after 1970s. A previous study showed that softwood plywood (sheathing wall material in after 1970s' buildings) has generally higher environmental impacts in comparison to pinewood bevel siding (siding wall material in before 1970s' buildings) [87]. This effect, in addition to the environmental impacts from other insulation materials in wall envelopes as well as lower usage of wooden materials (e.g., brick cladding instead of wood bevel siding) for buildings built after 1970s, compensated the recycling effect. It also resulted in a total negative impact on global warming (shown as positive percentage of contribution in Figure 8) for wall assemblies in buildings built after 1970s. Moreover, Athena Impact Estimator mainly focused on recycling of two main materials of steel and wood in buildings. Therefore, because residential buildings modeled in this study are all wood-based structures, the beyond building life phase mostly covers the recycling of wood-based assemblies in this study. Additionally, in the Athena Impact Estimator manual, it is stated that since forest growth results in the removal of atmospheric carbon dioxide, the negative emission is only applied to the carbon in the product. It then accounted similarly to other types of greenhouse gas emissions resulting in GWP impact [79].This is the reason why the effect of recycling and reusing is only shown for the GWP impact in Figure 8.

Figure 8 indicates the contribution of building assemblies to the embodied life cycle impact of the buildings. This figure shows that foundation covers more than 40% of the total embodied CO2 emission (GWP) in all building categories. The impacts of foundation are even higher (approximately 60%) for the eutrophication and ozone depletion potentials. The main reason is the high usage of cement-based materials in foundation, which is the main cause of producing CO2 emission. From building perspective, the contribution of foundation in all 6 environmental impact categories, are higher for buildings built before 1970s. This is mainly the result of less amount of cement-based materials in foundation designs for buildings built after 1970s. Additionally, the figure shows that roof consumes more than 40% of total embodied primary energy in all building categories, which is primarily due to the asphalt, and other energy intensive resources (e.g., wood fiber, limestone, coarse aggregate, dolomite, etc.) used in the roofing system.

It is also observed that floor has the lowest environmental impacts of all building assemblies. Floors generally follow an equal trend for all building categories, with less contribution in buildings built after 1970s for some environmental measurements such as GWP, AP and TPE. Walls have higher contribution to environmental impacts in buildings built after 1970s. This high impact is due to more chemicals used in wall insulation materials. An opposite effect is recognized for roofs, meaning that, in buildings built after 1970s, roofs have less environmental effect in comparison to older buildings for all impacts but ODP, GWP and TPE. Although the environmental effect of walls follows similar trend in both 1-story and 2-strory buildings built after 1970s, it has substantially greater effect when it comes to 2-strory buildings built before 1970s in comparison to same vintage 1-strory buildings, specifically in SP impact category. This difference is mainly because we have modeled the 1-story building with pine wood bevel siding and the 2-story building with stronger cedar wood bevel siding.

Figure 9 indicates the contribution of building assemblies per square meter of assemble area to the embodied life cycle impact of the buildings. This figure along with Figure 8 illustrate that the contribution of foundations and roofs are more due to the environmental density of their materials and component, whereas the contribution of walls is mainly due to the greater amount of total area of these assemblies in the buildings' structure. Additionally, Figure 8 clearly represents the greater contribution of walls in all environmental categories for buildings built after 1970s. This confirms the fact that the after 1970s wall components are more environmental intensive (mainly because of insulation components) in comparison to the wall assemblies before 1970s.

4.4 Interpretation

The embodied LCA results are normalized by the gross living area of the building in square meter (m2) to control for different building designs as discussed in system boundaries. The environmental effects of the buildings in 4 scenarios normalized by gross square meter are presented in Table 14.

In general, the results show that residential buildings built before 1970s have lower embodied environmental impacts per square meter than residential buildings built after 1970s. This difference is in its highest for GWP, which is 3.75-4.04 higher for buildings built after 1970s. AP, ODP and SP come next with approximately 72%, 45% and 22% increase respectively for their 1-story models built after 1970s and with approximately 75%, 75% and 15% increase respectively for their 2-story models built after 1970s. This increased trend for all six categories are mostly due to the usage of more materials such as walls and roof insulations following the implementation of energy codes in the region after 1970s. The only exception in this case is the HH particulate for 1-story buildings, which the ratio per square meter is higher for before 1970s buildings in comparison to after 1970s. This slight difference in higher PM2.5 per square meter for 1-story buildings is due to the reason that the highest contributors to respiratory impacts are associated with cement-based materials and asphalts (foundation and roof). Therefore, since there are the same amount of cement and asphalt (foundation and roof) in both 1-story and 2-story buildings, dividing them by a larger area for 2-story buildings, resulted in a smaller number per unit area. The reason of only seeing this issue for before 1970s buildings is particularly associated with the foundation wall system in before 1970s buildings. For after 1970s, the foundation system is slab on grade which required much lower amount of cement, resulting in lower HH Particulate in total.

The increase in environmental impacts for buildings built after 1970s is generally higher for 2-story buildings in comparison to the 1-story buildings except for the SP impact. This exception is associated with higher embodied foundation and roof SP impacts per unit area for 1-story buildings. Although the foundation thickness is doubled for 2-story buildings, the greater (almost doubled) gross living area substantially reduce the total SP impact per unit area for 2-story buildings. On the other hand, the increase in ODP impacts for buildings built after 1970s is considerably higher for 2-story buildings in comparison to other environmental impacts. As stated in the impact assessment section, this is mainly due to the higher contribution of insulating materials (e.g., glazed windows, vinyl, etc.) over the construction, maintenance and replacement phases for 2-story buildings due to the greater mass value of walls and windows per unit area. Additionally, 2-story buildings after 1970s are designed with triple glazed windows while the 1-story buildings after 1970s are designed with double glazed windows, which further affect the greater contribution of ODP for 2-story buildings in this study.

On the other hand, 2-story residential buildings have lower embodied impacts per square meter in comparison to 1-story residential buildings. The reason is that although the total mass value of materials increased for 2-story buildings, the greater gross living area still reduce the final contribution of total impacts per unit area in the normalized embodied energy and environmental impacts of 2-story buildings. This reduction trend is also aligned with the results of a previous study conducted on 1-story and 2-story residential buildings in Phoenix, AZ. This study concluded that the 1-story units are more energy intensive than 2-story units of equal size [66].

Figure 10 shows the total embodied primary energy over the 75 years of building life span. This includes production and construction phases, maintenance and replacements as well as end of life, demolition and reuse/recycle of potential materials. It can be concluded that residential buildings built before 1970s have lower (approximately 35%) embodied energy in comparison to buildings built after 1970s. Additionally, it is shown that 2-story buildings have lower embodied energy per square meter in comparison to 1-story buildings, which is the result of lower energy intensive material usage per unit area of 2-story buildings. Additionally, the results confirm the positive correlation between embodied energy and embodied carbon as previously indicated by researchers on residential buildings in Phoenix, AZ [66] and Norfolk, UK [26].

Table 14 shows that GWP is in the range of 28.3 – 29.4 kg CO2/m2 for buildings built before 1970s and 106 – 119 kg CO2/m2 for buildings built after 1970s. Although the calculated numbers are substantially lower than some previously defined ranges such as 250 – 750 CO2/m2 derived by modeling existing buildings with deQo at MIT [53], the numbers are closer (still lower) to the range of calculated results from 5 residential case studies in Australia [88]. Additionally, the numbers are also close to the embodied carbon benchmark study with a range between 32 – 1004 kg CO2/m2 initial embodied carbon for residential buildings [54]. However, the lower level of GWP impact in this study in comparison to other similar studies is mainly due to the effect of including beyond building life and material re-use phase in this study. As previously discussed in the impact assessment section, recycling and reusing the wood within the buildings' structure directly affect the total life cycle carbon emission of the building and consequently result in lower GWP impact in comparison to cradle to grave building LCA studies.

The TPE (embodied energy) calculated for building scenarios in this study varies between 1.8 – 3.9 Gj/m2 which is within the range of 1 – 12 Gj/m2 previously calculated based on 90 LCEA residential case studies [21]. Another study estimated 4.26 Gj/m2 as the embodied energy of a wooden 3-story office building [89]. A handbook of energy use for building construction in the US, calculated the embodied energy of a two family house to be around 5.3 Gj/m2 [90]. However, the number decreased to 4.16 Gj/m2 when removing the equipment (plumbing, HVAC, etc.) effect to align boundaries with the system boundary of this study.

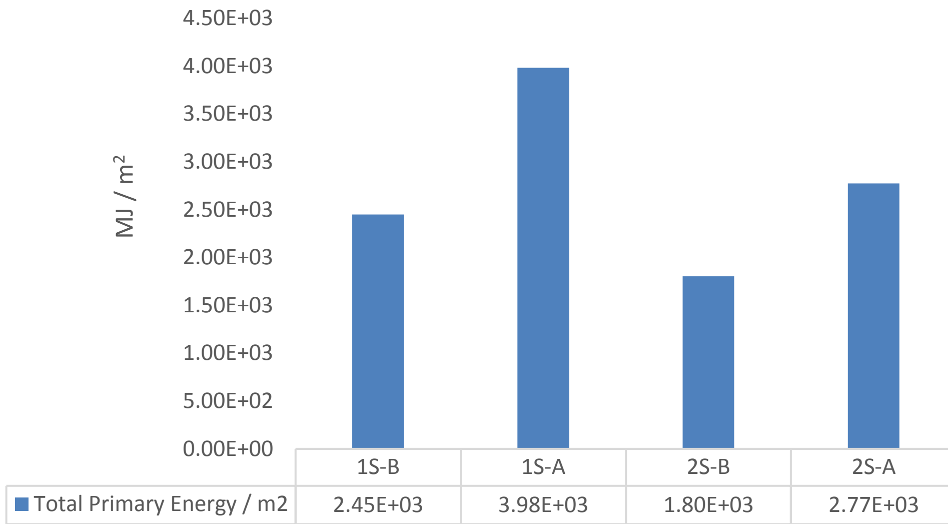


Figure 10 – Total embodied primary energy per unit area separated for four building scenarios

Combining the results of GWP from Table 14 and TPE from Figure 10, it is observed that despite the positive correlation between embodied energy and embodied carbon, there is an increase of about 3.7-4 times in the GWP indicator and only of about 1.5-1.6 times in the TPE indicator between the before and after 1970's buildings. One reason for this difference could be the lower impact of recycling on GWP indicator for buildings built after 1970s as those buildings' structures consist of lower amount of wooden materials (e.g., brick cladding instead of wood bevel siding). This would ultimately result in the absence of the positive effects of wood recycling including carbon savings for the after 1970's buildings while the amount of TPE is relatively the same for both building vintages and justify the greater gap between the before and after 1970's buildings' GWP in reference to TPE indicator.

The results are also normalized per person for a better comparison between household footprints. Based on the 2012 report on households and families from US census, the average number is 2.58 people per household in the United States [91]. The numbers are shown in Table 15. Moreover, the normalized embodied energy per person is also shown in Figure 11. Both results from embodied energy and embodied environmental impacts showed that the numbers are increased from 1-story to 2-story buildings as well as from before 1970s to after 1970s buildings.

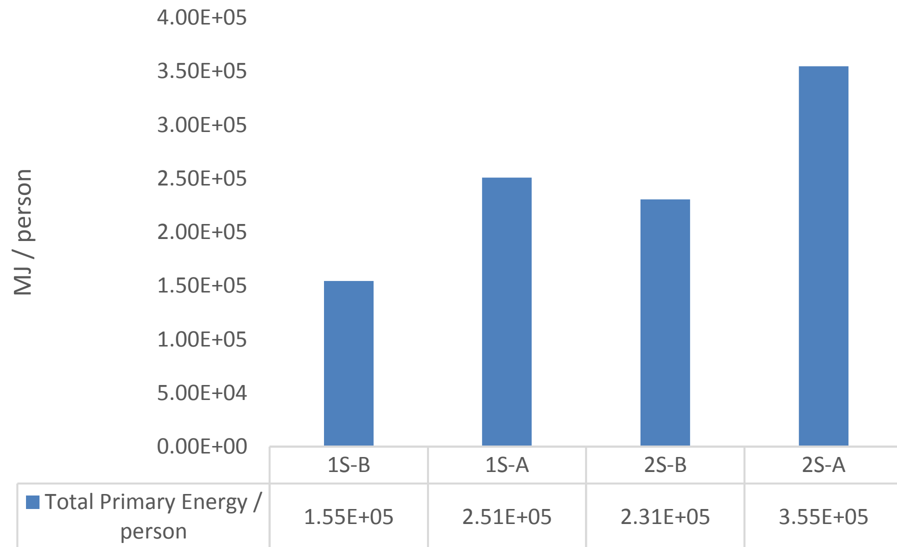


Figure 11 – Total embodied primary energy per person separated for four building scenarios

Comparing the results normalized by unit area with the results normalized by person showed the importance of choosing the suitable functional unit following the question that is needed to be answered. If the question asked for the building's footprint, it is a better idea to choose the unit area as the functional unit, however, if the person's footprint is of interest, the results may be completely different as shown in this analysis. Therefore, it is of high importance to understand what question your study is trying to answer before choosing the functional unit of the analysis.

CHAPTER 5. EMBODIED LCA COMPARISON OF SINGLE FAMILY RESIDENTIAL IMPROVEMENT OPTIONS: ATLANTA CASE STUDY

On January 1, 2011, the new building code became effective in the state of Georgia. As of then, the 2009 International Energy Conservation Code (IECC), along with the Georgia State Supplements and Amendments, have made up the residential buildings' energy code in the state. However, the implementation of the codes is still optional for one- and two-story dwellings [32].

Building energy codes are important for a number of reasons. They not only save energy and thereby reduce overall costs, but also result in healthier, more comfortable buildings [74]. Additionally, energy codes can help boost the local economy, by spending the energy savings on other goods and services in the local economy and consequently reduce foreign energy dependency.

On the other hand, the general goal of residential energy codes are to decrease the operational energy consumption rate by improving insulation, reducing air leakage, heat recovery and other improvement options based on the geographical location of the building. Although such measures result in lower operational energy demand, they increase material use, and consequently, the production energy demand. Therefore, the increase in the embodied energy of building materials, transportation and construction may even up the saved energy in the operational phase. Hence, the role of the life cycle energy performance should be considered before proposing retrofit actions for buildings.

A report from NAHB showed that more stringent energy conservation requirements for new homes can have a reverse effect of keeping people in older, less energy-efficient homes [92]. Studies discussed that an efficient housing renovation should reduce the environmental impact, increase the indoor comfort, and improve the architectural appearance of the building facades [93]. Therefore, an efficient retrofit can effectively reduce a significant amount of energy consumption as well as environmental impacts at relatively low cost.

The objective of this chapter is to identify the potential improvement options for single-family residential buildings in the Atlanta metropolitan area, considering that all aspects of a building's thermal envelope (e.g., walls, windows, ceilings, floors and foundation) have the potential to be better insulated and more effectively air-sealed. Furthermore, the embodied energy and impacts of selected retrofit options are calculated and compared in addition to their energy consumption savings to highlight the role of the life cycle approach for selecting the most effective options during the design and implementation of retrofit actions.

5.1 Identify Improvement Options

To identify the improvement options for benchmarked residential dwellings previously discussed in Chapter 3, various regional and national protocols and standards as well as real case studies were utilized. The major references and detailed descriptions of how they have been implemented in this study is summarized below.

5.1.1 Southface Prioritization Protocol

Southface Energy Institute (Southface) is an organization promoting sustainable development and green building through education, research, advocacy and technical assistance [94]. In 2003, they have proposed a priority list developed protocol based on experience with existing home retrofit projects and the feedback of industry experts for the Georgia Power Home Performance with ENERGY STAR® program [74]. This protocol is designed to help homeowners in Atlanta with a recommended set of measures and approaches to take in order to increase their home energy efficiency. A summarized version of the protocol is shown in Table 17. However, due to the evolution in equipment efficiencies, such as HVAC equipment, modifications to the original protocol are needed in for up to date analysis. In Table 17, the highest priority is for categories recognized as "A" and the lowest priority is dedicated to category "D". Following this prioritization protocol, priorities "A" and "B" were selected as potential improvement options for the four building scenarios. If the building already meets the requirement, no further improvement was chosen for that building scenario.

Table 17 – Southface 2003 prioritization protocol [74]

Improvement	Existing condition	Priority
Air sealing	≥ 0.75 ACH natural	A
	0.50 – 0.74 ACH natural	B
	0.4 – 0.49 ACH natural	C
Improve ducts	≥ 25% duct leakage	A
	16 – 24.9% duct leakage	B
	10 – 15.9% duct leakage	C
	5 – 9.9% duct leakage	D

Table 17 continued

Insulate attic (attic floor air sealing must precede insulation work)	R-0-R-9	A
	R-10-R-19	B
	R-20-R-29	C
Insulate attic knee walls	None	A
	Insulated, unsheathed or incomplete sheathing	B
	Insulated, sheathed, but only effective R-13	D
Insulate walls	None	C
Insulate floor	None	B
	Any	C
Insulate basement/crawlspace walls	None	B
	Any	C
Radiant barrier	No radiant barrier	D
Replace heating system	60-69 AFUE / 5 HSPF	A
	70-79 AFUE / 6 HSPF	B
	80-89 AFUE / 7 HSPF	C
Replace cooling system	6-7.9 SEER	A
	8-9.9 SEER	A
	10 SEER	B
Replace water heater	< 0.5 gas, < 0.85 electric	B
	< 0.56 gas, < 0.89 electric	C
Insulate water heater and pipe	Electric	B
	Gas	C
Improve windows	Jalousie windows	A
	Metal single pane	B
	Wood single pane	C
	Metal single pane with storm	C
	Wood single pane with storm	D
	Metal double pane	D

5.1.2 Advancing Residential Retrofits in Atlanta

Following the US Department of Energy (DOE)'s goal to reduce home energy use for 30 to 50 percent, researchers at Oak Ridge National Laboratory (ORNL) collaborated with Southface to conduct research on comprehensive energy retrofits implemented on Atlanta dwellings [74]. This research was focused on determining "what it takes" to generate deep energy savings for residential buildings of Atlanta metropolitan area. Through this study, nine residential buildings in the region were studied prior to upgrade, technical assistance with regard to the projected impact of various retrofit measures were provided by the ORNL team, and the dwellings were then upgraded following the homeowners' acceptance. The performance of the buildings was then analyzed to evaluate the actual impact of the proposed retrofit options. Table 18 provides a quick overview of the primary retrofit measures and number of buildings had to go through each measure among the total of nine, separated by building scenarios previously discussed in this study. This table was another source for identifying practical improvement options for selected scenarios.

Table 18 – Overview of the energy upgrades performed in the homes. The numbers represent the count of houses performed the specific upgrade.

Retrofit Actions	1-Story Before 1970s	2-Story Before 1970s	2-Story After 1970s
Exterior walls	2	1	1
Attic/Knee walls	3	3	2
Foundation	4	2	-
Foundation walls	2	1	-
Cooling	4	3	2
Heating	4	2	2
Domestic hot water	1	2	2
Windows	1	2	-

5.1.3 Southface residential energy code field guide

Code officials when inspecting residential construction projects intend this field guide for use. The field code illustrates key requirements of the energy code based on the DOE's building energy code program residential field compliance checklist [95]. The final improvement measures selected in this study were double-checked with this regional guideline and the required specifications and dimensions were adjusted accordingly.

5.1.4 ANSI/ASHRAE Standard 100

American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard Project Committee 100 developed a list in 2011 as part of the committee's rewrite of American Nation Standards Institute (ANSI)/ASHRAE Standard

100. This essential ASHRAE resource offers over 100 typical Energy Efficiency Measures (EEMs) that can be applied to enable buildings to meet energy targets, identifying commonly applied elements that can improve building performance. The list was developed as a reference guide to address commercial and residential occupancies.

5.1.5 Selected Improvement Options

Following the references discussed in the previous subsections, various improvement options were selected according to the unique features of the existing benchmarked models. Table 20, Table 21 and Table 22 and Table 22 present the detailed description of retrofit measures for each benchmarked building scenario.

Table 19 – The list of improvement options identified for 1-Story built before 1970s

Improvement Options	Description
Exterior Walls	House wrap on the exterior wall
	Insulating wall cavity of 3.5 inch fiberglass (R-15)
	3.5 inch R-13 blown cellulose
Attic/knee Walls	Attic insulation using open-cell foam spray between walls and attic 3.5 inch (R21)
	Ceiling plane insulated with blown fiberglass (R-38) - 14 inch
Foundation Walls	12-mil vapor barrier flash-coated to the foundation walls with foam
	3.5 inch closed-cell (foam) insulation on the foundation walls (R-20)
Crawlspace	Vapor barrier on the crawlspace floor
	R-13 fiberglass batts in the ceiling of the crawlspace using kraft paper
	3" of closed-cell insulation was sprayed on the band in the crawlspace (R-18)
	3" of medium-density, open-cell foam sprayed in the 2x8 joist cavities in the crawlspace subfloor (R-15)
HVAC System	Air conditioning added with a 3-ton capacity air conditioner with efficiency rate 14 SEER
	Heating unit was replaced with an 89/90 kBtuh 95 AFUE sealed-combustion gas furnace
Ducts	Insulated ducts with fiberglass
Water Heater	Upgraded water heater to a 50-gallon Rheem Heat Pump Water Heater with a 2.0 EF
Windows	Double-pane fiberglass windows
Exterior Shadings	Install exterior shading with softwood plywood

Table 20 – The list of improvement options identified for 1-Story built after 1970s

Improvement Options	Description
Exterior Walls	3.5 inch R-13 blown cellulose
Attic/knee Walls	Attic knee walls insulated with R-13 batts
	Encapsulate the attic with 2 inch open-cell spray foam (R21) on roofline
Crawlspace	R-11 insulation added to crawlspace band
	R-13 fiberglass batts in the ceiling of the crawlspace using kraft paper
HVAC System	Air conditioning replaced with a 3-ton capacity air conditioner with efficiency rate 14.5 SEER
	Heating unit was replaced with an 89/90 kBtuh 95 AFUE sealed-combustion gas furnace
Ducts	Duct system replaced with R-8 insulated flex duct
Water Heater	Upgraded water heater to a 50-gallon Rheem Heat Pump Water Heater with a 2.0 EF
Exterior Shadings	Install exterior shading with softwood plywood

Table 21 – The list of improvement options identified for 2-Story built before 1970s

Improvement Options	Description
Exterior Walls	House wrap on the exterior wall
	Insulating wall cavity of 3.5 inch fiberglass (R-15)
	3.5 inch R-13 blown cellulose
Attic/knee Walls	Attic insulation using open-cell foam spray between walls and attic 3.5 inch (R21)
	Ceiling plane insulated with blown fiberglass (R-38) - 14 inch
Foundation Walls	12-mil vapor barrier flash-coated to the foundation walls with foam
	3.5 inch closed-cell (foam) insulation on the foundation walls (R-20)
Crawlspace	Vapor barrier on the crawlspace floor
	R-13 fiberglass batts in the ceiling of the crawlspace using kraft paper
	3” of closed-cell insulation was sprayed on the band in the crawlspace (R-18)
	3” of medium-density, open-cell foam sprayed in the 2x8 joist cavities in the crawlspace subfloor (R-15)
HVAC System	Air conditioning replaced with a 3ton capacity air conditioner with efficiency rate 16 SEER
	For the second floor a new 3-ton, 14 SEER air conditioner added
	The atmospherically vented gas furnace replaced with an 89/90 kBtuh 95 AFUE sealed-combustion gas furnace
	For the second floor, a new furnace with a 70 kBtuh capacity and 95 AFUE efficiency rate is added
Ducts	Insulated ducts with fiberglass
Water Heater	Replaced water heater with an 80-gallon A.O. Smith heat pump water heater with 2.4 efficiency.
Windows	Double-pane fiberglass windows
Exterior Shadings	Install exterior shading with softwood plywood

Table 22 – The list of improvement options identified for 2-Story built after 1970s

Improvement Options	Description
Exterior Walls	3.5 inch R-13 blown cellulose
Attic/knee Walls	Attic knee walls insulated with R-13 batts
	Encapsulate the attic with 2 inch open-cell spray foam (R21) on roofline
Crawlspace	R-11 insulation added to crawlspace band - 3.5 inch
	R-13 fiberglass batts in the ceiling of the crawlspace using kraft paper
HVAC System	Air conditioning replaced with a 3ton capacity air conditioner with efficiency rate 16 SEER
	For the second floor a new 3-ton, 14 SEER air conditioner added
	heating unit was replaced with an 89/90 kBtuh 95 AFUE sealed-combustion gas furnace
	For the second floor, a new furnace with a 70 kBtuh capacity and 95 AFUE efficiency rate
Ducts	HVAC system ducts replaced with R-8 insulated flex duct
Water Heater	Replaced water heater with an 80-gallon A.O. Smith heat pump water heater with 2.4 efficiency.
Exterior Shadings	Install exterior shading with softwood plywood

5.2 Estimate Embodied Impacts

Following the embodied LCA analysis of Chapter 4, the same process-based LCA method was utilized to calculate embodied energy and associated environmental impacts of the identified improvement options. For this purpose, the identified improvement options were modeled within the Athena Impact Estimator for Buildings 5.2 [79] and added to the previously benchmarked models. Furthermore, the additional life cycle environmental impacts were calculated accordingly. In this case, the immediate embodied impacts after applying the retrofit options were calculated.

There were particular retrofit measures which were missing in Athena library including HVAC systems and heat pumps. Therefore, the missed components were modeled separately using SimaPro 8.1 LCA tool [96] and added manually to the analysis. The following paragraphs describe the details of important retrofit measures, the reasons behind choosing them and how they were modeled in either Athena or SimaPro.

5.2.1 House Wrap on the Exterior Wall

House wrap, first introduced in 1979 to provide a simple way to seal the exterior of a building and reduce air leakage. A previous study estimated the embodied and energy saving impact of housing wraps [97]. This study estimated the embodied energy in the house wraps based on energy analysis of the manufacture of high-density polyethylene and polypropylene resins and the range of type basis weights (lb/1000sqft) of the house wrap products in the US. Additionally, annual energy savings was calculated based on an estimated range of ACH reduction combined with DOE data for average residential air leakage. The similar materials were used to model house wrap in Athena and the numbers confirmed from this study for the embodied energy and further for estimating energy saving percentage for house wraps. We have also assumed that this action happen at the same time with maintenance of sidings, so there will not be any additional construction embodied energy and impacts involved.

5.2.2 Insulating the Band and Joist Cavities in the Crawlspace

In older homes, rim joists are often uninsulated. The only thing separating inside from outside is two inches of wood and outside siding material. Hence, insulating the band and joists is an easy way to improve home energy efficiency with minimal amount of materials. A report on the tips of energy efficiency for the city of Beatrice, Nebraska, showed 11.4 percent reduction in annual infiltration rate, by applying sprayed-in insulating foam in rim joist locations. They have also translated the results into an estimated annual cost savings of approximately 19.3 percent for heating and cooling [98]. However, I assumed that the impact is lower in Atlanta due to lower heating load in comparison to Nebraska.

5.2.3 Crawlspace Vapor Retarder

The energy code only requires a vapor retarder for vented crawlspaces but the 2009 International Residential Code (IRC) required a vapor retarder for both vented and unvented crawlspaces. Hence, I have chosen to add vapor barrier on the crawlspace floor of both 1-story and 2-story built before 1970s. The after 1970s models already have the vapor barrier in their base model.

5.2.4 Insulation on the Foundation Walls

The energy savings of basement wall insulation vary depending on the local climate, type of heating system, cost of energy, and lifestyle of the occupant. Typical annual savings estimated to be around $280 for Atlanta climate, for a standard, 1500 square-foot home with a conditioned basement that is heated by natural gas ($0.72/therm) [99]. Based on the defined 1-story building in this study, it will turn into around 7% annual energy savings. Considering the impactful energy saving percentage, this retrofit measure were chosen for buildings scenarios with foundation wall construction type which includes both 1-story and 2-story buildings built before 1970s.

5.2.5 Window Replacement

Double-pane fiberglass windows were replaced for both 1-story and 2-story built before 1970s. This decision is based on similar actions within the ORNL case studies. However, this retrofit measure could be a burden from the cost perspective.

5.2.6 Windows Exterior Shading

A previous study employed LCA to compare the effects of three different shading materials on building energy consumption and their impacts to the environment within five major climate zones in the US, including Atlanta [58]. Following the results of this article, wooden shading were chosen as an improvement option because of the lowest embodied impacts calculated for this type of shading material. However, there are studies indicating the negligible impact of post-construction energy reduction technologies such as window shading on the total building's energy consumption rate [100].

5.2.7 HVAC System

Similar to other retrofit measures, the potential benefits from replacing a new HVAC system with a more efficient one should also evaluated against the added burden associated with the creation of a new system and disposal of the old one. The reference HVAC system considered for embodied analysis in this study is taken from the case study done at the University of Pittsburgh on LCA of residential HVAC systems in four regions of the US [101]. Based on this study, the components of the HVAC system include a furnace and an Air Conditioner (AC) as well as a ductwork for the distribution system. Additionally, a heat pump is also considered as the source of Domestic Hot Water (DHW).

The material compositions and estimated life for the HVAC appliances and the distribution components were extracted from the mentioned case study for a 3-ton capacity AC with efficiency rate 13 Seasonal Energy Efficiency Ratio (SEER). SEER represents the average number of BTUs of cooling per Watt-hour of electricity input over a typical American cooling season. However, beginning January 1, 2015, the EPA required all AC brands to have a minimum SEER rating of 14 [102]. Therefore, the weights of the materials were adjusted based on a previous study on the LCA of HVAC systems in the US conducted at the University of Michigan [103]. As an example, based on this study, the weight of the outdoor unit can be adjusted using the Equation (1), where $m_{outdoor}$ is the mass of the outdoor unit in pound. The change in the size of the indoor unit was assumed negligible in this analysis.

$$m_{outdoor} = 17.1 * SEER - 31.6 \tag{1}$$

After calculating the material and component's weights, they were modeled in Athena for embodied analysis. The manufacturing and production phase of the missing materials from Athena library (e.g. R-22 refrigerant) were calculated through SimaPro and were manually added to the analysis. In terms of transportation for the missing materials in Athena library, the Michigan study is further used to calculate the associated impacts for the HVAC systems. In this matter, the closest residential HVAC manufacturing location to Atlanta identified as the Goodman located in Fayetteville, TN based on the Michigan case study [104]. Then, the distance between the manufacturing site and the destination (Atlanta) were calculated using Google map (d=220 miles). Finally, the distance and weight values along with the energy and environmental emission factors for an up to 32-ton diesel truck from the SimaPro database were used to model transportation burdens.

5.2.8 Duct Systems

The ducts were also modeled using the University of Pittsburgh case study [101]. Based on this case study, the ducts are made of 0.76 mm (22 gauge) galvanized steel sheets and are insulated with a 50 mm (2 inch) fiberglass layer. The numbers are however adjusted to our four building scenarios respectively. The adjusted numbers were used to modeled ducts in the Athena for embodied analysis.

5.3 Results Interpretations and Scenario Comparisons

After collecting the LCI as discussed in the previous section, the improvement options were modeled within Athena and the associated embodied energy and environmental impacts were calculated, separated by life cycle stages, for the four building scenarios. Additionally, the embodied numbers were normalized by the original embodied numbers of the base cases to represent the percentage of embodied impacts of improvement options in relation to the original four scenarios.

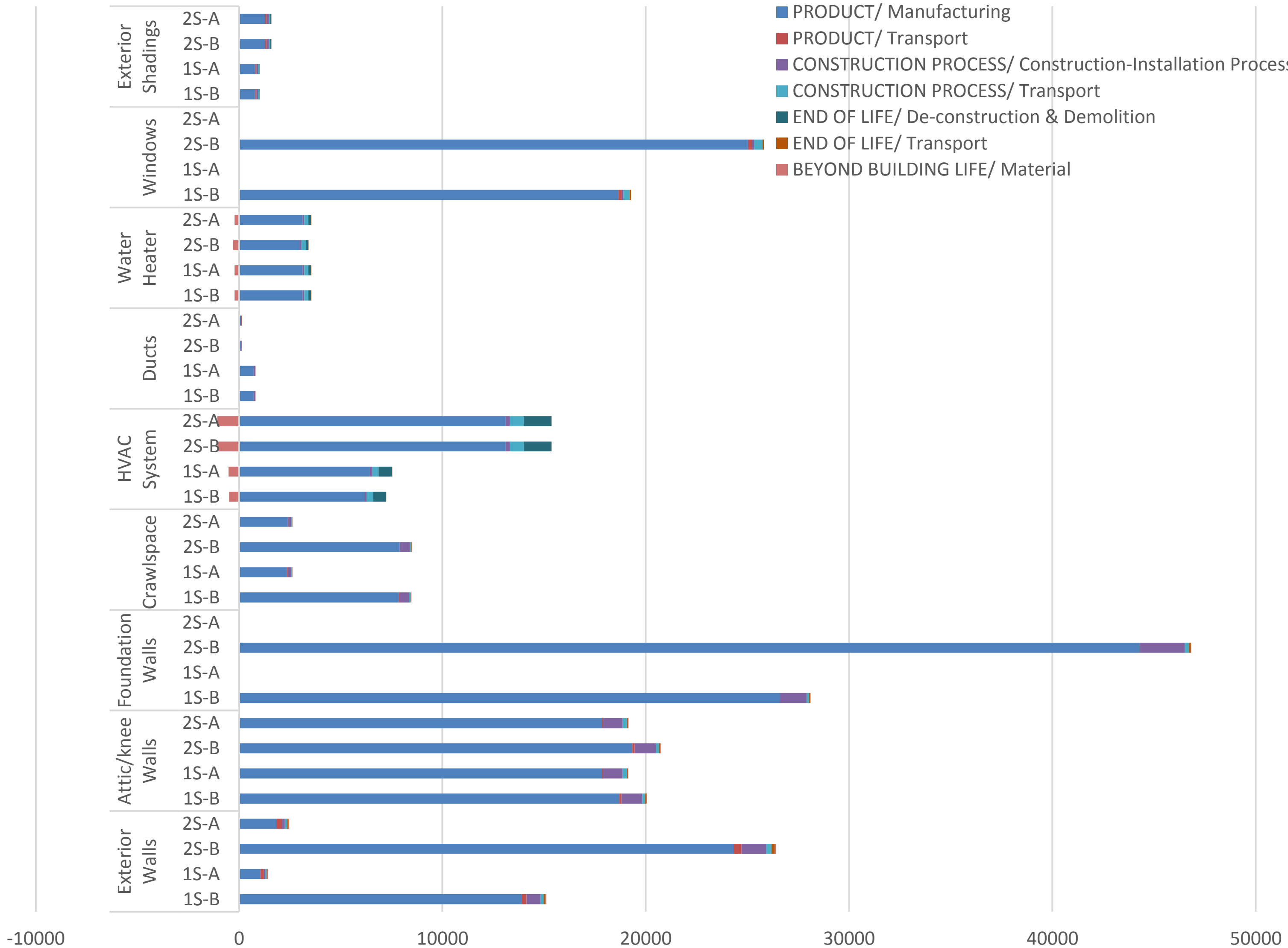


Figure 12 – TPE (MJ) of improvement options by life cycle stages for four building scenarios

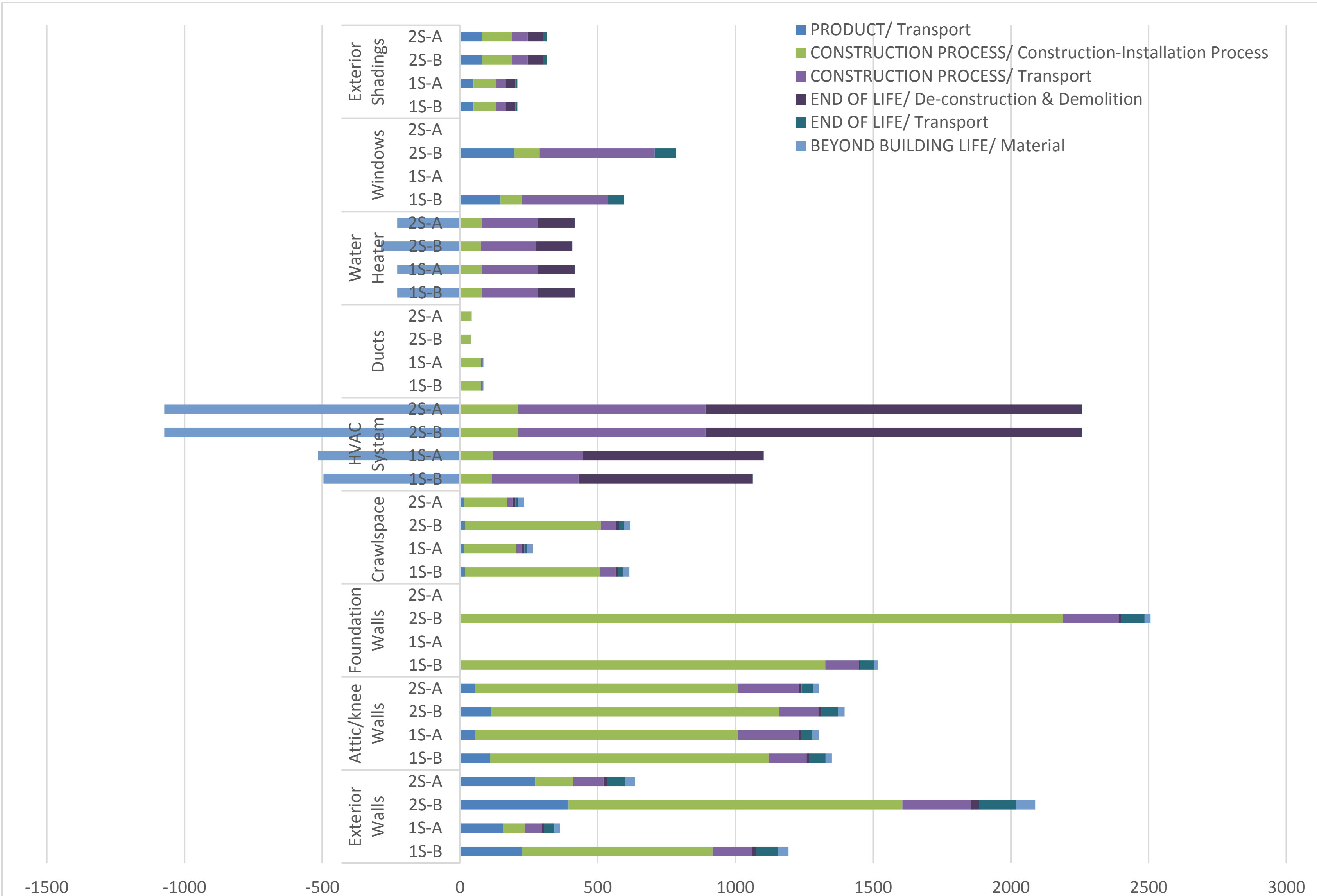


Figure 13 – TPE (MJ) of improvement options by life cycle stages (except product/manufacturing) for four building scenarios

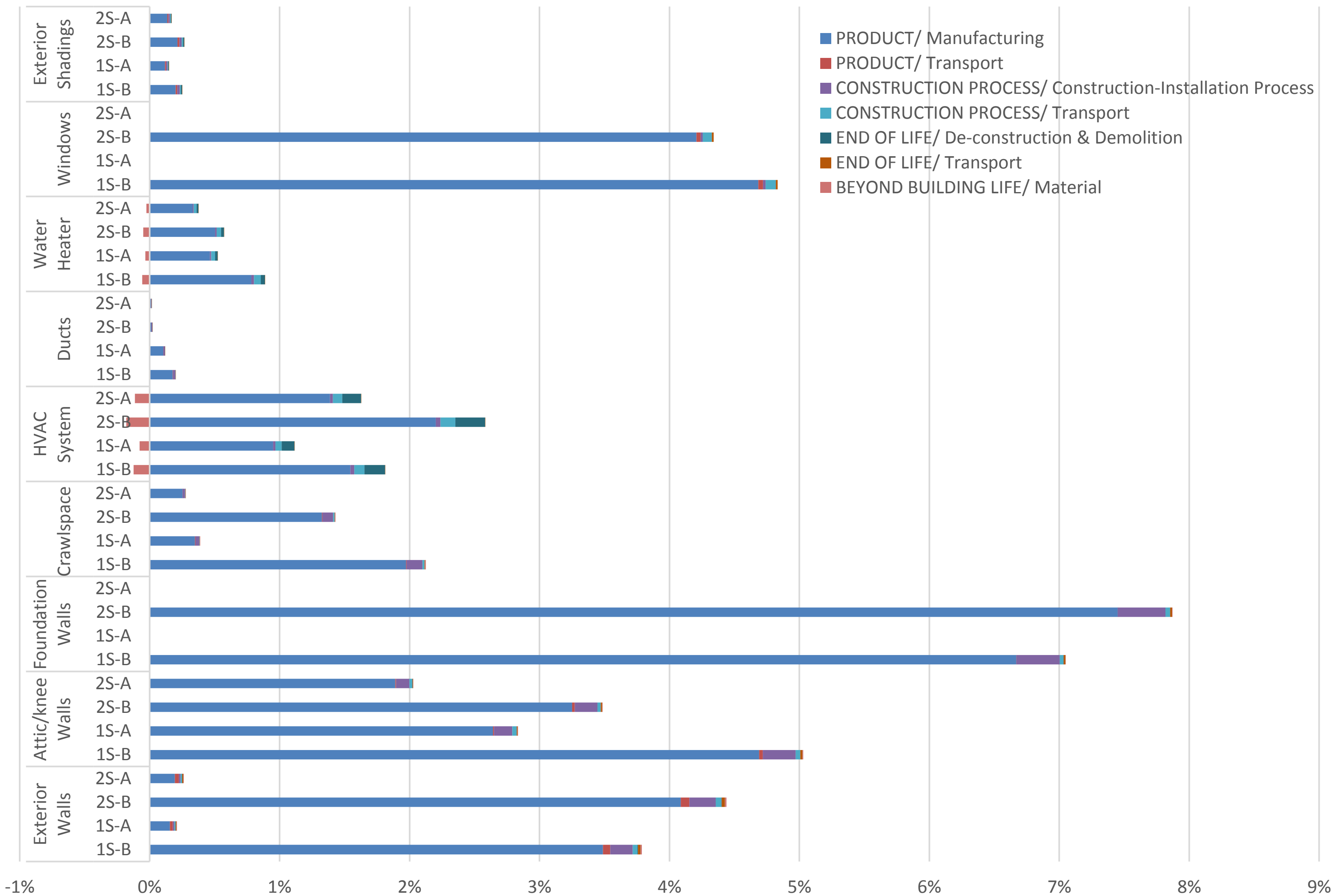


Figure 14 – TPE percentage of improvement options in relation to the original models by life cycle stages for four building scenarios

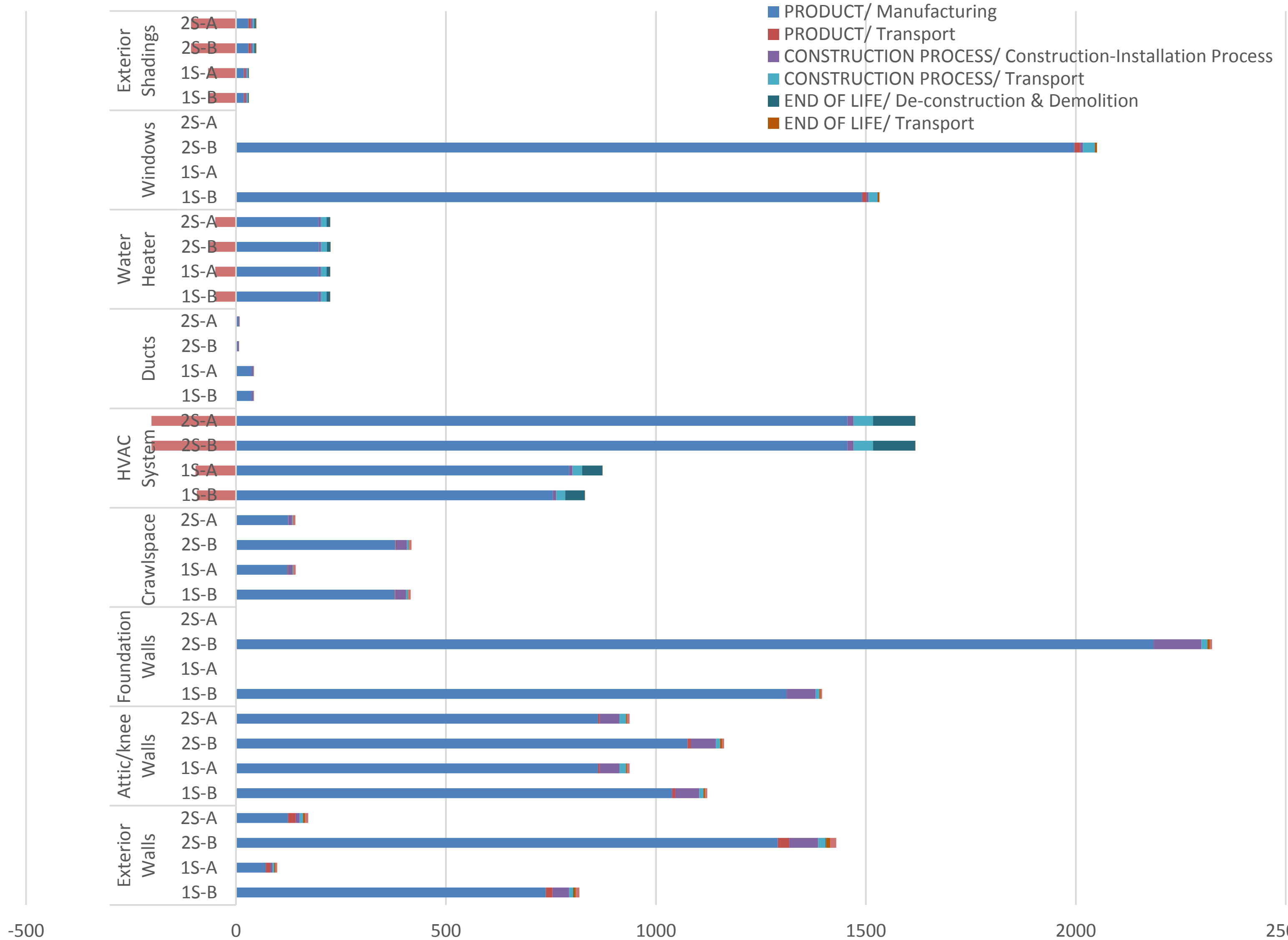


Figure 15 – GWP (CO_2 equivalent) of improvement options by life cycle stages for four building scenarios

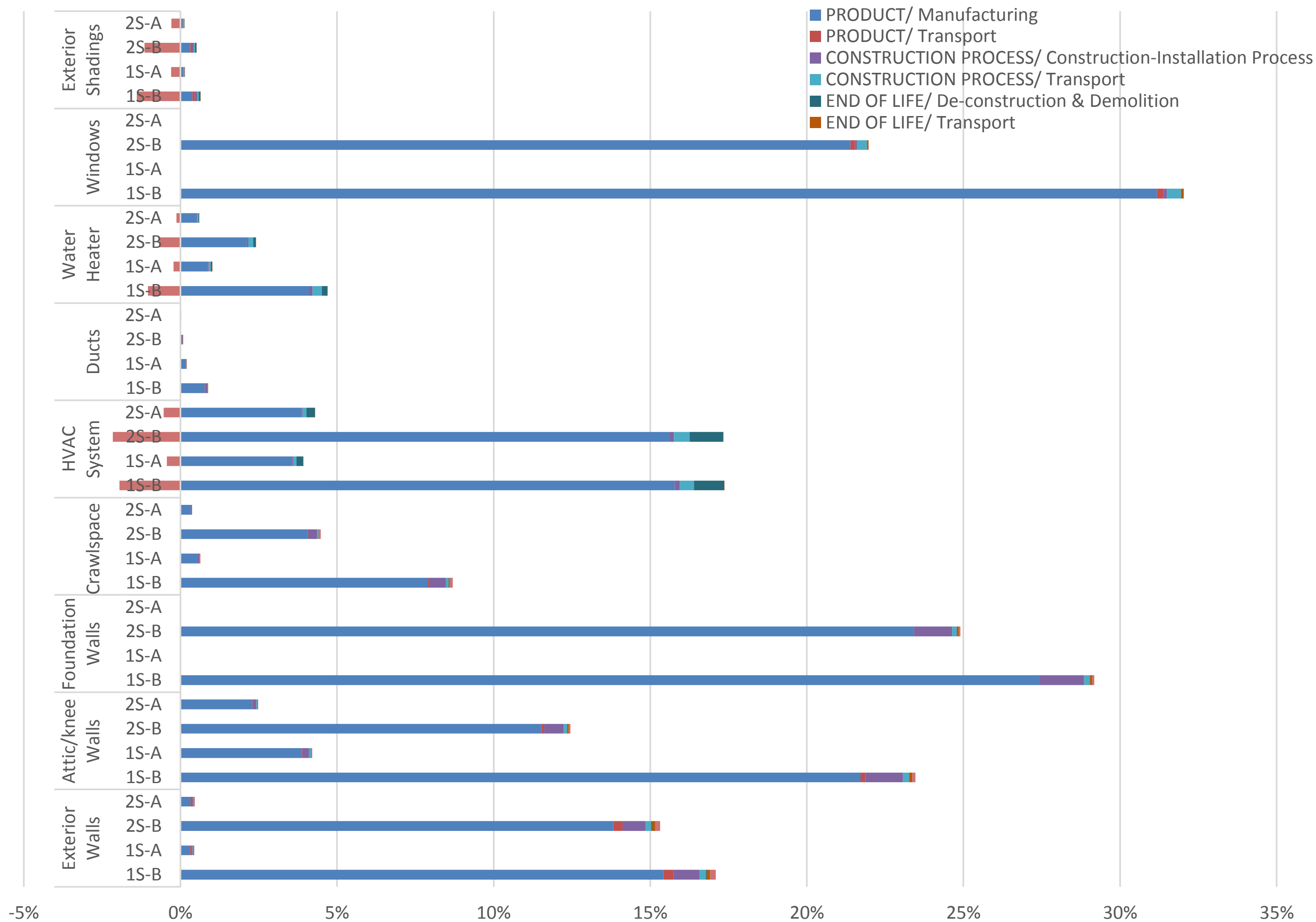


Figure 16 – GWP percentage of improvement options in relation to the original models by life cycle stages for four building scenarios

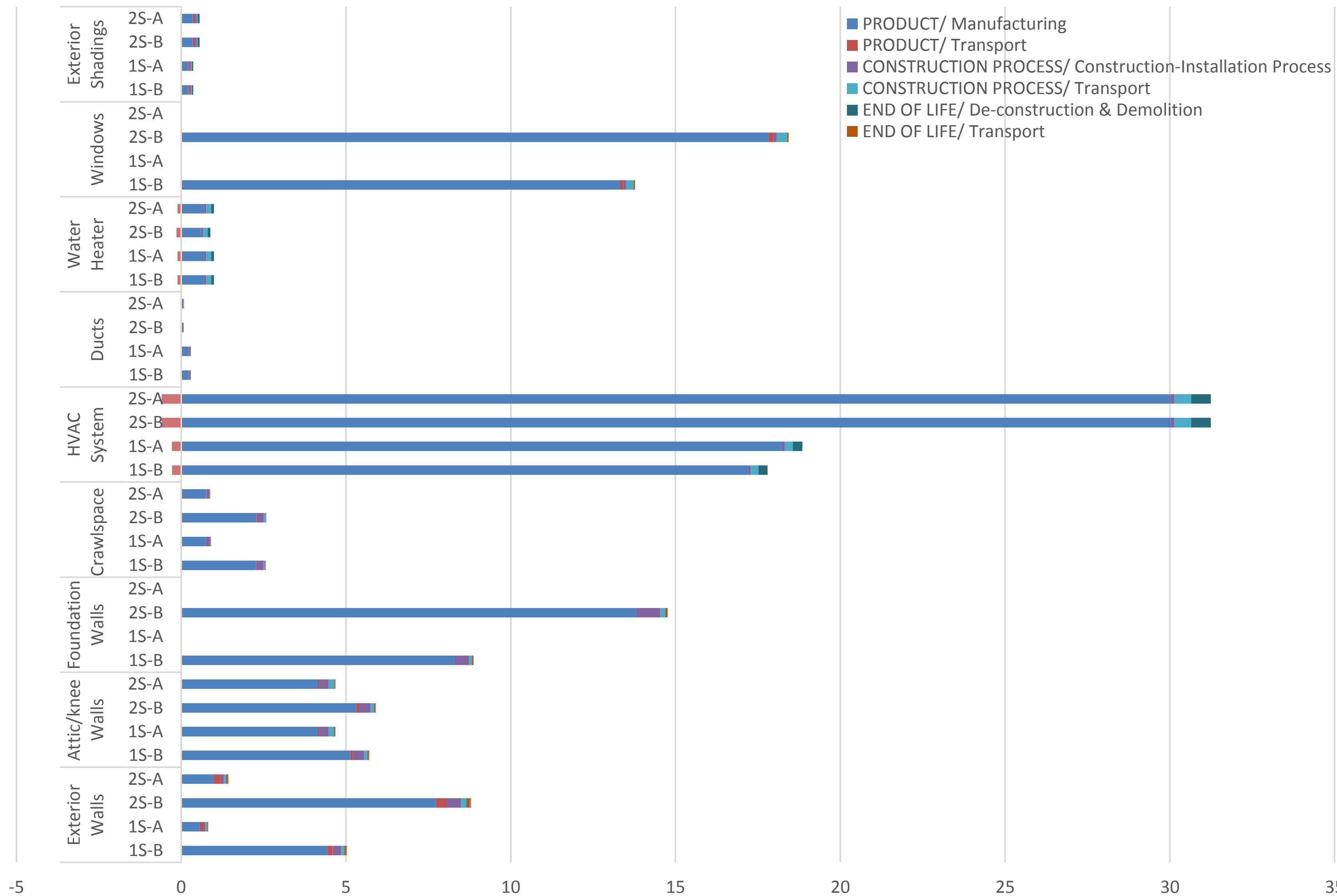


Figure 17 – AP (SO_2 equivalent) of improvement options by life cycle stages for four building scenarios

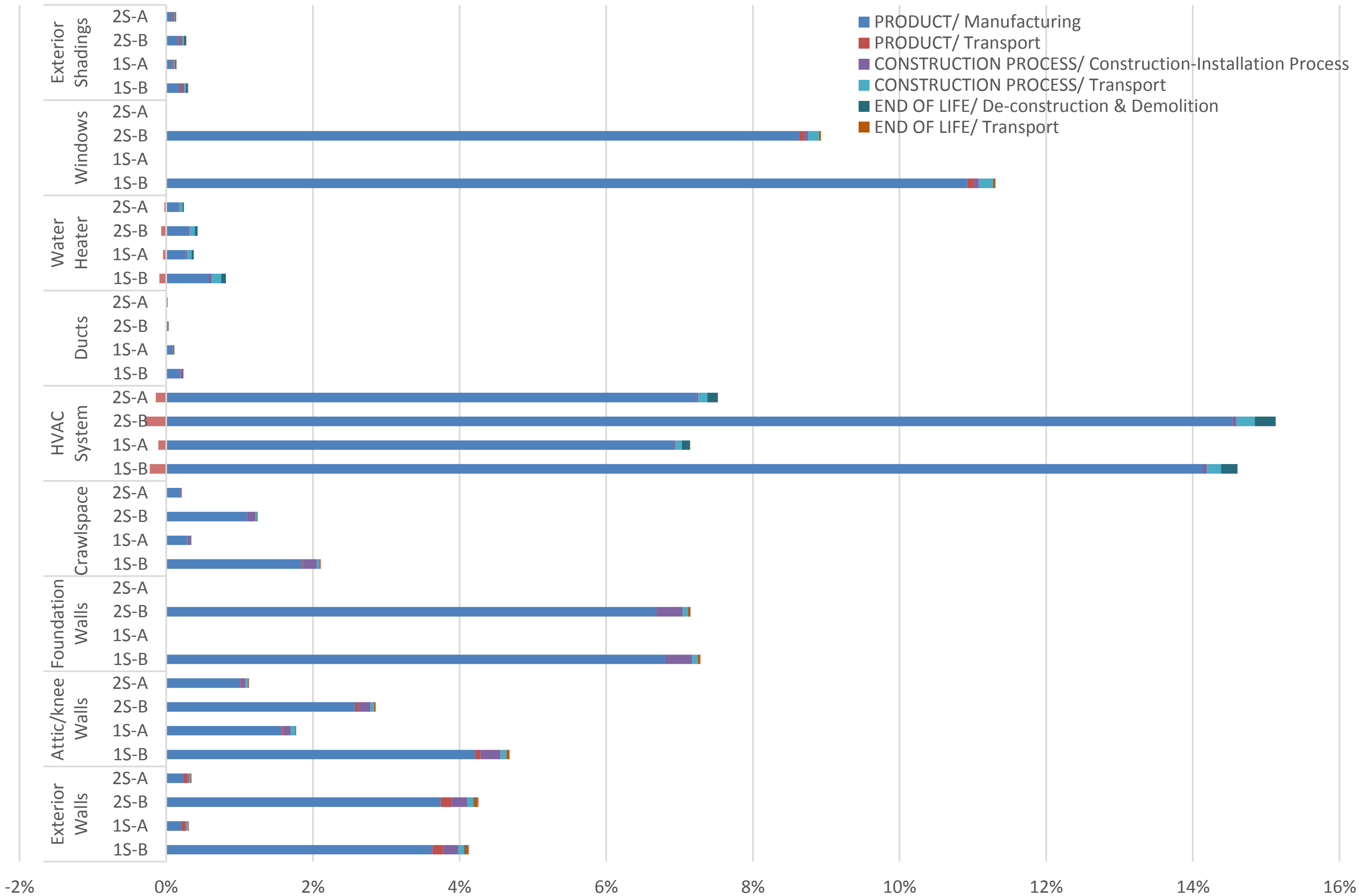


Figure 18 – AP percentage of improvement options in relation to the original models by life cycle stages for four building scenarios

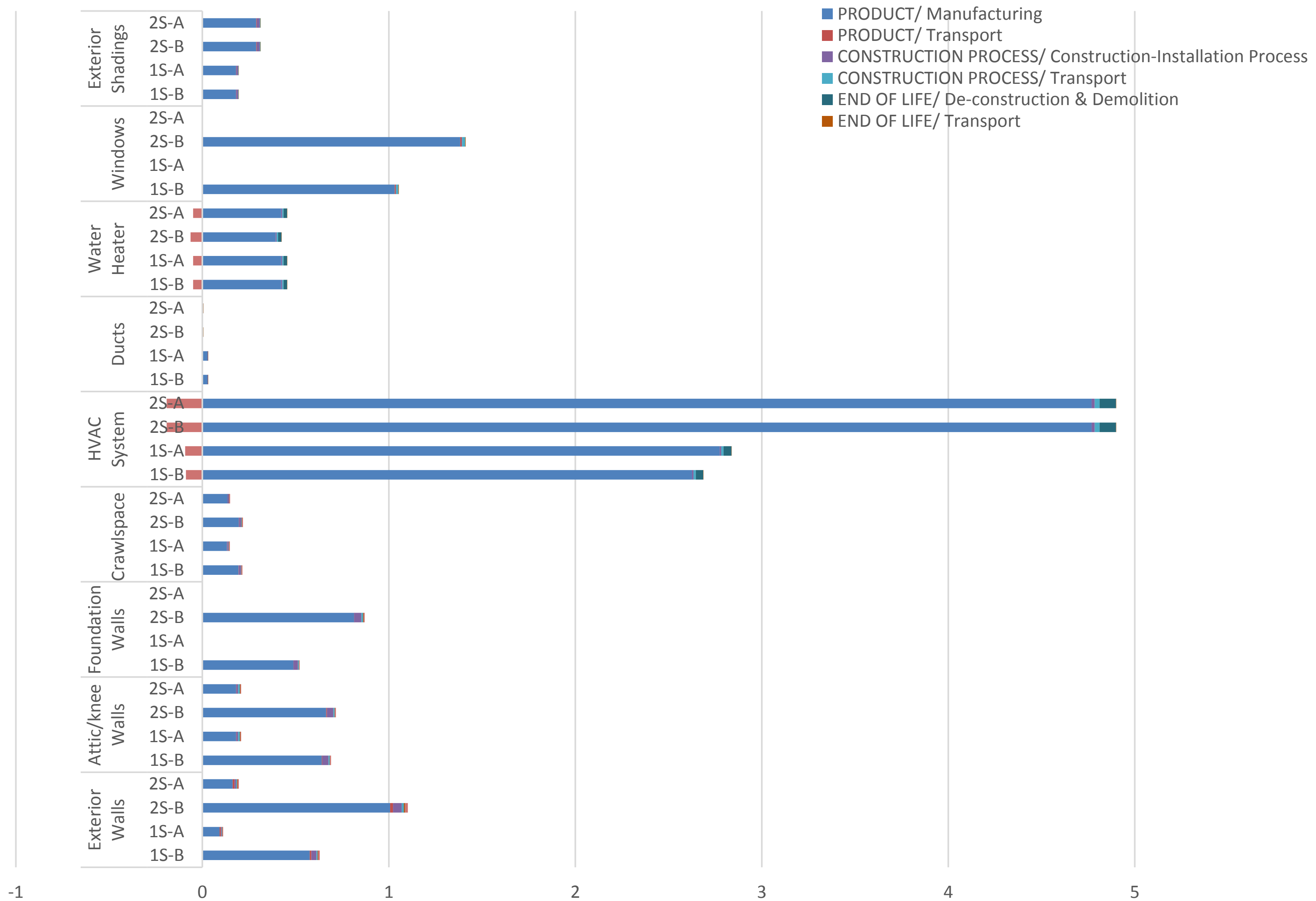


Figure 19 – HH Particulate (PM2.5 equivalent) of improvement options by life cycle stages for four building scenarios

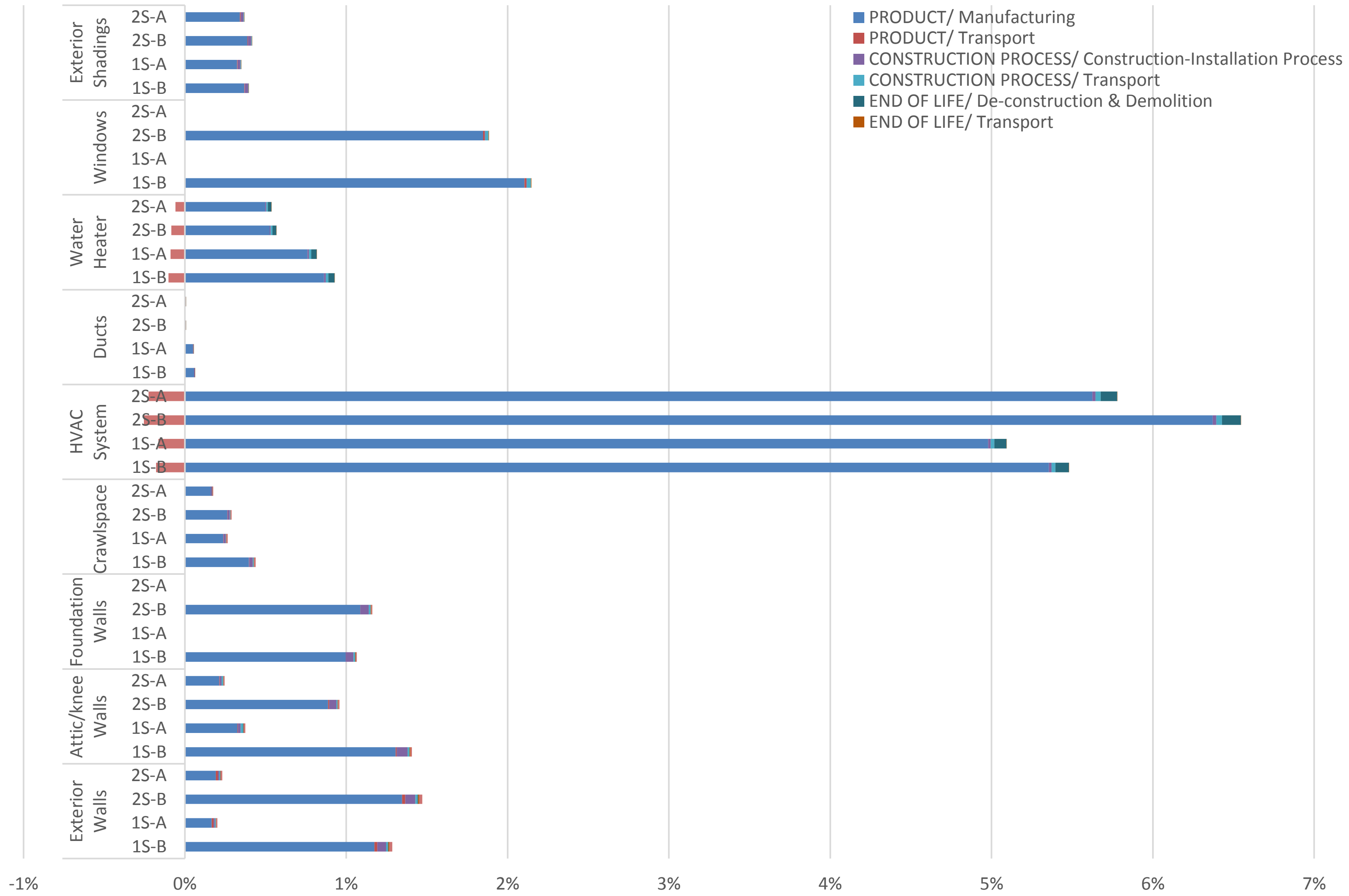


Figure 20 – HH Particulate percentage of improvement options in relation to the original models by life cycle stages for four building scenarios

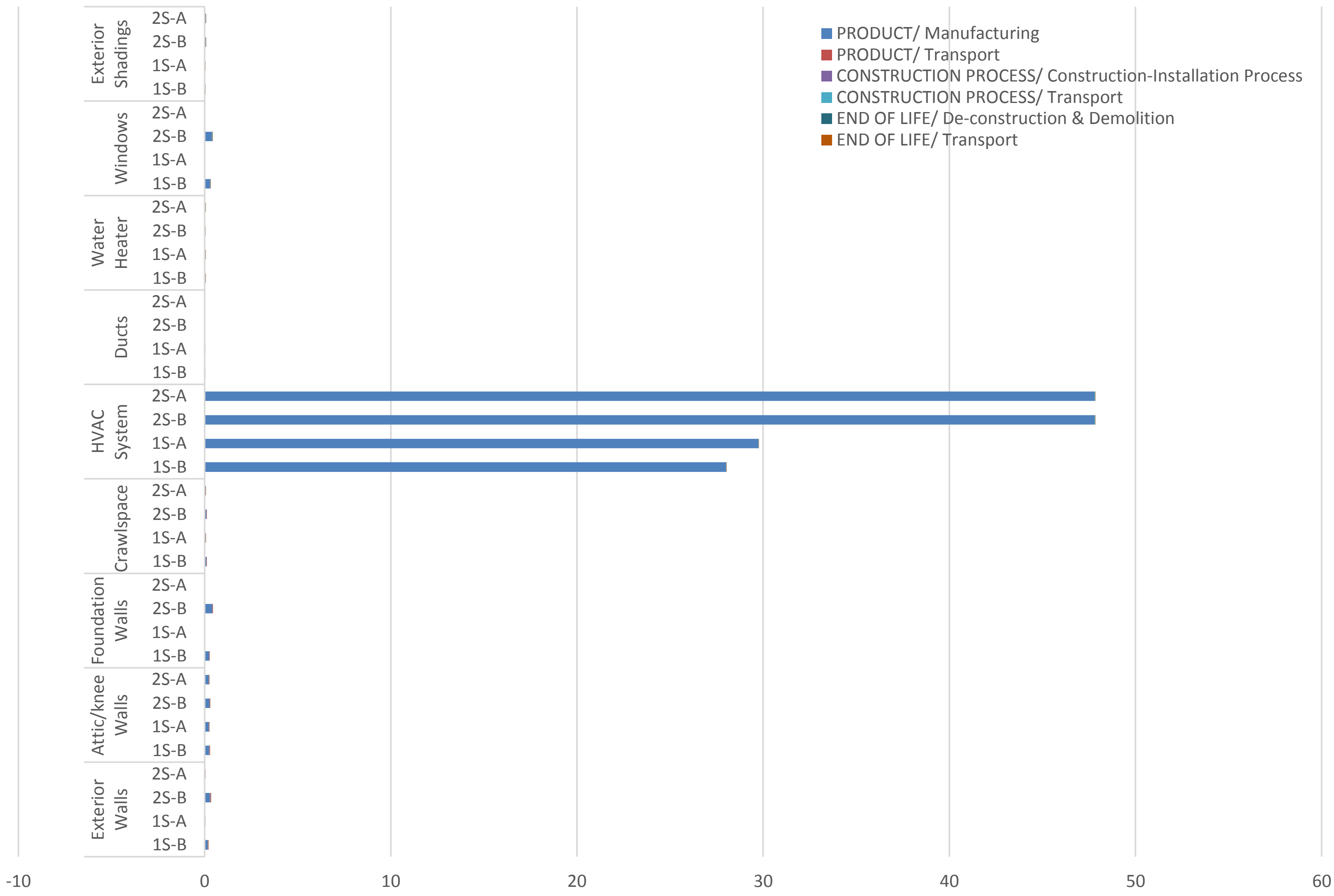


Figure 21 – EP (Nitrogen equivalent) of improvement options by life cycle stages for four building scenarios

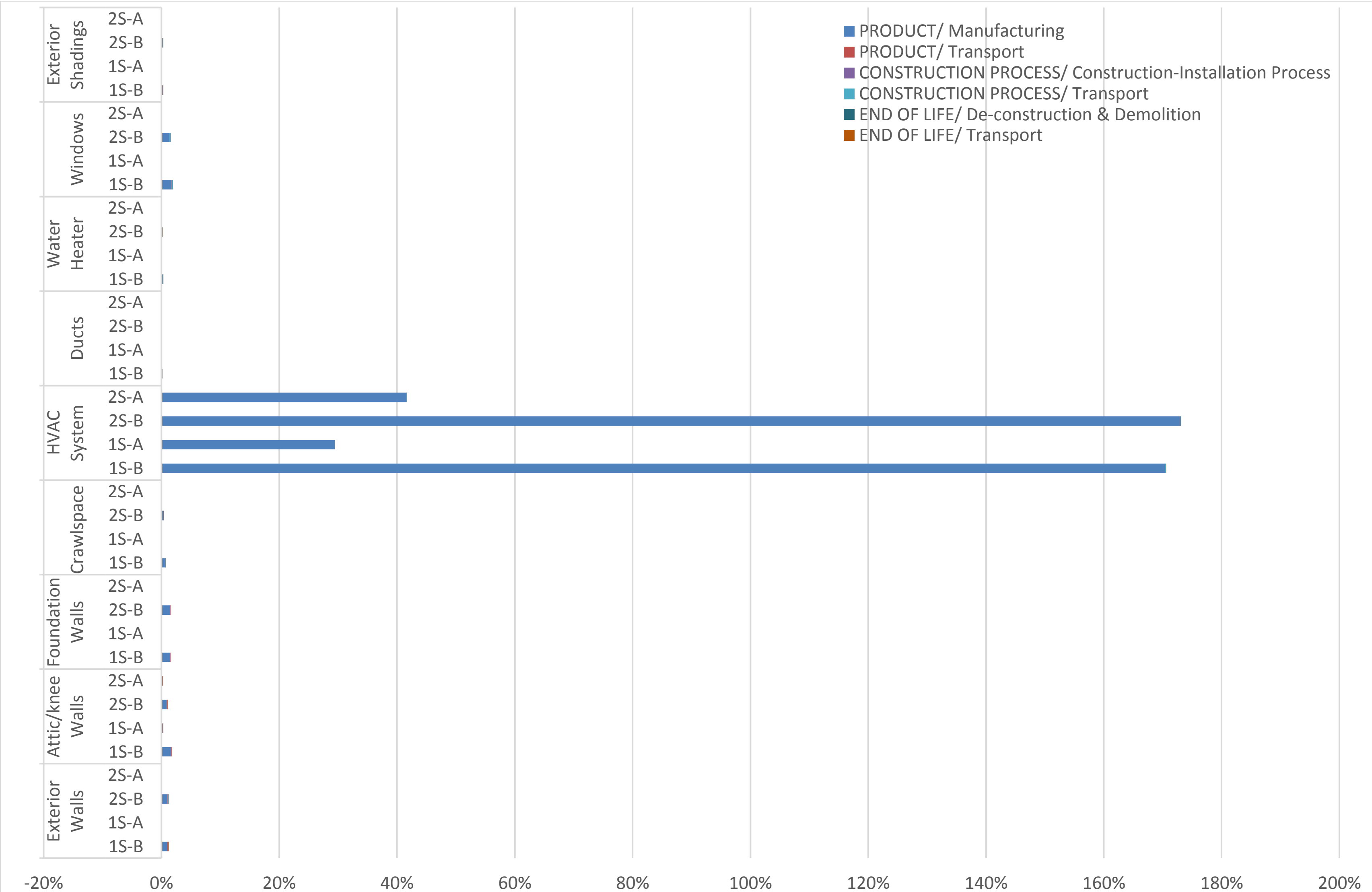


Figure 22 – EP percentage of improvement options in relation to the original models by life cycle stages for four building scenarios

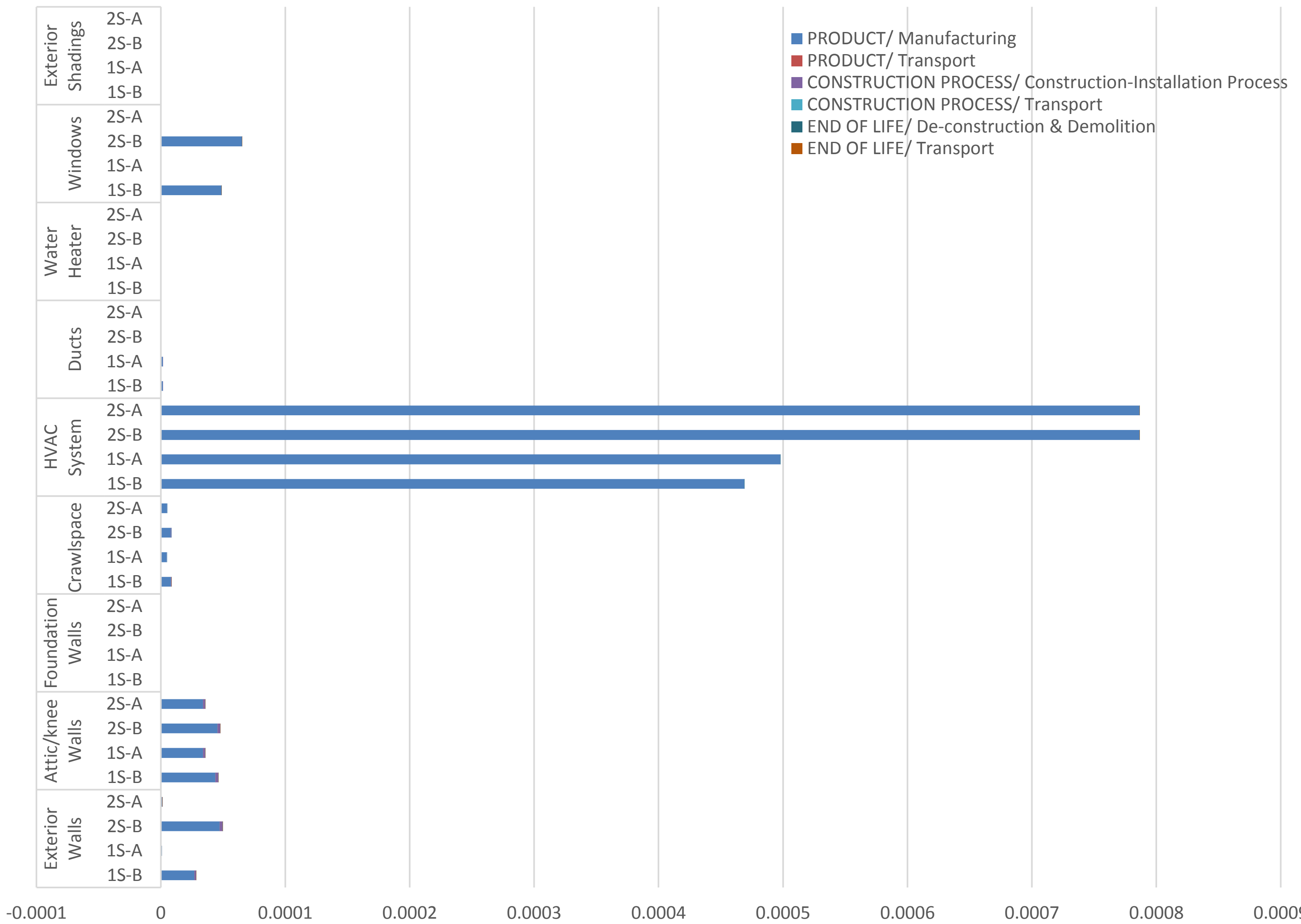


Figure 23 – ODP (CFC-11 equivalent) of improvement options by life cycle stages for four building scenarios

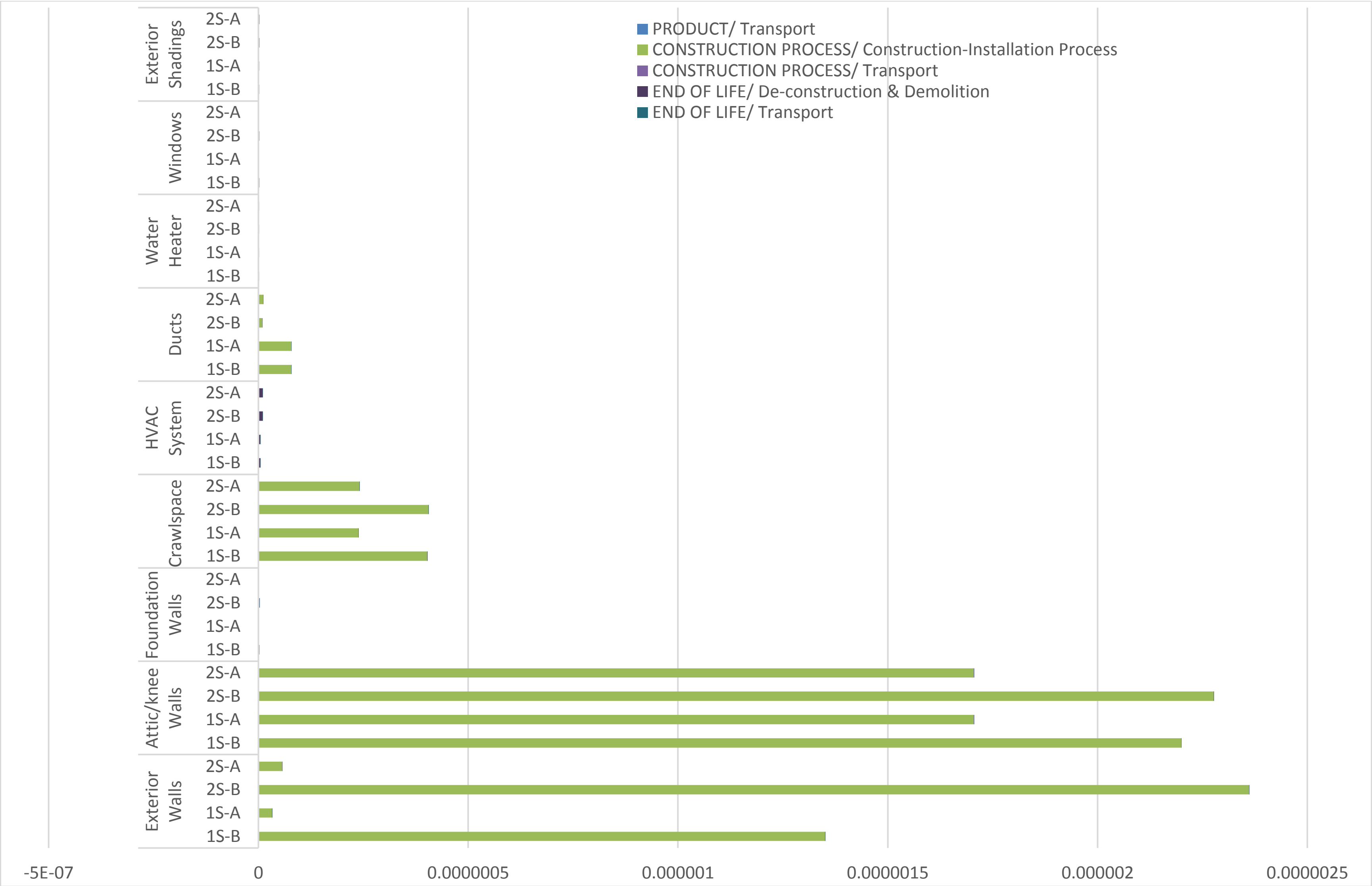


Figure 24 – ODP (CFC-11 equivalent) of improvement options by life cycle stages (except product/manufacturing) for four building scenarios

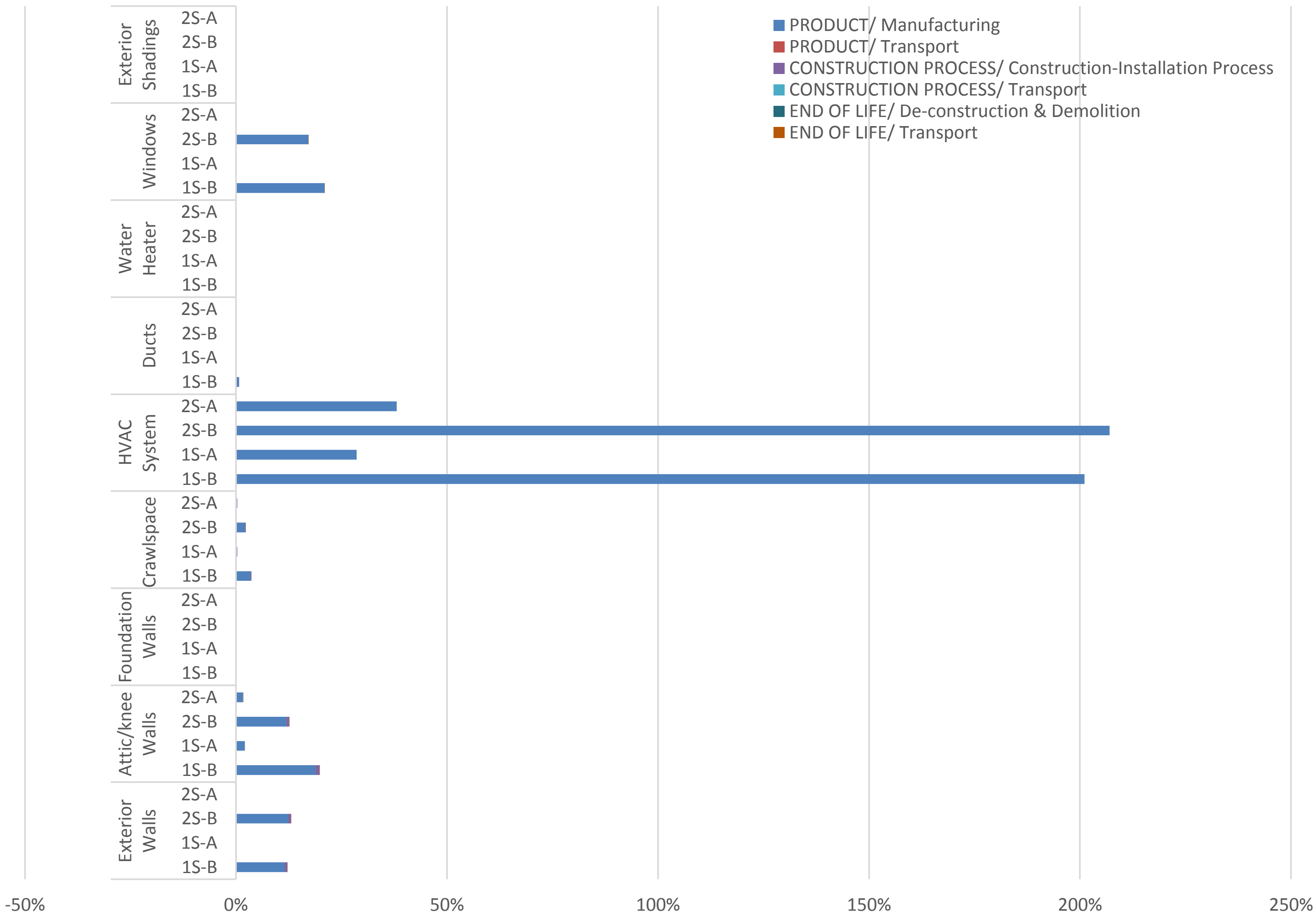


Figure 25 – ODP percentage of improvement options in relation to the original models by life cycle stages for four building scenarios

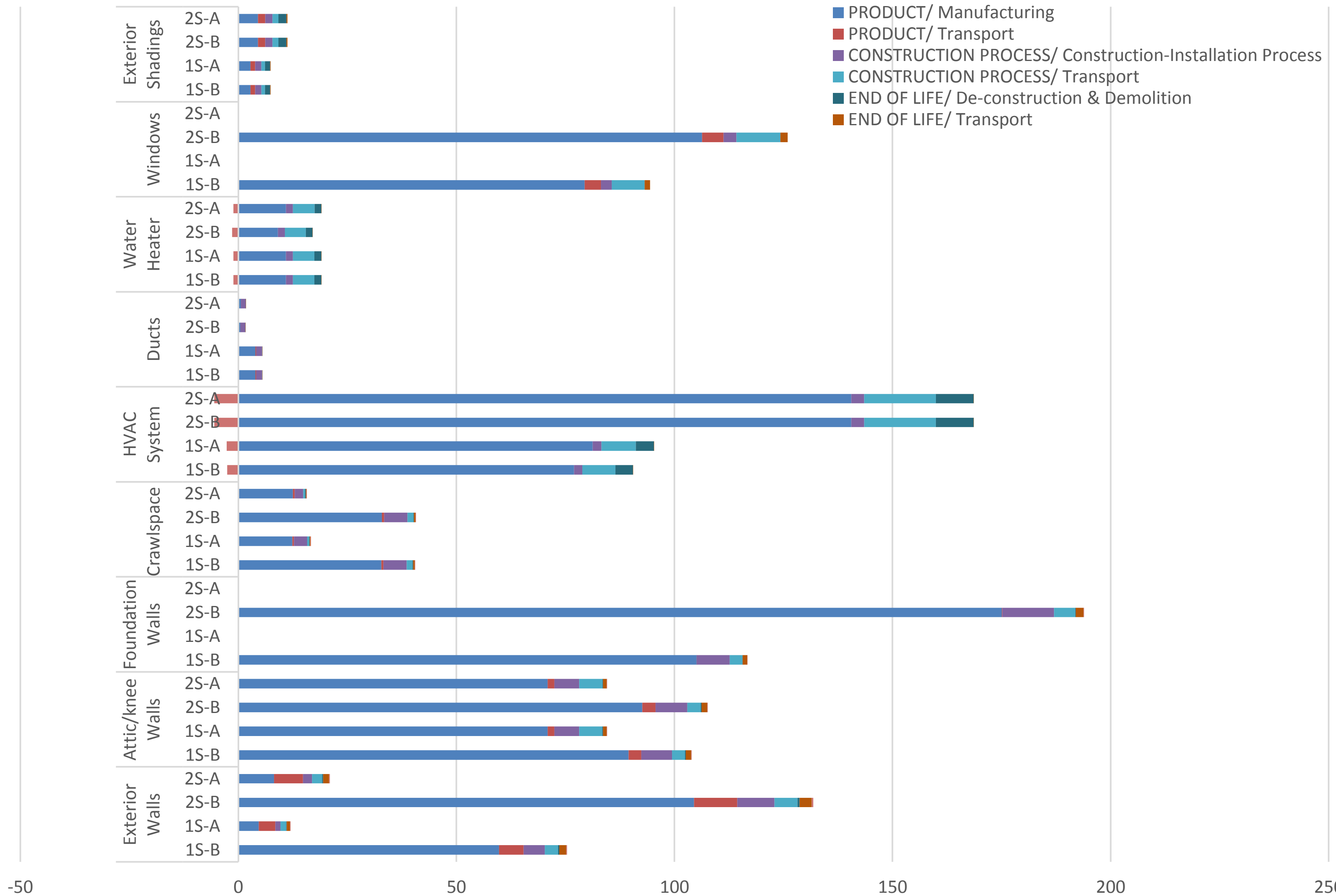


Figure 26 – SP (O_3 equivalent) of improvement options by life cycle stages for four building scenarios

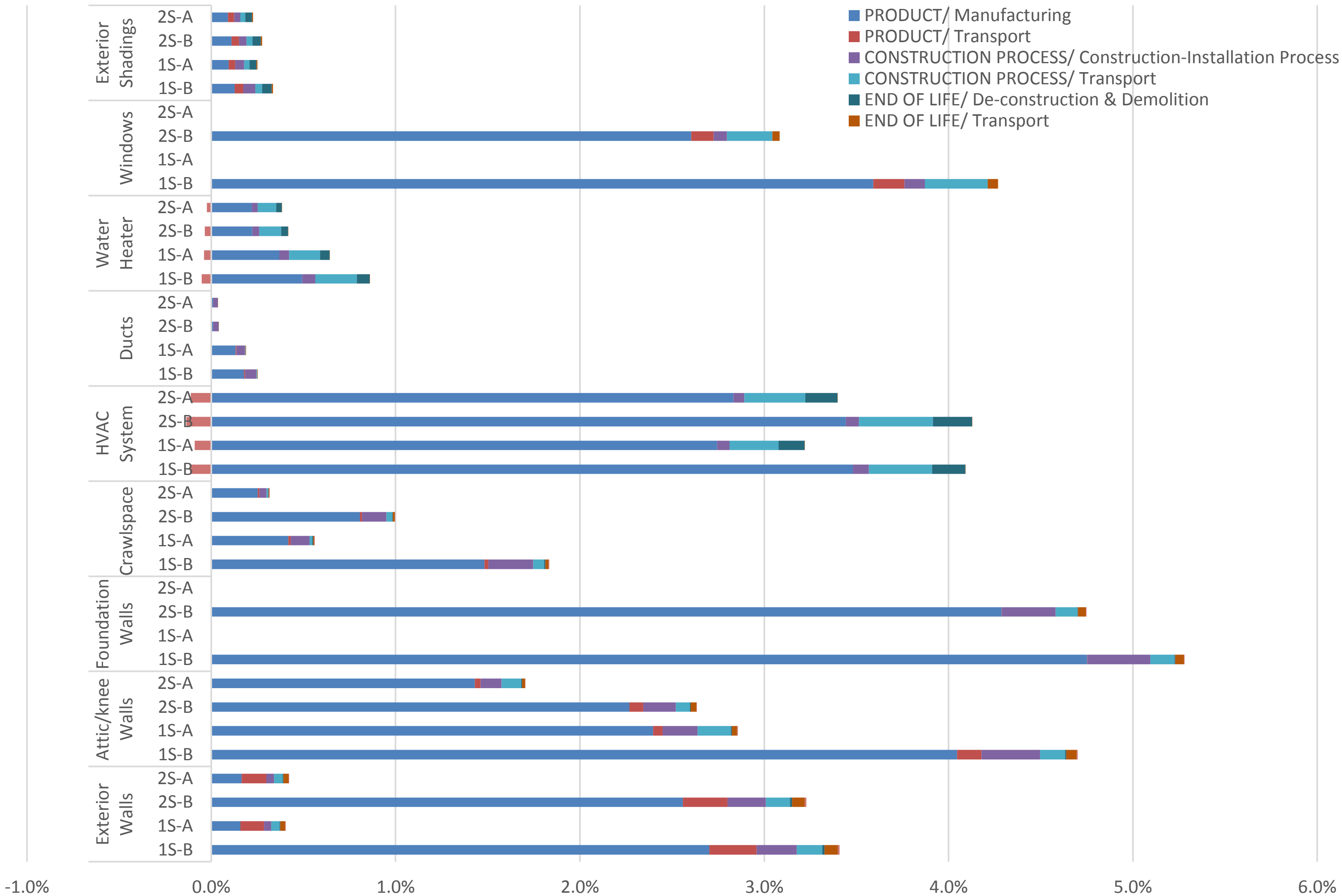


Figure 27 – SP percentage of improvement options in relation to the original models by life cycle stages for four building scenarios

The results are shown in Figure 12 through Figure 27 for different environmental impacts. Each figure represents one environmental impact for all improvement options and all four building scenarios. One set of figures represent the absolute value of the embodied impact of improvement options, separated by life stages for all building scenarios while another set of figures show the normalized numbers (in percentages) by the original embodied impact of the base case scenarios.

From Figure 12, it is observed that insulating foundation walls, windows replacement and insulating exterior walls improvement options have the highest embodied energy respectively in buildings build before 1970s. After those three options, insulating attic/knee walls and replacing HVAC systems come with the next two highest contributors to embodied energy for buildings built before 1970s and the first two contributors to embodied energy for buildings built after 1970s. One thing to notice from this figure is that as expected, a significant amount of embodied energy is associated with manufacturing procedure. However, if we remove the impact of manufacturing product, as it is shown in Figure 13, we can see that the second life stage contributor to embodied energy differs for different improvement options. For example, the de-construction and demolition has the second highest contribution of life cycle stages on HVAC systems, while the construction installation process is the second highest contributor for foundation walls insulation, attic/knee wall insulation as well as exterior wall insulations. On the other hand, we can see that the highest contributor for windows upgrade is the transportation stage.

Figure 14 represents the TPE or embodied energy of improvement options normalized by the original embodied impacts of base case scenarios. Hence, the percentages on the horizontal axis in this figure show the percentage of embodied energy added to the original embodied energy of the base case scenarios. For example, we can see that the highest contributors are still the foundation walls insulation for building built before 1970s, with close to 8% additional embodied energy in comparison to original embodied energy for 2-story buildings and around 7% additional embodied energy for 1-story buildings. These numbers are around 4% for window replacement of 2-story buildings and around 5% for 1-story buildings built before 1970s.

The similar trend is observable in Figure 15 as well, which confirms the direct correlation between embodied energy and embodied carbon as discussed in previous chapters. One difference is that the impact of HVAC system is now greater than the exterior wall insulation for buildings built before 1970s and almost the same as attic/knee walls insulation for buildings built after 1970s. In summary, we can conclude that the embodied carbon dioxide emission is relatively higher for HVAC upgrading than attic/knee walls insulation. However, from the other perspective, we can also observe the negative impact of recycling materials for HVAC systems and exterior shadings which could eventually result in a lower total impact for these two improvement options. This negative impact have the highest impact on exterior shadings, which will completely compensate the embodied carbon of exterior shadings after recycling.

Figure 16 represents the GWP or embodied carbon of improvement options normalized by the original embodied impacts of base case scenarios. Before analyzing the numbers in this figure, by looking at the percentages on the horizontal axis, we can see much higher percentages in comparison to the embodied energy. This shows that the global warming impact of improvement options are generally cover a larger percentage of the initial embodied carbons in comparison to the embodied energy, and it could even go up to 30% of the original global warming impact while the highest percentage was only around 8% in terms of total primary energy. Another thing to notice in this figure is that unlike embodied energy, the percentages are generally lower for 2-story buildings. Additionally, this figure shows that unlike embodied energy, the highest contributor to embodied carbon is window replacement, followed by foundation wall insulation and attic/knee wall insulation for buildings built before 1970s. Moreover, upgrading HVAC system have a higher global warming impact than exterior wall insulation unlike embodied energy. For buildings built after 1970s, the contribution of HVAC system upgrading is a little higher than exterior wall insulation, which used to be the highest contributor for embodied energy.

Figure 18 and Figure 18 represent the absolute numbers and normalized percentages for the acidification (SO_2 equivalent) impact respectively. Based on these two figures, we can see that the greatest contributor to acidification potential is upgrading HVAC systems for both buildings built before and after 1970s. This contribution is round 14% of original acidification impact for before 1970s buildings and close to 7% for after 1970s buildings. The next contributors to acidification are window upgrading (10%), foundation walls insulation (7%) and exterior wall insulation (4%) for before 1970s buildings and attic/knee wall insulation (1%) for after 1970s buildings.

Similar trend is also observed from Figure 20 and Figure 20 for embodied human health respiratory impact. However, the impact of replacing HVAC systems is almost four times the impact of next improvement option, which is windows replacement for buildings built before 1970s. The reason of this difference mainly related to the high amount of copper in the air conditioner and furnace system [105]. One thing to notice is that although the relative impact of replacing HVAC systems are higher in this impact comparing to AP impact, the percentage is only 6% of the base case embodied HH Particulate. The percentages are lower than 2% when it comes to other improvement options. Another difference between HH particulate potential and AP is the greater impact of insulating exterior walls than insulating foundation walls for before 1970s buildings. Moreover, for after 1970s buildings, the HH Particulate impact is higher for replacing water heater and adding exterior shading, than insulating attic/knee walls.

Figure 22 and Figure 22 respectively represent the absolute numbers and normalized percentages of eutrophication impacts associated with the identified improvement options. By a quick look at this figure, we can see that the effect of HVAC replacement on this environmental impact is not comparable to any other improvement option. Replacing HVAC system increase the eutrophication potential by 170% for before 1970s buildings and by 40% for after 1970s buildings. The next contributor to the eutrophication impact is window replacement with only 2% of the base case affect for before 1970s buildings and the rest of the improvement options have less than 1% contribution to eutrophication impact for all other building scenarios. The reason behind the huge eutrophication impact of HVAC systems is the usage of galvanized steel material in HVAC systems, which require nitrogen-hydrogen mix gas for galvanizing of steel sheets. Additionally, the reason of 170% impact for before 1970s buildings is that the original models for buildings built before 1970s did not have any HVAC system at all.

Figure 25 and Figure 25 show the highest contribution of HVAC replacement to the ozone depletion impact for all four building scenarios. However, the percentages are 200% for before 1970s buildings, 29% for 1-story built after 1970s and 38%, for 2-story built after 1970s. The greater percentage for 2-story buildings are mainly due to the additional HVAC requirement for the second floor. The reason behind the high ozone depletion impact of HVAC system replacement is associated with the high amount of refrigerant in the HVAC systems. For before 1970s buildings, the other contributors to ozone depletion are window replacement, attic/knee wall insulation and exterior wall insulation with 20%, 15% and 12% increase in the impact respectively. The second contributor to ozone depletion for after 1970s buildings is attic/knee insulation with only 2% increase in the impact. One interesting point about ODP is that when removing the process manufacturing impact from the life cycle stages, as shown in Figure 24, unlike other impacts, the second highest life cycle stage contributor to the ozone depletion is construction-installation process. It has the highest impact for insulating attic/knee walls and crawlspace for all four building scenarios and insulating exterior walls for before 1970s buildings.

Figure 27 and Figure 27 represent the photochemical smog impact of improvement options. From these figures, we can see that the impacts of HVAC replacement for 2-story buildings are slightly higher than all impacts except foundation wall insulation for 2-story buildings built before 1970s. Other than HVAC systems, we can observe the similar trends as for primary energy, global warming and acidification impacts in photochemical smog impact as well. In terms of the percentages, we can see that the foundation wall insulation for before 1970s buildings have the highest percentage of 5%. After that, upgrading HVAC system have the highest percentages of 4% for buildings built before 1970s and 3% for buildings built after 1970s.

One general conclusion from all the seven figures is the highest contribution of product manufacturing life cycle stage to the environmental impacts. After that, we can see that construction-installation process, transportation, de-construction, and demolition contribute the highest, but their contribution is all negligible comparing to material manufacturing stage.

Returning to the seven impact categories analyzed in this study, in conclusion, we can see that the foundation wall insulation has the highest contribution to embodied energy, carbon and smog potential for buildings built before 1970s, followed by window replacement and HVAC replacement interchangeably as the second and third contributors. Exterior wall insulation and attic/knee wall insulation are the next two contributors. On the other hand, for after 1970s buildings, we can see that the except for embodied energy which the attic/knee insulation is the highest contributor, HVAC replacement is the highest contributor to all the other impact categories. This trend is also similar for AP, HH Particulate, EP and ODP for before 1970s buildings, followed by the second contributor as the window replacement. However, replacing HVAC systems contribute significantly larger in terms of acidification, human health respiratory, eutrophication and ozone depletion impacts, in comparison to other improvement options, among all four building categories.

5.4 Energy Saving Estimation

To estimate the energy saving percentages, the nine case studies of ORNL used as the references [106]. As mentioned previously, these case studies had conducted on 1-story and 2-story residential dwellings in Atlanta metropolitan area and the achieved energy saving percentages were collected in response to implemented retrofit actions. By separating their results for our four building scenarios, the energy saving percentages were extracted for identified improvement options of building scenarios. The results of this analysis are presented in Figure 29 and Figure 29. One note is that the percentages shown in these two figures refer to the energy saving percentage on the climate-related energy consumptions including heating, cooling and water heating.

As it is shown in the figures, the maximum possible energy saving is 45% for 1-story and 50% for 2-story built before 1970s. The saving percentages are lower (35% for 1-story and 40% for 2-story) for buildings built after 1970s. One thing to notice in these figures is that foundation wall insulations is considered under "crawlspace category" for buildings built before 1970s and duct insulation is merged into the "HVAC upgrade" category in all building categories. These simplifications were conducted as the detailed numbers for energy saving percentages were not available. Additionally, the after 1970s examples in the ORNL case studies were more concentrated on 1980s and 1990s buildings and not the modern energy efficient dwellings of after 2000.

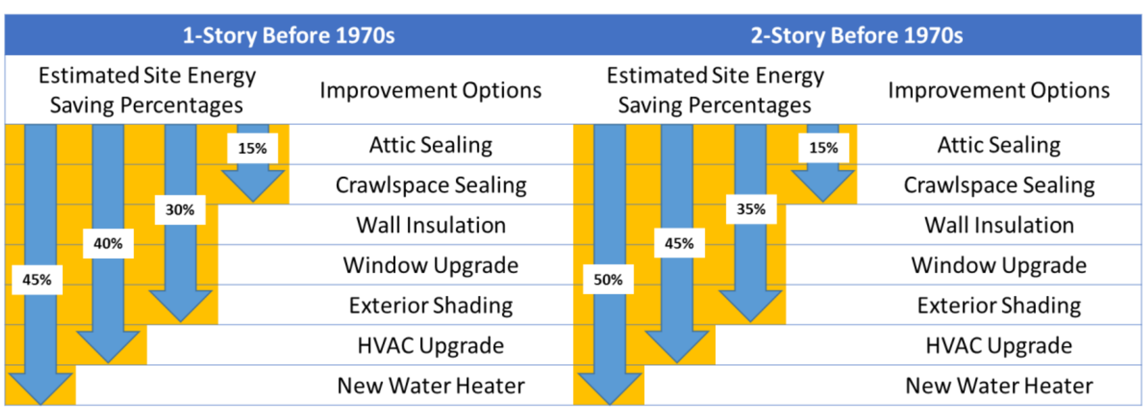


Figure 28 – Identified improvement options and estimated site energy saving percentages of 1-story and 2-story built before 1970s

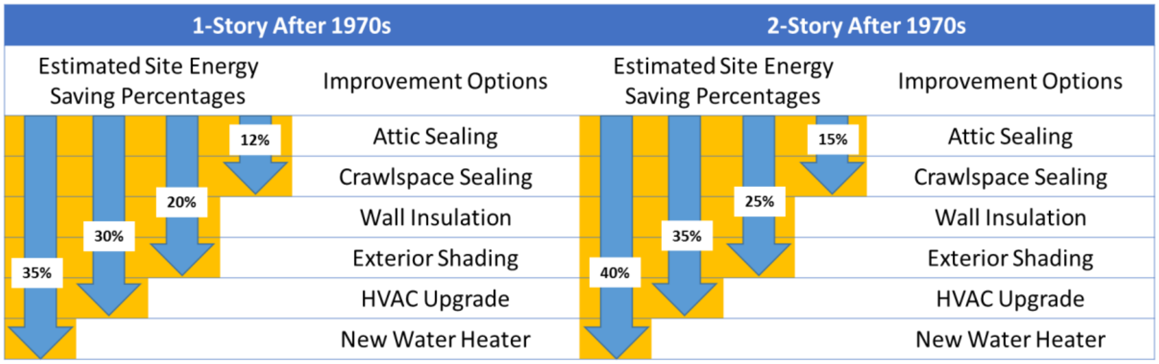


Figure 29 – Identified improvement options and estimated site energy saving percentages of 1-story and 2-story built after 1970s

The embodied energy saving percentages are also presented in Figure 30 and Figure 31 for building of before 1970s and after 1970s correspondingly. Comparing the percentages, we can see that although the generated embodied energy percentages are higher for before 1970s, their energy consumption saving rates are higher as well. Additionally, the initial average energy consumption rates are also higher for before 1970s buildings (13.8 thousandbtu/sqft higher for 1-story buildings and 22.5 thousandbtu/sqft higher for 2-story buildings), which in total result in a double effect of higher savings for before 1970s.

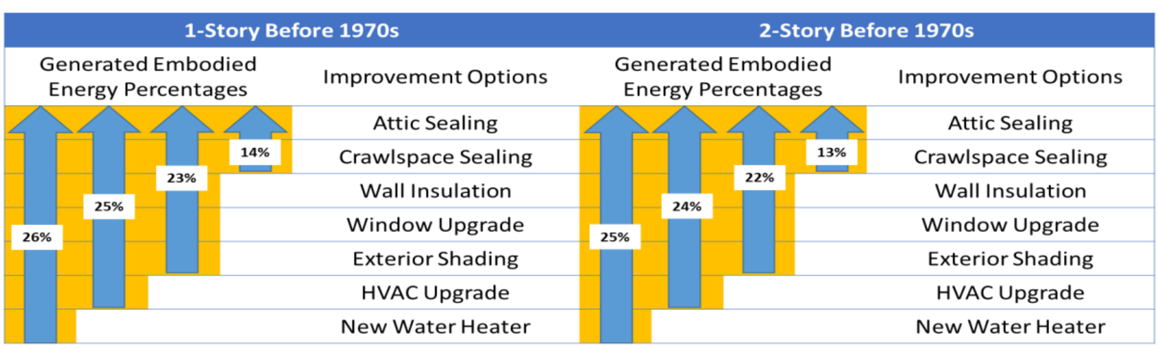


Figure 30 – Identified improvement options and generated embodied energy percentages of 1-story and 2-story built before 1970s

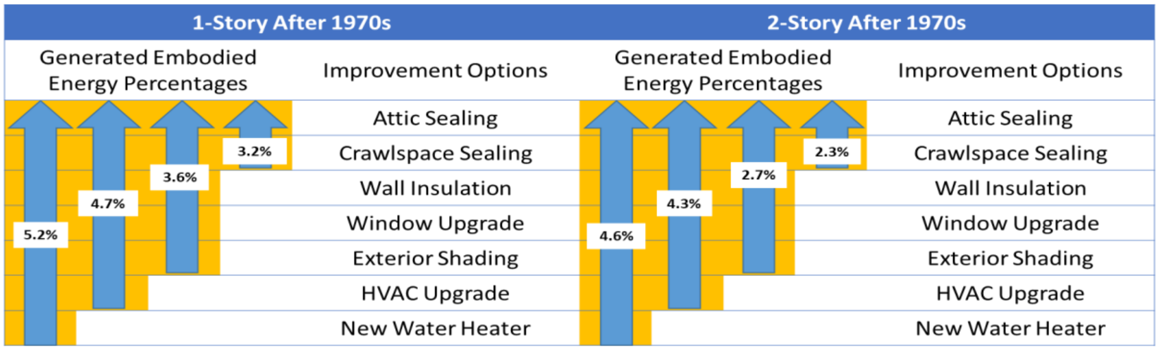


Figure 31 – Identified improvement options and generated embodied energy percentages of 1-story and 2-story built after 1970s

Using the estimated energy saving percentages and taking the average between energy consumption rates previously extracted (discussed in Table 7and Table 8), the amount of energy saving per year is calculated (thousand btu/sqft/year) by multiplying the energy saving percentage by the energy consumption rates. Moreover, to be able to more directly compare the impacts with energy savings, the energy savings were further model in Athena for a 1-year building life cycle to be able to estimate the environmental impacts of operational energy consumption phase. Based on data from EIA, I have assumed 70% of the energy consumption in Georgia comes from electricity and the remaining 30% comes from natural gas. The embodied impacts of improvement options have also been normalized by the building's footprint for an easier one to one comparison. Additionally, for better understanding of the lifetime embodied impacts versus operational savings, an average life span of 20 years was assumed for all the retrofit options [101]. Following this assumption, the AEE as well as annualized environmental impacts were calculated by dividing the total impacts by the 20 years.

The results are shown in Figure 33 to Figure 45. One thing to notice in these figures is that the numbers for both embodied impacts and environmental savings are cumulative in regard to adding improvement options. It means that the first point refers to the attic sealing and crawl space insulation, while the second point refers to adding wall insulation, exterior shadings as well as window upgrade (for before 1970s buildings) on top of the previous improvement options already added during first point.

Figure 32 represents the trade-off between embodied energy generated during implementing improvement options versus the yearly energy savings through upgrading. As we can see from this figure, both the embodied energy and saved energy are significantly lower for after 1970s buildings in comparison to before 1970s buildings. On the other hand, 1-story built before 1970s have the highest embodied energy per living are specially starting from adding wall insulation and window upgrades (average of 15 thousandbtu/sqft higher). However, the 2-story built before 1970s not only have lower embodied energy per living area comparing to 1-story before 1970s, they also have higher energy savings rate (average of 3.7 thousandbtu/sqft/year higher). Another results we could achieve from this figure is that based on how many of the improvement options were applied, the payback period of embodied energy is between 2.5 - 4.5 years for before 1970s buildings and between 1.6 – 3.2 years for after 1970s buildings. A better representative of the lifetime tradeoff between annualized embodied energy and yearly energy savings is shown in Figure 33. In this case, we can observe that since all the building scenarios' energy savings are higher than the embodied energy generated in the long run, retrofitting could be a good solution in terms of embodied energy generation.

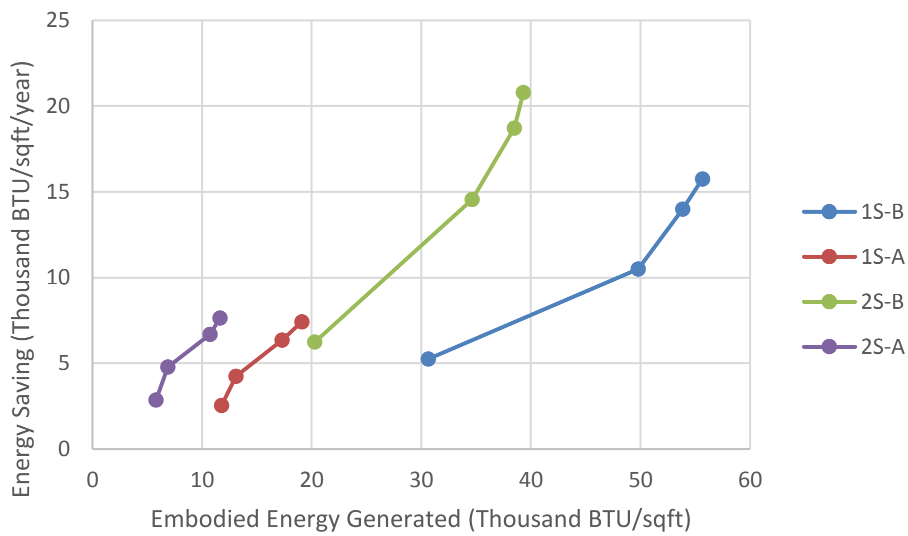


Figure 32 – Tradeoff between generated embodied energy and saved operational energy through improvement implications for four building scenarios

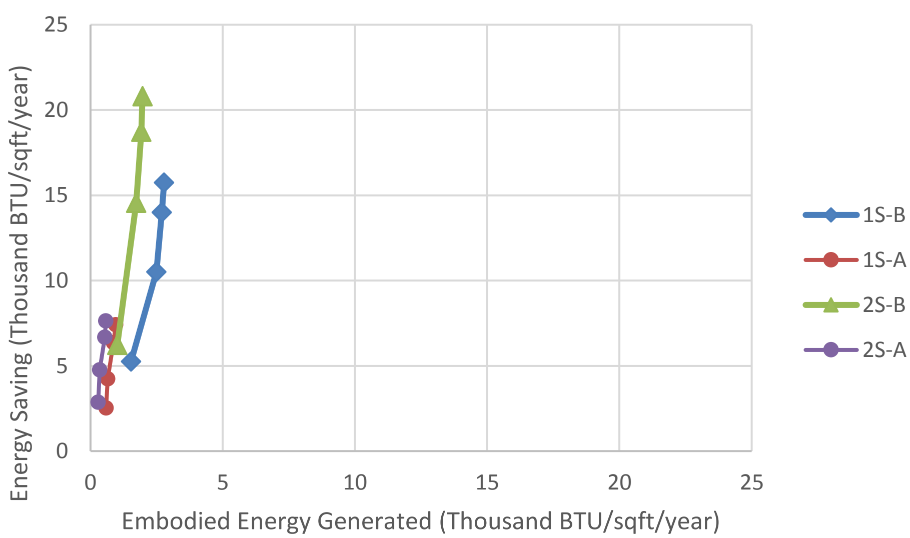


Figure 33 – Tradeoff between annualized generated embodied energy and saved operational energy through improvement implications for four building scenarios

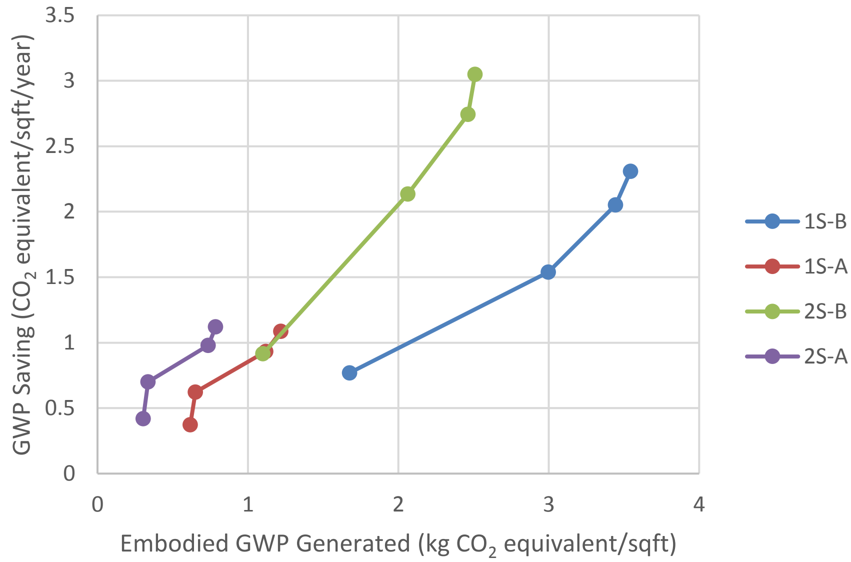


Figure 34 – Tradeoff between generated embodied carbons and saved operational carbon through improvement implications for four building scenarios

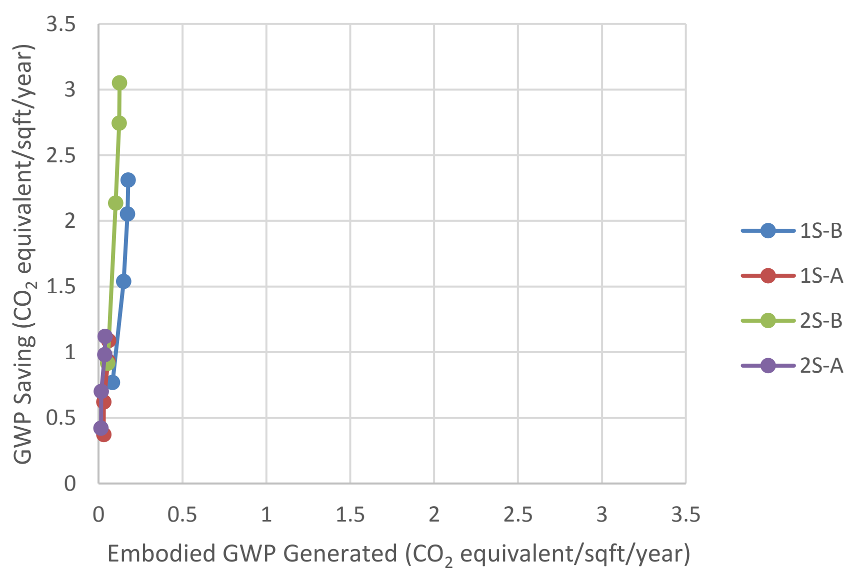


Figure 35 – Tradeoff between annualized generated embodied carbons and saved operational carbon through improvement implications for four building scenarios

Figure 34 represents the embodied carbon associated with the improvement options. The trend of embodied carbon in relation to the carbon savings is similar to the embodied energy trend. However, we can see that completely retrofitting 1-story buildings from after 1970s works better in terms of carbon saving in comparison to some initial insulation for 2-story buildings built before 1970s. Additionally, we can observe that 1-story buildings of before 1970s on average have 0.88 (kg CO_2 equivalent/sqft) more global warming impact while on average save 0.54 (kg CO_2 equivalent/sqft/year) less global warming impact in comparison to 2-story buildings of before 1970s. The results from this graph also reveals that the payback period of embodied carbon is between 1-2 years for before 1970s buildings and between 0.6 – 1.2 years for after 1970s buildings. Additionally, based on the annualized embodied carbon numbers shown in Figure 35, we can see the retrofitting decision is also supported in terms of long-term embodied carbon generation.

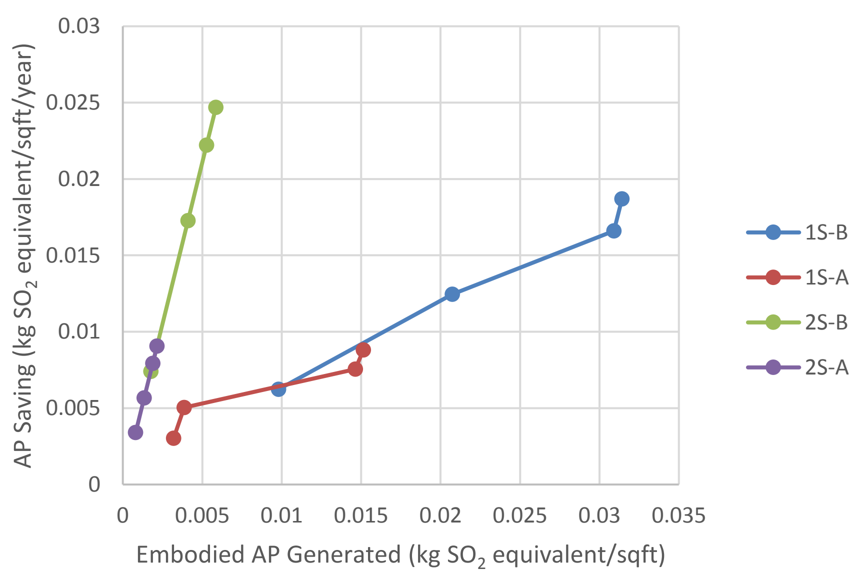


Figure 36 – Tradeoff between generated embodied acidification and saved acidification through improvement implications for four building scenarios

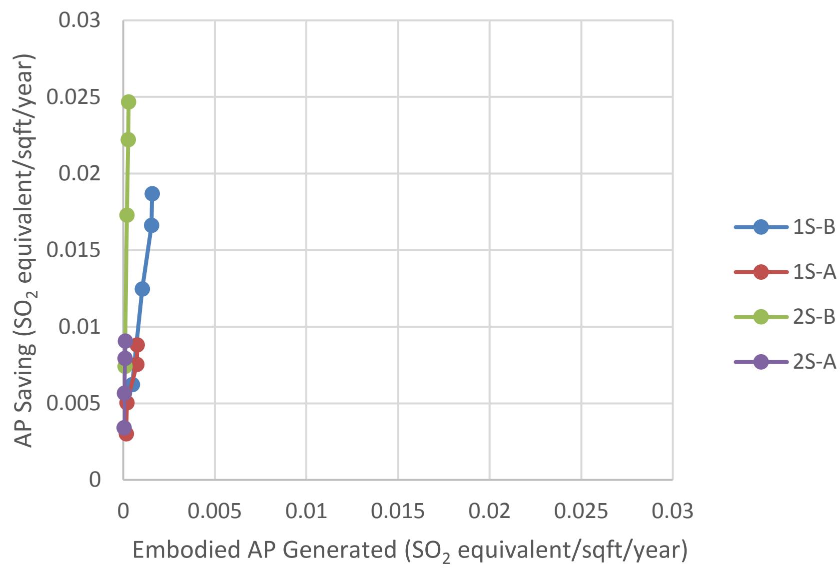


Figure 37 – Tradeoff between annualized generated embodied acidification and saved acidification through improvement implications for four building scenarios

Figure 36 shows the trade-off between embodied acidification impact and potential savings of acidification through energy savings. The graph indicates that the embodied acidification impacts per unit area are very small for 2-story buildings comparing to the 1-story buildings in all scenarios. Additionally, it shows a large amount of acidification savings for buildings built before 1970s in comparison to after 1970s. On the other hand, 1-story buildings seems to have a high embodied acidification impacts in comparison to 2-story buildings which make it a harder decision to make about retrofitting 1-story buildings. We can also observe that the huge embodied impact associated to 1-story buildings is through adding window upgrades for before 1970s and HVAC upgrade for both before and after 1970s scenarios. Another results we could achieve from this figure is that based on how many of the improvement options were applied, the payback period of embodied acidification is between 1.3-1.7 years for 1-story buildings and around 0.2 years for 2-story buildings. Additionally, from Figure 37 we can observe the compensation of operational acidification savings over the 20 years of retrofit options life span for all building scenarios.

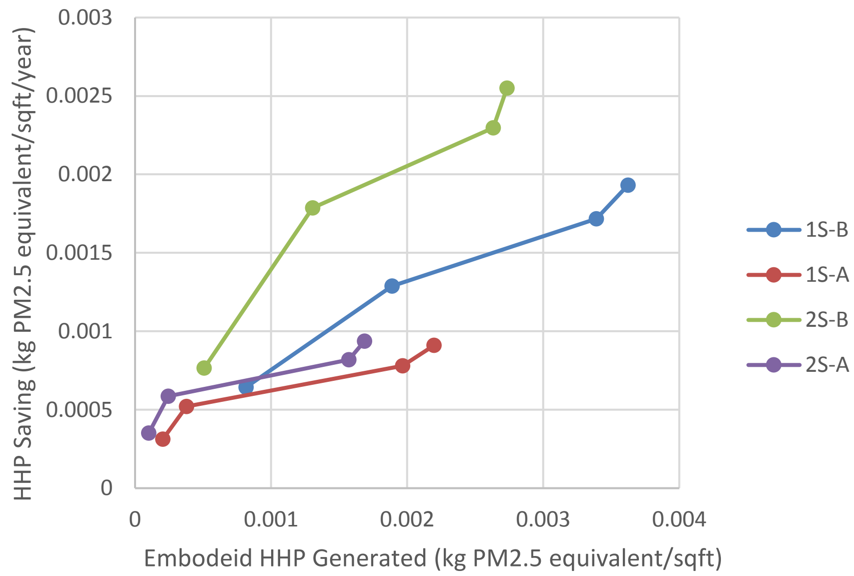


Figure 38 – Tradeoff between generated embodied respiratory impacts and saved respiratory impact through improvement implications for four building scenarios

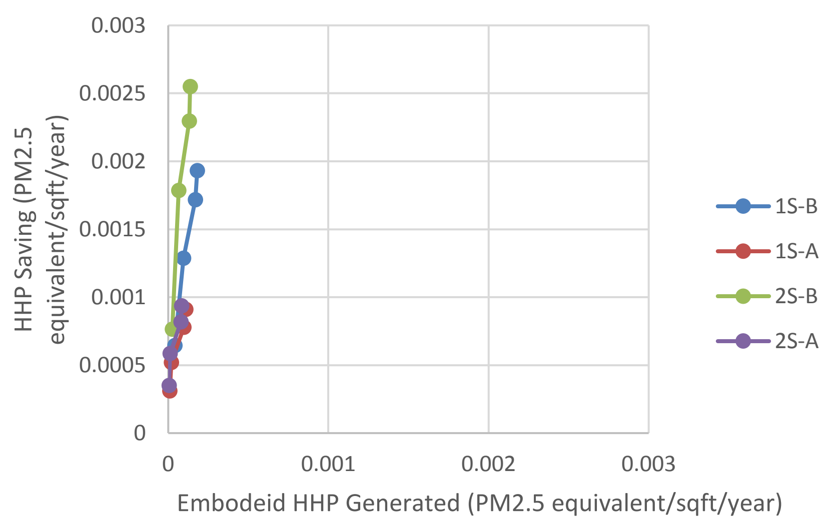


Figure 39 – Tradeoff between annualized generated embodied respiratory impacts and saved respiratory impact through improvement implications for four building scenarios

Figure 38 represents the tradeoff between embodied human health respiratory impact in improvement options and the amount of respiratory impact saved by saving energy through retrofit. As it is shown from the figure, although the embodied impacts are still higher for before 1970s buildings, we can see the embodied impacts are also significant when it comes to adding/upgrading HVAC systems for after 1970s buildings as well. However, the respiratory saving is still higher per unit area for 2-story buildings in comparison to 1-story buildings. Based on this figure, we can also observed that the payback period of embodied respiratory effect is around 1 year for 2-story buildings and around 1.5 years for 1-story buildings. The 20 years lifecycle trade-off is also shown in Figure 39.

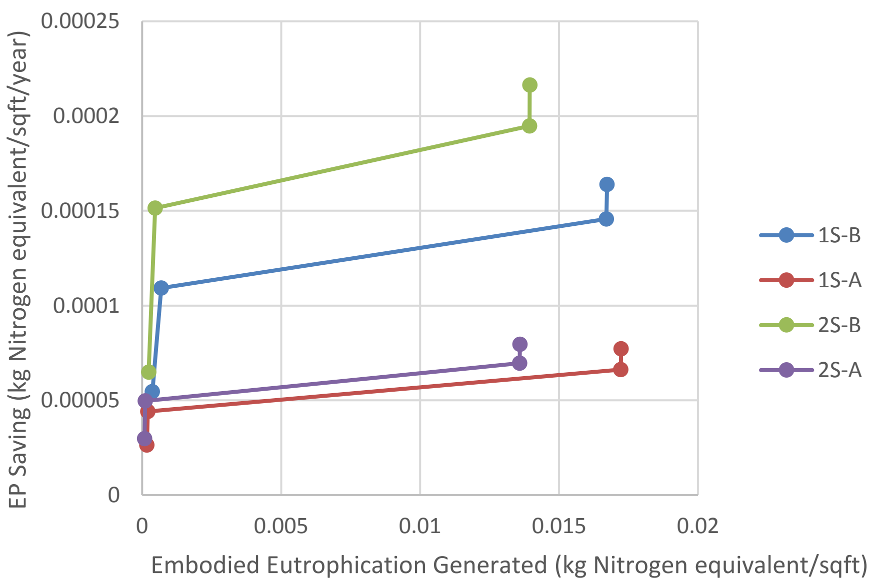


Figure 40 – Tradeoff between generated embodied eutrophication impacts and saved eutrophication through improvement implications for four building scenarios

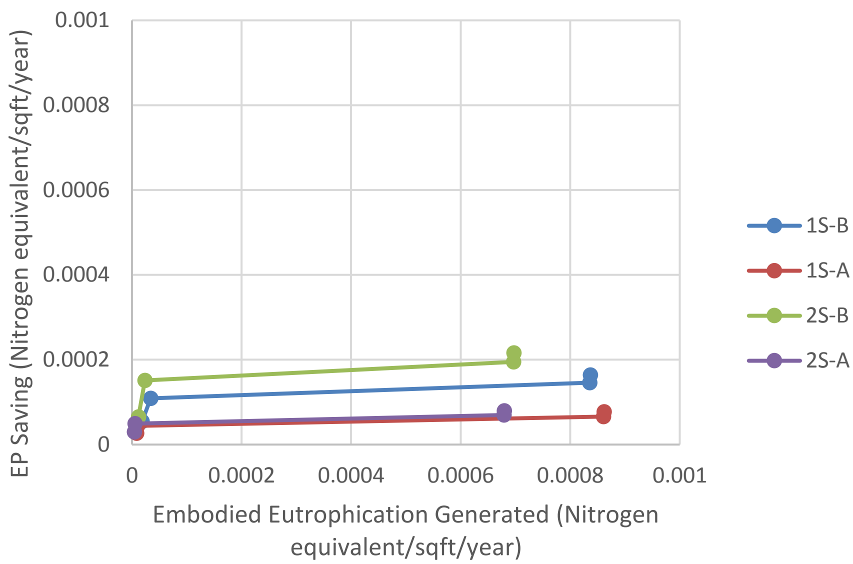


Figure 41 – Tradeoff between annualized generated embodied eutrophication impacts and saved eutrophication through improvement implications for four building scenarios

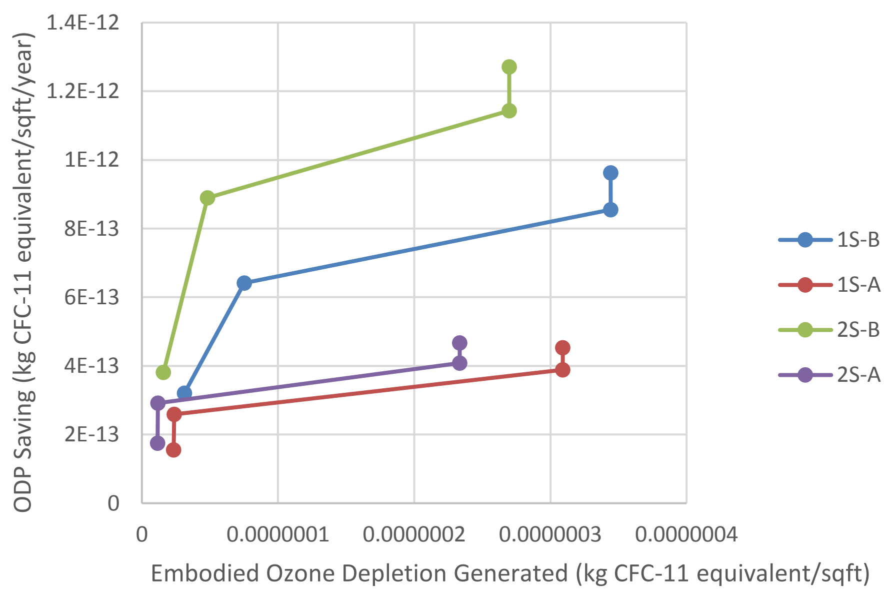


Figure 42 – Tradeoff between generated embodied ozone depletion impacts and saved ozone through improvement implications for four building scenarios

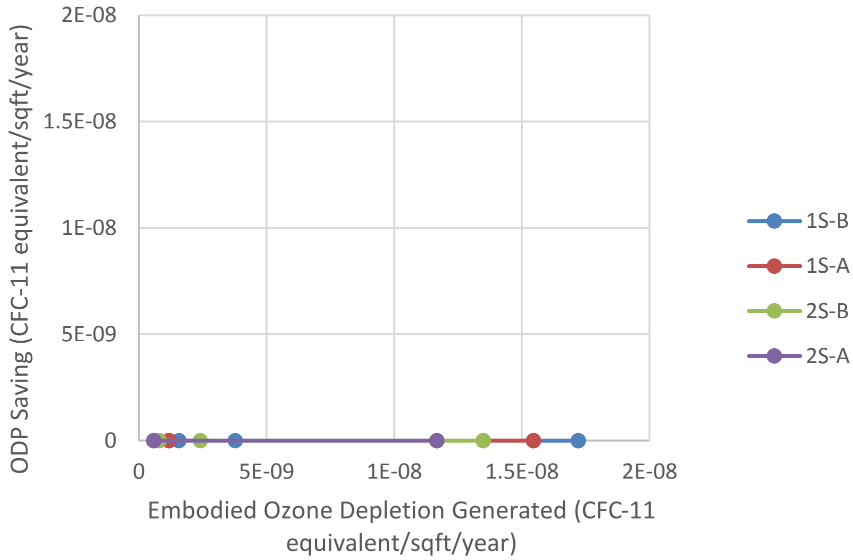


Figure 43 – Tradeoff between annualized generated embodied ozone depletion impacts and saved ozone through improvement implications for four building scenarios

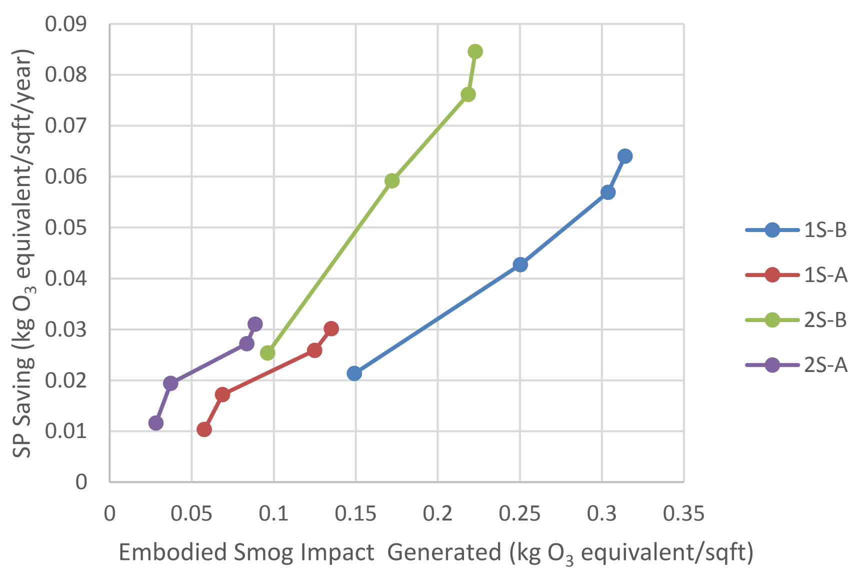


Figure 44 – Tradeoff between generated embodied smog impacts and saved smog impacts through improvement implications for four building scenarios

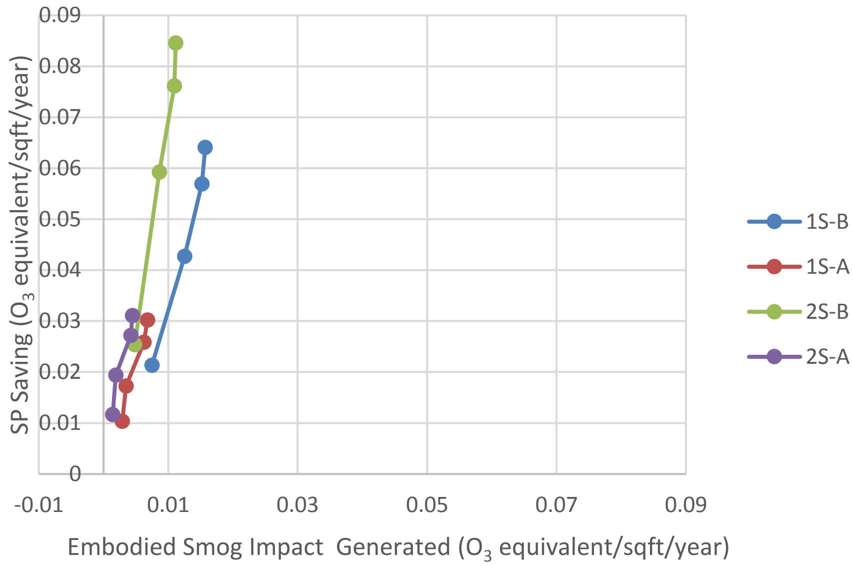


Figure 45 – Tradeoff between annualized generated embodied smog impacts and saved smog impacts through improvement implications for four building scenarios

Figure 40 and Figure 42 show the total and annualized trade-offs between eutrophication potential and ozone depletion potential respectively. As we can see from the figures, they both follow the similar trend. In both cases, the effect of adding/upgrading the HVAC system on embodied impacts is well beyond any other improvement option for all building scenarios. Additionally, we can see that in both cases of eutrophication and ozone depletion, the 2-story of before 1970s have the highest saving impacts per unit area, followed by 1-story of before 1970s, 2-story of after 1970s and 1-story of after 1970s, respectively.

Figure 41 and Figure 43 show the annualized embodied impacts over the 20 years of the retrofit options life span. The payback period for eutrophication potential is between 2.5-6.5 years before implementing HVAC systems and suddenly rises up to around 100-200 years when the HVAC improvements are applied. On the other hand, the payback period for ozone depletion impact is higher than thousands years even before implementing the HVAC systems. These numbers highlight the importance of HVAC systems in eutrophication potential. Additionally, although the numbers are quite low in generating CFCs, we can see that there is almost no way of compensation when they are used. Therefore, based on this analysis, the author highly encourage of switching to other none CFC-based materials in building construction, particularly for cooling systems.

Figure 44 represents the relation between embodied smog impacts and the saved smog impact associated with potential energy savings through retrofitting the buildings. The graph shows a similar trend as embodied energy and embodied carbon. Based on the numbers, there is an average of 0.077 (kg O3/sqft) higher embodied smog impacts and 0.015 (kg O3/sqft/year) lower impact savings associated with 1-story before 1970s comparing to 2-story before 1970s. Moreover, the numbers shows a payback period of around 4.7-5.7 years for 1-story and 2.5-3 years for 2-story buildings. The lifecycle analysis over the 20 years of the retrofit options' life span which is presented in Figure 45 also confirms the compensation of embodied smog generated throughout the retrofit process.

The results of the trade-off analysis and comparisons showed that generally, the best option is to retrofit 2-story buildings of before 1970s, which while have lower embodied energy comparing to 1-story buildings of the same age, save more impacts per unit area as well. This fact is also true in terms of after 1970s buildings, however, those buildings seems to save much lower impacts while their embodied impact generation is also low which is a positive criterion. Lastly, it seems the 1-story buildings of before 1970s have generally the highest contribution to embodied impacts, while their saving impacts are always lower is comparison to 2-story buildings of the same age, and sometime even lower than 1-story buildings of after 1970s.

On the other hand, we can also observe that the embodied impacts are more sensitive in general to window upgrading as well as HVAC upgrading particularly in terms of eutrophication and ozone depletion, which the embodied impacts cannot be compensated through the lifespan of the building and energy saving impacts.

CHAPTER 6. CONCLUSIONS, LIMITATIONS AND FUTURE WORKS

The focus of policymakers and city planners on regulating energy use and emissions of buildings has been mostly on operational energy, often overlooking other life cycle components such as embodied energy, which can account for a significant portion of life cycle emissions. This study, presented the results of a systematic LCA comparison between buildings built before and after 1970s in the City of Atlanta, in order to show the effects of changes in the embodied energy usage and consequential environmental impacts of the buildings considering various building structural assembly groups and life cycle stages.

The results of this study show that material manufacturing and material replacement, respectively, dominate the embodied environmental impacts of all stages. From assembly group perspective, foundation covers more than 40% of the total embodied CO2 emission. Comparing the buildings built before 1970s and after 1970s, it can be observed that after 1970s, product manufacturing, construction and end of life phases contributes more in all environmental measurements.

In general, the results show that residential buildings built before 1970s have lower embodied environmental impacts per square meter than residential buildings built after 1970s. This difference is in its highest for GWP which is 3.75-4.04 higher for buildings built after 1970s. AP, ODP and SP come next with approximately 72%, 45% and 22% increase respectively for their 1-story models built after 1970s and with approximately

75%, 75% and 15% increase respectively for their 2-story models built after 1970s. Residential buildings built before 1970s also have lower (approximately 35%) embodied energy in comparison to buildings built after 1970s.

On the other hand, 2-story residential buildings have lower embodied energy and impacts per square meter in comparison to 1-story residential buildings. GWP is in the range of 28.3 – 29.4 kg CO2/m2 for buildings built before 1970s and 106 – 119 kg CO2/m2 for buildings built after 1970s. The TPE (embodied energy) calculated for building scenarios in this study varies between 1.8 – 3.9 Gj/m2. The lower level of GWP impact in this study in comparison to other similar studies is mainly because of including beyond building life and material re-use phase in this study. Moreover, as shown in Figure 9, the longer assumed life span in this study (75 years) in comparison to usual 50-60 years of life time assumption in building LCAs could also cause the lower embodied impacts of this analysis.

The findings of this study can be integrated with the operational phase energy consumption of the buildings, to conduct a complete LCA analysis over the whole life cycle of the buildings. It is critical to examine whether the upfront raise in embodied energy in newer buildings will save the operational energy consumption along the way over the total building life span. Therefore, it is important to consider the correct trade-off between embodied and operational phases in discussing energy efficiency in the residential building industry. Additionally, the LCA of buildings constructed with different systems as discussed in this study, can give information about strategies to rehabilitate, to change the building process or to select materials.

The results, can then be used by policy makers and city planners to improve the sustainability of Atlanta metropolitan area for future development plans of the region. One of the limitations of this study is that we have assumed that the construction transition only affects the structural and building envelope changes and did not take into account other changes such as material manufacturing and electricity mixes over the years.

Considering the potential improvement options in the region, the life cycle analysis revealed that the highest contribution of product manufacturing life cycle stage to the environmental impacts. After that, we can see that construction-installation process, transportation, de-construction, and demolition contribute the highest, but their contribution is all negligible comparing to material manufacturing stage.

Moreover, the results of this study on improvement options showed that the foundation wall insulation has the highest contribution to embodied energy, carbon and smog potential for buildings built before 1970s, followed by window replacement and HVAC replacement interchangeably as the second and third contributors. Exterior wall insulation and attic/knee wall insulation are the next two contributors. On the other hand, for after 1970s buildings, we can see that the except for embodied energy which the attic/knee insulation is the highest contributor, HVAC replacement is the highest contributor to all the other impact categories. This trend is also similar for AP, HH Particulate, EP and ODP for before 1970s buildings, followed by the second contributor as the window replacement. However, replacing HVAC systems contribute significantly larger in terms of acidification, human health respiratory, eutrophication and ozone depletion impacts, in comparison to other improvement options, among all four building categories.

The results of the trade-off analysis and comparisons showed that generally, the best option is to retrofit 2-story buildings of before 1970s, which while have lower embodied energy comparing to 1-story buildings of the same age, save more impacts per unit area as well. This fact is also true in terms of after 1970s buildings, however, those buildings seems to save much lower impacts while their embodied impact generation is also low which is a positive criterion. Lastly, it seems the 1-story buildings of before 1970s have generally the highest contribution to embodied impacts, while their saving impacts are always lower is comparison to 2-story buildings of the same age, and sometime even lower than 1-story buildings of after 1970s.

On the other hand, we can also observe that the embodied impacts are more sensitive in general to window upgrading as well as HVAC upgrading particularly in terms of eutrophication and ozone depletion, which the embodied impacts cannot be compensated through the lifespan of the building and energy saving impacts. However, one solution to this issue is to switch to new technologies particularly in HVAC systems. For example, by moving towards non R22 refrigerants in HVAC systems, a lot of issues in terms of ozone depletion would be solved. This transition has been started by implementing the Montreal protocol and the production and import of R22 in the US is continually reduced by law until 2020, when all production and import will eventually be eliminated. One introduced solution is switching to R-410A HVAC systems which uses a hydro-fluorocarbon (HFC) which does not contribute to ozone depletion any more.

In conclusion, the primary contributions of this research to the body of knowledge are: (1) benchmarking the generic characteristics of existing residential buildings considering building codes and construction changes in the region; (2) investigating the trend of embodied energy and emissions of benchmarked buildings considering the 1970s transition in the construction industry; and (3) identifying potential improvement options for benchmarked buildings and comparing the embodied energy and environmental impacts of identified options.

The main findings of this research showed: (1) lower embodied energy and environmental impacts per unit area for houses built before 1970s; (2) lower embodied energy and impacts per unit area for 2-story houses; (3) a range of 1.8 to 3.9 Gj/m2 embodied energy for residential buildings in the region; (4) highest environmental impacts for attic/knee insulation and heating, ventilation and air conditioning (HVAC) units replacement through retrofitting residential buildings; and (5) significant environmental impacts for foundation wall insulation and window upgrading through retrofitting dwellings built before the 1970s.

One limitation of this study was to use the TRACI midpoint LCA method. In this case, we cannot exactly identify the final impacts of emissions on environment and human health as the end methods do. Rather, we only will have the amount of emissions released into water, air and landfills. This lack in correctly representing the impacts on people and planet could be count as a limitation of the LCA analysis in this study. Moreover, depending on the question that the study is trying to answer, it is important to choose the correct functional unit while conducting the LCA analysis. Studies showed that although more certain decisions can be made using the midpoint indicators, the results can have a lower relevance for decision support in some cases [107]. Another limitation of this study was finding the appropriate data for the LCI. Although Athena included Atlanta as the region in its library, the software lacked having many older materials and components which were generally used for before 1970s buildings. Therefore, the author ended up making much more simplifying assumptions in terms of building components particularly for before 1970s building scenarios.

In this study, the focus was mostly on the buildings as the systems and the emissions per unit area as the functional unit. However, it is also of high importance to study the impacts per person. Particularly in current time that people tends to live in bigger houses, the person's footprint could be of higher importance rather than the building's footprint per unit area.

The future study direction is to calculate the operational energy consumption of building types in various scenarios (status quo, major renovation, reconstruction, etc.) and investigate the potential improvements of energy usage, safety, and modernization while reducing life cycle emissions by renovating existing residential buildings of a decade. Furthermore, it is an interesting idea to investigate scenarios of residential development plans such as retrofit old buildings or construct new ones and analyze environmental payback time of different housing scenarios. The authors believe that these analysis, in addition to cost scenarios and socioeconomic characteristics of the region, can result in a sustainable residential development plan for the city of Atlanta.

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