Lifecycle Assessment LCA comparison for different prefabricated modular construction systems with the conventional construction system for affordable houses in Egypt

دراسة حول
مقارنة مختلف أنظمة وحدات سابقة التجهيز مع نظام البناء التقليدي للمنازل منخفضة التكاليف بجمهورية مصر العربية على مدار العمر الافتراضى للمبنى

by

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ABSTRACT

Egypt is considered as the most populated country in the Arab world with its high population that exceeds 94 million (CIA, 2017), 62.6% of them are in working age and the young generation forms 19.24% of the overall population. This overpopulation puts a huge pressure on many sectors including affordable housing which suffers from severe supply shortage. All conventional housing solutions that the different governments have put to solve this issue along the last 70 years, they are still fare away from being affordable to the majority of population in many cities in Egypt. This research focuses on studying the environmental viability of introducing prefabricated modular systems as an alternative sustainable solution to the current conventional construction system in affordable housing sector. To achieve the goals of this research, a comparison was conducted between four prefabricated and modular construction systems to the conventional construction system and studied their different impacts on the environment. The conventional construction system that is widely used in Egypt is cast in situ and masonry work. In this research, this conventional construction has been compared to the following four prefabricated construction systems: 1) Pre-cast Concrete PCC, 2) Glass Reinforced Concrete GRC, 3) Light Gauge Steel LGS, 4) Adapted Shipping Containers. Life Cycle Assessment (LCA) has been used as the research methodology to compare the environmental impact of the four construction system to the conventional system which was used as the base case for this comparison.

This research aims to assess these prefabricated systems that exist in Egypt and evaluate their impacts on environment from the perspective of the used resources and land emissions over the life-cycle of each system, total primary energy consumption and global warming potentials over the life cycle of the building. Five building models, one for each of the previous mentioned construction systems, have been designed and used in the LCA analysis. All the 5 models share the same physical dimensions and the same spatial components for the building under study but vary in their construction materials. The building is composed of a 4-storey building that holds 3 residential units per floor.

Athena Impact Estimator was the software used for the LCA assessment tool and eQUEST was the energy analysis software used.

After running the LCA analysis we concluded that among the four construction systems and over the 50 years of their life cycle, both GRC and LGS options proved a lot of reduction in their impacts on environment. During the production and the construction stages as compared to the convention construction system, LGS and GRC reduced 66% and 46% of the used solid resources respectively. These reductions are due to the reduction in the materials mass used in these 2 construction systems. Accordingly and for the same reasons, the land emissions for the same systems (amount of waste generated along the life cycle of the building), have been reduced as well. LGS saved 60% while GRC saved 54% of the amount of waste that the conventional system produced. For the total primary energy consumption, LGS saved 40% of the total embodied energy compared to the conventional construction system while GRC saved 18%. For the Green-House Gas GHG emissions, LGS saved 64% while GRC saved 25% of the embodied emissions that the conventional system produced.

With their reduced environmental impacts, these two prefabrication systems are recommended to be used for the affordable housing projects in Egypt. Besides all the environmental benefits of these two systems, their prefabrication process in factories improves quality, reduces construction time and saves cost due to the economy of scale of the large housing projects especially those which are supported by the government.

مختصر البحث

تعتبر مصر من اكثر الدول العربيه اكتظاظا بالسكان حيث يتجاوز تعداد سكانها 94 مليون حيث تبلغ نسبة من هم فى سن العمل الى 62.6% وكذلك نسبة الشباب الى 19.24% . هذة النسبه المرتفعه فى عدد السكان تضيف الكثير من الضغوط على العديد من القطاعات الخدميه بالدوله ومن ضمنها الاسكان منخفض التكاليف والذى يعانى من نقص حاد فى الامدادات. على الرغم من كل الحلول التقليديه والتى قدمتها الحكومات المتعاقبه على مدى ال70 سنة الماضيه الا انها لاتزال بعيدة عن تلبية احتياجات الاسكان للاغلبيه العظمى من سكان العديد من المدن المصريه. يركز هذا البحث على دراسة الجدوى البيئيه لاستخدام نظم أنشاء الوحدات سابقة التصنيع كبديل مستدام لطرق الانشاء التقليديه فى قطاع الاسكان منخفض التكاليف. ولتحقيق اهداف هذا البحث فأنة تم اجراء دراسة مقارنة بين اربع من نظم الوحدات سابقة التصنيع ونظام الانشاء التقليدى المتبع بمصر ودراسة تاثيرها على البيئه. يعتمد نظام الانشاء التقبيد ى المتبع على نطاق واسع بمصر على استخدام الطوب والخرسانه المسلحه . فى هذا البحث تم مقارنة هذا النظام الانشائى مع الانظ الاربع التاليه:(1 الالواح الخرسانيه سابقة الصنع (PCC) (2 الالواح الخرسانيه سابقة الصنع والمقواه بالالياف الزجاجيه (GRC), (3 الالواح الحديديه قليلة السماكه (LGS), (4 حاويات النقل المعدلة (ASC). استخدم تقيم الدورة العمريه (LCA) كنظام بحث لدراسة التأثير البيئى لأنظمة الانشاء الاربعه ومقارنتها بالتأثير البيئى للنظام الانشائى التقليدى.

يهدف البحث الى تقييم نظم الانشاء سابقة الصنع الموجودة فى مصر ومدى تأثيرها على البيئة من حيث كمية الموارد المستخدمه والهالكه و كم الطاقة المستنفذة و مقدارالانبعاثات الغازيه المسببه للانبعاث الحرارى على مدى العمر الافتراضى للمبنى. ولأجراء هذة المقارنه تم تصميمي خمس نمازج مختلفه (نموزج لكل نظام انشائى) للمبنى الذى سيتم اجراء تقيم الدورة الحياتيه عليه. تشابهت النمازج الخمس من حيث الابعاد والمقاييس الفراغيه للمبنى موضوع الدراسه بينما اختلفت من حيث مواد البناء حسب النظام الانشائى المتبع. يتكون المبنى موضوع الدراسه من اربع طوابق فى كل طابق ثلاث وحدات سكنيه. استخدم برنامج (ATHENA Impact Estimator) لتقييم الدورة العمريه (LCA) وبرنامج (eQUEST)لحساب كمية الطاقة المستخدمه لكل نموزج.

بعد اجراء دراسة (LCA) تبين انه من بين الانظمه الانشائيه الخمسه وعلى مدى العمر الافتراضى للمبن والمقدر ب 50 عاما فأن نظامى (GRC) و (LGS) قد حققا العديد من الانخفاض فى اثارهما البيئيه. ففى خلال مرحاتى التصنيع والانشاء ومقارنة بالنظام الانشاء التقليدى اثبت نظامى (LGS) و (GRC) نسبتا انخفاض تقدرا ب 66% و 46% على التوالى لمقدار اوزان الموارد المستخدمه. هذا الانخفاض يعزى الى قلة حجم مواد الانشاء المستخدمة لكلا النظامين. وعليه ولنفس السبب فنسب المواد الهالكه والناتجه عن كلا النظامين قد انخفضت بنسب 60% و 54% على التوالى كذلك مقارنة بوزن المواد الهالكه والتى نتجت عن نظام الانشاء التقليدى. اما عن مجموع الطاقه المستهلكه, فأن نظام (LGS) قد سجل انخفاض قدره 40% بينما سجل نظام (GRC) انخفاض قدره 18% من مقدار الطاقه المستهلكه من قبل نظام الانشاء التقليدى. وعليه جاءت نتائج انبعاثات الغازات المسببه للاحتباس الحرارى لنظام (LGS) مؤكدة انخفاض قدره 64% بينما جائت بنسبة انخفاض 25% لنظام (GRC).

مع تاثيراتهم البيئيه المنخفضه فأنه يوصى بأستخدام هذان النظامان سابقى التصنيع فى مشاريع المساكن منخفضة التكاليف فى مصر. فبجانب الفوائد البيئيه لهذان النظامان فخطواط التصنيع المسبق بالمصانع المتخصصه تؤدى الى تحسين الجودة وتقليل وقت الانشاء وكذلك الى تقليل تكلفة الانتاج نتيجة الاقتصاد الناتج عن الزياده فى حجم المنتج خصوصا بالنسبه لمشاريع الاسكان المدعمه من قبل الحكومه.

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CHAPTER 1

INTRODUCTION

1.0 A Brief About the Research

Egypt is suffering from many housing issues of shortage in supply for houses compared to the volume of demand, non- affordability for the available houses in the market for a large sector of Egyptians and the spread of slums and scattered settlements along a large area of the whole country. The history of the housing issues in Egypt goes back to 1970s during the era of President Al Sadat. With the increase in population and the declination of the economy of Egypt in general, the housing issues became more complicated to be resolved through the conventional methods. This research studies introducing different sustainable modular construction systems into the social housing programs. Different prefabricated modular construction systems and materials have been analyzed; pre-cast concrete (PCC), Glass Reinforced Concrete (GRC), Light Gage Steel (LGS), and Adapted Shipping Containers (ASC). All the previous systems have been compared with the conventional construction system that is used currently in the social housing programs which uses concrete and masonry work system. The study adapted the Lifecycle assessment LCA methodology to study the environmental impact of the previous systems along their life cycle to conclude the best suitable modular system for affordable housing in Egypt.

1.1 Egypt, Overview

Egypt is a nation for eighty eight million people in north east corner of Africa. It includes Sinai Peninsula which is located on the western side of Asia (Figure 1.1). Suez Canal has been created by Egyptian hands in 1869 linking the Red Sea and the Mediterranean Sea together and is considered as the most important trading route in the world. Many reasons helped Egypt to develop its early civilization 3000 years BC. The rich flood of the river annually and the abundance of drinkable water of Nile created a status of stability for people to settle down along the river Nile. The vast east and west deserts provided natural protection to Egypt.

In 2011, youths and opposition groups started the revolution against the government of Hosni Mubarak as a result of the police brutality, inflation, rise in food prices, unfair elections, high unemployment and low wages. During the last 6 years and since the revolution, the country has suffered from the instability status in all areas of economy, security, social and political conditions of Egypt (The Encyclopedia of Earth 3013). The economical and the social conditions in Egypt were the main drivers for the 2011 revolution and the youths were the main participants in it. That was one of the main motivations for this research to provide non-traditional solutions to affordable housing for young generations in Egypt.

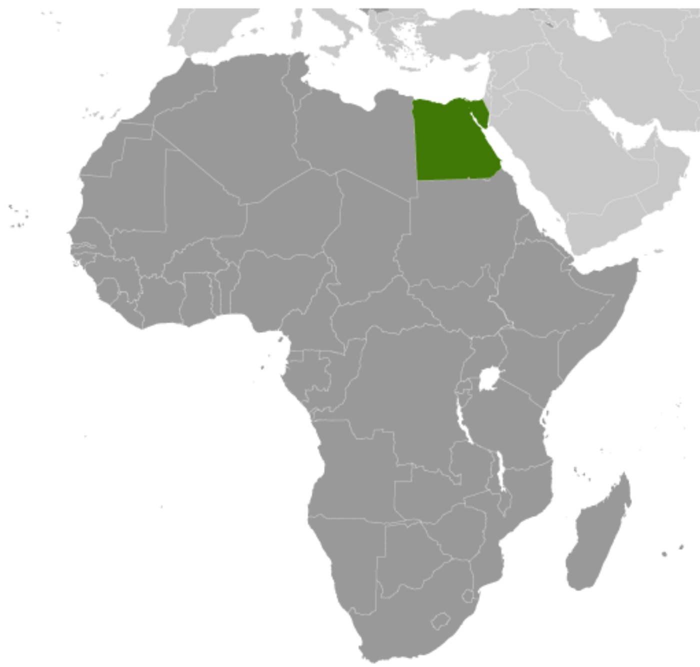

Figure 1.1: The Location of Egypt within Africa (The Encyclopedia of Earth 3013)

1.2 Motivation for the Study

The residential industry in Egypt suffers on different levels. On economical level, although the apartment prices are extremely high compared to the mid income salaries; it is a trend in the whole Egypt that people used to buy not to rent to live due to the unavailability of the rental apartments. The cost of conventionally constructed buildings is high due to the cost of the construction materials like concrete and the finishing materials. Although the availability of cheap labors in Egypt should contribute to reducing the overall construction cost, the majority of the available resources are not skilled enough for minimum construction quality. This is due to the lack of professional training institutes in general and most of these labors learn through experience. Accordingly, large sector of people are not able to live in properly planned and well served districts and had to live either in slums or scattered settlements. Accordingly, young generations cannot build their families due to their inability to buy even small apartments. This leads to many social defects on the Egyptian society.

On the environmental level, Egypt is a country that suffers from major scarcity in natural resources of water, energy and some essential building materials like iron, aluminum and timber. Besides the construction industry is considered the main contributor to the GHG emissions, solid wastes generation and increase in air pollution level.

So, it was essential to think of a sustainable alternative to the current concrete and masonry construction system that can provide a solution to these interrelated issues and to approach the affordable housing from a different innovative perspective. Similar to many other developing countries, the prefabricated and industrialized building systems are introduced into the affordable housing to reduce their cost and their construction time. Prefabrication has many advantages and limitations which make it successful methodology in some countries and may fail in others. This research studies the validity of introducing prefabricated modular systems into the affordable housing in Egypt and the environmental advantages of its use. A Life Cycle Assessment LCA has been conducted for four prefabricated construction systems in comparison to the current conventional construction and analyzed the environmental impact of each.

1.3 Aims and Objectives

This research studies the viability of introducing prefabricated modular construction systems into the affordable housing industry and analyzes their environmental advantages in comparison to the current conventional construction system. Prefabricated modular systems can reduce the amount of construction waste on site as well as offsite. Many researches proofed that the prefabrication reduces the construction time due to running the construction activities on site in parallel to the offsite manufacturing process. According to the large size of the affordable housing projects that the government is constructing currently, the mass production allows for economy of scale savings which makes these prefabrication systems more convenient than the current conventional systems.

So, the aim of this research is to find out a better construction methodology that is more environmentally sustainable to be used for affordable housing. This objective will be conducted through running a life cycle assessment LCA for four pre-fabricated modular systems in comparison to the conventional construction system that uses concrete and masonry in the current affordable housing projects in Egypt. These four modular construction systems have some presence in Egypt which could be developed to provide a competitive solution. To achieve this aim the following objectives are set to be met:

- Conducting an intensive literature review of the use of the prefabricated systems in affordable housing and their environmental impact comparison to the conventional systems.
- Running an LCA analysis for four pre-fabricated modular systems in comparison to the conventional construction system. The four modular systems are: pre-cast concrete (PCC), Glass Reinforced Concrete (GRC), Light Gage Steel (LGS) and Adapted Shipping Containers (ASC).
- Analyzing the results of the LCA for the four modular systems and compare them to the LCA of the conventional construction system.
- Conclude the best sustainable modular system that has the least negative impact on the environment to be used as an alternative construction system for the affordable housing industry in Egypt.
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CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This research focuses on the introduction of pre-fabricated modular systems into the affordable houses in Egypt. It compares four different modular systems with the current conventional system along their life cycle to evaluate their environmental impact during construction, operation and beyond building life as well. To run this comparison, a base model of a modular building of four floors was designed to run the LCA analysis on. The building is designed to be composed of 12 similar modules. The design has the same spatial dimensions with five different modular systems. LCA simulations ran on the five models and the assessments have been compared to each other.

It was important to run an intensive literature review to set the base for this study. The literature review section is concerned about three main areas; the efficiency of using the pre-fabrication construction with particularity of the modular systems as a solution for affordable housing, the different modular systems with their different materials and the validity of using LCA as analytical tool to compare the pre-fabricated modular systems with the conventional construction system. Many researches have been viewed in these three main areas to gather the basic information about this study and to highlight the research gabs that this study can add value to.

2.1 Main country challenges

Egypt is one of the third world countries that is facing lots of challenges on all levels. The following sections will discuss the different environmental, economic and social challenges that face Egypt and their impacts on housing sector.

2.1.1 Environmental Challenges

Egypt is facing many environmental challenges which are either driven from its geographical location and its nature or from the bad management of its natural resources. As per (The Encyclopedia of Earth 3013), these challenges could be briefed as follows:

- Limited natural water sources other than the Nile. Egypt is suffering from a severe water scarcity during the last years. The misuse of water sources, the use of old inefficient techniques for irrigation and uneven water distribution are the main reasons for this issue. This problem is elected to increase due to the high dam in Ethiopia which will reduce the volume of water.
- Egypt is susceptible to storms, windstorms and that blow in spring called Khamasin. Egypt is threatened by frequent earthquakes and landslides as well.
- The depletion of agricultural land due to urbanization and sandstorms.
- Increase of soil salinity due to high dam in Aswan.
- Coral reefs, beaches and marine life have been affected due to oil pollution.
- Water pollution due to pesticides, herbicides, row sewage and industrial waste discharge.
- Reduction in water quantity due to the high dam of Ethiopia (countries Quest, 2015).
- High Dam in Aswan has reduced the river flow and trapped the Nutrient rich slit which is very important for the land fertilize.
- High airborne pollution in large cities like Cairo and Alexandria due to means of transportation, construction sites, factories which are not located far away from the center of these cities.
- Limited sources of energy

All of these challenges could be solved and find their proper solutions but the economic status of Egypt as a poor country plays the main hurdle in front of these solutions.

2.1.2 Economic Challenges

Along its deep history, Egypt depended on farming as the base for its economy although 95% of its land is desert. Cereals were the main crop for local consumption as well as for exporting. Cotton began to become the cash crop in 19th century and Egypt is still known with its high quality cotton. At the beginning of 20th century, industry was introduced to become part of the economy sources which has gradually increased till to date. Oil and gas sector has been introduced lately along with tourism, remittances of Egyptians who work in the gulf countries. Suez Canal is considered as one of the important source of economy as well. (Country Esquest, n.d.). The Egyptian economy was so centralized during the former President Gamal Abdel Naser then was opened widely during former presidents Anwar Al Sadat and Hosney Mubarak. Egypt is considered as poor country by world definition. The increase of unemployment and poverty led to a dissatisfaction status among Egyptian which led to the revolution in 2011. The economy has been affected significantly after the revolution due to the political uncertainty and the lack of security situation. Egypt is the third most indebted country in the world after Spain and Greece according to economist magazine. The general public debt is currently evaluated at US$206.999 billion, which is equal to 82 per cent of GDP. The loan interest reaches 22% of the total GDP of Egypt which deprives other sectors from their fair share of the budget. This situation could lead to full financial crises (Daily News, 2015).

The budget deficit is growing during the last 10 years. In 2010, the deficit was 134 billion pounds and increased to 205 billion pounds in 2013 and is estimated to reach11.5% of GDP in year 2014/2015 (Nawara, 2013). Due to borrowing from the local banks, the private sector is affected and financing the private investments becomes more expensive. The decline source of foreign currency is another challenge for the Egyptian economy. The instability situation and the terrorist attacks affected many economic sectors that are considered the main sources for the foreign currency like Suez Canal, tourism and the presence of the foreigner investors. In addition to that, the Egyptian pound has devaluated due to the slowdown of the economy in general. According to the shortage in the foreign currency, it becomes more difficult to import the row materials and the intermediates for many industries and factories. This leads to a general slowdown for the economy in general and increase in the unemployment rate from 9% to 13% (Nawara, 2013).

Some facts about the Egyptian economy as per CIA (2015):

- GDP - $286.4 billion (2014 est.)

- Growth rate - 2.2% (2014 est.), 2.1% (2013 est.), 2.2% (2012 est.)
- GDP per capita PPP - $10,900 (2014 est.), $10,600 (2013 est.), $10,400 (2012 est.)
- GDP composition by sector of origin - agriculture: 14.6%, industry: 38.9%, services: 46.5% (2014 est.)
- Agriculture products - cotton, rice, corn, wheat, beans, fruits, vegetables; cattle, water buffalo, sheep, goats.
- Industries - textiles, food processing, tourism, chemicals, pharmaceuticals, hydrocarbons, construction, cement, metals, light manufactures.
- Labor force - 28.26 million (2014 est.)
- Labor force by occupation - agriculture: 29%, industry: 24%, services: 47% (2011 est.)
- Unemployment rate - 13.4% (2014 est.), 13.2% (2013 est.)
- Population below poverty line - 25.2% (2011 est.)

2.1.3 Social Challenges

Overpopulation Challenge

Egypt is considered as the most populated country in the Arab world with its high population that exceeds 88 million (CIA, 2015). This overpopulation causes a lot of pressure on the physical infrastructure including sewage systems, roads, water and electricity. The population growth rate reached 1.79% which is considered the 65th in the world. This high population growth rate with the poverty status of Egypt creates severe shortage in many social services like healthcare, education and other social sectors especially for over-crowded cities like Cairo and Alexandria. Med class housing is unaffordable to the majority of people and there is a shortage in housing supply chain in general. Looking at the population diagram of Egypt (figure 3), it shows that the majority of population is young and 38.45 % of population is in the working age. This fact could lead to changing our consideration for the population as a resource asset for the future development. This fact is one of the main motivations for this research as it shows an increasing high demand for affordable housing from the young generation sector.

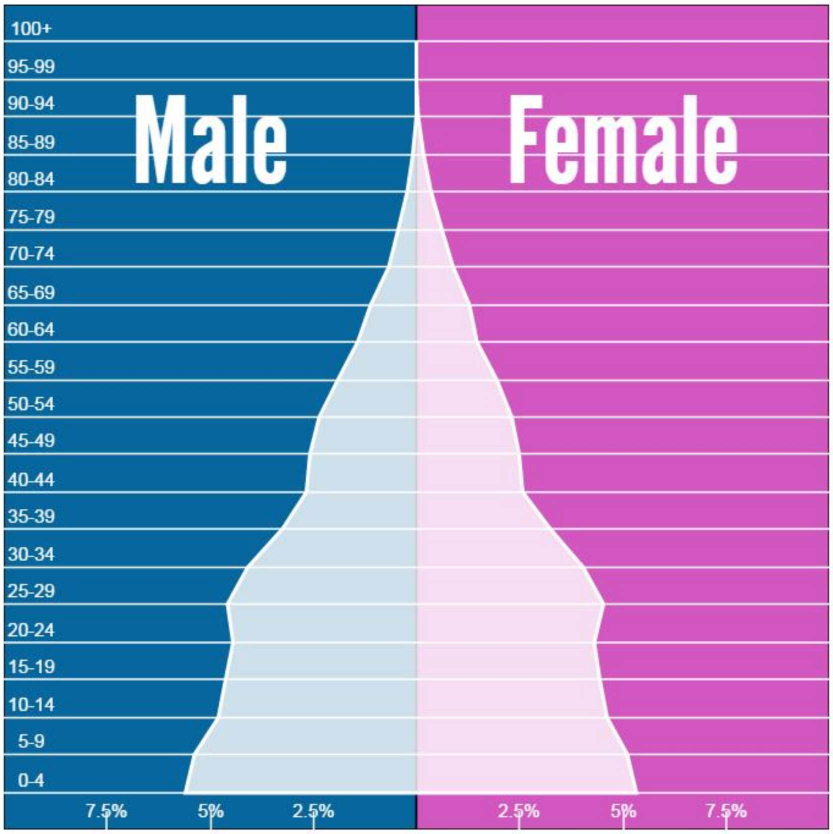


Figure 2. 1: The Population Pyramid for Egypt in 2015 (Population Pyramid, 2015)

The following some of the facts related to population in Egypt as per CIA (2017).

- Population - 94,666,993 (July 2016 est.)
- Age structure –

  0-14 years: 33.21% (male 16,268,862/female 15,169,039)

  15-24 years: 19.24% (male 9,371,819/female 8,839,999)

  25-54 years: 37.47% (male 18,020,332/female 17,448,871)

  55-64 years: 5.91% (male 2,771,399/female 2,826,094)

  65 years and over: 4.17% (male 1,937,119/female 2,013,459) (2016 est.)
- Median Age

Total: 23.8 years

Male: 23.5 years

Female: 24.1 years (2016 est.)

- Population growth rate – 2.51% (2016 est.)
- Birth rate- 30.3 births/1,000 population (2016 est.)
- Death rate - 4.7 deaths/1,000 population (2016 est.)

Poverty Challenge

Poverty and overpopulation are the source for all the social issues in Egypt. There are many causes for poverty in Egypt which came worse and worse during the last five years. (UNEP 2014) put the unemployment on the top of the causes list for poverty which reached 13.2 % with around 3.6 million unemployed Egyptian compared to 2.3 million before January revolution in 2011. Many economic sectors have been affected after the revolution due to the political instability situation that Egypt has experienced. Inflation is another important factor behind the poverty in Egypt. From 2011 to 2013 Egyptian pound lost around 12% of its value. In 2015, the Egyptian pound reached its lowest value against the US$ with a reduction that reaches 36% since end of 2010. This reduction of the Egyptian pound value increased the price of food which increased the intensity of poverty. The other main reason behind poverty is inequity and the unfair distribution of wealth among people. In 2008 the UNDP Human Development report for Egypt mentioned that 20% of Egyptians owned 80% of wealth of the country. Even within this 20% category of the top privileged class, 1% of the rich own more than 50% of the wealth of the country. So, when the economy grew with 7%, poor people did not benefit from this increase. South of Egypt (Upper Egypt) is the poorest of the country due to lack of the development programs.

2.2 Housing Issues in Egypt

The roots of the housing problem in Egypt go back to after the revolution of 1952. The government of the revolution tried to gain the support of people in the cities through issuing series of laws that reduced the housing rents and prevented the landlords from evacuating their houses from their tenants at the end of their contracts. These actions did not encourage the investors from building houses for rent. During the same era of Nasir government, he extended the construction of the low cost houses extensively besides the construction of new districts for labors and employees at the new industrial cities. The new agricultural laws moved the investors from investing in agricultural lands to investing in properties and real estate. Although there was an intensive focus on low cost housing projects, there was no care for the associated facilities and community services that these new settlements would need like schools, hospitals, and entertainment centers.

In 1960s the number of new houses has declined for the following reasons:

- Application for the Publication policy for most of the private contracting companies.
- The series of laws that protected the tenants on behalf of the landlords.
- Yemen war and 1967 war reduced the amount of spending on low cost houses.

At the same time, the focus of the government has shifted to the mid-class housing in the new cities while the involvement of the private investors in housing construction has been reduced due to the new renting laws.

In 1970s and during President Al Sadat, he changed the economy from communism to capitalism. This change led to a fundamental change in the sociological structure of the Egyptian society. The impact of this change on the housing sector was as follows:

- Enormous increase in the land prices and property prices.
- Scarcity in construction labors due to the uncontrolled immigration to the gulf countries.
- A shift in the real estate market from build to rent to build to sell strategy.

In 1970s, the government lost interest in the low cost housing projects. At that moment and due to the setback of the government, the slums and the scattered settlements started to emerge in many areas all over Egypt to satisfy the needs of people for houses. As a result of the change to capitalism, the focus of all investments moved to big cities like Cairo and Alexandria and some canal cities

(Port Saeed, Suez and Ismalia). Accordingly, an internal immigration started from other farming cities to these big cities for better income opportunities. This immigration complicated the housing problem and intensified the need to new houses. With the reduction of the government role, the new immigrants built their houses at the outskirts of these cities outside any control of the government creating slums and scattered houses.

In 1980s till today, the private construction companies came to play the main role in housing sector instead of the government. The focus of these companies was towards the mid to high class for sell and the low cost housing was left over. Samir (2015) has stated that Egypt needs around 8 million housing unit to solve the housing problem as per the recent declarations of the previous Prime Minister, Mr. Ibrahim Mihleb.

2.2.1 Slums and Scattered Houses Phenomena

The slums are one of the results of the housing problem in Egypt. Marii (2011) mentioned deferent definitions for scattered settlements based on the angle we look from to this phenomenon. Formally and as per the governmental definition, scattered settlements are illegal settlements that are established in absence of any master planning with an encroachment on the state property. Accordingly, these areas are denied of the main utilities or services like water lines, electricity, police stations, medical units, schools or public transportation. Due to the lack of basic services for living, these areas suffer from diseases, lack of education and spread of all kinds of crimes and become sources of criminals and terrorists.

Historically, many researchers stated that the beginning of the slums in Egypt started with the establishment of "Ezbet El Saida" in Impapa district in 1924. A person from Upper Egypt called Abdelmonem Asran has moved from Qina with some of his family and built some temporary cottages in Zamalik district. The government at that time decided to move him away from this rich district and compensate him with a large plot in Impapa district. Since that time, this slums area has been enlarged till it becomes one of the largest slums areas in Cairo holding around 77,000 in 1996.

Similarly many slums have been established in similar situations like "Ezbet Al Hagganah" which has been established by Hassan El Noby who was a solder in Haggana force. Ezbet Al Hagganah force holds more than a million capita currently.

Reasons behind Slums Spread

There are many reasons stand behind the spread of this phenomena that will be discussed below.

- Housing strategies

The housing strategies have been changed during the last 70 years according to the different governments who adapted different political and economic policies and strategies which affected the social spending of these governments. Before 1952 there was no sign of housing problem as there was a natural balance between the demand and supply in housing market. After 1952 and after July revolution, President Naser focused his effort on creating social equality policies through applying different policies that the social housing was one of them. Naser focused on building social houses for poor with minimum rents. He built new cities like Naser city and Muderyet Al Tahrir and extended some current districts like Maadi, Helwan and Al Moqatam. He established promising programs for labors housing in the new industrial areas like in Shoubra, Helwan, Impapa and in Al Giza. The housing Cooperatives have been established at the same time and used to be called Naser Housing Cooperatives. In parallel to all these efforts, the internal immigration to Cairo and Alexandria was increased remarkably which increased the need to more houses. The spending of the government was limited and has been decreased further with 1967 war. During 1960s, a number of laws have been issued to control the rents of the houses to be affordable for the majority of people. These laws had negative impacts on the housing investors who were reluctant to continue building houses for rent.

During 1970s and during the presidency of President Al Sadat, he adapted capitalism policies and applied the free market mechanisms. The private investors went back into real estate market but this time with build to sell strategy. Accordingly, the focus of the government was shifted from the low to mid class who can afford to pay either high rent or buy relatively expensive private houses. As a result to this change and due to the increased immigration to the main cities, the number and the size of slums have been increased to accommodate the increase in need for housing.

Since 1980s and during Mubarak presidency, the same policies of Alsadat era have been applied. He increased the number of the new cities with incomplete infrastructure or with bad planning that resulted in low level of basic services like schools, hospitals and entertainments.

- Internal immigration

The main reason behind the internal immigration from the countryside to the urban cities like Cairo and Alexandria is the intention of the different governments to focus the development only on these cities and neglect all other countryside cities. This focus could be understood within the context of the centralization policy that the different governments follow. The countryside and the Upper Egypt have been neglected and the farming strategies have been weakened to the extent that the Egyptian farmers have left farming their lands to other professions with higher income. The status of the farming cities is getting worse and worse and the basic services of education and medical are getting lower. The water supply, sewerage, electricity, transportation are getting worse as well during the last 70 years (Marii, 2011). According to all these reasons, people from the rural cities moved to the big and urban cities to receive the basic services that they need. This internal immigration not only worsen the level of services in these big cities, but worsen the productivity of these farming cities which has been reflected negatively on the economy of Egypt in general. The population growth rate within the urban cities has been increased remarkably. Statistically and during the 20^{th} century, the population in the urban areas has been multiplied 13 times while in the countryside has been multiplied 4 times only. The population in the urban areas has been developed from 17.5% of the overall Egyptian population in 1907 to 43% in 1996. In addition to the internal immigration, the population growth rate has been increased during the 20^{th}

century. The population was 11.2 million in 1907 (Marii, 2011) and reached 92.4 million in 2017 with a population growth rate of 2.4% (central agency for public mobilization and statistics, 2017).

- Absence of national urban planning policies

The absence of the master-plans of the urban cities that define the boundary of the cities and the coverage ratios on the different plots of these cities allowed the irregular growth of these cities and the slums to grow on the outskirts of the big cities.

- The rise in land prices

The continuous increase in the land prices at the planned areas is one of the factors that make it difficult for poor to build their houses on. In addition to the land prices, building on planned plots needs authorities' approval with expensive fees as well. In contrary to that, building on illegal plots at slums area is more affordable and saves time and money for authority approvals.

Volume of the Slums in Egypt

According to the formal statistics, there are around 1221 slums areas holding around 16 million capita in Egypt (Suliman et al, 2012). Out of which, 35 areas are in danger of collapse including 13,431 flat and 281 inhuman areas. In Cairo alone there are 80 slums areas at the outskirts of the capital holding more than 3.13 million capita. According to the recent reports of Central Agency for Public Mobilization and Statistics, Greater Cairo holds around 53.2% of the total number of people that live in the slums in the whole country and this number forms around 38.8% of the total population of Greater Cairo. According to the same report, the area of the slums in Greater Cairo has multiplied 18 times since 1950 when it was 6.6 sq.km and increased to 119.5 sq.km in 2006. The population density at greater Cairo has reached 54,100 capita/ sq.km with around 6.5 million capita living in slums which forms around 48% of its whole population. The area of slums reached at certain cities 77% of its areas like in Al Minya and 87% in Al Giza and 25% in Asyout.

Slums population reached 35% of the overall population of Alexandria. Mr. A. Al Faramawi, the CEO for the slums development, stated that the cost of the slums development in Egypt needs 4.0 billion EGP while the available budget is 800 million only.

The Government Efforts

Since 1970s, the government has started building the new cities to face the internal immigration from all over Egypt to Cairo and Alexandria. They spent 50 billion Egyptian Pound EGP; 15 billion of which were spent on the infrastructure, 4.6 billion on the new houses and the rest was spent on the new factories. Although the plan was to accommodate 8 million people in these new cities, only 800,000 have been accommodated (Imran, 2015). In 2001, (Al Ahram centre for the political and strategic studies) has issued a study about the government's achievement through the new cities in solving the housing problem. The study showed the following:

- The 6th of October city- the overall area is 360 km.sq. 60 sq.km of which is assigned for housing to build on but 17.4 sq.km only are utilized.
- 10th of Ramadan City- the overall area is 398 sq.km, 90 sq.km are assigned for housing to build on but 21.6 sq.km only are utilized.
- 15th of May City- the overall area is 27 sq.km, 2.8 sq.km is assigned for housing to build on but 21,000 units only are built.
- Burj El Arab- overall area is 220 sq.km and only 8649 units have been built.

The study showed that not only the utilized areas are not as per planned but the percentage of occupation of the built units did not exceed 40%. This low occupation shows a deep problem in the planning of these new cities. The connectivity to the old cities, the incomplete infrastructure and the low level of services of schools, hospitals and transportation are some of the reasons that people did not like to move to these new cities for. The Institute of the New Communities which was in charge of these new communities and after their debts have exceeded 8.8 billion EGP, they increased the prices of the new houses and added another reason for people to be reluctant to move to these new cities.

The other mechanism that the government has adapted to solve the housing issue was to encourage the housing cooperatives. The establishment of these organizations was supposed to help building affordable houses and issue lands for people to build their houses. The number of these housing cooperative organizations reached 1850 organization succeeded in building around 400,000 units and distributed 102,000 plots. The issue of the housing cooperative organizations was in their corruption that did not help the wright category of people to reach these built units which were distributed on their relatives.

With the current government of President El Sisy, who hold the presidency responsibility in 2014, the Egyptian army formed an economic power that controls the whole economy of Egypt. Construction industry is not far from their reach either for the infrastructure or housing sector. They play the role of the main contractor for all the big projects in Egypt and they appoint sub-contractors who have good connections with the big colonels in the Egyptian army.

In 2014, the ministry of housing has launched the social housing project which holds a million units that are dedicated to the low income people. The distribution of the social housing doesn't reflect the actual geographical distribution of people all over Egypt. Cairo, for example which holds around 27% of population has received 45% of the assigned social houses which reduces the amount of the distributed houses on other cities. One of the conditions for any applicant to apply for a social unit is to be a government employee which excludes a big segment of Egyptians who are working in the private sector. The minimum wage for applicants is 1200 EGP which adds another constraint on a large segment as well. It is important to mention that as per the budget of 2014/2015 it was stated that less than 1% of the government subsidy reached the poor people.

2.3 Impact of the Housing Industry on Environment in Egypt

The construction industry in Egypt has its negative impact on the natural resources which are limited as well as its impact on the environment in general. As was discussed previously, Egypt suffers from scarcity of water which is considered as one of the main materials of concrete, the base of the conventional construction method. On another hand, the local steel billet production in Egypt is not sufficient for the steel rebar manufacturing as the iron ore concentration in Egypt is 53% while the steel rebar industry needs at least 73% concentration. Accordingly, Egypt imports 1.2 million tons of steel billets every year which has a major impact on the cost of construction (Selim, 2006).

Construction and demolition industry is the largest producer of solid waste in the world. In Egypt, there is no waste management policy other than disposing wastes legally or illegally into landfills which creates a lot of damages to the local environment. Marzouk and Azab (2013) briefed these environmental impacts as follows:

- Diminishing landfill spaces due to the incremental volume of the dumped solid wastes.
- Depleted building materials
- According to the amount of illegal waste disposal, not all landfill sites are properly designed following the international codes. Accordingly, this leads to an increase in contamination from these landfills which have a severe impact on public health as well as on the environment in general.
- Increase in energy consumption for transporting these solid wastes to the landfills as well as the required energy for producing new materials instead of the dumped ones.

On another hand, construction waste contributes to the global warming phenomena which lead to climate change, depletion of farming agriculture and other natural disasters. The amount of construction and demolition waste is estimated as 10,000 tons per day which is equivalent to one third of the total municipal solid waste per day in Egypt (El-Ansary, Al-Haggar & Taha, n.d.).

Considering these negative impacts on the environment in Egypt, a new sustainable construction methodology needs to be introduced to the construction industry in general and to the affordable housing sector in particular.

2.4 Modular Construction for Affordable Housing Problems

Many researches have been conducted to study the validity and the efficiency of using pre-fabrication in affordable housing in the developing countries which have similar situation as in Egypt. India, Colombia, Central America, Hong Kong, Singapore, Malaysia and Africa are some of these countries that are covered in these researches. Roy, Roy and Saha (n.d.) argued that there is 24.7 million house-shortage in India as per the National Building Organization, NBO & NHHP 2007 which is continuously increasing. There is 1 each 10 households (HH) doesn't have a house in the rural are while this ratio in the urban area is 1 in each 6 HH. The authors stated that as per their study to the national plans and policies it was noted that the Indian government has taken out its role as a house provider and limited its effort into facilitating the private sector to take over this role. Along the last six decades and along analyzing the policies that the different governments have adapted, the following reasons have been concluded as the barrier to supply the volume of housing required:

- Housing finance and affordability
- Institutional and policy framework
- Availability of land for housing
- Advancement and availability of building materials
- speedier technology and housing system
- Supply of skilled and unskilled labor

Among the previous six issues, the speed of technology and housing supply were the most prime barriers followed by housing finance and affordability. Accordingly a construction methodology that is much speedier than the conventional systems was required. Prefabrication was proposed as an alternative solution for the Indian housing shortage. The authors classified the prefabrication into three main categories; open, open/close and close systems. The open system includes the prefabrication of some of the building components, the open/close system prefabricate 2D structure elements while the closed system prefabricate the larger scale building components fully finished in 3D. According to the authors' analysis, they found out that the most suitable system for the Indian affordable housing market was the open system.

Colombia has a successful experiment in adapting the modular construction methodology to solve reconstructing a destroyed rural area. Lizarralde (2000) discussed in his research the reconstruction program that responded to the destruction consequences followed the 1999 earthquake in Colombia. Coffee Growers Federation CGF is a non-profit organization that has been formed by some of the coffee growers to manage the coffee market. It was founded under the supervision of the Colombian government and financed by the taxes on coffee exportation. After the earthquake incident, CGF conducted a census to evaluate the damage magnitude and found that 6648 houses needed to be reconstructed and 2972 coffee factory needed to be repaired. CGF managed the entire reconstruction process on the physical and the social dimensions. The houses were built out of steel modular units with internal masonry walls.

They proposed the prefabrication technology for the following reasons:

- Speed of construction.
- The pre-fabrication companies are usually big and capable of providing support on infrastructure, financing and technical support.
- The acceptance of the pre-fab technology into the construction market.
- The pre-fab companies provide seismic resistant buildings which is not the case for the other contractors.
- Light weight of the units that allows for easy construction and less costly foundation.
- Competitive prices compared to the conventional construction.

In the Central American region, the composite cement wood panels were proposed as a prefabricated system for low cost housing. Coretti, Eckelman and Wolfe (1997) discussed the validity and workability of this technology compared to the conventional concrete and masonry construction system. The Central American region is composed of 7 countries which are Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, Belize, and Panama. All the 7 countries are considered developing countries that share the same economical difficulty and natural disaster of earthquakes, volcanos and hurricanes. The shortage of housing reached 3.6 million units in 1997. Historically and since the 16^{th} century till early 20^{th} century, the houses used to be built in Spanish style using stone and brick materials then moved to concrete and masonry later on. The proposed composite cement wood panels system brings to the industry many advantages as following:

- Used as base for the modular construction technology.
- Aliens with the cultural preference of using cement based materials.
- Satisfy the required health and safety measures.
- Since the Central American area is a tropical zone, attacks of fungi and decay are important to be defended which these panels can provide.
- Panels are fire rated.
- Light in weight which is important factor for seismic active areas.

The composite cement wood panels were made of wood strands, recycled wood chips and fibers mixed with bonding cement material to form prefabricated walls that could be used with other structural elements as bearing walls.

Hong Kong government adapted the prefabrication as a mandatory construction technology for public housing projects. They subsidized 30,000 units per annum which made it the only major client in the prefabricated housing industry. The Hong Kong Construction Industry Review Committee (CIRC,2011) stated in their report ‘‘(p)refabrication, coupled with the use of standardised and modular components, will contribute to improved buildability and should be widely promoted, with public sector clients taking the lead’’. The government adapted the prefabrication as a tool for increasing quality, reducing time and waste especially for the public housing. Chiang, Wan Chan and Lok (2006) stated that Hong Kong authority started the prefabrication strategy in mid 1980s after the "housing scandal" when they had to put down 26 blocks due to their non-compliance with the structural safety requirements. The government engineers after their survey between 1985 and 1986, they discovered that among 843 public houses, only 114 houses were compliant with the structural codes.

In Singapore, the local authority indirectly pushed for the prefabrication technology through the mandatory compliance to the "buildability" provision in their building control system. The Building Construction Authority put a scoring system for the building designs to meet related to the buildability regulations. Both Hong Kong and Singapore governments chose prefabrication technology for the public housing programs for its quality and time saving advantages although it was more expensive in these countries.

Malaysia started its journey with the Industrial Building Systems IBS in 1964 with two pilot projects with total units of 6699. Both projects required 27 months to complete. The first pilot project reported 8.1% higher cost than similar construction cost while the second project reported a savings of 2.6%. Since then, Malaysia adapted this IBS for residential buildings for their overall better performance and higher quality than the conventional buildings. Thanoon et al, (2003) reported that the main suppliers of IBS were originated from USA, Germany and Australia. However, the construction industry defended the growth of IBS in Malaysia in general for the following reasons:

- Contractors preferred to use intensive labor construction methodologies as it is easier to lay them off during difficult times.
- Lack of skilled workers that are required for IBS systems which led to low quality and high construction cost in contrary to developed countries like in Sweden or Japan.

- IBS requires a consensus between the different stake holders of construction industry however; the industry lacks the required knowledge about the economic advantages of the IBS to create this consensus.
- All the used IBS systems are imported from developed countries due to the lack of R&D in Malaysia in this field.
- The availability of cheap foreign workers in Malaysia made the conventional construction relatively cheaper than the IBS.

Amado et al (2014) proposed a different system to overcome the need to skilled labor in IBS that allowed unskilled intensive labors to be used. They proposed a modular wall solution as a structural element that is complemented with a local material that was made by a non-specialized workforce. Amado et al in their research intended to help the developing African countries to solve their housing deficit problem through the application of this pre-fabricated modular wall system. The modular wall system was composed of thin modular prefabricated panels made with reinforced concrete that form the main structural element. A layer of local insulation material was added in between these modular panels and the masonry walls on site. This composite layered wall succeeded in meeting the thermal, the acoustic and the structural requirement for sustainable buildings. That was achieved through developing three main factors: the prefabrication that helped in achieving a low cost/ high quality product, the use of local materials that helped the local economy and the use of locally used materials which achieved an efficient thermal insulation. This system achieved 30% reduction in cost and 50% reduction in produced waste. Other advantage for this system was its easy construction by the residents themselves and allowed for future expansions as well. Socially, this flexibility was important for these poor societies to expand their houses according to the growth of their family sizes.

2.5 Definition of Modular Houses

Modular houses are defined as prefabricated volumetric components that fabricated in factories off-site. These components are to be transported to the site to be assembled to form a complete building. The modules are between 80% to 90% complete offsite with internal/ external finishes with internal furniture as well (Quale et al, 2015). Schoenborn (2012) stated that the prefabrication is off-site manufacturing process at specialized factories where the different materials and building systems are joined together to form all or parts of a larger final component.

Schoenborn (2012) argued that the construction prefabrication varies in relation to the amount of off-site work versus on site work, the number of building trades that participate in forming the prefabricated components and the number of labors required to finish the work on site.

Quale et al (2015) demonstrated the differences between the conventional and modular construction on both material used and material transportation. Regarding the materials, the main difference between the conventional and the modular construction is in two main areas. The first is related to the marriage walls and the double slabs that the prefabricated modules need to have for the structure stability during the module transport to the site. This additional walls and slabs increase the material usage for the modular houses by 25% (John et al, 2012). On another hand, the amount of wastage that the conventional construction normally produces varies between 5% to 15% according to the type of the used materials. Construction sites don’t always have enough space for bulk materials storage and normally follow “order as you go” policy which is more costly and normally leads to more wastage. A survey on modular factories has been conducted which reported that the majority of the wasted materials are being reused in the production process except a small portion of some materials like gypsum (0.7-0.8 lb/sq.ft.) and copper wires (0.03-.1lb/sq ft). On another hand, the over ordered materials are assumed to be equal to the amount of wastages that reached 4.4 lb/sq.ft (EPA, 2009).

The energy consumption for transporting the materials from the suppliers to the conventional construction site is equivalent to the same from the suppliers to the factories. The difference in energy consumption for the modular construction is briefed in the following two main areas:

- Transporting the over ordered materials that are equivalent to the material wastage for the conventional construction sites.
- Transporting the modules from the factories to the construction sites.

During the survey that Quale et al have run in 2015, the interviewed contractors of the conventional construction contractors stated that they used to add 50% safety factors on the task durations due to repeated tasks or scheduling delays which is not the case for the modular construction.

2.6 Benefits, Conditions and Limitations of Modular Houses

Taur & Davit (2009) argued that the prefabrication advantages are briefed in the following points:

- Saving in shuttering cost
- Savings in timing of prefabricating the main elements off-site as well as the early start of the onsite activities after installation.
- Economy of scale due to the large number of repeatedly produced components.
- Increase in quality due to the enhancement of the off-site work conditions.
- Faster turn of investment due to the shorter production cycle.

Quale et al (2015) stated that the modular construction saves construction time by 30% to 50% due to the following reasons:

- The modules are usually constructed in parallel to the construction of the building foundations.
- The parallel construction of many modules at the same time.
- The controlled work environment increases the productivity of the labors and increases the quality of the products as well.

In addition, cost is also reduced due to the mass production, the bulk order of the materials and the reduction of the labors and machinery at the building site.

In 2000, Lu Na has conducted a survey on a mix architects and engineers in the University of Clemson to get their feedback on the benefits to use the modular construction. The study confirmed the benefits of the modular construction in reducing the construction time due to the parallel activities, reducing the environmental impact, increasing the labor productivity due to the controlled work environment and increasing their safety as well as increasing the overall quality of the final product. On challenging side, the increased upfront cost is one of the challenges of using the modular construction. The transportation network and the limitation on the modules design due to the limited truck sizes that the local roads can afford are additional challenges. The module design needs carful intention to details and coordination as well.

Schoenborn (2012) advised for the modular construction to be cost effective, the amount of onsite work should be reduced as much as possible and the reliance on mechanical process of off-site process should be increased. The use of the recycled materials in the manufacturing process is adding to the cost effective strategies.

Atkinson et al, (2001) examined the feasibility of using modular construction for houses of elderly disabled people from project management perspective. The purpose of the use of the modular construction was to provide an extension to existing properties for special needs of elder disabled users. The research focused on ensuring that the needs of the disabled users are identified and the planning requirements are addressed. The research used unstructured interviews methodology with the different stake holders of the subject including users, user representatives, modular manufacturers, local authority representatives. Users' feedback was welcoming the usage of modular construction for their property extension. They liked the fact that the modular extensions could be moved in the future "removability" which helps in keeping the commercial and aesthetic value of their properties. The reusability of the added modular elements helped in reducing the overall extension cost. Time factor was one the important factor that users preferred the modular construction for. In addition to that, modular construction reduced the inconvenience and danger during construction that associated the traditional construction methods which could affect the disabled users' comfort.

Amado, Lopes and Ramalhete (2013) discussed the use of prefabricated modular wall system for affordable housing in Africa. They stated that modular construction can have 52% less construction waste, 50% less water and energy consumption, 35% reduction in construction time and 30% reduction in construction cost.

Maxian (1989) analyzed the cost of developing affordable housing using the modular construction in Boston. She concluded that the modular construction doesn't save in hard cost but has a relative savings in soft cost which is briefed in management and financing cost. She based her research on studying 7 case studies. The conventional construction time of 20 units each of 1000sq.ft were 12 months and 6 months using modular construction. The reduced construction time reduced the construction management cost by 50%. She stated that the saving of financing cost could be achieved if the on-site construction time (button up) could be achieved in 5 months only.

Thanoon et al, (2003) discussed the characteristics of the Industrialized Building Systems IBS reporting their advantages and disadvantages. They mentioned 11 characters that identify the successful use of the prefabricated buildings. The different open and closed fabrication systems vary in their design flexibility and their compatibility to other systems. Modular coordination and standardization of the prefabricated components are essential characters for efficient implementation of IBS. For the building prefabrication industry to be profitable, a certain market volume should be guaranteed to allow for mass production to cover the invested relatively high capital cost. Building industrialization shares with other fabrication industries the need for good organization to the fabrication process as well as high integration with all related stakeholders (designers, fabricators, owners and contractors). Building industrialization requires a capital investment in off-site factories with specialized skilled labors, equipment, plants and trained management.

On site, extra heavy cranes should be provided to handle the prefabricated elements. Transportation is an important factor for the building industrialization. The availability of the suitable roads, local roads regulations and the cost of transportation, all affect the feasibility of the process.

Among the different advantages that Thanoon et al (2003) mentioned in their study, cost savings, high productivity, time savings and high quality for the end products were the main advantages they focused on. On another hand, lack of scientific researches about the benefits of IBS is hindering its propagation among the building owners. Lack of assessment criteria for local authorities to evaluate the prefabricated components doesn't allow them to accept its usage. Standardization is perceived as an advantage and cost saving for buildings, however; authors mentioned a side effect that could harm the building cost if standardization is considered as an average factor that conflicts with efficient use of materials. They gave an example of using standard 300mm thick slab all over a building that some of its floors need 260mm thick slab only. For cheap labor countries, conventional construction systems become always more competitive to the IBS systems. The attachment of prefabrication with mass produced low cost housing schemes with low quality production has negatively affected the image of building prefabrication image in the market.

Cameron and Carlo (2007) concluded in their study the benefits and limitations of the modular construction. Through their case studies, they argued that the modular construction achieved better thermal insulation, better structural integrity, better sound proofing and less probability for mold/ moisture issues. They concluded that the main challenge is still the transportation restrictions which limit the height and widths of the modules. However, they stated that these limitations don't prevent the application of modular for multifamily houses. The site conditions and limitations are considered as one of the important design parameters that affect the module design and manufacturing. The plot size, the low overhead power lines, the small sites and narrow streets could dictate the module design and delivery process. Cameron and Carlo highlighted the coordination process complexity that associates the manufacturing of modules between the manufacturers, the contractors and subcontractors. They concluded that to simplify the process, an experienced team who worked on similar modular construction before should be appointed, a close contact between the factory team and the on-site team should be established with clear responsibility matrix and up front design and execution plan should be in place. The involvement of the module manufacturers at early stages could inform the design and eliminate many of the complications during construction. From marketing perspective, they mentioned that each market has its own perception about the modular construction which should be considered carefully. To overcome any misperception about modular construction, they claimed that the green nature of the modules performance that associates their production process could be used for their marketing. Financially, the reduced construction cost due to the use of the modular construction reduces the interest of the construction loan, reduces the soft cost and accelerates the revenue generation. On another hand, it reduces the market risks which increase with the longer construction time. The main saving of the hard cost lies in eliminating the inaccurate allowance and materials price inflation due to the accurate details of the modules design.

Luther (2009) argued through his study that to achieve affordability, three main approaches should be integrated together, automated building fabrication, integrated building services and application of sustainable design principles. Although the beginning of industrialized construction could be dated back to 1851 with the Crystal Palace of Sir Joseph Paxton, the delay of success of modular construction could be referred to the dependency on public acceptance, the development of the distribution facilities and more importantly on mass production. These three main factors are so related to each other and are essential for the modular construction success.

2.7 Different Materials and Systems for Modular Houses

Luther (2009) studied several pre-fabrication systems in regards to the used materials, flexibility, constructability, structure integrity and delivery. He classified the modular construction into the following 3 main categories:

- Panel systems

In this system, many components could be integrated in a panel form to be used as an external façade element, doors or windows including the required insulation, acoustic, structural, lining and finishing materials in one integrated unit. Such panel has been manufactured by Jean Prouve for his Tropical House, 1949 when he manufactured his house based on prefabricated aluminum modular panels that formed the external envelop of his house (figure 2.1). Jean Prouve has shipped his house disassembled from France to Africa where he assembled it there. He based his panels design on one meter grid system and limited the length of the panels to be less than 3.96m considering the capacity of the rolling machines. The weight of each panel was designed to be less than 100kg to be handled by two men only.

Figure 2.2: Jean Prouve House-The Used Aluminum Panel (Luther, 2009)

- Skeletal systems

Skeletal system is prefabricated structural modules that are assembled together to form the structural system of the building. They could integrate the different building services within and are independent from the building envelop. Renault Centre (figure 2.2) by Foster associates which has been built in 1982 in England is a good example of the skeletal system.

Figure 2.3: The Renault Centre, Swindon, England (Luther, 2009)

- Cellular systems

Cellular is a system that is composed of a volumetric unit. The module integrates all its envelope, interior, mechanical and structural systems in one prefabricated unit that is assembled off-site and is transported to the site to be assembled with other units to compose a building.

Schoenborn (2012) has a different classification for pre-fabrication construction which categorizes the components into four categories:

- Prefabricated materials like pre-cut or customized cladding materials or prefabricated structural elements.
- Prefabricated components include the simple prefabricated building elements of a single trade like unitized curtain wall panels, precast panels or pre-assembled steel structure elements.

- Panelized structures include the manufactured building elements that can be shipped compacted on flat back trailers.
- Modular structures refer to volumetric off-site fabricated buildings that enclose livable spaces. These modules include more than one trade and are structurally independent.

Roy, Roy and Saha (n.d.) classified the Industralized Building Systems into three categories:

- Frames or post and beam system – in which the loads are carried through the beams to the columns and to the ground.
- Panel system (2d structure elements) in which the loads are carried through walls and slabs.
- Box system (3D elements) which form a volumetric structural system.

These three categories could be fabricated following either closed or open production system.

- **Closed system** - follows the client's design or the manufacturer's design and could not be integrated with any other manufacturer's product in both cases. This system puts a lot of limitation on the designers to meet the right details that are specific for each manufacturer.
- **Open system -** in contrary to the closed system, the open system enjoys a level of flexibility that allows it to integrate with other open systems. this system has a major setback due to the interfacing joints between the different components from different manufacturers.

2.7.1 Pre-Cast Concrete Systems

Hernandez and Cladera (2011) classified the precast concrete systems into two main categories; frame systems and wall systems.

- Frame systems - is the most common and wide distributed pre-cast system all over the world due to its flexibility and its level of freedom they give to the architects in their design. According to the way of connection between the beams and the columns, there are two main framing systems are manufacturing; hinged beam-column frame system and moment resisting beam-column frame system.

- Hinged beam-column frame system (figure 2.3) is composed of one piece columns to which the beams are supported through corbels or on the top of the columns based on the number of the floors of the building.

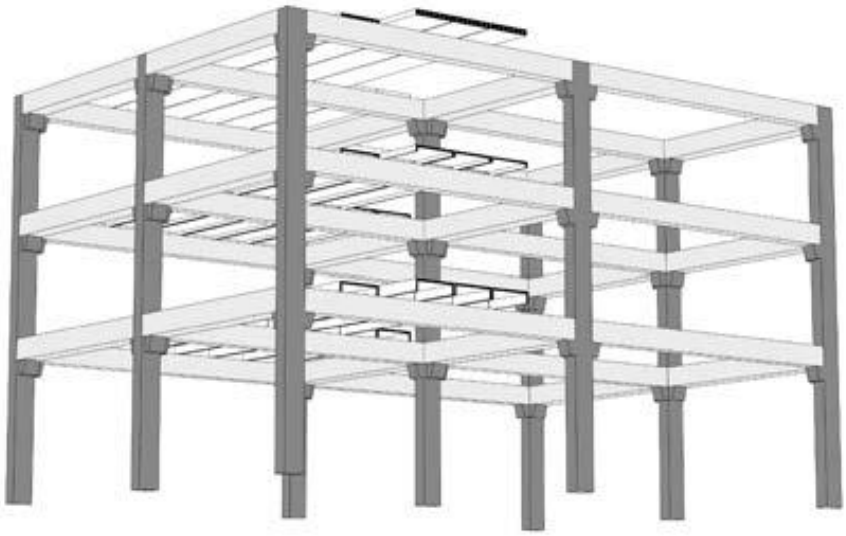


Figure 2.4: Hinged Frame System (Hernandez and Cladera, 2011)

- Moment resisting beam-column frame system (figure 2.4) is composed of precast columns and beams that are connected to each other to form a stable frame system.

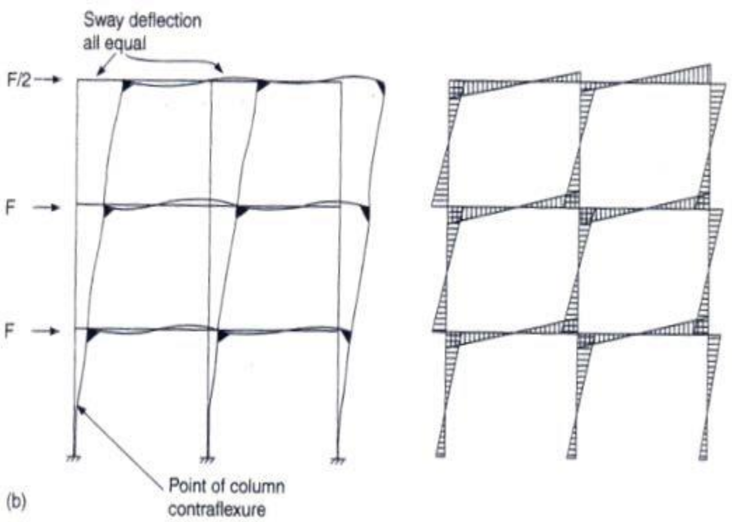


Figure 2.5: Moment Resisting Beam-Column Frame System (Hernandez and Cladera, 2011)

- Wall systems (figure 2.5) in this system the precast walls are used as wall bearing structure elements which are always come in fare face and do not need any plaster application. The system is composed of hollow core panels and solid panels that are used for walls, floors and roofs.

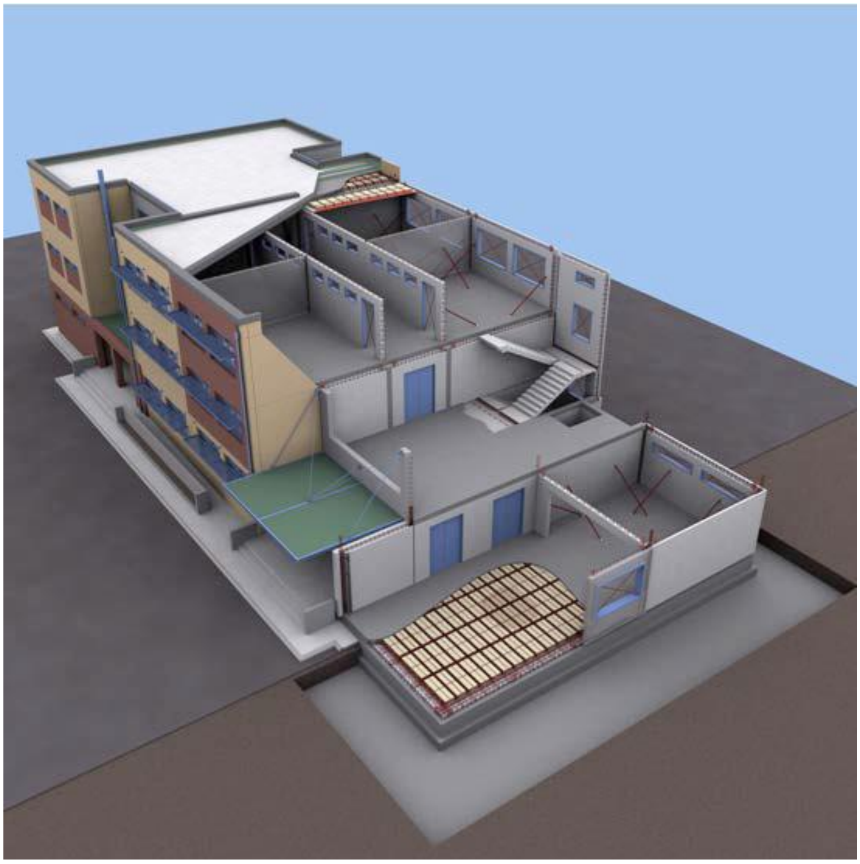


Figure 2.6: Precast wall System (Hernandez and Cladera, 2011)

2.7.2 The Light Gauge Steel Modules LGS

Lawson et al (2005) have discussed the light Gauge steel modular houses. They stated that the capital cost of high automated modular factory cost around £10M. The business model of these factories is based on producing between10,000 to 20,000 modules a year. The efficiency of the production increases with the increased size of the modular projects. They argued that the cost of the small projects could be more expensive with around 5% while large projects could reach a savings of around 20%. Lawson et al in their study described the module

forms which are manufactured in light steel. They are composed of light steel framing system which consists of C section with depth of 65mm to 200mm and with thickness of 1.2mm to 2.4mm. Walls are constructed in framed panels and the slabs are constructed in 2D cassette slabs. In volumetric construction, modules are assembled in load-bearing boxes with framed walls and cassette slabs. There are two main forms of modular boxes according to the structure system of the building; 4 sided modules (figure 2.6) and point supported modules (figure 2.7). In 4 sided modules, the vertical loads are transmitted through the walls. In the point supported modules, the loads are transmitted through corner or intermediate columns with deeper connecting edge beams. The horizontal loads are resisted by wall bracings. For buildings higher than 6 stories, a separate bracing system will be introduced. The modules are connected to each other through plates, bolts and additional bracings through the corridors. Some precedents have been mentioned in the study to proof the successful use of the system in various projects. Murray Grove in Hackney which has been completed in 1999 (Figure 2.8) used modular boxes based on Yorken system. Lillie road building in Fulham (figure 2.9) which has been completed in 2003 used bathroom pods, light steel framing system. The Royal Northern College of Music student houses project (figure 2.10) is one of the large modular projects in UK that is consisted of 6 to 9 stories comprised 900 modules. Similarly, the mixed commercial residential development at Wilmslow Road, Manchester included
Using 1400 Modules on A Steel-Composite Podium Structure For the Ground Floor and Basement.

Figure 2.7: Continuously Supported Module in Light Steel Framing (Lawson et al, 2005)

Figure 2.8: Corner-Supported Module (Lawson et al, 2005)

Figure 2.9: Installation of Modular Units at Murray Grove, Hackney (Lawson et al, 2005)

Figure 2.10: Completed Mixed Panel and Modular Project At Lillie Road, Fulham (Lawson et al, 2005)

Figure 2.11: Royal Northern College of Music, Manchester, Consisting of 900 Modules (Lawson et al, 2005)

Figure 2.12: Mixed Commercial Residential Development at Wilmslow Road, Manchester, (Lawson et al, 2005)

2.7.3 <u>Adapted Shipping Containers</u>

Kim & Kim (2016) stated that the main advantage of the modular houses is that they are prefabricated in factories and get easily assembled onsite. Accordingly, they could be dismantled and reassembled on other sites if needed. Since 1990, shipping containers have been used as labor houses on construction sites. Their reusability as efficient residential modules encourages many architects to use them as a solution for affordable housing due to their durability and reusability characteristics. Shipping containers have been introduced for shipping industry with certain materials, sizes and designs which developed an entire industry around them. So, they became more attractive as a competitive modular alternative to the conventional construction for the affordable housing.

2.8 <u>Research methodologies review for Modular Construction assessment</u>

Many researches have been conducted to compare the environmental impact of conventional construction systems with different modular construction systems using a range of research methodologies. Generally, the research methodologies are divided into two categories; quantitative and qualitative. Quantitative methodology deals with tangible figures and numbers while the qualitative methodologies allow for personal interpretation of the information by the researcher. A large number of research papers have been reviewed and reported in this chapter. The main goal of this review of methodologies is to select the most suitable research methodology to the aims and objectives of the current research.

2.8.1 Case Study Methodology

Yin (2009) has defined the case study methodology as:

"*An empirical inquiry that investigates a contemporary phenomenon within real-life context, especially when the boundaries between phenomenon and context are not clearly evident"*.

In his literature review he stated that the case study methodology concerns how and when things happen in reality and investigates the differences between what was planned and what actually happened in reality. Case studies becomes a valid methodology for areas where a problem or situation could be studied in depth with the help of available information provided by similar cases.

Case studies are always carried out through interviews, observations and study of available documents. The researcher should collect as much information as possible for the research and needs to be empathetic and a good communicator. Yin (2009), mentioned that there are three types of case study methodologies; exploratory, descriptive and explanatory. Exploratory is useful for business related researches. Descriptive approach is helpful for researches that describe cases like what happen for a product when it is launched. The explanatory case studies are used when for example internal processes for companies are researched.

In prefabricated modular construction researches, case studies are analyzed to highlight the advantages and disadvantages of these systems in reality compared to the conventional systems. In these cases, buildings are studied through conducting interviews with owners, contractors, designers and modular manufacturers as well as studying the design documents of these buildings.

Gunawardena et al. (2014) studied use of prefabricated modular structures to provide temporary housing as a post disaster housing solution. In their research, they adapted the case study methodology to study the benefits that modular construction can bring to people who suffer from these disasters. They followed the same methodology in studying 5 modular buildings as well as 4 disaster cases. The research focused on time as the main factor for post disasters for people to restore their livelihoods. Through studying these cases, they could proof saving of 50% of the conventional construction time.

Sorri, Kähkönen and Rannisto (2013) focused in their research on pushing forward the modular structure for the residential building. In their research, they adapted the base case methodology while using the interviews as a means of data gathering about the case buildings. Their paper represents the results of a joint effort of four modular construction related companies and one academic partner working on a project called Concells research project. They chose two built residential projects as study cases with one virtual project that has been designed in collaboration with architects and engineers. The first case project A was a three 2-storey apartment building while other project B was a 5-storey apartment building. Both projects were made of offsite prefabricated modular units. In both cases data was collected through a series of interviews with the three main modular construction stake holders; the panel manufacturer, the modules manufacturer and the main contractor on the construction site. The interviews focused on the lessons learned regarding modular construction as experienced from different stakeholder perspectives.

Nahmens and Ikuma (2012) discussed the application of lean construction as a tool to improve the environmental, economic and social performance of prefabricated modular houses. They adopted case studies as the bases for their research. They applied one lean kaizen tool with safety and environmental analysis on three case studies in a plant for modular houses where each case addressed one sustainable dimension. In each of the case studies they used Safety and Lean Integrated Kaizen (SLIK) tool to achieve improvements in the three stations which were considered as three case studies; base framing, gypsum boards hanging and interior painting. In case study 1 they addressed the environmental sustainability through reviewing the board hanging station. They reviewed all the steps that form this process and succeeded in rearranging them in a way that reduced the amount of waste by 63.6%. In case study 2 (base frame), they could improve the safety aspect of this process (social sustainability). They applied Job Safety Analysis (JSA) as part of kaizen steps to highlight the major steps that associate hazards to workers and recommended ways to eliminate or control each hazard. In case study 3 the economic dimension was achieved by reviewing the whole painting process. They proposed different process that achieved a reduction of man hours of 31.3h per module and overall cycle time of 26.4%.

Velamati (2012) studied the benefits of use of modular construction for high-rise buildings in the United States. He discussed the engineering, design, sustainability, cost and legal consideration of modular construction from the developer perspective. Velamati adopted the literature review methodology to study the technical aspects of the modular construction while he researched the available modular projects as case studies. In addition, he ran series of interviews with modular manufacturers, contractors and financiers that were involved in modular construction for high-rise buildings. Based on these three combined methodologies, he concluded key measurements that were tested financially to evaluate the modular benefits on the conventional construction methods.

Arif and Egbu (2010) discussed adaptation of prefabrication systems to meet the growing housing needs in China. They combined both literature review and case studies as adapted methodologies. They used the literature review to highlight the housing need and the introduction of prefabrication in China while case studies methodology was used to demonstrate other experiments in solving housing issues in UK. The findings were concluded to draw the way forward for China relying on its advanced manufacturing industry.

Rogan, Lawson and Bates-Brkljac (2000) studied seven case buildings to conduct a comparison between the modular construction and the conventional construction systems. The seven case studies are constructed of prefabricated light steel modules. Their case study methodology included interviews and questionnaires with the projects' designers and contractors. The case study buildings varied in their typologies between hotels, a hospital, a residential building, a retail building, an educational building and a students' accommodation building.

2.8.2 Interviews

Interviews methodology is used to gather information from the industry experts that could not be gathered through observations. Researchers use this methodology to extract valuable information and to look at their research topic from the perspectives of different industry stakeholders which helps them to study their topic holistically. Lessing (2006) has divided interviews into four main types:

- Completely Open interview: it is like a well prepared conversation without predefined questions in advance.
- Focused open interview: where the main questions are prepared but sub questions are left to the development of the interview.
- Semi structured interview: where both the questions and sub-questions are prepared but the answers are kept between open or fixed answers.
- Structured interview: it is similar to the survey format where all the questions and sub-questions are predefined.

Following are some examples for the interviews methodology as used to study prefabricated construction.

Lessing (2006) used the interviews methodology to establish a framework for the concept of industrialized house-building and to describe its process. Structured interviews were adapted as the main tool for information gathering in the research. All information gathered in this research related to the case studies have qualitative nature while these qualitative data have been structured and analyzed in a quantitative way. Three cases in three industrialized house companies were selected which represent different approaches in this field. All information gathered through focused open question interviews and direct observations. Lessing prepared one set of questions for all interviews with both the expert and the operation managers. All the interviews were carried out in the field and in the interviewees work environment while observations were carried out in the factories, offices and building sites.

Bildsten (2011) explored in his research the opportunities and barriers to use prefabricated components in the housing industry. He adopted interviews with two industrial house manufacturers as a methodology for his research. He argued in his research that a few number of cases can be important for an enhanced knowledge. The interviews are conducted through personal meetings in the companies while the observations are conducted in one factory only to emphasize the results of the interviews and the answers were verified.

Ganiron and Almarwae (2014) studied the prefabricated modular houses as an advanced construction methodology that can help Philippines to lessen the cost of their houses without compromising their quality. They interviewed 33 Civil engineers who worked in the VAZbuilt /VAZcrete Construction to run a comparison between the prefabricated modular houses and the conventional construction houses in terms of cost, time, efficiency and effectiveness. Through this comparison, they could highlight all the advantages that the prefabricated modular construction has on the conventional methods.

2.8.3 Questionnaires Research Methodology

Similar to the interviews methodology, questionnaires is a qualitative methodology where the researcher becomes the center of the information gathering of the research and their analysis as well. Lessing (2006) argued that the advantage of the qualitative research methodologies is that the researcher can tailor his research according to his possibility of collecting the available information that is suitable to the research. On the other hand the personal interpretation of the gathered information may lead to personal mistakes.

Apaydın (2011) studied the effectiveness of marketing activities of prefabricated houses and the buying intentions of Turkish customers. His survey methodology was based on a questionnaire that was designed on Likert-like scale of one end (1) fully disagree and another end (5) fully agree. The questionnaire was formed of 16 points 10 of which reflected the manufacturers and suppliers view about the features the prefabricated houses have. In addition, 3 more questions were added to address the misconception that customers may have about prefabricated houses. The last 3 questions were developed to test the customers' consideration for houses as long term investment. The survey was conducted online and 107 responses were received which were considered sufficient for this research.

2.8.4 Literature Review

Literature review methodology has a theoretical nature that put it forward for researches that discuss others findings to conclude statements. Steinhardt, Manley (2013) organized their literature review in a well-structured process using online search in Compendex data base. The scope of the research considered the latest researches published since 1990. Over 9 million articles from journals, articles and technical reports were indexed. All the abstracts were reviewed for relevance and the most related articles to the topic were referenced. A total of 185 relevant publications were reviewed, comprising journal articles, conference papers, reports or theses. All the selected references were coded according to their relation to the main sections of the research: research questions, continuum locations and participants and activities.

Nawi, Lee and Nor (2011) studied the barriers to the implementation of Industrialized Building Systems (IBS) in Malysia. They discussed the issues and perceptions that the conventional construction stakeholders have that obstruct the adaptation of IBS into the construction market. They based their research on literature review methodology as they surveyed a number of local researches to identify a list of barriers they considered the literature review is a valid methodology in organizing a theoretical approach with developing research questions before stating hypothesis to be tested. They considered in their research books, national and international articles, reports, proceedings and bulletins. They concluded a matrix of barriers based on the different literature reviews showing the intersections between the different opinions of the researchers to highlight the weight of each barrier.

Abdullah and Egbu (2010) discussed the criteria to select the right Industrialized Building System IBS in UK and in Malaysia. They used the literature review methodology to conclude the tools, criteria and the selection process to the right IBS system. They summarized the findings of the previous researches that were issued between 2002 and 2006 to highlight the factors that dictate the IBS type selection. They concluded a matrix highlighting the different selection criteria which included the client, cost, design, environment, knowledge, law, materials, organizational factors' process, quality, risk and time.

Azman, Ahamad and Hussin (2012) discussed the challenges that face the construction industry to integrate the prefabricated construction with the conventional construction systems in three countries, UK, Malaysia and Australia. They based their research on an intensive literature review to the latest researches.

Neelamkavil J (2009) studied the automation in prefab and modular construction industry. He studied the role of automation in different stages of the construction process starting from Design, passing through use of BIM in design documentation and coordination till the use of automation in off site and on site construction. He adapted literature review in his research.

Davis (2010) discussed the history of the prefabricated houses through his literature review. Although the methodology is based on historical facts and on the literature views of other researchers, Davis discussed the influence of architects in the prefabrication industry as a new idea which has not been discussed in any of the referenced literature reviews. He stated that 80% of the prefabricated buildings are designed by non-architects.

2.8.5 Life Cycle Assessment (LCA) Methodology

LCA is a tool to assess the environmental impacts of a product or a service through its life (Finnveden, 1998) assessment includes all the environmental aspects related to the materials extractions, production, transportation, construction, use, maintenance and end of building life disposal. Complete LCA passes through four main stages; goal and scope definition, data gathering and the Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA) and impact evaluation and interpretation. In stage 1, the goal of the study, the scope and the level of details of the analysis are defined and accordingly all the other stages follow. In this stage, the boundaries of the study will be defined highlighting all the inclusions and exclusions of the study. Stage 2 Life Cycle Inventory (LCI) involves data gathering about the product or service inventory including all the inputs and outputs (materials, energy consumption, water use, gas emissions and solid waste) of the related systems. Stage 3, the Life Cycle Impact Assessment (LCIA) is the stage in which the assessment of all the impacts of the product inventory is conducted. The final stage evaluates and interprets the inventory impacts on the environment. In this stage, an improvement of the product is proposed to reduce its negative impact.

Through a review of several researches, LCA proved to be the best suitable research methodology for my study. Some examples of the researches that adapted LCA as a research methodology for construction system and their environmental impact comparisons are reviewed as follows.

Bribián, Capilla and Usón (2010) used the LCA analysis to compare the most common construction materials with some eco-materials highlighting the impact on three different environmental categories. They used their analysis to propose specific measures to reduce these impacts on all stages: production, manufacturing, transportation and final disposal. The three impact categories they focused on were the primary energy demand (in MJ-eq), the GWP (in CO2-eq) and water demand (in liters). Ecoinvent V2.0 database 2007 inventories were used in all analyzed stages and Simapro v7.1.8 software tool was used. One kg is selected to be the function unit for life time of 100 years.

Rossi, Marique and Reiter (2011) carried an LCA analysis for two different construction systems; steel frame and traditional masonry. They studied three different life cycle scenarios for the steel frame houses in three different locations (Belgium, Portugal and Sweden). The aim for their study was to compare the embodied energy with the operation energy along the life cycle of both systems. The three different locations have been selected to test the impact of the different climate as well as the different heating technologies. In this research, two databases have been used; the Building for Economic and Environmental and economic Sustainability (BEES) developed by the national institute of standard and technology and the database published by the Centre de Ressources Henri Tudor (CRTI). The results and calculations have been verified by the software Pleiades + Comfie combined with Equer. The research concluded that the operation phase represents 62 to 98% of the overall life cycle impact.

Moroz and Lissel (n.d.) used LCA in their research to compare two different construction materials; steel reinforced concrete with masonry with bamboo as reinforced material. The aim of the research was to conclude a construction system that is cost effective and eco-friendly for developing countries. To set the boundaries for their LCA analysis, they considered only the structural skeleton of a single family house and only the impacts of the materials and their transportation to the construction site. Accordingly, their assumptions included common details and materials for the building envelop, construction, usage and demolition phases. They relied in their research on Carnegie Mellon University Green Design Institute's EIO-LCA database. The outputs were compared with the outputs using the data from the National Renewable Energy Laboratory (NREL) U.S. Life-cycle Inventory database (NREL, 2007). The first step of this LCA was the design of the standard house. 160sq.m. two storey house was architecturally designed with two separate structural designs including the different structural materials. The quantity of materials for both buildings were calculated which formed the basis for the Life Cycle Impact Assessment LCIA.

Gustavsson and Joelsson (2008) adapted LCA to compare primary energy use and CO2 emissions for residential buildings during construction and operation stages and for a range of energy supply systems. They focused their research on the primary energy consumption during production and operation stages only. The energy used for onsite construction is excluded as well as the energy for demolition and renovation of the buildings as they stated that they account for neglected proportion to the overall life-cycle energy consumption. They used one square meter of produced and operational building area as a function unit for a period of 50 years. They conducted their LCA analysis on 11 case study buildings; two of them were low-energy while others were considered conventional.

Monahan and Powell (2011) applied LCA analysis to compare the embodied energy and embodied carbon of low energy affordable house constructed in a prefabricated timber frame with another two conventionally constructed houses. In the first scenario, the timber modular frames were constructed off-site with a larch timber boards for façade cladding. In the second scenario, the larch boards were replaced with brick veneer. However in scenario 3, the timber frames and the larch cladding have been replaced by conventional masonry construction. In this paper, the LCA analyses were limited to the construction phase without considering the operation or end of life phases. In scenario 1, the case study house used an embodied energy of 5.7GJ/m^2 and an embodied carbon of 405 kgCO2/$m^{2.}$ The construction materials excluding the wasted volume were responsible of 82% of the total embodied carbon. The balance was due to the transportation of materials and to the construction waste.

Concrete contributed with the highest ratio of 36% in the embodied carbon due to the used cement which was high in embodied energy (0.83 $kgCO^2$ per each kg of product). The prefabricated timber structural frames were responsible of 12% of the embodied carbon. Timber in general including the roof and walls contributed with 30% of the embodied carbon. Transportation contribution to the total emission was only 2% while the construction waste, either from the site or during manufacturing, produced around 109 kgCO2/m^2. For the second scenario with the brick clad house, the embodied energy has increased by 35% to 7.7 GJ/m^2 and embodied carbon has increased by 32% to 535 kgCO2/m^2 compared to scenario 1. This increase could be explained by the increase in brick, cement and sand. Accordingly the transportation of heavier materials increased the transportation emissions by 25% and the overall construction energy due to the mixing machines by 14%. With scenario 3 where the conventional masonry construction was applied, the embodied carbon has been increased to 612 $kgCO2/m^2$ and the embodied energy has increased to 8.2 G/m^2. With an increase of 35% embodied carbon and 51% of embodied energy compared to scenario 1. Walls and increased foundation sizes to accommodate the additional loads of the walls accounted for this increase.

Zygomalas et al (n.d.) studied the environmental impact of the use of steel as a selected material for prefabricated houses using LCA analysis methodology. The selection of steel as a material for prefabricated houses was based on many advantages of steel including its high strength to weight ratio which makes it suitable for different sizes and typologies for buildings. This advantage helped in minimizing the used materials and waste volume as well. The light weight of steel reduced the overall loads of the building and accordingly reduced the size of its foundation. The off-site fabrication process is relatively easy and takes less time than other materials. The reusability of the steel members at the end of the building life is the most important advantage. It was noticed at the results of the LCA analysis that the environmental impacts along the building life cycle were comparable with the environmental benefits at the end of its life. This was due to the reusability of the steel members and the steel panels of the prefabricated house without extra manufacturing process as the materials were reused as initially manufactured. The overall impact of the building life cycle was 1.18 kPt with a 3.6 kPt impact during construction and 2.42 kPt benefit at the end of life. The two main environmental indicators that were most affected were the human health and the natural resources. In the human health, concrete that was used in the basement floor and the foundation contributed with 739,3 Pt and the steel contributed with 437,4Pt in the overall impact. The impact on “resources” category was similarly due to these two materials with almost the same values (772,7 pt and 498,8 Pt respectively) in addition to the thermal insulation material that was used in the steel panels. The “ecosystem quality” category was affected by a lower degree by the same materials (165,8 Pt and 141,7 Pt respectively).

Aye et al (2012) agreed with the findings of Zygomalas et al. In their research the authors ran a life cycle analysis for prefabricated steel and timber residential buildings in comparison to a conventional concrete building to test the difference in their environmental impact. They discovered that although the total mass of the concrete building was around four times the mass of the steel and timber buildings, the embodied energy of the steel building was 50% more than that of the concrete building and around 10% more in case of the timber building. The high embodied energy in case of the steel was due to the intensive energy consumed in the steel manufacturing process. The total embodied energy figures were 14.4, 10.9 and 9.3 GJ/m^2 of occupied area for the prefabricated steel, prefabricated timber and conventional concrete building respectively. By analyzing the volume figures of all the three cases, they concluded that the external walls and the floor slabs hold the highest volumes of the overall building volume reaching 49%, 47% and 39% in cases of steel, timber and concrete respectively. Regarding the operation energy, there was a slight difference between the three case studies due to the difference in the thermal mass and the heat transfer of each of the used materials which affected the consumed heating and cooling energy. The overall life cycle energy was calculated over life cycle of 50 years for all the three cases. For the prefabricated steel building, the life cycle energy was 36GJ/m^2 compared to the concrete building which was 30GJ/m^2. For all cases the operation energy was higher than the embodied energy. The embodied GHG emission results came aligned to the embodied energy for the three case studies with 864 kgCO2/m^2, 630kgCO2/m^2 and 578kgCO2/m^2 of occupied area of steel, timber and concrete respectively. The embodied GHG emissions contributed with 21-27% of the total life cycle emissions. The study concluded the importance of the usability of the construction materials at the end of life to compensate the initial embodied energy. In case of steel building, 81.3% of the embodied energy could be compensated by reusing around 50% of its mass. In case of the timber, 69.1% could be compensated by reusing 30% of its mass. The lowest reuse is for the concrete case where 32.3% only could be reused. These results highlight the advantage of the prefabricated construction strategy especially with the steel case for reducing the overall life cycle impact on the environment.

Olivares (2010) in his master research has used the life cycle analysis methodology to compare the environmental performance of the adapted shipping container house to a conventional concrete and conventional timber houses. He ran his analysis on three built case studies. Olivares concluded the life cycle energy consumption as 37.6 GJ/m^2 for the shipping container house, 29.4 GJ/m^2 for the timber house and 26.2 GJ/m^2 for the concrete house. The embodied GHG emissions were 1954 kgCO2/m^2 for the shipping container house, 333 kgCO2/m^2 for the timber house and 83.5 kgCO2/m^2 for the concrete house. While the life cycle emissions were 4,889 kgCO2/m^2, 3,796 kgCO2/m^2 and 2,224 kgCO2/m^2 for the shipping container, timber and concrete houses respectively. Looking at the ratios of CO2 emissions per the different lifecycle stages, for containers house, the CO2 emissions during construction was 40% while it was 8.8% and 3.8% for timber and concrete houses respectively. For all the 3 houses, the majority of the emissions happened during the operation stage which was around 50% for containers and timber houses and reached 80% for the concrete house. The least emission during the end of life stage was for the shipping container due to its reusability character. Olivares noted that the large embodied emission for the shipping container could be saved if used containers are adapted.

Kim (2008) compared the LCA for a timber prefabricated module to a conventional timber house. The life cycle energy for the modular house was 64GJ/m^2 and its embodied energy was 3.2 GJ/m^2. While it was 67.77GJ/m^2 for the life cycle energy and was 4.32 GJ/m^2 for the embodied energy for the conventional house. It is noted that the embodied energy for both cases was between 5-6.5 % and the transportation energy was between 0.2%-0.3% of the total life cycle energy. The life cycle emissions value for the modular house was 3486.15 kgCO2/m^2 while the embodied emissions value was 79.84 kgCO2/m^2. For the conventional house, the life cycle emissions was 3669 kgCO2/m^2 and its embodied emissions was 151.7 kg CO2/m^2. Kim referred the difference between the modular and conventional houses either for the life cycle energy or the life cycle emissions to the air tightness that the modular house enjoy and led to saving in the energy consumption either for cooling or heating during their operation stage.

2.8.6 LCA Advantages

LCA provides distinct advantage in two main areas:

- Run Comparative analysis for different systems to highlight the least impact on environment.
- Identification and quantification of the environmental impact of different products or services.

2.8.7 LCA Disadvantages

- LCA is known as a time and money consuming tool due to the amount of information required for the impact assessment besides the need for certain expertise in the impact assessment and improvement stages.
- The system boundary selection and data sources selection associate certain level of subjectivity which affects the accuracy of the results.
- Most of the analysis software are western oriented which lack data about the Middle East region. Similarly all the LCA databases are western oriented as well. A lot of assumptions were made to overcome this shortfall of data availability.

2.8.8 LCA, The Selected Research Methodology

Through studying the different research methodologies, LCA is found to be the most suitable tool to the current research topic. The goal of this research is to compare different modular prefabricated systems with the conventional construction system to conclude a sustainable construction system to be used for affordable housing in Egypt. Accordingly, the research topic is addressed by the main two advantages that distinguish LCA from other methodologies; the environmental impact quantification and different systems comparison.

LCA identify the main building stages, components and processes that contribute to environment impact the most. It provides the tools to develop and improve the systems to reduce their impacts on the environment and compare different alternatives together to conclude the least impacting ones. These characteristics of LCA are essential to achieve the goal of this research.

CHAPTER 3

LCA METHODOLOGY

3.0 Life Cycle Assessment LCA Conducting Steps

The purpose of this research is to study the sustainability of introducing different prefabricated modular construction systems into the social housing programs and to compare their environmental performance against the current conventional construction system. Life cycle assessment LCA methodology has been used to run this comparative study. The way to adapt this methodology is described in this section.

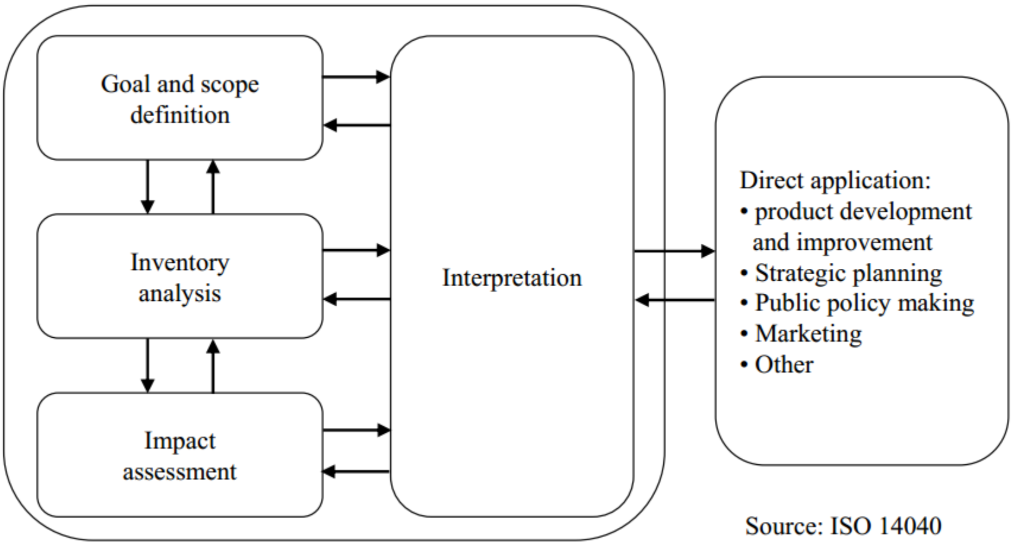


Figure 3.1: Stages of LCA, (ISO 14040, 2006)

International organization for standardization ISO has developed a standard 14040/14044 for LCA assessment. It provides a framework for LCA tools to run comparisons between different systems running in similar contexts (figure 3.1, ISO 2006). The analysis steps are described in details in the following sections.

3.1 Step 1- Goal and Scope Definition

Describing the goal of this research is essential to define its scope and the application of its results. This research goal is to compare the current conventional construction methodology that is used currently in the affordable housing industry in Egypt with other construction systems to find out a sustainable system suitable for the affordable housing market in Egypt. A comparative analysis will be conducted of four prefabricated construction systems in additional construction system which will serve as the baseline for assessing the environmental impact along their life cycle of the proposed prefabricated systems. The four prefabricated construction systems included in this study are:

- Precast concrete (PCC)
- Prefabricated glass reinforced concrete (GRC)
- Light Gaged concrete (LGS)
- Adapted shipping containers (ASC)

These four pre-fabricated systems have been selected due to their availability in Egypt. Although they are not commonly used in housing sector, there are limited factories that are available in Egypt which use these systems for certain purposes. PCC system is the most common pre-fabricated system that is well known and widely used in many building typologies. GRC is commonly used in decorative and façade cladding purposes; however there is one factory that experimented in using it as a full construction system as will be explained in detail in chapter 5. LGS system is used in mobile houses "Caravans". ASC system is used in portable cabins for construction sites. All these previous systems have the potential to provide sustainable solutions for the affordable housing as have been tested and used in many other places in the world.

The purpose of this research is to find the most sustainable construction system for affordable housing industry in Egypt. The results of this research are expected to add useful information about the environmental impact of the different prefabricated modular systems in comparison to the conventional construction systems along their lifecycle. Beside the importance of this research results for the affordable housing industry, it adds more information about the sustainability of different modular construction systems in general. The literature reviews did not show many LCA researches about the construction industry in Egypt. This research adds information about five different construction systems and their environmental impacts in Egypt. The scope of this study is limited to a 4-storey residential base case building composed of 12 modular residential units. This research scope is defined by the system, system boundary, reference units, function units, assumptions and limitations. The previous scope parameters will be discussed in detail hereon.

3.1.1 System-Case Study Building

The system initially was defined at the beginning of this research to be all the process associated with the construction, operation and after life of a low cost residential building. The system constituted a comparative analysis between the conventional construction methodology in Egypt with four different prefabricated and modular construction systems with their environmental impacts. All these construction systems are described in detail in chapter 4 of this research. This section describes this residential building model with its design parameters that has been defined to suite the goal of this research.

3.1.2 Location

The location of the building is proposed to be in Cairo since the main goal is to find an alternative construction solution to affordable housing in Egypt. There is no specific location within Egypt was defined as this information was not required for the research.

3.1.3 Building Function

The function of the building is 100% residential for multifamily units.

3.1.4 Building Description

For the purpose of studying the different proposed construction systems, a modular building has been designed as a base model for comparison. The proposed base model is a residential building composed of 12 modules each form a residential unit with an area of 32.4 m^2 with a total construction area of 38.4 m^2 The proposed building is composed of four floors each with 3 units per floor. The height of the building is limited to G+3 floors which is the common building height for affordable houses in Egypt. The number of units is limited to 3 units per floor to test the cases where the units are located on the periphery or in the middle of the floor. The staircases and the corridors are not considered as part of the study to focus on the module designs and their construction alternatives. The main principle of design was to fix all the design components and limit their variations within the used materials and the construction systems only. By fixing all the design components of the base model except the construction systems highlights their impact on the environment and provide a fare platform for comparison. The following 5 construction systems are applied as alternatives for constructing this base model. This base model has been designed as per the following design parameters to achieve a suitable platform for the study.

- **Common volume**

The base module that forms the whole building was designed to be common in size and volume between all the 5 different construction systems. All the first four systems are flexible in the unit sizes that they can construct except the Adapted Shipping Containers ASC system which is prefabricated to serve the marine industry with fixed dimensions. Accordingly and to be able to provide a common volume, the base model was designed as per the same shipping containers dimensions. So, the basic module that forms the base model building is designed with dimensions of the “40’high shipping container” with inside dimensions of 12.0x2.35x2.7m.

- **Common indoor comfortable spaces**

To compare the environmental impacts of the different construction systems, the occupation stage contribution should be limited to the maintenance impact and doesn’t include the operation impact. To unify the operation impact for all the different five systems, the indoor spaces should enjoy the same comfort zone for heating and cooling. Accordingly, the external envelops were designed to have the same thermal resistance characteristics of their materials. The walls, roofs and ground floor slabs are insulated to achieve almost the same U value for the indoor spaces. Chapter 5 shows the details of these insulation details.

- **Common life time**

The life time of all the different systems are set to 50 years.

- **Variable materials and construction systems**

Four construction systems are compared to the base case model to find out the least impacting system to the environment. The following are the proposed construction alternatives with their used construction materials.

1- Conventional construction system (Base case model) - concrete and masonry
2- Pre-cast concrete (PCC) – precast concrete and masonry
3- Prefabricated Glass Reinforced Concrete (GRC) – precast GRC hollow panels
4- Light Gauge Steel (LGS) - steel with gypsum boards
5- Adapted Shipping Containers (ASC) – steel with gypsum boards

3.1.5 The System Boundary

The system boundary is divided into main 4 phases: pre-occupancy, occupancy, post occupancy and beyond building life. The details of each phase will be explained below.

Pre-Occupancy Phase

- (A1-A2) phases include resources extraction, materials manufacturing and fabrication.
- (A3) phase represents the transportation of the materials and resources from the refineries and extraction sites to the manufacturing factories and then to the construction site for installation and on site assembly.
- (A4-A5) phases include all the onsite construction activities as well as transportation of the site labors to and from the construction site.

Occupation Stage

- (B2) - This stage represents the maintenance and renovation activities during the occupation phase of the building.
- (B4) - This stage represents the transportation of the materials and resources from the factories to the building during the maintenance activities along the life span of the building.

- (B6) - Includes heating, ventilation, air conditioning, cooling, lighting, water heating and all other operation activities.

Post-Occupation Phase:-
(C1-C4) includes all the activities related to demolition, deconstruction, disposal, and waste processing including the transportation of the demolished materials to the landfill dump fields.

Beyond Building Life BBL Phase:-
(D) Includes the recycle and reuse of some or all of the building components or materials.

3.1.6 Reference Units

For the sake of comparison between two or more systems, a reference system should be selected as a reference base for evaluation. In our study, the base case model is the conventional construction system that is commonly used in Egypt which comprises a cast in situ concrete and masonry work. The comparative analysis was conducted between the four alternative pre-cast systems and this base model.

3.1.7 Function Units FU

The ISO 14044 standard defines the Functional Unit (FU) as
"The quantified performance of a product system for use as reference unit in a life cycle assessment study"
In buildings, most commonly and worldwide used FU is 1 sq.m. of living space with an assumption of a 50 years of building life span. Accordingly, the life time assumed for my research is decided to be 50 years.

3.2 Step 2-Life Cycle Inventory Analysis (LCI)

This step concerns the data collection, calculation and analysis for all the processes associated with the building lifecycle. The data collection was based on the current design of the 5 scenarios. The calculation was conducted through a computer software. There are many softwares available for LCA analysis. Athena

Environmental Impact Estimator EIE, BEES, Simapro and Gabi are some of these softwares while they are different in their focus, intend, and use in the different design stages (Trusty, n.d.). SimaPro and Gabi are only commercially available and usually used by LCA practitioners accordingly they are not within means of this study. BEES focus more on individual products or simple building components like window assemblies or floor coverings. BEES usually used to run an environmental and/ or economic comparison between different products. It is suitable for specifications stage when material selection makes a lot of difference in the overall building performance. Athena EIE is usually used for overall building analysis and provides support to decision making along the building design stages from concept to detailed design. It provides data about the life cycle environmental performance of the building including its embodied energy and operation energy (Trusty, n.d.). Accordingly, Athena EIE has been selected to be the suitable software for this research LCA analysis.

3.2.1 Athena Overview-Version 5.1.0102

Athena has two main applications, EcoCalculator and Impact Estimator. EcoCalculator is usually used to run a quick calculation for the carbon footprint of buildings. Athena Impact Estimator (Athena IE) is used to calculate the environmental implications of buildings along their LCA. It allows for comparing five different scenarios with the possibility to select one to be the baseline design of the comparison which was fundamental in this research.

One limitation of Athena IE is that it doesn't calculate the overall operation energy consumption. However, it has the possibility to input the calculated energy data into its calculation (Okodi-iyah, 2012). Accordingly, the eQUEST software was used to calculate the consumed energy along the life cycle of the building used for space heating, cooling, lighting, water heating and mechanical ventilation.

3.2.2. eQUEST Overview-Version 3.64

The Quick Energy Simulation Tool eQUEST software was used to calculate the operation energy consumption of the 5 different construction systems in form of electricity and natural gas. Version 3.64 was used with DOE – 2 simulation engine. For the purpose of this study, the external skins of the five different scenarios share almost the same U value to keep the same internal environment for residents which is reflected on the mass of materials used to achieve these conditions. Accordingly, almost the same values for the consumed electricity and the natural gas have been concluded for the five different scenarios.

3.2.3 <u>Data Collection And Calculation Process</u>

In this stage, the inventory of all the stages, processes, materials and equipment that are part of the construction process have been collected. It starts with the materials extractions, materials manufacturing and transportation from the factories to the construction sites. All the activities during on site/ off-site construction activities, the building operation, the building maintenance, end of life and after building life are considered as inputs to the building life cycle inventory. All the materials of the five scenarios are calculated accurately and the material quantities were fed into ATHENA for their impacts calculation. All the steps of calculating the materials' quantity and data inputs into ATHENA software are discussed in detail in chapter 5.

The data collection process started with several interviews with different manufacturers for the five construction methodologies in Egypt to gather the technical data of each system. All the data about these systems are gathered and the details of the 5 buildings were developed accordingly.

3.2.4 <u>Materials Consideration</u>

For the five construction systems, the used materials are different. In the conventional scenario, the concrete and masonry work are the main construction materials besides the other common materials for doors, windows, finishes,..etc. The quantities of the used materials are calculated from the drawings and all assemblies were fed into ATHENA through the input dialogue boxes. The precast concrete scenario relies on prefabricated hollow core slabs and precast concrete walls. The volume of all materials have been calculated and fed directly into ATHENA. For the GRC scenario, a new concrete type has been introduced through a tool in ATHENA that allows changing the components of the concrete as per the used type. For the Light Gage Steel LGS scenario, the quantity of steel is directly calculated by ATHENA through the pre-defined LGS system in the software. For the Adapted Shipping Container scenario, the quantity of materials has been calculated through the container drawings provided by Crepeau (2008).

3.2.5 Geographical Location Consideration

ATHENA is a software that is designed for North America. All data base are USA oriented. Defining the location of the building under study is part of the main input information for the LCA calculation. (USA) location takes an average figure out of all other specific locations within North America on the data base. Accordingly, (USA) is chosen to be the location of the project.

3.2.6 Transportation Consideration

Transportation plays an important role in the overall LCA impact due to its consumed energy and the Green House Gas GHG emissions. Throughout the different stages of the building lifecycle, transportation is considered for moving materials from extraction site to manufacturing factories then to supplier stores to construction sites. Transportation is also considered for moving labors to and from the construction sites and moving the prefabricated assemblies from factories to construction sites. During operation stage, moving the used materials, equipment and labors to the building for maintenance is considered as well. At the end of life, moving the demolished materials to landfill sites is part of the overall transportation impact. ATHENA considered all the previous mentioned trips for all used materials during all the stages through the software database. It is assumed that all transportations are done using diesel fueled trucks.

3.2.7 Electricity Consideration

The main source for the production of electricity in Egypt is gas and oil with 91% followed by hydro with less than 7.5%. Renewable resources are limited to 1.5% (Osman S., 2015). Source of electricity generation is part of the study that ATHENA takes in consideration due to its energy consumption and due to generated GHG. In general, electricity used for materials extractions, prefabrication, construction activities and during the operation are taken in consideration for the LCA calculation.

3.2.8 Construction Consideration

Construction associates energy consumption during onsite/ offsite activities. The pattern of construction considerations vary vastly according to the different scenarios under study. Concrete pouring onsite for the conventional base case and the prefabrication for the building assemblies for the other prefabricated systems consume energy and produce waste. ATHENA considers the consumed energy for each of the stages as well as the caused air emissions, land emissions and water emissions as well. The pattern of construction considerations vary vastly according to the different scenarios under study.

3.2.9 Occupancy Considerations

The function of the base case building is residential. The occupancy pattern and the space activities are related to this residential function. This assumption is common between all the different five scenarios. All the energy consumption related to the operation activities of cooling heating, lighting, water heating, used electricity for house hold equipment were considered and calculated through eQUEST software. The selected cooling and heating is DX coils system. The cooling set point is (25.5 C) and the heating set point is (20.0 C). The water heating is electrical and the cookers are using natural gas. Occupation hours are considered for 17 hours daily including the weekends. Water consumption is assumed to be 145 liter per person per day as per the common use in Egypt. These considerations are identical for all the five scenarios to provide similar studying conditions. On another hand, the performance of the external building envelops is almost the same as well to provide similar internal living conditions for all the five scenarios. Accordingly, the operation energy for all scenarios is almost the same. I intentionally fixed the performance of the internal conditions to focus the study on the environmental impacts on the external environment for the different five scenarios. However, the different used materials for the five scenarios had an impact on the consumed energy during the operation stage especially due to maintenance process as will be discussed in Chapter 5.

3.2.10 Maintenance Consideration

Along the life span of the building which in our case considered being 50 years, and due to the normal wear and tear and weather factors, the building will be exposed to regular maintenance activities. This includes equipment changing, paintings, repairing and reconfiguring of the building components. The effect of these activities associates energy consumption, materials use, transportation, gas emissions, waste and disposal which all are considered. All the five scenarios differ in their impact during this stage due to the different used materials and different construction materials which have different maintenance requirements. For example, due to the fare face surfaces that GRC option provides, we eliminated painting item for internal and external surfaces. Accordingly, the maintenance stage impact of GRC comes less than other scenarios.

3.2.11 End of Life Considerations

ATHENA considers the end of life of the buildings and calculates their impact on environment through the consumed energy, waste, gas emissions and air pollution. ATHENA starts with calculating the amount of energy consumed in demolishing the building and the energy consumed through transporting these materials from the building site to the landfill sites. The amount of gas emissions, waste and air pollution are calculated according to the mass and type of demolished materials. The five scenarios are different in terms of the amount of materials and components that could be recycled, reused or used for landfills. The conventional construction scenario holds the majority of its components for landfills while the structural steel components of the light gage steel LGS option will be recycled or reused. The consideration of this stage includes the mass of the demolished materials, the energy consumption due to the demolition process, transportation, waste generation and air pollution.

3.2.12 Building Parameters

ATHENA starts data input by defining the project name, location, type, height, gross floor area, and the used units as shown in Figure 3.1. The life expectancy for the building is considered as 50 years. The five different scenarios are named according to their construction systems. The conventional system base model is referred to as Base case model (BCM). The other four construction options are referred to by their name abbreviations. As PCC, GRC, LGS and ASC as described before.

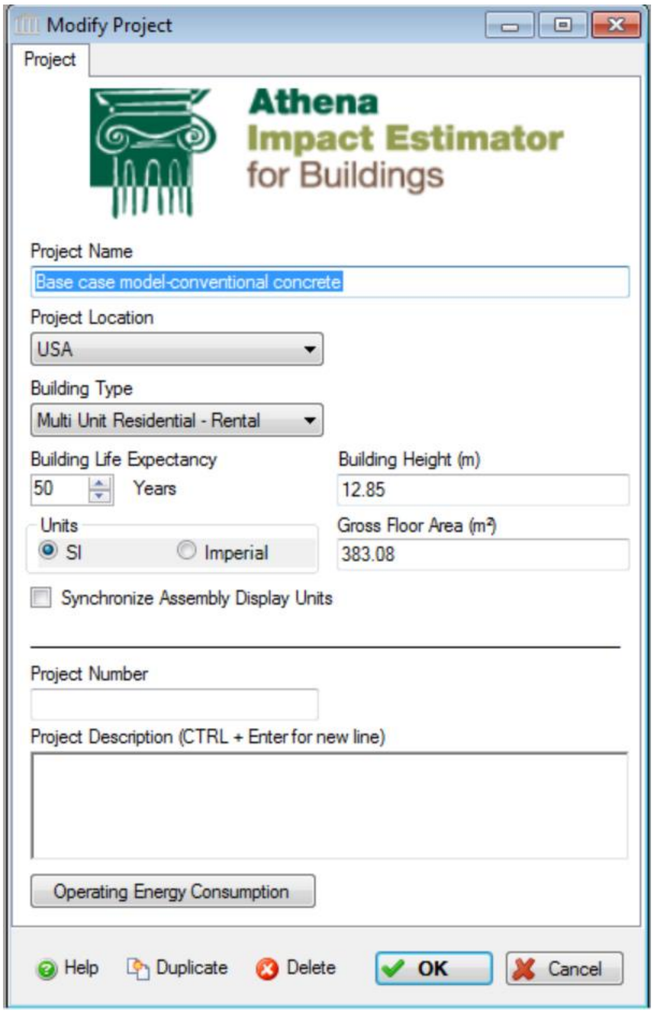


Figure 3.2: Input Dialogue Box for the Project Information in ATHENA

All the building materials are calculated for all the options and get fed into ATHENA software. ATHENA classifies the material inputs into six assemblies; foundation, wall, columns and beams, floor, roof and extra basic materials. In each assembly, all the build-up layers are defined and specified as per the designed system. After feeding the software with all the materials and their quantities, ATHENA simulates the impacts for each option. The conventional construction system is used as a base of comparison between all the options. Figure 3.2 shows an example of a dialogue box for pre-cast concrete wall data input. It starts with the wall name, the length and the height of the wall. The selected wall type on the right side was selected from the list on the left side which includes different types of walls. The details of the wall are input through another dialogue box as shown in figure 3.3 where the concrete grade, the wall thickness and the wall rebar are defined. The wall openings including doors and windows are defined through another dialogue box where all their areas and materials were input as in figure 3.4. All the layers of the walls either for insulation and finishes for the external walls or for the plaster and paint layers for the internal walls are defined through another dialogue box as in figure 3.5.

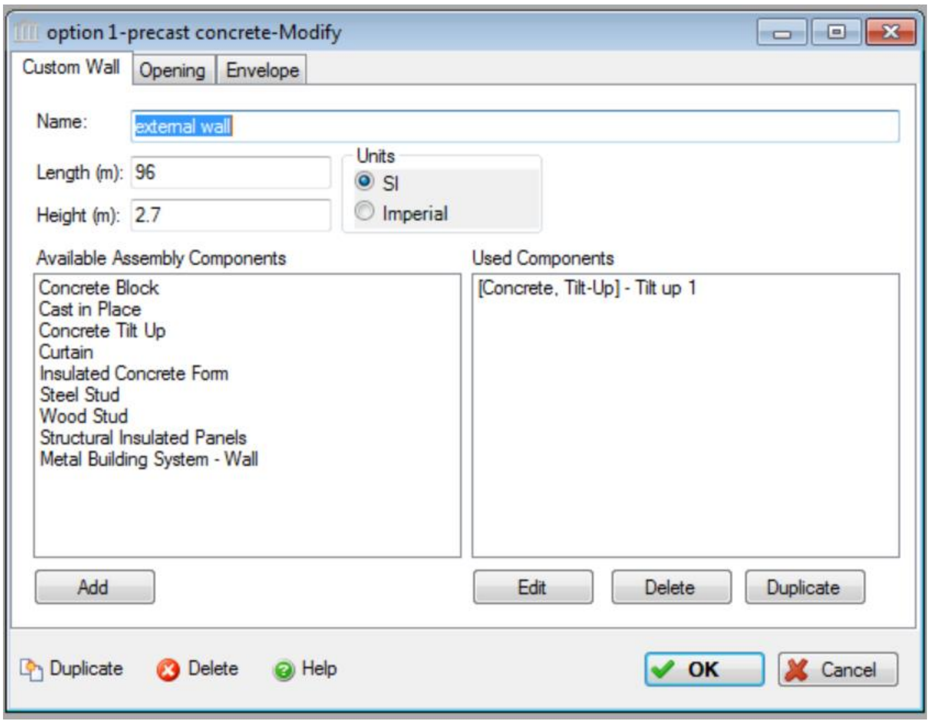


Figure 3.3: Custom Wall Input Dialogue Box

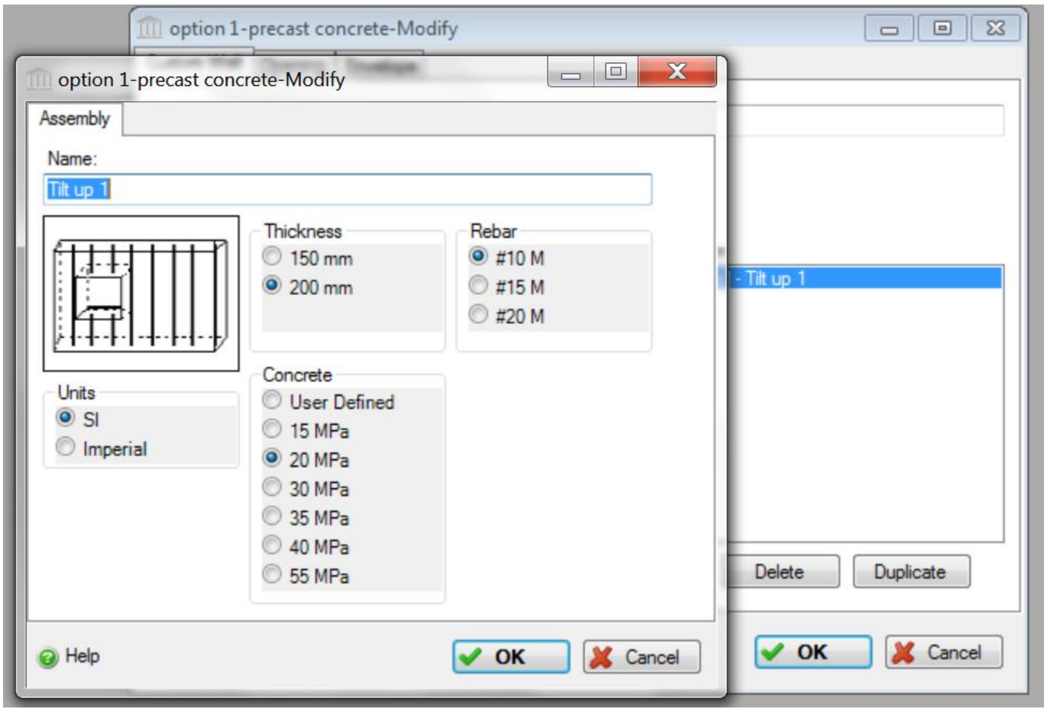


Figure 3.4: Details Input of Precast Tilt up Concrete Wall

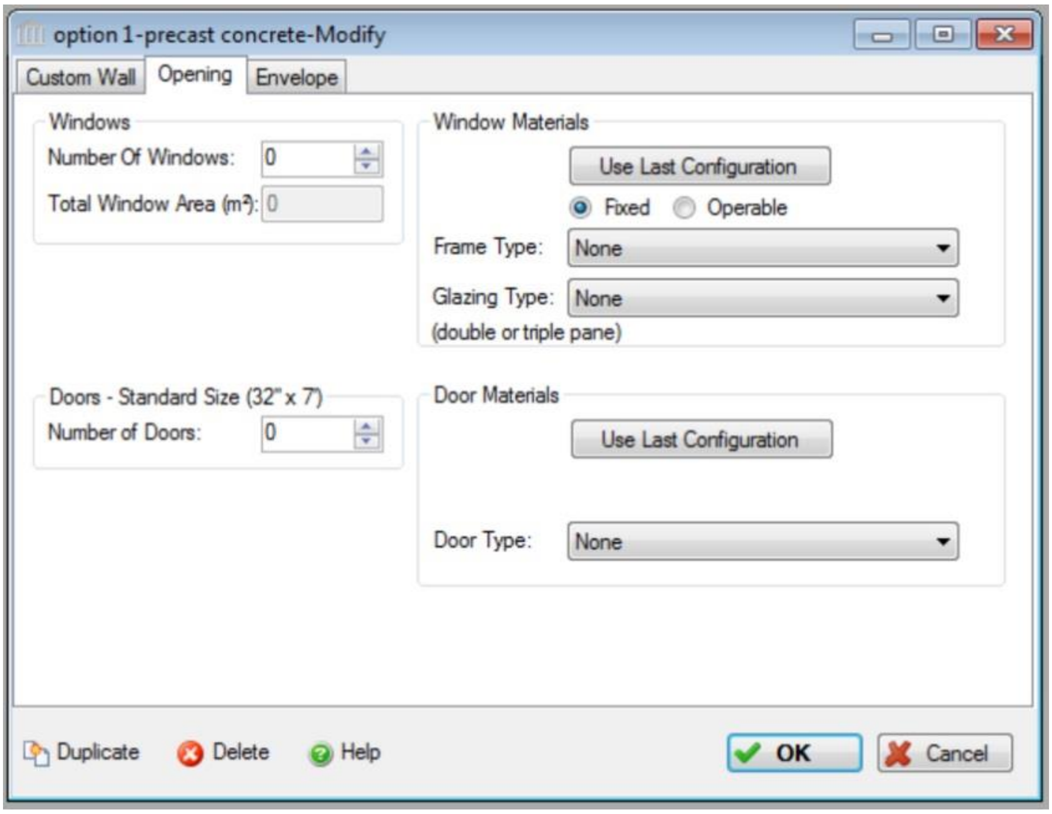


Figure 3.5: Input Dialogue Box for the Wall Opening

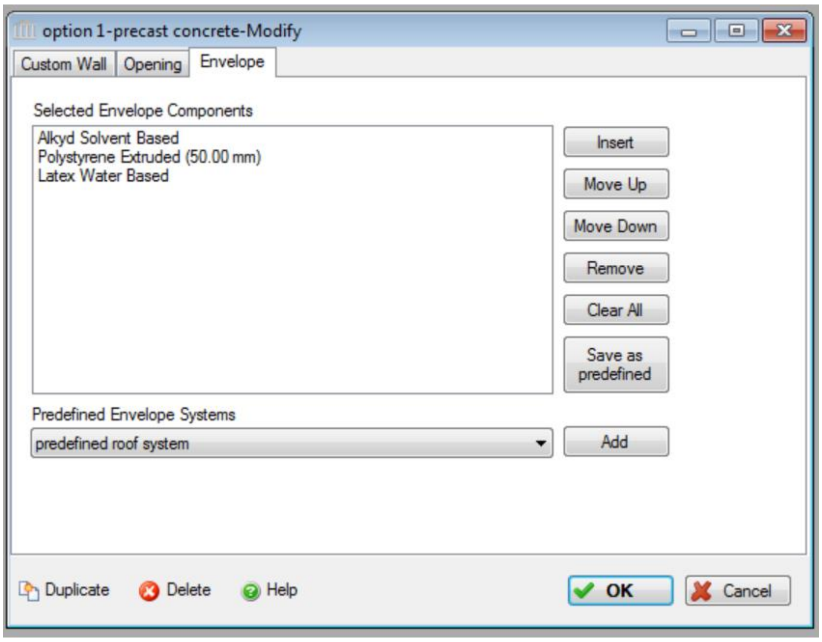


Figure 3.6: Input Dialogue Box for the Precast Wall Envelop Layers

3.2.13 Operation Energy Calculation – eQUEST

The operation energy is the total energy that is consumed by the building users during the operation stage due to HVAC, lighting, electricity, water heating, and cooking gas as well. ATHENA doesn't calculate the operation energy and accordingly eQUEST software was used to run this calculation. Five different models were built in eQUEST to calculate the operation energy for the five options with different assigned materials for the external envelop of each option. The total figures of the consumed electricity and gas are inputted into ATHENA for the Life Cycle Inventory LCI calculations as shown in figure 3.6.

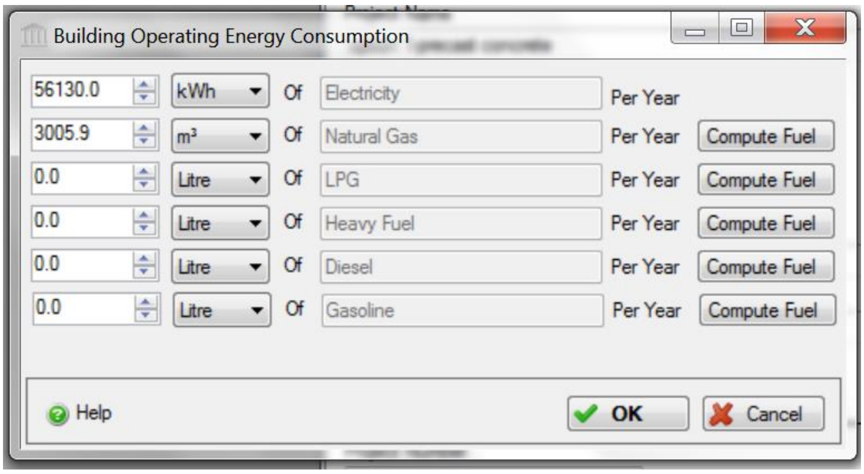


Figure 3.7: Building Operation Energy Consumption

Different parameters were included in each model that EQUEST uses for its simulation like building location, orientation, size, materials, external envelop performance, the used cooling and heating systems with their set points. The operation schedule and occupancy pattern are important for the energy calculation as well. Figure 3.7 shows the first of 50 dialogue boxes for the schematic building design wizard for the base case model as an example.

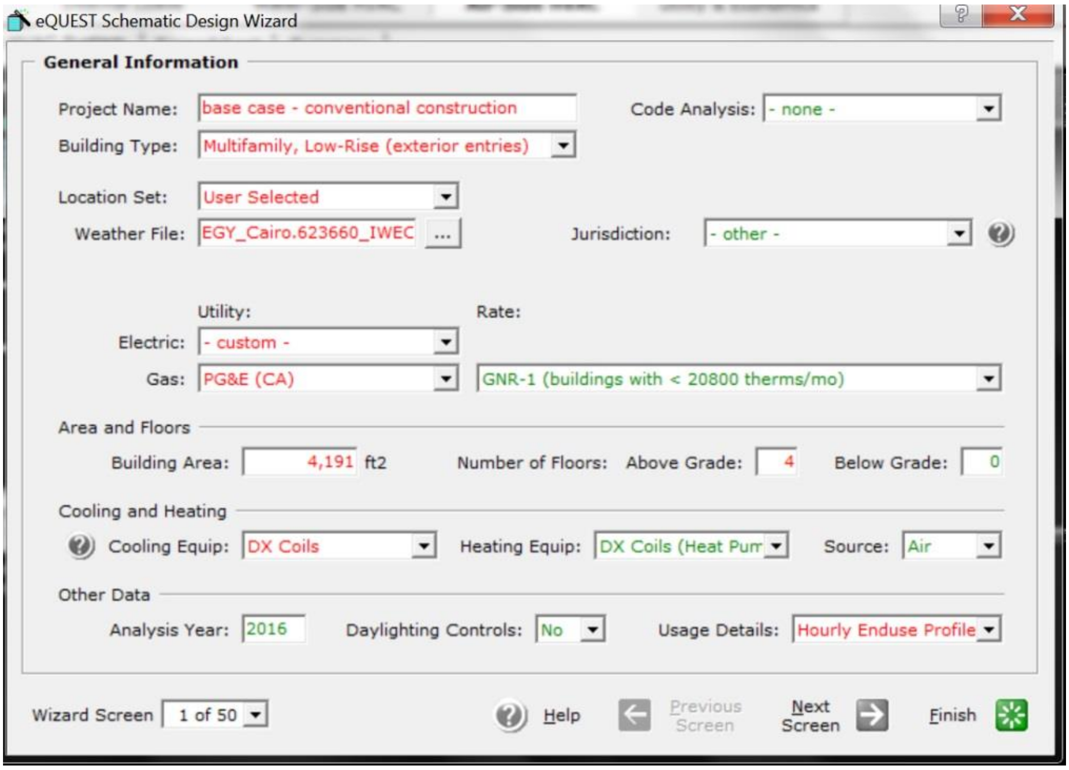
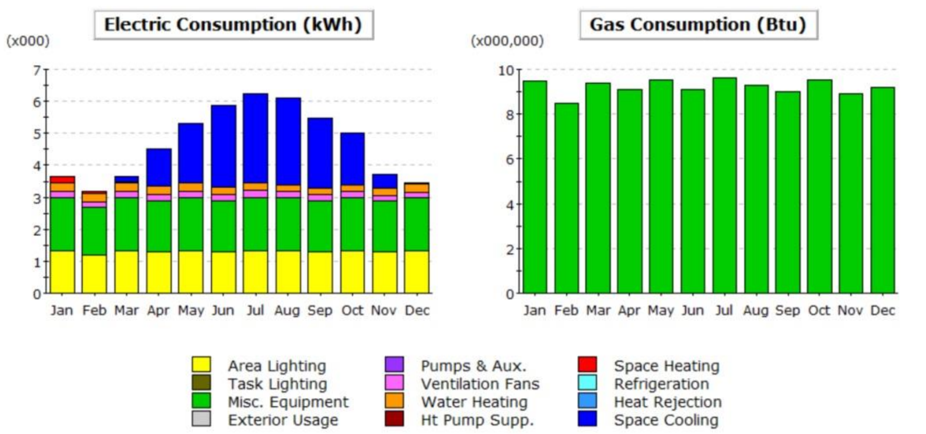


Figure 3.8: eQUEST Schematic Building Design Wizard Dialogue Box for The Base Case Model

eQUEST calculates a comprehensive monthly consumption for the building showing the detailed consumption for each element as shown in figure 3.8. The figures of operation energy consumptions that are inputted in ATHENA refer to the yearly consumption. ATHENA forecast the overall operation energy during the 50 years life expectancy of the different options.

Project/Run: base case - conventional constrcution - BaselineRun Date/Time: 12/24/16 @ 17:02



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	0.17	1.16	1.85	2.53	2.79	2.70	2.21	1.60	0.42	-	15.43
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.20	0.06	0.01	-	-	-	-	-	-	-	-	0.02	0.29
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.28	0.26	0.29	0.27	0.26	0.23	0.22	0.20	0.20	0.22	0.22	0.25	2.90
Vent. Fans	0.19	0.17	0.18	0.18	0.20	0.20	0.22	0.21	0.19	0.19	0.18	0.18	2.28
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	1.66	1.49	1.65	1.60	1.66	1.60	1.66	1.65	1.60	1.66	1.59	1.65	19.44
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	1.33	1.21	1.34	1.30	1.34	1.30	1.34	1.34	1.30	1.34	1.29	1.34	15.77
Total	3.66	3.19	3.64	4.50	5.30	5.86	6.22	6.10	5.49	5.00	3.71	3.45	56.11

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	9.46	8.48	9.38	9.11	9.54	9.11	9.62	9.30	9.01	9.54	8.92	9.20	110.68
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	9.46	8.48	9.38	9.11	9.54	9.11	9.62	9.30	9.01	9.54	8.92	9.20	110.68

Figure 3.9: Monthly Distribution of the Operation Energy Consumption for The Base Case Model

3.2.14 Assumptions

A- One of the main assumptions of this study is the selection of the project location in Egypt. For the region selection, it is important to input the location of the project as one of the main input parameter for the LCA simulation. The project location defines the energy and electricity grids and transportation grids of that location which has an impact on the final LCA results. There is no available LCA tool that has the Egypt information as part of their data base. Due to the fact that ATHENA is designed for North America, it includes the data for 8 locations in

America and another eight locations in Canada with one general location which named as USA location which includes an average data. Software designers recommend using USA location for those cities which are not listed within the locations list. Accordingly our choice for our building location was USA average.

B- The main purpose of this study is to run a comparison between the different construction systems for modular housing and test their environmental impacts along their life cycle. Accordingly, the study focused on the housing modules more than the building as a hole. The design under study included a simple configuration of 3 attached modules repeated for 4 floors without considering any corridors, staircases or service rooms as part of this study.

C- The site specifics are not part of this study for two main reasons. First, the five scenarios including the base case model are considered as prototype units which can be constructed anywhere in Egypt. Second, ATHENA focuses on building design not the site specifics of land disturbance, damage to vegetation or alteration to the ecosystem.

D- ATHENA bases its analysis on predefined database for the environmental impacts of all the construction activities, operation activities and even end of life of the building. These data are not subject to customization by users other than selecting the site location of the project which dictate which database to be used.

E- Electricity supply was assumed to be constant during the operation stage along the building life cycle without any losses during importing or exporting.

3.2.15 Limitations

There is lack of LCA studies for construction industries in regions like Egypt which makes it difficult to compare and verify the results with similar studies. The environmental impacts are region specifics and the materials, construction methodology, transportation grids and energy sources have big difference from one region to another. And due to the fact that most of the LCA data are for US and Europe, this is considered as the main limitation to this study.

3.3 Step Three - Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment as per ISO 14040 could be conducted in three stages: classification, characterization and valuation (Figure 3.9). Hauschild (2005) added normalization as well.

3.3.3 Classifications

Classifications include identifying the environmental impact categories. The common impact categories that ATHENA analyzes are as follows:

A- Resources used
B- Land emissions
C- Fossil fuel consumption – total primary energy consumption
D- Global warming potential
E- Acidification potential
F- Human health criteria
G- Eutrophication (air & water) potential
H- Smog (air) potential
I- Ozone (air) potential
J- Fossil fuel consumption

The study focused on the first four categories which have direct relation to the study topic. Most of LCA researchers focus on two main criteria; the total energy consumption and the global warming.

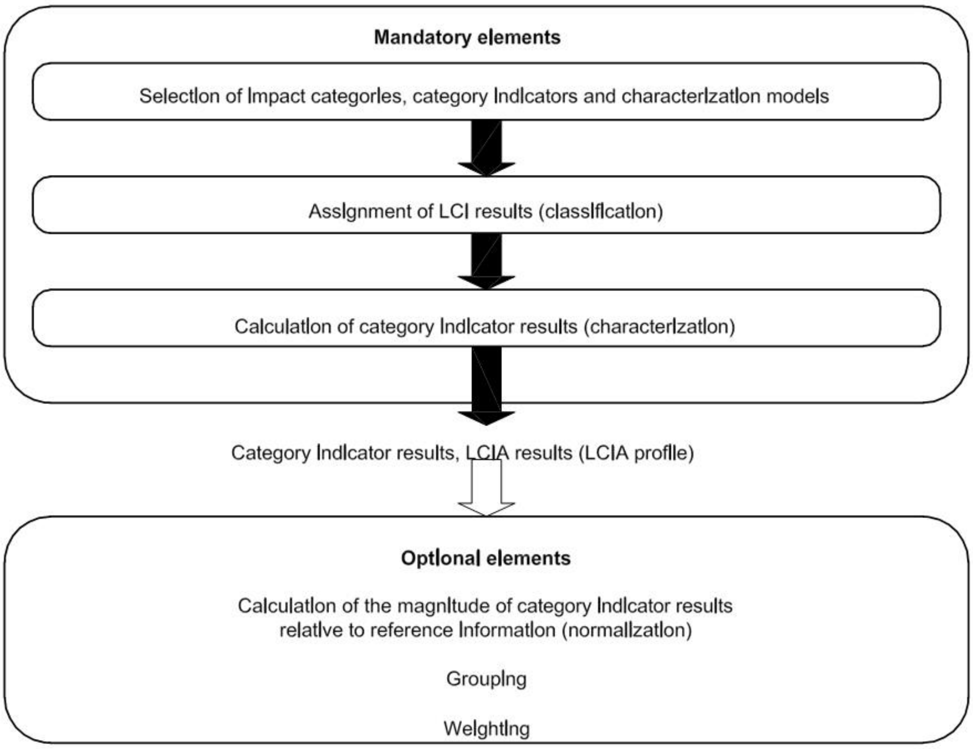


Figure 3.10: Elements of LCIA (ISO 14040, 2006)

3.3.4 Characterization

Characterization models the impact of each category and expresses its score in a common unit for all contributions within the category (eg. Kg CO2-equivalent for all GHGs contributing to the climate change). This interprets the inventory data into a profile of environmental impact scores and resource consumptions (Hauschild , 2005).

3.3.5 Normalization

Normalization puts the different impact scores into common scale for comparison between different categories. This process is important to facilitate comparison between the different categories when the improvement in one category affects negatively the score of the other. So, Normalization helps in creating a common reference for all category impacts. (Hauschild, 2005).

3.3.6 Valuation

Valuation is an optional process through which the data from the impact categories are valued by applying different weight for each (Hossain, NA).

However, ISO doesn't allow weight due to the lack of scientific standard for weight values and end up being subjective. ATHENA adapts Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) which doesn't apply weights. Accordingly, this optional step has not been applied and the final results have not been affected (Okodi-iyah E., 2012).

3.4 Step Four- Interpretation

Interpretation is the last stage of the LCA analysis. It analyzes the results of the last two stages (LCI and LCIA) and reaches conclusions aligned with the scope and the goal that have been established in step one of the LCA study. ISO 14040 recommends running a peer review for the results by external experts to identify any errors or discrepancies before being published. Validation (step three) and interpretation (step four) are referred to as results and discussions in chapter 6 of this research.

CHAPTER 4

SYSTEMS DESCRIPTION

4.0 Introduction

This research studies the viability of introducing prefabricated modular systems into affordable housing from environmental perspective. A comparison between four prefabricated systems is conducted against the conventional construction system as the base model. The Life Cycle Assessment LCA was used as the tool for this comparison assessment. To conduct this comparison, a base case building was designed in a way that allows these different systems to be applied in its construction.

In this section, the base case building will be described with its variations when applying the different prefabricated construction systems.

4.1 Base Model Building Description

For the study purpose, 4 stories residential building was designed that holds 3 modules per floor. Figure 4.1 shows a typical floor plan and a cross section for the proposed building layout. The focus of this design was on the modules design which could be constructed in four different modular scenarios besides the conventional system. Accordingly the common corridors, the vertical staircase and common service rooms are excluded from this design. As will be explained in details below, the base case model and the four proposed prefabricated modular options are as following:

- Base Case Model - Convention cast in situ concrete and masonry work
- Option 1- pre-cast concrete system (PCC)
- System 2- prefabricated Glass fiber Reinforced concrete (GRC)
- System 3- prefabricated Light Gage Steel LGS
- System 4- Adapted Shipping Containers (ASC)

All the systems above are flexible in their sizes except the ASC option which is fixed with the industrial shipping container sizes. Accordingly and to have all the options with the same size for their comparison, all the modules followed the dimensions of the 40ft shipping container with internal dimensions of 2.35m width x12.0m length x2.7m height and total floor area of 32.4sq.m. The overall built up area of the building is 389.36sq.m.

The building is proposed to have the best orientation (north/south) direction along its longitudinal axis to guarantee the least exposure to the sun. The solid back side of each module is facing south while the module window is facing north. The base case model which resembles the conventional construction methodology in Egypt is considered to be the base of the comparison for all the other proposed prefabricated modular systems.

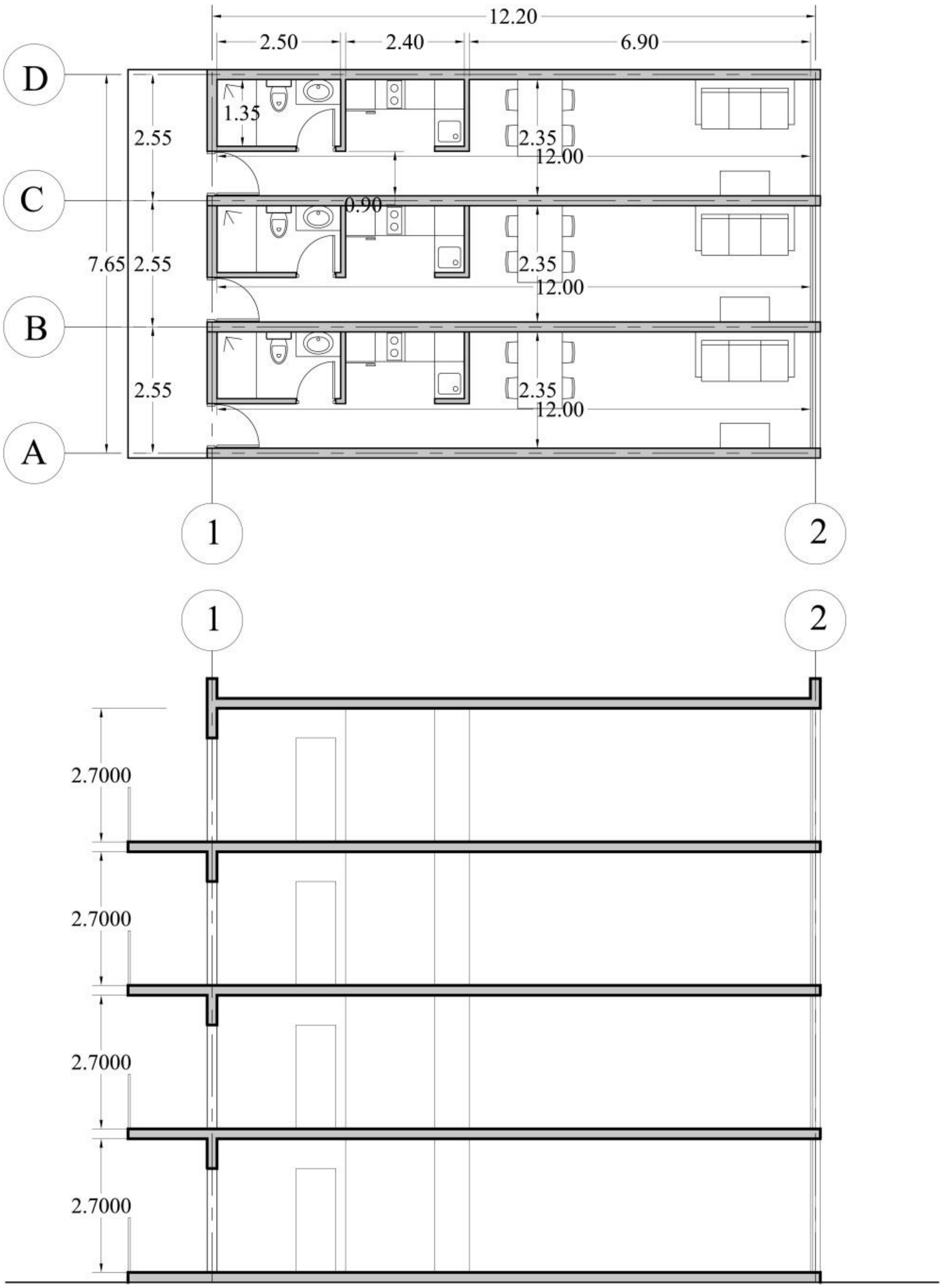


Figure 4.1: Typical Floor Plan and Cross Section for the Proposed Building Layout

The external skin of the five options is designed to meet the required U value to accomplish the regulated thermal insulation. Egypt lies between latitude 22 and 32. Along the whole area of Egypt, it is divided into 8 climatic regions (Hanna, 2013). With this variation the estimated U values for walls vary within these 8 zones between 0.56 W/m2.K at South of Upper Egypt to 1.4 W/m2.K at North Coast. For the roof, its U values vary between 0.33 to 0.5 W/m2.K. Accordingly, the design will consider the average of these figures as the base of design. For the walls, the U value will be 0.98 W/m2.K and the U value for the roof will be 0.41W/m2.K.

4.2 Base Case Model-Conventional Construction System

The convention construction system is based on cast in situ concrete beams and columns supporting flat concrete slabs with masonry walls. This is the common construction system that is used for the majority of the buildings in Egypt. The structure system is reinforced concrete columns, beams and slabs with average strength of 3000psi for slabs and 4000psi for columns and beams.

4.2.1 Base Case Description

Floor Slabs

Slabs are supported by 12 columns, 3 in each of the 4 walls that form the floor plan with span of 2.35m. Figure 4.2 shows the Athena input data sheet for the columns and beams. Figure 4.3 shows a detailed wall section for the different layers that compose the walls, roof and the slabs.

Foundation

The foundation is 200mm thick concrete slab on grade under the footprint of the building. A 6mm polyethylene layer is added between the natural ground and the slab as a vapor barrier. All slabs are finished with ceramic tiles and all ceilings are rendered with 20mm cement plaster.

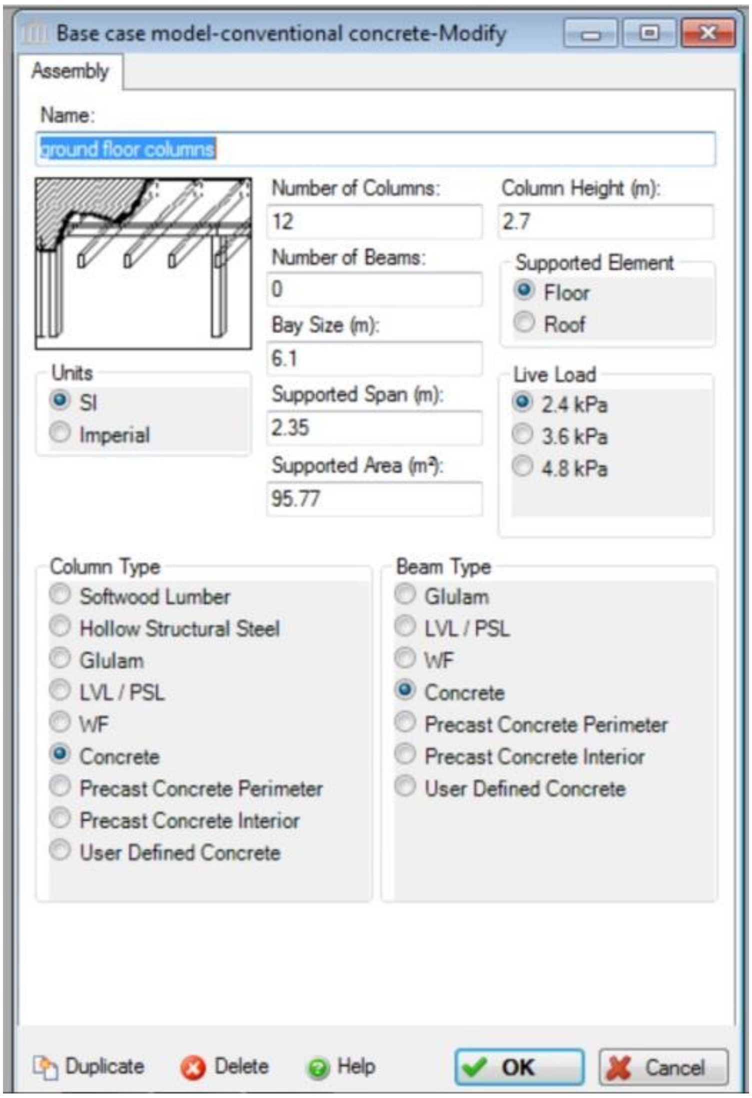


Figure 4.2: Athena Input Data Sheet for the Columns and Beams of the Base Case Model

Walls

The external walls are composed of two layers of 100 mm concrete blocks with 50mm layer of polystyrene boards in between for thermal insulation. 200mm solid concrete block are used for the demising walls and 100 mm thick solid concrete blocks for the internal walls.

Roof

Roof is cast in situ steel reinforced concrete slab. The roof is thermally insulated with a 50mm layer of polystyrene boards to accomplish the required U value for the. A 50mm average layer of light concrete is used for rain fall cast on 3mm layer of bituminous membrane for waterproofing.

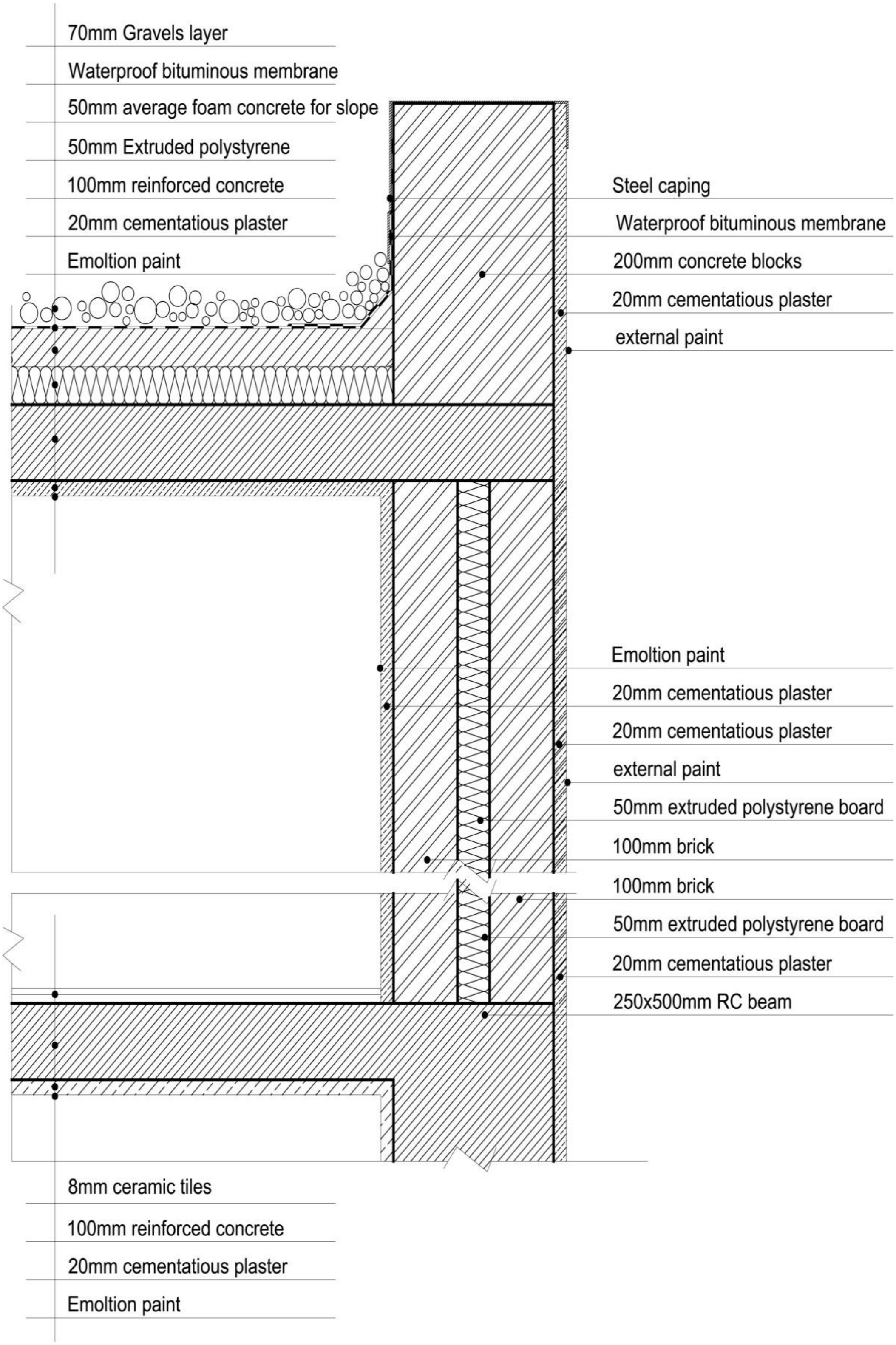


Figure 4.3: Detailed Wall Section through the Base Case Model

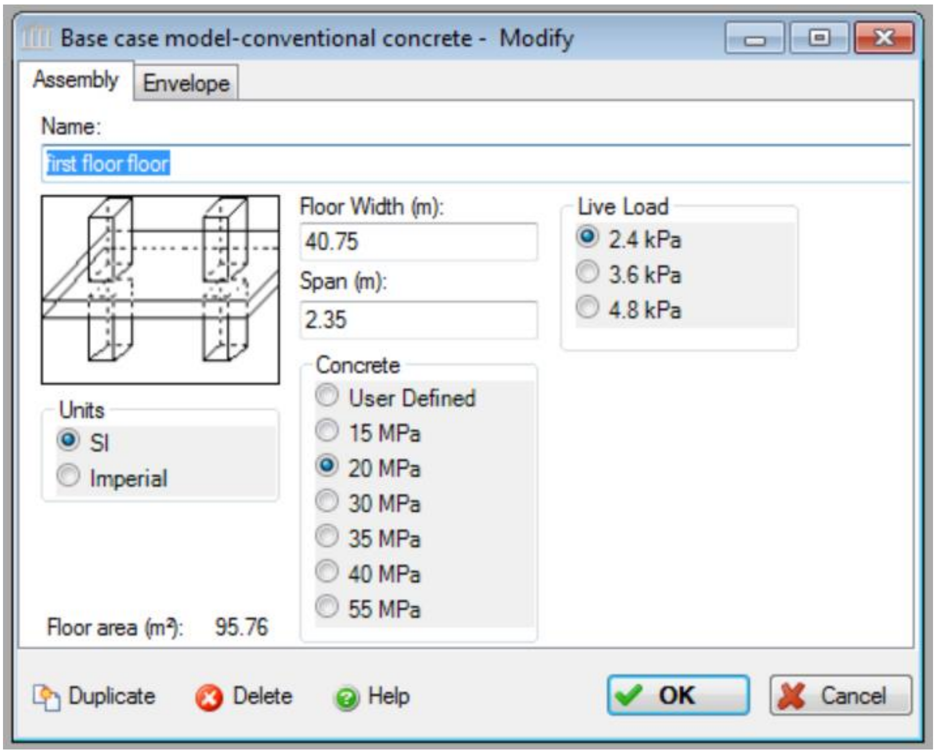


Figure 4.4: Athena Input Data Sheet for the Base Case Model Slabs

Finishes

All the internal surfaces are finished with water based latex paint on 20mm cement plaster and the external surfaces are plastered and painted with alkyd based paint. Table 4.1 shows the calculated B.O.Q of the base case model calculated from the architectural drawings while table 4.2 shows the B.O.Q of the materials calculated through Athena with their weight in kg.

Table 4.1: B.O.Q of the Used Materials of the Base Case Model as Per The Architectural Drawings

COMPONENT	ASSEMBLY	WIDTH	LENGTH	THICKNESS	NUMBER	VOLUME	volume+CW	MATERIAL	UOM
GROUND FLOOR SLAP									
	ground floor slap	8.85	13.2	0.2	1	23.36	23.36	CONVENTION CAST IN SITUE-25	m3
	reinforced concrete					2.10	2.10	REBAR, ROD, LIGHT SECTION	ton
	water proof	8.85	13.2			116.82	116.82	bitumen	m2
WALLS									
	parti walls	10.5	2.2	0.2	8	184.80	184.80	Concrete brick (solid)	m2
	Internal walls	6	2.2	0.1	12	158.40	158.40	Concrete brick (solid)	
	long external walls	10.7	2.2	0.2	8	188.32	188.32	Concrete brick (hollow block)	m2
		12.2	11.4		2	278.16	278.16	Extrudeded Polysterene	m2
	short external walls	7.45	2.2	0.2	4	40.36	40.36	Concrete brick (Hollow block)	m2
		7.45	12.35		1	92.01	92.01	Expanded Polysterene	m2
	parabet	39.3	1.5	0.2	1	58.95	58.95	Concrete brick (solid)	m2
	windows	2.35	2.7		12	76.14	76.14	double glass with aluminium frame	m2
	doors	1	2.1	0.05	12	1.26	1.26	SOLID WOOD DOOR	m3
	wall internal finish	2.7	37.95		12	1229.58	1229.58	WATER BASED LATEX paint	m2
		2.7	37.95	0.02	12	24.59	24.59	20mm mortar	m3
	wall external long finish	12.2	12.9		2	314.76	314.76	WATER BASED LATEX paint	m2
		12.2	12.9	0.02	2	6.30	6.30	20mm mortar	m3
	external short finish	7.85	12.9		1	100.01	100.01	WATER BASED LATEX paint	m2
		7.85	12.9	0.02	1	2.00	2.00	20mm mortar	m3
COLUMNS AND BEAMS									
	columns	0.5	2.2	0.2	48	10.56	10.56	CONVENTION CAST IN SITUE-25	m3
	long beams	0.5	12	0.2	16	19.20	19.20	CONVENTION CAST IN SITUE-25	m3
	short beams	0.5	7.65	0.2	8	6.12	6.12	CONVENTION CAST IN SITUE-25	m3
	reinforced concrete					2.87	2.87	REBAR, ROD, LIGHT SECTION	ton
FLOORS									
	slaps	7.85	12.2	0.1	3	28.73	28.73	CONVENTION CAST IN SITUE-25	m3
	reinforced concrete					2.59	2.59	REBAR, ROD, LIGHT SECTION	
ROOF									
	slaps	7.85	12.2	0.1	1	9.58	9.58	CONVENTION CAST IN SITUE-25	m3
	reinforced concrete					0.86	0.86	REBAR, ROD, LIGHT SECTION	ton
	thermal insulation	7.85	12.2	0.05	1	191.54	191.54	expanded polysterene (25MM)	m2
	water proof	8.85	13.2		1	116.82	116.82	bitumen	m2

4.2.2 U Value Calculation

Thermal transmittance U value (w/m^2k) = 1/R value

Thermal Resistance R value ($m^2.k/w$) = thickness (m)/thermal conductivity (m.k/w)

- R value for the roof = (70mm gravel+50mm foam concrete+50mm polystyrene+100mm concrete)
- Thermal conductivity of Gravel, foam concrete, polystyrene and concrete are 0.7, 0.2, 0.03, 0.8 and 0.2 m.k/w respectively (the engineering toolbox 2012).
- R for the roof = (.07/0.7)+(0.05/0.2)+(0.05/0.03)+(0.1/0.6)+(.02/.2) = 0.7+0.25+2.5+0.125+0.1= 2.6 m^2k/w

Roof U value=1/2.6=0.38 w/m^2k less than 0.41w/m^2k

- R value for the wall=(20mm plaster+100mm brick+50mm polystyrene+100mm brick+20mm plaster)

- Thermal conductivity values for the plaster, brick and polystyrene are 0.2, 0.6 and 0.03 w/m^{2}k respectively
- R value for the wall = (.02/0.2)+(.1/.60)+(.05/.03)+(.1/.60)+(.02/.20) = 0.1+0.16+1.66+0.16+0.1= 2.18 m^2.k/w

U value for the wall =1/2.18=0.458 less than 0.98 W/m^{2}k

Table 4.2: B.O.Q of the Used Materials of the Base Case Model as Per Athena Input Data Sheet

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
#15 Organic Felt	m2	545.8641	0	0	0	545.8641	0	0	0.3984	Tonnes
1/2" Moisture Resistant Gypsum Board	m2	105.3388	0	0	0	105.3388	0	0	0.9491	Tonnes
6 mil Polyethylene	m2	123.9227	0	0	123.9227	0	0	0	0.0186	Tonnes
8" Concrete Block	Blocks	10356.1607	0	0	0	0	10356.16	0	196.7671	Tonnes
Aluminum Window Frame	kg	214.9297	0	0	0	0	214.9297	0	0.2149	Tonnes
Clay Tile	m2	362.088	0	0	0	0	0	362.088	18.4665	Tonnes
Coarse Aggregate Crushed Stone	Tonnes	7.14	0	0	0	0	0	7.14	7.14	Tonnes
Concrete Benchmark 2500 psi	m3	4.998	0	0	0	0	0	4.998	11.4457	Tonnes
Concrete Benchmark 3000 psi	m3	80.5123	0	41.9954	24.5184	13.9985	0	0	184.6637	Tonnes
Concrete Benchmark 4000 psi	m3	11.3334	11.3334	0	0	0	0	0	26.1355	Tonnes
Double Glazed No Coating Air	m2	103.089	0	0	0	0	103.089	0	1.6693	Tonnes
Extruded Polystyrene	m2 (25mm)	793.8063	0	0	0	198.0847	595.7215	0	0.9764	Tonnes
Galvanized Sheet	Tonnes	0.0354	0	0	0	0.0354	0	0	0.0354	Tonnes
Modified Bitumen membrane	kg	1839.7642	0	0	0	1839.764	0	0	1.8398	Tonnes
Mortar	m3	33.0269	0	0	0	0	33.0269	0	42.2745	Tonnes
Nails	Tonnes	0.1064	0	0	0	0.0493	0.0571	0	0.1064	Tonnes
Rebar, Rod, Light Sections	Tonnes	13.1053	5.7594	2.838	0	0.946	3.5618	0	13.1053	Tonnes
Roofing Asphalt	kg	1610.6448	0	0	0	1610.645	0	0	1.6106	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	1.5552	0	0	0	0	1.5552	0	0.6926	Tonnes
Solvent Based Alkyd Paint	L	425.18	0	0	0	0	425.18	0	0.3189	Tonnes
Stucco over porous surface	m2	3186.2905	0	0	0	0	2524.719	661.5714	114.7065	Tonnes
Water Based Latex Paint	L	3672.3428	0	339.9186	0	0	3332.424	0	2.7543	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0.1056	0	0	0.1056	0	0	0	0.1056	Tonnes
TOTAL WEIGHT									**626.3951**	Tonnes

4.3 System 1- Pre-Cast Concrete PCC

Precast concrete is a prefabricated system in which the walls and the slabs are manufactured off-site and moved to the construction sites in flat panels. This system could form fully assembled/fully finished modules as well but due to the weight of the concrete modules, it becomes more efficient to be transported in flat panels. The system will be described in details hereon.

4.3.1 System Description

This construction system is composed of pre-cast concrete walls for the vertical structural elements and hollow core slabs for the floors. These prefabricated elements are cast in factories and get shipped to the site in slabs. Precast Concrete Sandwich Panels generally span vertically between foundations and floors or roofs to provide an insulated outer shell to buildings carrying mostly axial loads. PCSP with shear truss connectors is typically fabricated of two concrete wythes tied together with truss-shaped shear connectors equally spaced along the length of the panel as depicted in Fig. 4.5

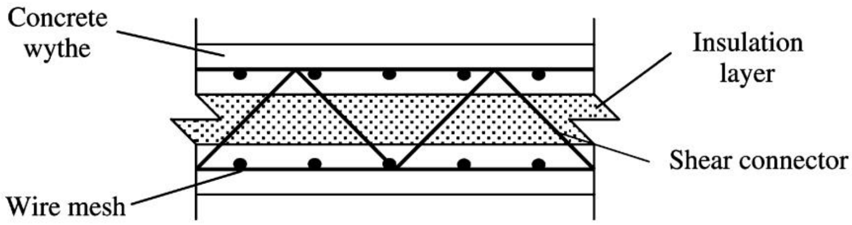


Figure 4.5: Precast Concrete Sandwich Panel – (Benayoune, 2008)

Hollow-core floor slabs are precast pre-stressed concrete elements with continuous voids provided to reduce self-weight and achieve structural efficiency. Widths are generally 1200 mm. Depths vary from 110 mm to 450 mm. They are economic across a wide range of spans and loadings; with an imposed loading of 5 kN/mm^2 spans of about 12 m can be achieved. Figure 4.6 shows the hollow core slab details.

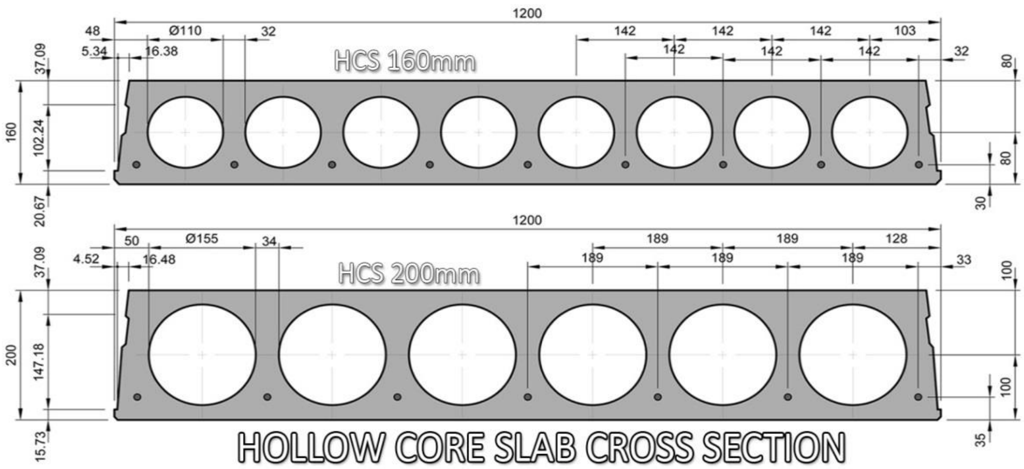


Figure 4.6: Hollow Core Slab Details

4.3.2 <u>Option Description</u>

To highlight the differences between the base case model and this option, all the building components are fixed and the only changed components are the walls and the slabs. Figure 4.7 show a detailed wall section for this option system.

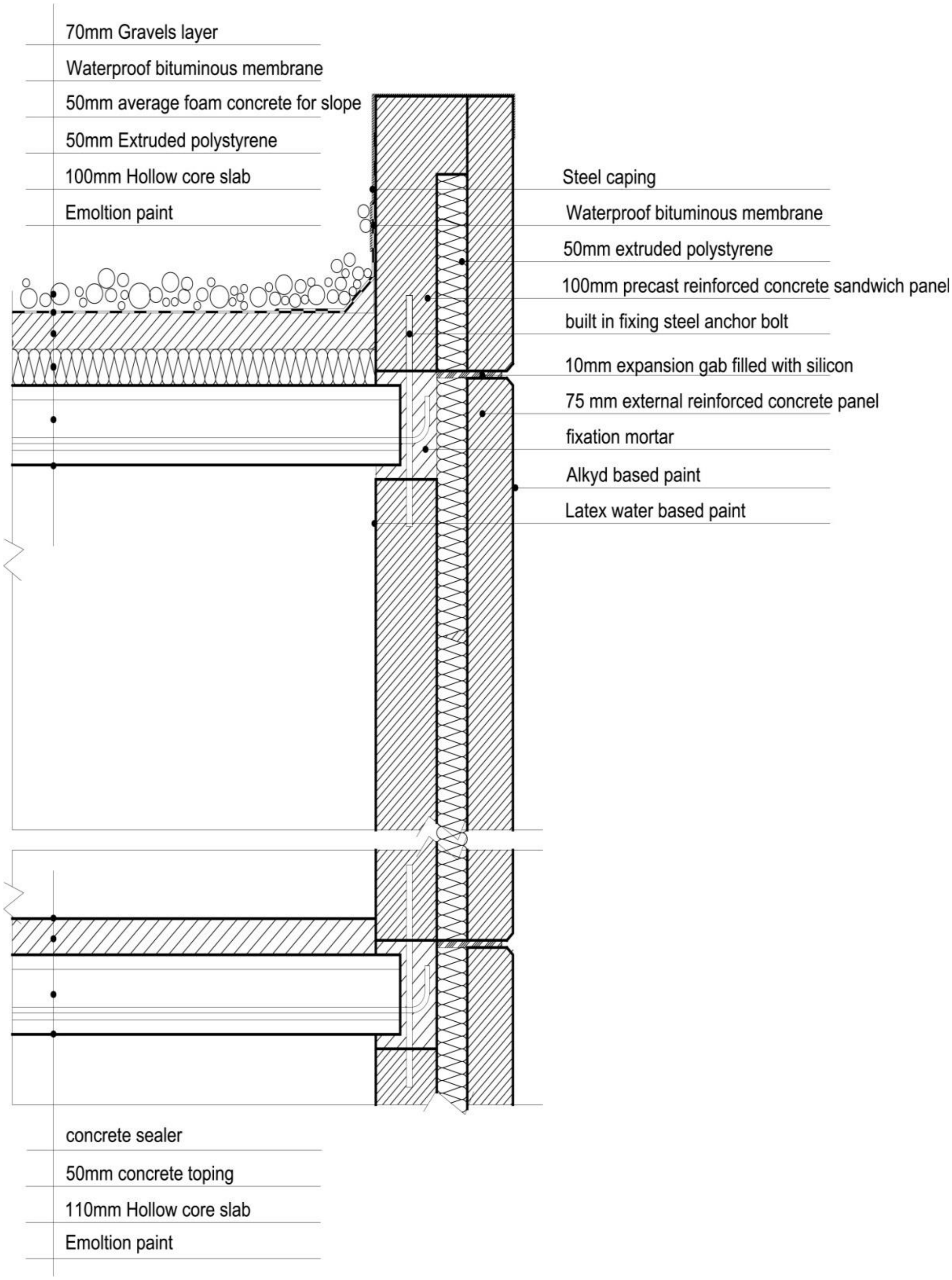


Figure 4.7: Detailed Wall Section for the Precast Concrete PCC

Foundation

The foundation of this option is on grade slab same as the base case model.

Walls

The external walls are made of precast concrete sandwich panels of 225mm thick walls. The demising walls and the internal walls are made of 150mm and 100mm single layer precast panels respectively. A 50mm thick polystyrene layer is sandwiched between the 2 layers of concrete panels. Figure 4.8 shows the Athena input data sheet for the walls.

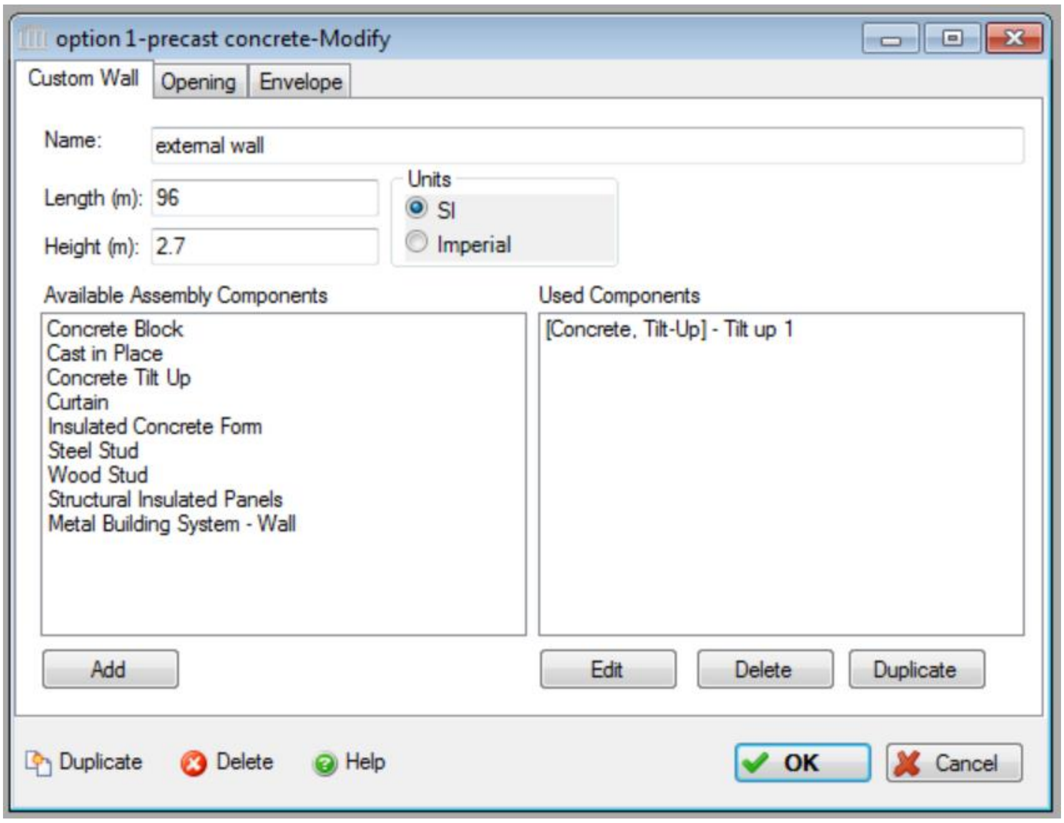


Figure 4.8: Athena Input Data Sheet for the Pre-Cast Concrete Walls

Slabs

The used hollow core slabs are with thickness of 110 mm. and width of 1200mm spanning for 2.35m between the two shear walls of each apartment unit. For the precast hollow core slabs, a layer of 50mm concrete toping is added on the top to tie the slabs together and to fill the gabs in between. This layer is added as an extra material in ATHENA which volume is (95.16mx4x.05m) =19.0m3

The underside of the slabs is not rendered as the slabs are usually fare faced. Accordingly, no plaster layer is considered and only latex water based paint is specified. Clay tiles for the floors are added as extra materials with total area of 338.4 m2. Figure 4.9 shows the Athena input data sheet for the slabs.

Roofs

The same waterproofing and thermal insulation layers are added on the top of the roof slab. Coarse aggregate layer of 70mm is added on the top of the waterproof membrane for protection. Coarse aggregate has been added to ATHENA as an extra material. The volume of this layer is 0.07x95.16=6.66 m3. The density of the coarse aggregate is 1500kg/m3 and the weight of the required volume is = 1500x6.66=9990 kg. The thickness of the insulation layers for the external walls and the roof for this system are calculated in Appendix A

Finishes

The same external and internal finishes as of the base case model are used for this option. Tables 4.3 and 4.4 show the bill of quantities BOQ of this option.

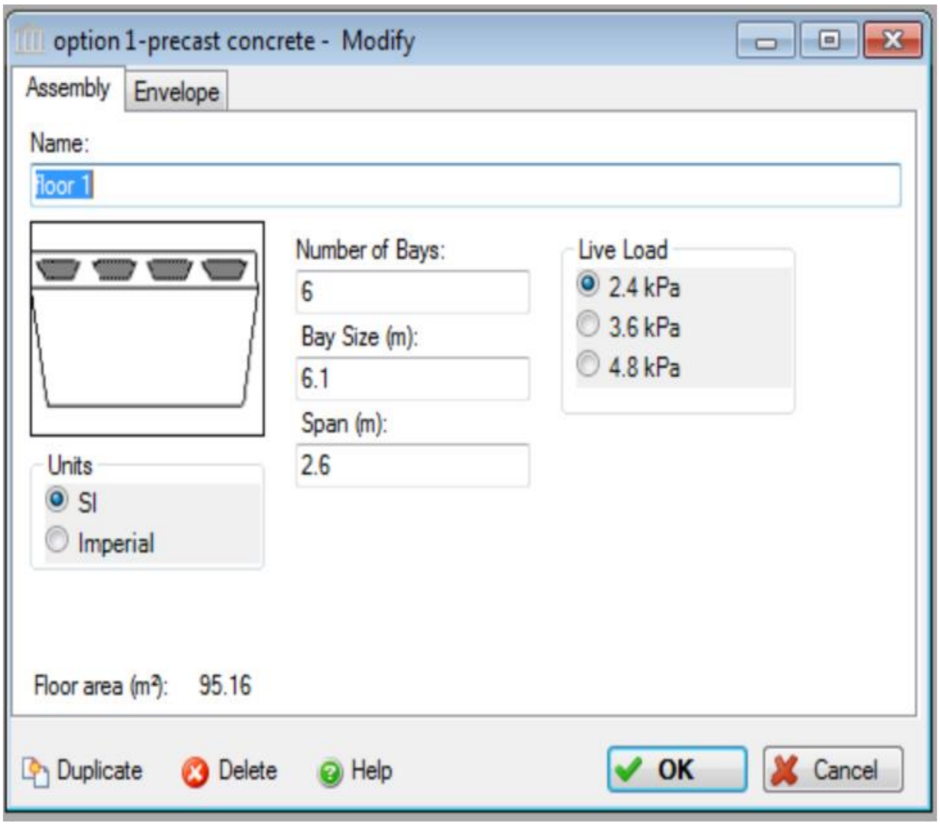


Figure 4.9: Athena Input Data Sheet for the Slabs of the Pre-Cast Concrete Option

Table 4.3: BOQ of Pre-Cast Concrete Option as Per Architectural Drawings Calculation

COMPONENT	ASSEMBLY	WIDTH	LENGTH	THICKNESS	NUMBER	VOLUME	Quntaty	MATERIAL	UOM
GROUND FLOOR SLAP									
	ground floor slap	8.85	13.2	0.2	1	23.36	23.36	CONVENTION CAST IN SITUE-25	m3
	reinforced concrete					2.10	2.10	REBAR, ROD, LIGHT SECTION	ton
	water proof	8.85	13.2			116.82	116.82	bitumen	m2
WALLS									
	parti walls	11.8	2.7	0.15	8	38.23	38.23	PRECAST CONCRETE WALL	m3
	internal walls	6	2.7	0.1	12	19.44	19.44	PRECAST CONCRETE WALL	m3
	long external walls	12	12.9	0.2	2	61.92	61.92	PRECAST INSULATED WALL	m3
		12	12.9	0.05	2		619.20	Expanded polysterene (25MM)	m2
	short external walls	7.65	12.9	0.2	1	14.70	14.70	PRECAST INSULATED WALL	m3
		7.65	12.9	0.05	1		197.37	Expanded polysterene(25MM)	m2
	windows	2.35	2.7		12	76.14	76.14	double glass with aluminium frame	m2
	doors	1	2.1	0.05	12	25.20	12.00	SOLID WOOD DOOR	m2
	wall internal finish	2.7	37.95		12	1229.58	1229.58	WATER BASED LATEX paint	m2
	external long finish	12.2	12.9		2	314.76	314.76	WATER BASED LATEX paint	m2
	external short finish	7.85	12.9		1	76.07	76.07	WATER BASED LATEX paint	m2
		7.85	12.9	0.02	1	1.52	1.52	20mm mortar	m3
FLOORS									
	slaps	7.85	12.2	0.1	3	28.73	28.73	concrete hollow core	m3
ROOF									
	slaps	7.85	12.2	0.1	1	9.58	9.58	concrete hollow core	m3
	thermal insulation	7.85	12.2	0.05	1	191.54	191.54	expanded polysterene(25MM)	m2
	water proof	8.85	13.2		1	116.82	116.82	bitumen	m2

Table 4.4: BOQ of Pre-Cast Concrete Option as Per Athena Input Data Sheet

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
#15 Organic Felt	m2	542.4298	0	0	0	542.4298	0	0	0.3959	Tonnes
1/2" Moisture Resistant Gypsum Board	m2	104.676	0	0	0	104.676	0	0	0.9431	Tonnes
6 mil Polyethylene	m2	123.9227	0	0	123.9227	0	0	0	0.0186	Tonnes
Aluminum Window Frame	kg	214.9297	0	0	0	0	214.9297	0	0.2149	Tonnes
Coarse Aggregate Crushed Stone	Tonnes	7.14	0	0	0	0	0	7.14	7.14	Tonnes
Concrete Benchmark 3000 psi	m3	196.9271	0	14.9304	24.5184	4.9768	152.5015	0	451.6739	Tonnes
Double Glazed No Coating Air	m2	103.089	0	0	0	0	103.089	0	1.6693	Tonnes
Extruded Polystyrene	m2 (25mm)	854.5149	0	0	0	196.8385	657.6765	0	1.0511	Tonnes
Galvanized Sheet	Tonnes	0.0352	0	0	0	0.0352	0	0	0.0352	Tonnes
Modified Bitumen membrane	kg	1828.1891	0	0	0	1828.189	0	0	1.8282	Tonnes
Nails	Tonnes	0.108	0	0	0	0.049	0.059	0	0.108	Tonnes
Precast Concrete	m3	35.606	0	26.7045	0	8.9015	0	0	87.0923	Tonnes
Rebar, Rod, Light Sections	Tonnes	8.465	0	0.9748	0	0.3249	7.1653	0	8.465	Tonnes
Roofing Asphalt	kg	1600.5113	0	0	0	1600.511	0	0	1.6005	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	1.5552	0	0	0	0	1.5552	0	0.6926	Tonnes
Solvent Based Alkyd Paint	L	486.0876	0	0	0	0	486.0876	0	0.3646	Tonnes
Water Based Latex Paint	L	1794.7855	0	337.7799	0	0	1457.006	0	1.3461	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0.688	0	0.4368	0.1056	0.1456	0	0	0.688	Tonnes
TOTAL WEIGHT									**565.3273**	Tonnes

4.4 <u>Option 2- Glass-Fiber Reinforced Concrete GRC</u>

This option is another prefabricated option that is manufactured off-site and moved to the site in flat panels not in modular form as in the PCC option for the same transportation reasons. The description of the system will be described in details hereon.

4.4.1 System Description

There are many artificial fiber types that are produced from several materials like carbon, basalt and glass which have good structural and mechanical characteristics. In addition to the artificial fiber, there are natural fibers like asbestos and rock wool and organic fibers like linen and jute that are used in several applications in the construction industry. Fifty years ago, a British scientist team succeeded in developing fiber glass by adding zirconium dioxide to convert it to alkalis resistant fiber A.R.Fiber (Arabian Construction House).
A.R.Fiber is the main material to manufacturing the Glass reinforced concrete GRC. It consists of water, Portland cement, fine sand (1x1mm) with A.R.Fiber. The ratio of the mix is as follows:

- Sand to cement is 1:1
- Water to cement is 33%
- Fiber to cement is 2:3
- Polymer to cement is 5%
- Additives to cement is 1%

GRC Wall

Wall thickness is 100 to 120 mm hollow sandwich panel that consists of 2 GRC layers each of 10 to15 mm each with a layer for sound and thermal insulation in between. Walls vary between 2.4m to 6m height which are installed through using interlocks at the perimeter of the walls and the slabs and by casting a GRC mortar between the panel joints. Walls are fixed to the footings using GRC railways that are fixed with steel bolts. Figure 4.10 shows the details of the walls and slabs fixation.

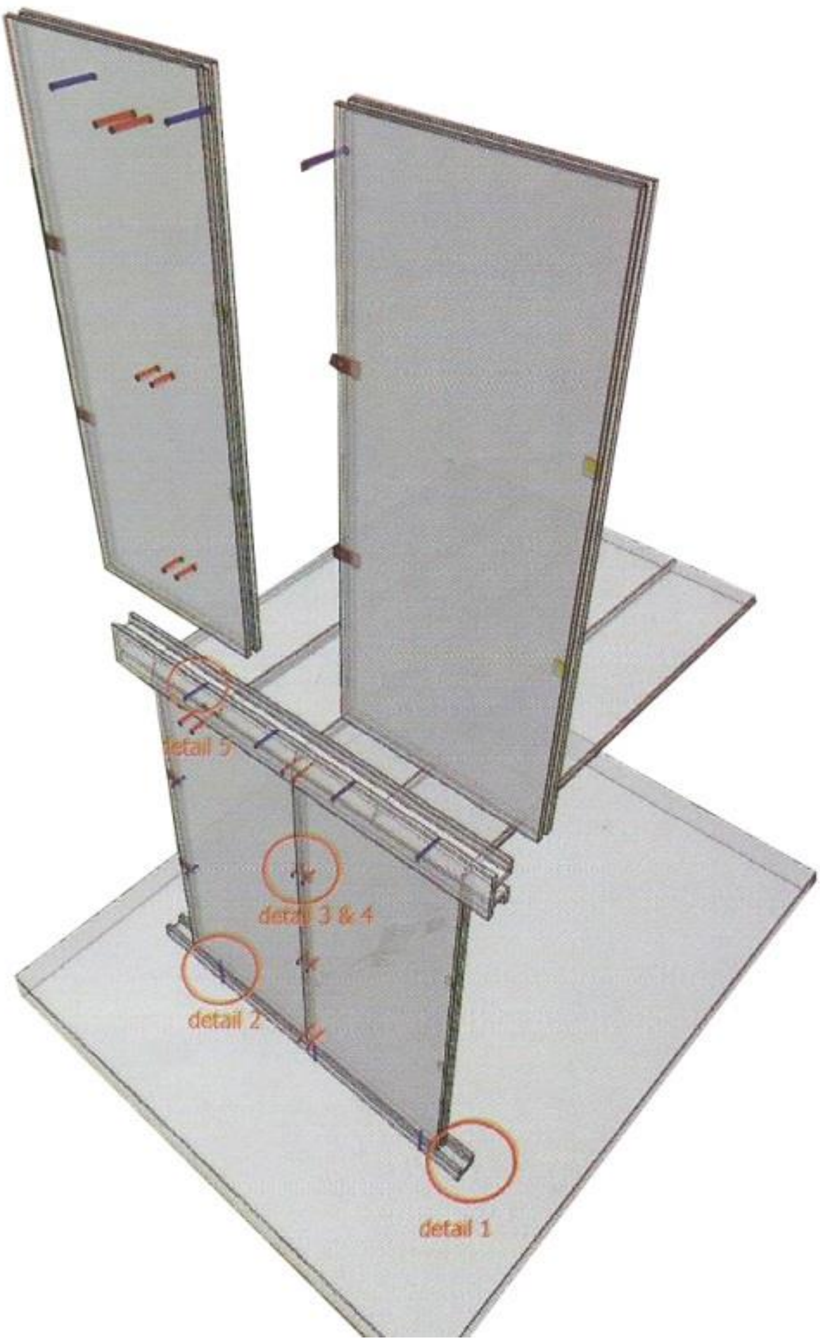


Figure 4.10: Components Installing Details (Arabian Construction House, 2016)

GRC Roof

Similar to the walls, the slabs are between 100 to 140mm thick hollow core panels composed of two precast layers each of 10 to 15mm thick. There are different slab cross sections that could be used either flat or with ribs based on the span. The dimension of the slab is 0.6m wide and up to 6m long slab fixed together with interlocks at the perimeters. Figure 4.11 shows the details of the different GRC components.

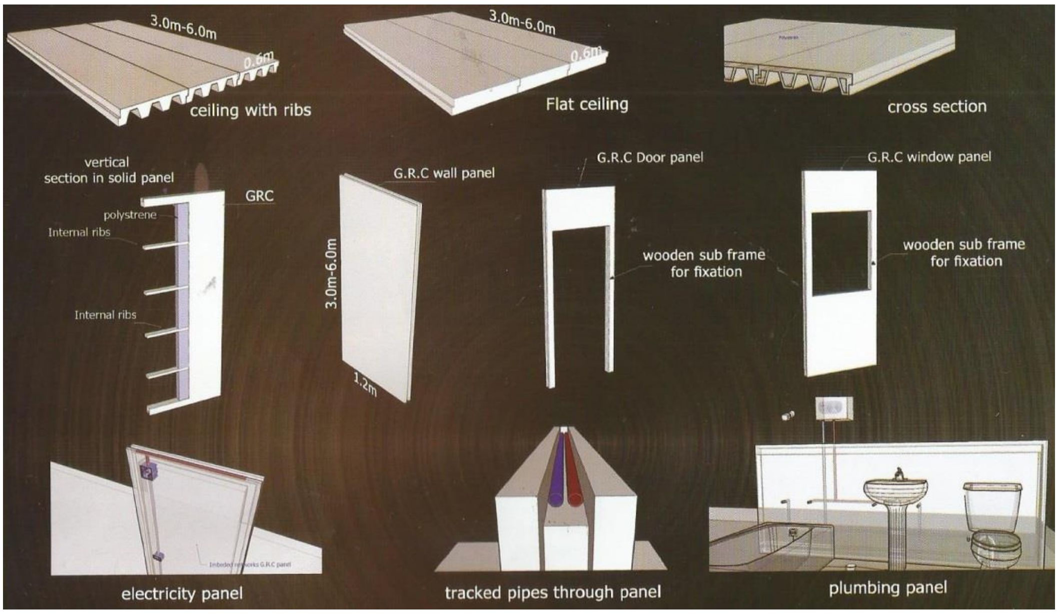


Figure 4.11: GRC Component Details (Arabian Construction House, 2016)

Advantages of the GRC

This system uses 20% only of the cement and sand compared to the conventional construction system which leads to a great reduction of green gas emissions due to the cement manufacturing as well as a reduction of the consumed energy. Due to the low thermal conductivity of the GRC (0.3 w/m2k) it reduces the amount of the used thermal insulation layer which leads to a reduction of GHG emissions, energy consumption and the overall cost of the building. The external and the internal surfaces of the GRC panels are fare faced and don’t need plaster or painting layers. The overall weight of the panels is much lighter which varies between 40 to 50 kg/m2 for the walls and 45 to 55kg/m2 for the slabs. This light weight reduces the foundation thickness; reduces the foundation materials and reduces transportation fuels and lifting machines at the construction sites. The volume of waste during construction in the factory is reduced according to the reduction of the used materials while the waste on site is close to zero.

Local Manufactures

There are many GRC companies in Egypt that work on façade cladding. The Arabian construction house is the only company that manufactures structural walls and slabs for buildings. They are currently running many in-house researches to manufacture their required fiberglass locally to reduce its environmental impact of their product, its cost and enhance the overall performance of their system.

4.4.2 Option Description

Athena has no reference for the Glass Reinforced Concrete GRC material. Accordingly all the components, except the foundation, has been added to Athena as Extra Material as shown in Figure 4.12.

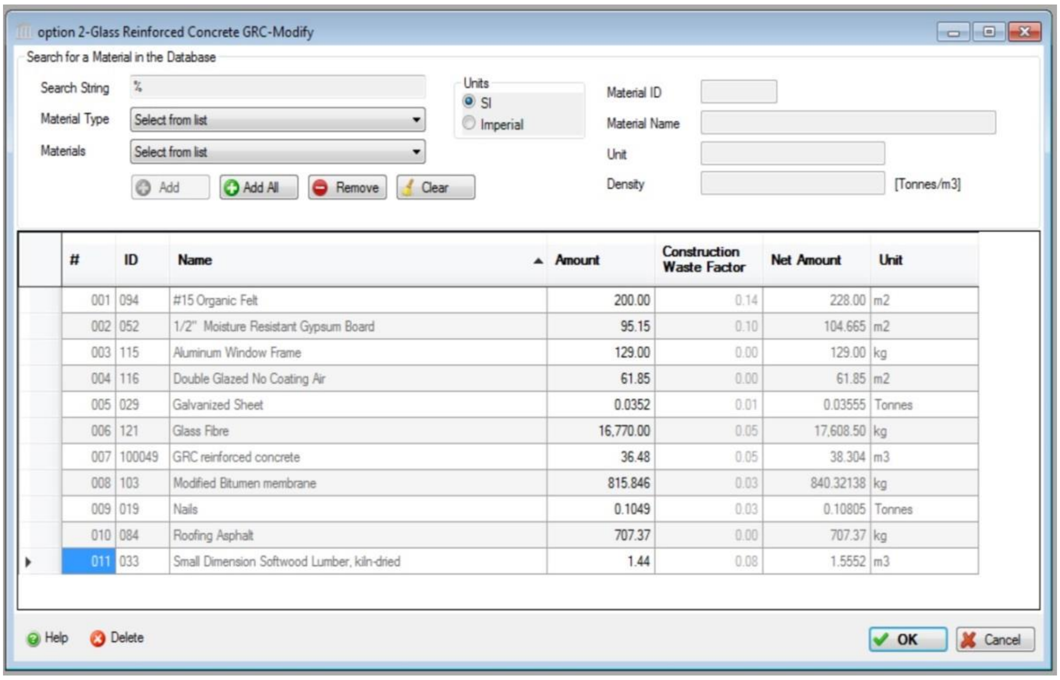


Figure 4.12: Data Input Sheet for the GRC Option

Foundation

Although the weight of this option is much lighter compared to the base case model (158 VS 471 tones), the foundation has the same design of the base case model with a 200mm thick slab on grade. Due to the size of the proposed building, this reduction of the building weight doesn't make much difference in the foundation design.

Walls

Four vertical 100mm hollow wall panels are supporting the whole building, two of them are external and other two are demising walls in between the three apartments in each floor. Due to the low U value of the GRC (0.3 w/m2k) a 50mm only of polystyrene layer is sandwiched between the two wall layers. The internal walls are with the same width of 100mm walls. Figure 4.13 shows the details of the walls, slabs and the roof of this system.

Slabs

100mm GRC hollow core slabs composed of two layers are used with 600mm width. Slabs are spanning between the walls with the full width of each apartment (2.35m). There are no finishing tiles specified for the floors relying on the fare face surfaces of the slabs. This is one of the advantages of this option which reduces its embodied energy as well as its operation energy consumption.

Roof

The roof is thermally insulated with a layer of 75mm of extruded polystyrene board and a bituminous membrane layer for water proofing. The thickness of the polystyrene layers for the walls and the slabs are calculated according to the Egyptian code in Appendix B

Finishes

The fare faced GRC walls will not require any plaster or paint layers which will reduce the environmental impact of this option not only during the construction stage but during the operation stage as well. Table 4.5 shows the BOQ of the materials calculated from the architectural drawings while table 4.6 shows the Athena calculated sheet for the same materials.

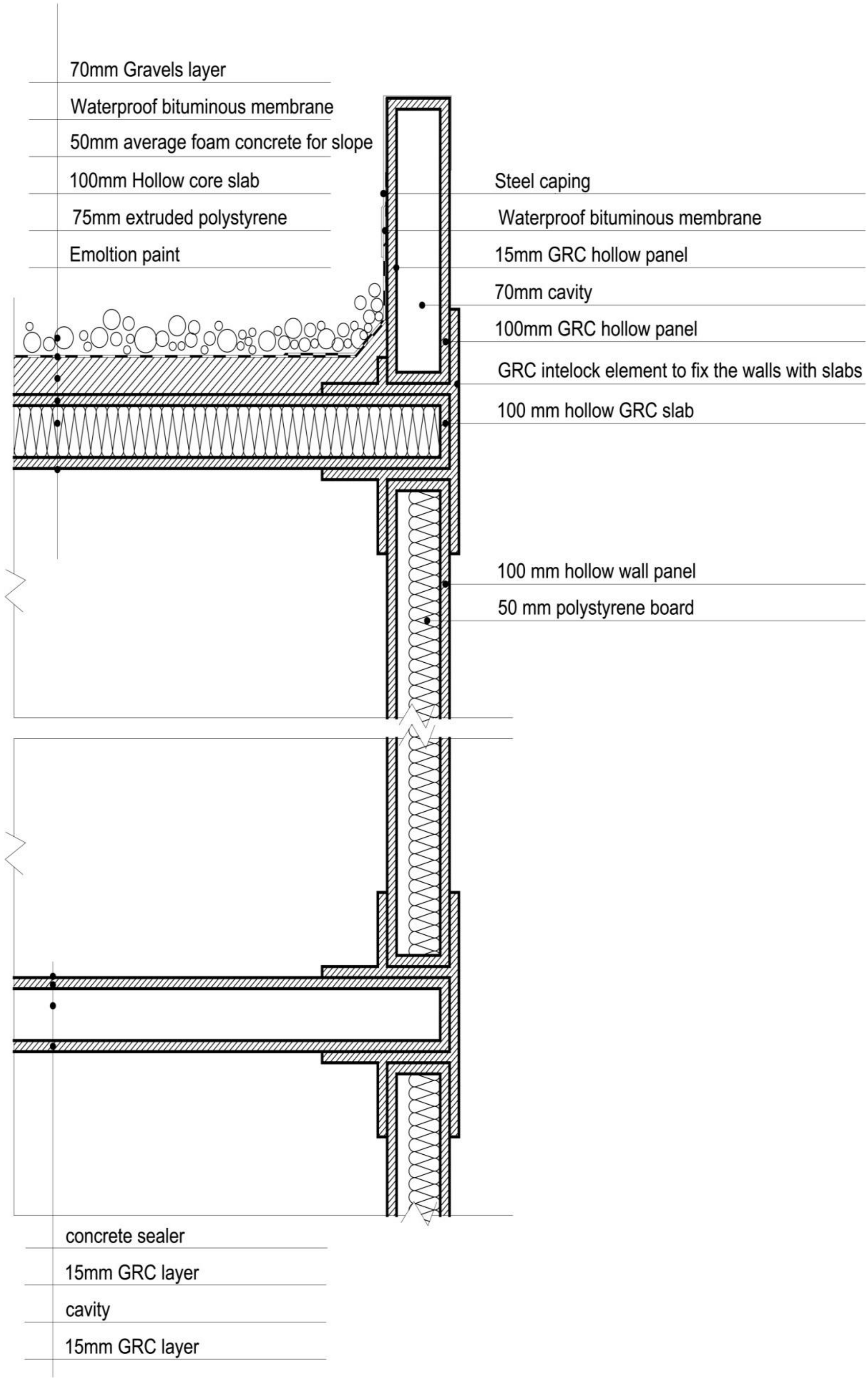


Figure 4.13: Detailed Wall Section for the GRC Option

Table 4.5: BOQ of GRC Option Calculated From the Architectural Drawings

COMPONENT	ASSEMBLY	WIDTH	LENGTH	THICKNESS	NUMBER	VOLUME	volume+CW	MATERIAL	UOM
GROUND FLOOR SLAP									
	ground floor slap	8.85	13.2	0.2	1	23.36	23.36	cast in situe concrete	m3
	reinforced concrete					2.10	2.10	rebar	ton
	water proof	8.85	13.2			116.82	116.82	bitumen liquid applied	m2
WALLS									
	parti walls	2.7	12	0.03	8	7.78	7.78	PRECAST GRC WALL	m3
	internal walls	2.7	6	0.03	12	5.83	5.83	PRECAST GRC WALL	
	long external walls	12.2	12.7	0.03	2	9.30	9.30	PRECAST GRC WALL	m3
	short external walls	7.45	12.7	0.03	1	2.08	2.08	PRECAST GRC WALL	m3
	GRC						11.49	GRC	tonnes
	windows	2.35	2.7		12	76.14	76.14	GLASS	m2
							103.09	Double Glazed no coating air	m2
							214.90	Aluminium Window Frame	kg
	doors	1	2.1	0.05	12	25.20	25.20	TIMBER	m2
							12.00	wooden doors	no
							1.56	small Dimension softwood lumber, Kiln-dried	m3
FLOORS									
	slaps	7.85	12.2	0.03	3	8.62	8.62	HOLLOW CORE GRC SLAPS	m3
	GRC						3.96	GRC	tonnes
ROOF									
	slaps	7.85	12.2	0.03	1	2.87	2.87	HOLLOW CORE GRC SLAPS	m3
	GRC						1.32	GRC	tonnes
	thermal insulation	7.85	12.2	0.05	1	191.54	191.54	expanded polysterene(50MM)	m2
	water proof	8.85	13.2		1	116.82	116.82	bitumen liquid applied	m2
							542.43	#15 Organic Felt	m2
							104.67	1/2" Moisture Resistant Gypsum Board	m2
							0.0352	Galvanized sheet	tonnes
							1828.18	Modified Bitumen membrane	kg
							0.049	Nails	tonnes
							1600.5	roofing Asphalt	kg

Table 4.6: BOQ of GRC Option as Per Athena Input Data Sheet

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
#15 Organic Felt	m2	570	0	0	0	0	0	570	0.416	Tonnes
1/2" Moisture Resistant Gypsum Board	m2	104.665	0	0	0	0	0	104.665	0.943	Tonnes
6 mil Polyethylene	m2	123.9227	0	0	123.9227	0	0	0	0.0186	Tonnes
Aluminum Window Frame	kg	215	0	0	0	0	0	215	0.215	Tonnes
Coarse Aggregate Crushed Stone	Tonnes	7.14	0	0	0	0	0	7.14	7.14	Tonnes
Concrete Benchmark 2500 psi	m3	4.977	0	0	0	0	0	4.977	11.3976	Tonnes
Concrete Benchmark 3000 psi	m3	24.5184	0	0	24.5184	0	0	0	56.2356	Tonnes
Double Glazed No Coating Air	m2	103.0833	0	0	0	0	0	103.0833	1.6692	Tonnes
Extruded Polystyrene	m2 (25mm)	957.6	0	0	0	0	0	957.6	1.1778	Tonnes
Galvanized Sheet	Tonnes	0.0356	0	0	0	0	0	0.0356	0.0356	Tonnes
Glass Fibre	kg	17608.5	0	0	0	0	0	17608.5	17.6085	Tonnes
GRC reinforced concrete	m3	38.304	0	0	0	0	0	38.304	76.7145	Tonnes
Modified Bitumen membrane	kg	1826.7856	0	0	0	0	0	1826.7856	1.8268	Tonnes
Nails	Tonnes	0.108	0	0	0	0	0	0.108	0.108	Tonnes
Roofing Asphalt	kg	1607.6591	0	0	0	0	0	1607.6591	1.6077	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	1.5552	0	0	0	0	0	1.5552	0.6926	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0.1056	0	0	0.1056	0	0	0	0.1056	Tonnes
TOTAL WEIGHT									**177.9121**	Tonnes

4.5 Option 3-Light-Gauge Steel LGS System (Modular)

This option is different from the previous two options in its construction materials and the level of industrialization that is associated with it. Units are constructed in factories as finished modules ready to be installed in place on the construction sites. Figure 4.14 shows Installation of modular units at Murray Grove, Hackney.

4.5.1 Steel Construction Systems

There are different systems for steel construction for residential buildings based on the way that the structural elements, walls and slabs are designed to suite the building heights. Accordingly the level of manufacturing and the prefabricated elements differs. The different steel forms and mixed construction systems are described below:

Figure 4.14: Installation of Modular Units at Murray Grove, Hackney (Lawson Et Al 2005)

Light Steel Framing-Elemental and Panel Systems

In light steel framing, 65mm to 200 mm deep galvanized C sections are used with a thickness of 1.2 to 2.4mm. Walls are assembled as 2D high panels while floors are either assembled as joists or as 2D -cassette. For 2 stories buildings, floors are resting directly on walls while for higher buildings a structural integrity should be achieved. Accordingly, floors are supported by Z purlins attached directly to the top of the walls to achieve a continuity of the loads along the walls. Figure 4.15 shows this panel system (Lawson et al. 2005). In this system, walls and slabs are transported to the site in flat panels not in modular units.

Figure 4.15: Light Steel Framing for Housing (Lawson et al. 2005)

Modular Construction System

For modular construction, modules are constructed of 2D walls and floor cassettes assembled in load bearing boxes manufactured in factory and transported to construction sites. There are 2 types of modular construction as follows:

- 4 sided modules where the loads are transmitted through the walls like in figure 4.16.
- Point supported modules where vertical loads are transmitted through corner and intermediate columns like in figure 4.17. this type requires a deeper edge beam to connect all the columns together

In both types, the horizontal loads are supported by bracings imbedded within the wall structure. For buildings above six stories, separate bracing system attach to the central core should be provided. The modules are transported as 3D assembled and almost finished modules to be fixed in its location on site. This system is the selected system that is used in our research (Lawson et al. 2005).

Figure 4.16: 4 Sides Supported Module in Light Steel Framing (Lawson et al. 2005)

Figure 4.17: Corner Supported Module in Light Steel Framing (Lawson et al. 2005)

Hybrid Modular and Panel Systems

The hybrid system is mixing the modular and panel systems and use each in its best location to optimize the use of space utilization and manufacturing cost. The modular system is used in the higher value components like bathroom pods and the wall panels and floor cassettes are used for flexible open spaces. There are two types of this hybrid application, either load bearing modules supported by other modules or non-load bearing modules supported by floors (Lawson et al. 2005).

Hybrid Modular, Panel and Primary Steel Frame

The load bearing modular system is limited in height for its use. Accordingly, with the introduction of main steel structural framing system, modules could be installed on higher buildings. There are three systems that could be briefed below:

- A podium structure where the parking and communal spaces are located in a grid system that is multiplication of the modules width introduced to form a support for the modules above.
- A skeletal structure is used as the main supporting system providing the open flexible plan where the modules are used in the service areas like bathroom pods
- A skeletal structure where non load bearing modules are used and plugged in supported by the floors (Lawson et al. 2005).

4.5.2 Option Description

In this research, the modular system was selected as one of the prefabricated options to be assessed. Following the same building design as for the previous two options, the building is composed of 12 load bearing modules, 3 in each floor for 4 typical floors as per the main building configuration. Each module is constructed using galvanized C sections for the wall and slab fabrications. Figure 4.18 shows the details of the walls, the slabs and the roof of this option as per the architecture design.

Foundation

A 200mm thick concrete slab on grade was used similar to all other options.

Columns and Beams

Due to the dimensions of the modules, 6 galvanized box section columns are used to support each module, one on each corner and 2 intermediate columns in the middle. The 6 columns support wide flange beams that run on the top of the four walls to tie the columns and walls together and to support the floor sections.

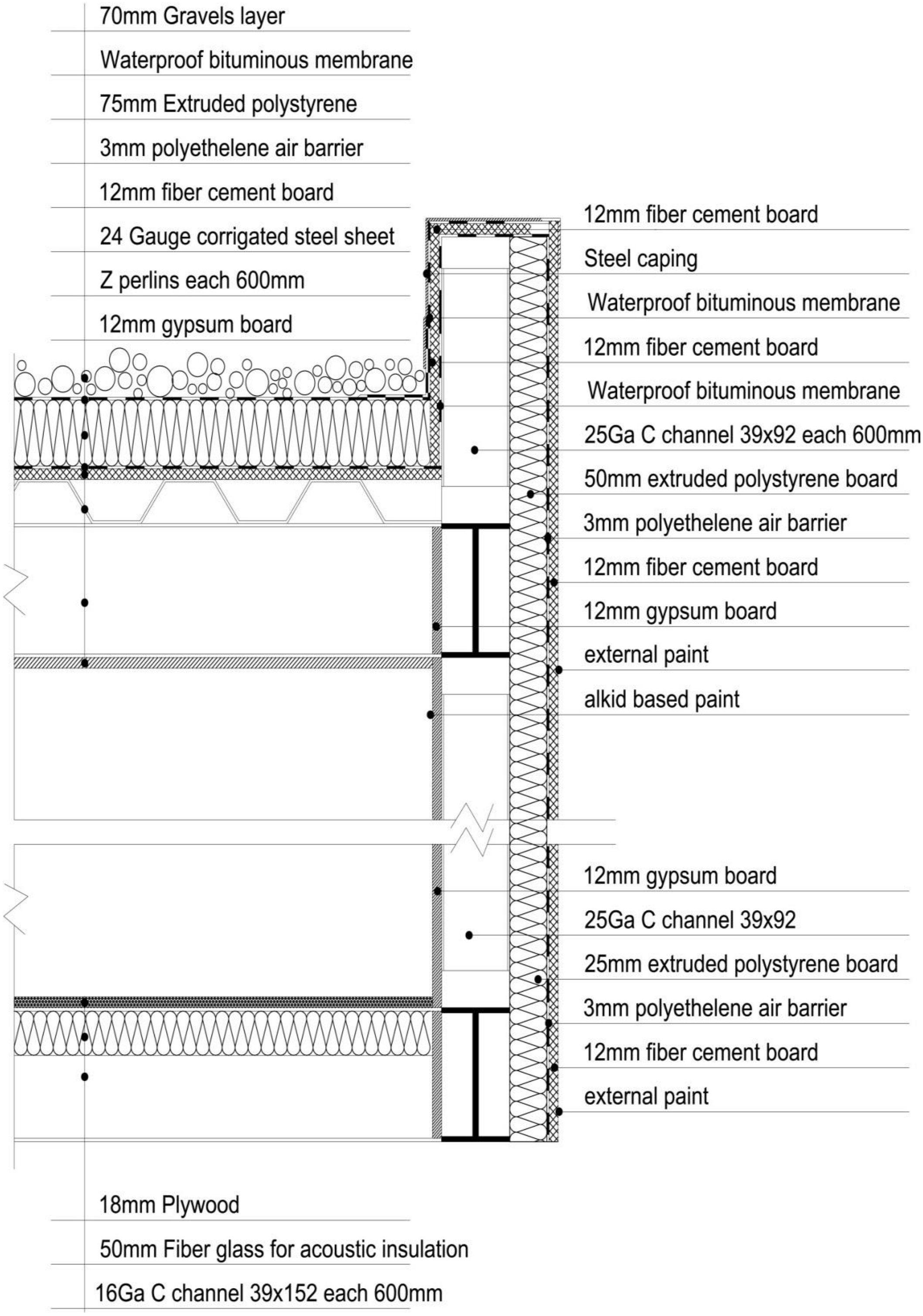


Figure 4.18: Detailed Wall Section for the LGS Option

Figure 4.19 shows the input data sheet of Athena software for the beams and the columns in which the number of columns, the column height, the number of beams, the structural spans and the bay sizes are defined.

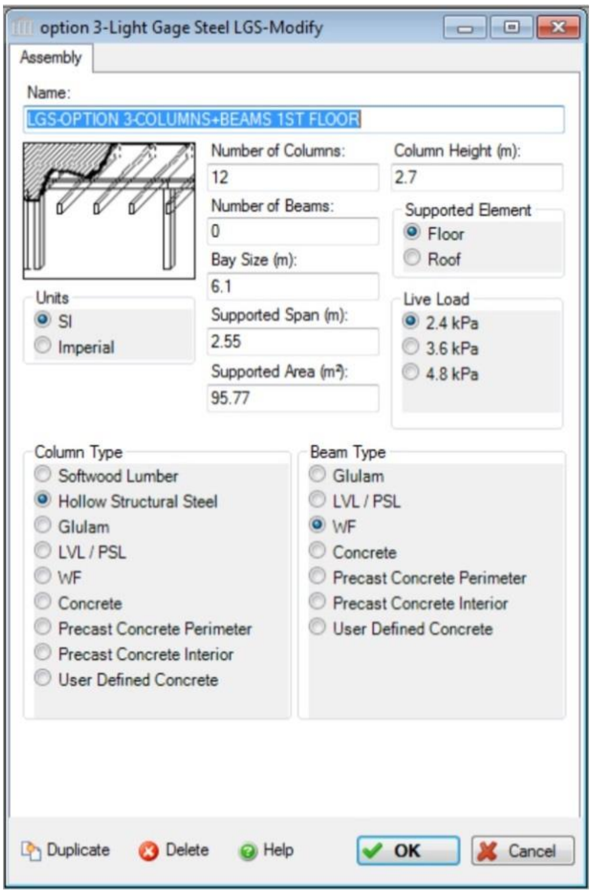


Figure 4.19: Athena Input Data Sheet for the Columns and Beams of the LGS Option

Slabs

Each module is manufactured in the factory with two slabs that form the floor and the roof of each module. Slabs are formed of 16Ga galvanized C sections of 39x152mm with 600mm space in between. Floor decking is made of plywood boards of 12mm thick. Ceiling is covered with gypsum boards to receive painting finish. Figure 4.20 shows the data input sheet for the slabs. A 50mm acoustic layer of Fiber Glass is added underside of each of the slabs of a total area of 275m2.

Roofs

The modules that will be located on the 4th floor, their top slab will have different configuration as in figure 4.18. The roof will be constructed of Z purlins that support steel corrugated sheets. The roof will be waterproofed and thermally insulated through adding bituminous sheet and 75mm extruded polystyrene board respectively. The thickness of the polystyrene board is designed to achieve the required U value as per the calculations in appendix C. A layer of 3mm polyethylene is added as an air barrier on the top of cement fiber board. The roof of the module will be covered with gravels to protect the water proof membrane.

External Walls

External walls are manufactured of galvanized 25Ga C sections of 39x92 each 600mm. The walls are thermally insulated with 50mm layer of extruded polystyrene boards as per the U value calculation in appendix C. A 3mm sheet of polyethylene is added as an air barrier. The external surface of the module is cladded with cement fiber boards that are painted with alkyd based paint. Figure 4.20 shows the input data sheet for the LGS walls.

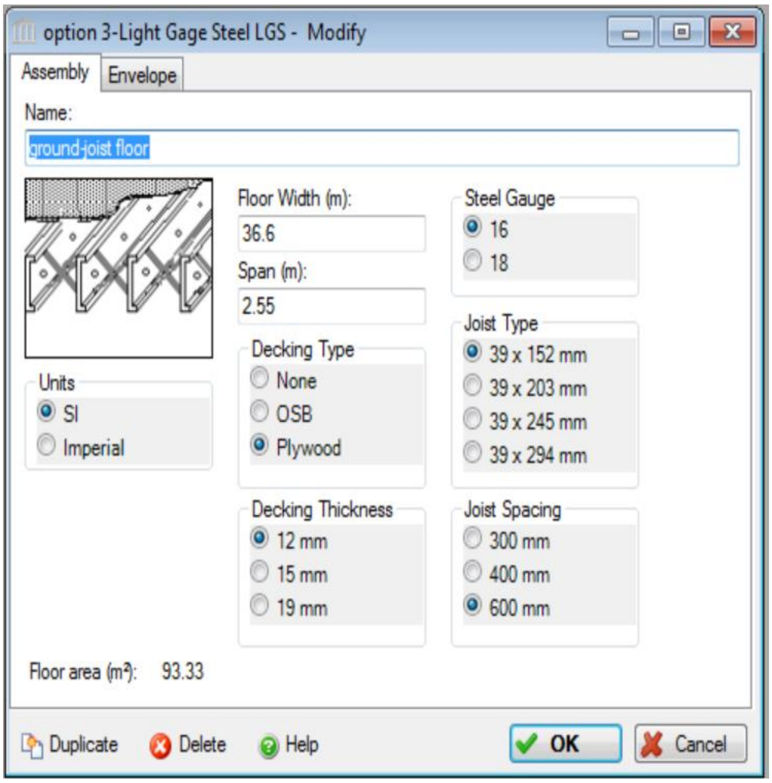


Figure 4.20: Input Data Sheet For the Walls of the LGS Option

Internal walls

Similar to the external walls, the internal walls are manufactured from C sections without adding any thermal insulation layer or air barriers. Both sides of the internal walls are covered with 12mm gypsum boards for finishing.

Finishes

The external walls are finished with Alkyd based paint. All the floors are made of 18mm plywood boards that are fixed on the floor C sections. The ceiling gypsum boards are painted with water based latex paint.

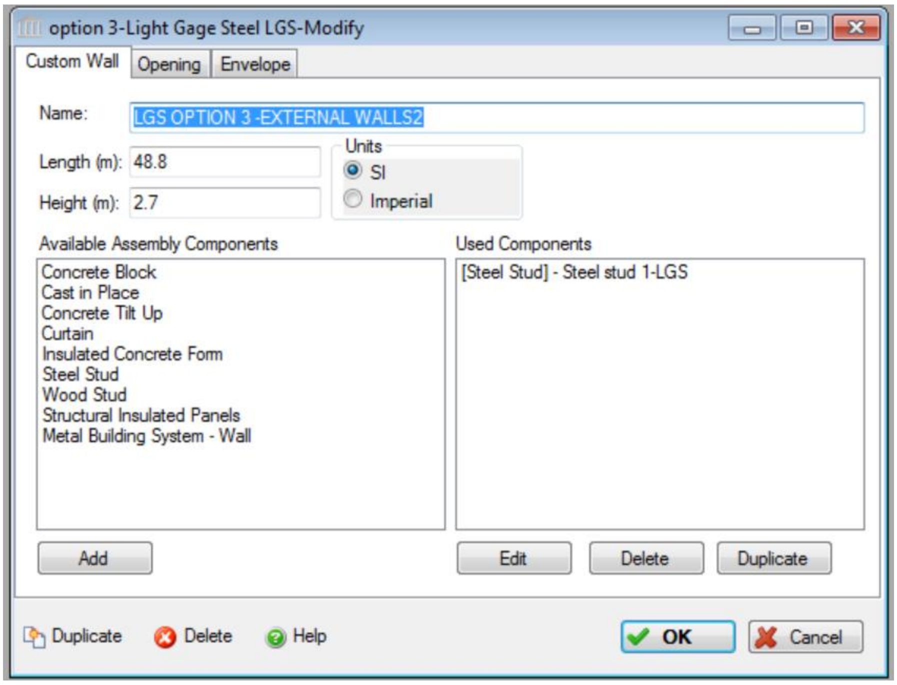


Figure 4.21 – input data sheet for the walls of the LGS option

4.6 Option 4-Adapted Shipping Containers ASC

Since 1990, shipping containers have been used as labor houses on construction sites. Their reusability as efficient residential modules encourages many architects to use them as a solution for affordable housing due to their durability and reusability characteristics. Shipping containers have been introduced for shipping industry with certain materials, sizes and designs which developed an entire industry around them. So, they became more attractive as a competitive modular alternative to the conventional construction for the affordable housing.

Table 4.7: BOQ of LGS Option as Per Athena Input Data Sheet

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
#15 Organic Felt	m2	1486.0094	0	0	0	545.9069	940.1025	0	1.0845	Tonnes
1/2" Moisture Resistant Gypsum Board	m2	105.347	0	0	0	105.347	0	0	0.9492	Tonnes
1/2" Regular Gypsum Board	m2	1678.2477	0	307.989	0	0	1370.259	0	13.5267	Tonnes
6 mil Polyethylene	m2	123.9227	0	0	123.9227	0	0	0	0.0186	Tonnes
Air Barrier	m2	349.9046	0	0	0	0	349.9046	0	0.0214	Tonnes
Aluminum Window Frame	kg	214.9297	0	0	0	0	214.9297	0	0.2149	Tonnes
Bolts, Fasteners, Clips	Tonnes	0.0161	0	0	0	0.0161	0	0	0.0161	Tonnes
Concrete Benchmark 3000 psi	m3	24.5184	0	0	24.5184	0	0	0	56.2356	Tonnes
Double Glazed No Coating Air	m2	103.089	0	0	0	0	103.089	0	1.6693	Tonnes
Extruded Polystyrene	m2 (25mm)	1247.2036	0	0	0	297.1504	950.0533	0	1.5341	Tonnes
FG Batt R11-15	m2 (25mm)	288.75	0	0	0	0	0	288.75	0.0904	Tonnes
Fiber Cement	m2	362.8347	0	0	0	0	362.8347	0	5.0771	Tonnes
Galvanized Sheet	Tonnes	0.0354	0	0	0	0.0354	0	0	0.0354	Tonnes
Galvanized Studs	Tonnes	5.3179	0	3.1936	0	0	2.1243	0	5.3179	Tonnes
Hollow Structural Steel	Tonnes	3.3117	3.3117	0	0	0	0	0	3.3117	Tonnes
Joint Compound	Tonnes	1.6749	0	0.3074	0	0	1.3675	0	1.6749	Tonnes
MBS Metal Roof Cladding - Commercial (24 Ga.)	m2	96.7277	0	0	0	96.7277	0	0	0.5535	Tonnes
MBS Metal Roof Cladding - Commercial (26 Ga.)	m2	4.8694	0	0	0	4.8694	0	0	0.0217	Tonnes
MBS Secondary Components (purlins,girts,bracing)	Tonnes	0.7139	0	0	0	0.7139	0	0	0.7139	Tonnes
Modified Bitumen membrane	kg	1839.9083	0	0	0	1839.908	0	0	1.8399	Tonnes
Nails	Tonnes	0.1493	0	0.0029	0	0.0493	0.0971	0	0.1493	Tonnes
Paper Tape	Tonnes	0.0192	0	0.0035	0	0	0.0157	0	0.0192	Tonnes
Roofing Asphalt	kg	1610.771	0	0	0	1610.771	0	0	1.6108	Tonnes
Screws Nuts & Bolts	Tonnes	0.1656	0	0.0538	0	0	0.1117	0	0.1656	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	1.5552	0	0	0	0	1.5552	0	0.6926	Tonnes
Softwood Plywood	m2 (9mm)	618.9304	0	618.9304	0	0	0	0	2.9238	Tonnes
Solvent Based Alkyd Paint	L	617.3419	0	0	0	0	617.3419	0	0.463	Tonnes
Water Based Latex Paint	L	1897.6763	0	331.2842	0	0	1566.392	0	1.4233	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0.1056	0	0	0.1056	0	0	0	0.1056	Tonnes
TOTAL WEIGHT									**101.46**	Tonnes

4.6.1 Description of the System

ISO shipping containers are made from weathering steel as specified within BS EN 10025-5:2004. It is also known as Cor-ten steel. It is corrosion resistant steel that is used in many industries that use exposed steel like building facades or outdoor sculptures. Cor-ten steel has comparable properties to Grade S355 steels to BS EN 10 025 S.

ISO Shipping Containers

ISO shipping containers come in the following dimensions:

- External dimensions: 8' wide (2.44m) x 8' 6"(2.6m) high or 9’ 6” (2.89m) high cube, and the usual lengths are 20' (6.1 m) and 40' (12.2 m).
- Internal dimensions: 7' 10" (2.353 m) wide, 7' 8.625" (2.388 m) high, and 19' 4.25" (5.899 m) or 39' 5.375" (12.024 m) long.

The following is the specifications of 40ft, high cube container as per Steinecker containerhandel company (2012).

Base Frame Structure

The base frame is composed of two bottom side rails each of 48x158x30x4.5mm thick cold-formed channel section steel made in one piece. Cross members made of C channel section steel with a dimension of 45x122x45x4.0mm are welded to the base frames. The cross members are supporting the floor and form the base structure to the container box. The floor is made of six pieced of 18mm plywood wood sorted longitudinally on the transverse members between the steel floor center rail.

Rear Side

Figure 4.23 shows the rear side where the container door exist which is composed of door sill, door header, two corner posts and four corner fittings welded together to form the door frame. The door sill is made of 4.5mm pressed open section steel. Each of the hollow section rear corner posts is composed of two pars. The outer part is fabricated of 6mm thick pressed steel and the inner part is made of a hot-rolled channel steel section with dimensions of 40x113x12mm. Both parts are welded together with a section that allows the maximum opening width of the door. The door header is made of 4mm pressed U section steel. Each door is composed of 3mm thick channel sections for the horizontal part of the door frame. The vertical frames are made of hollow sections of 100x50x2,3mm. The frame holds a 2mm horizontally corrugated steel sheet which is welded to the frame.

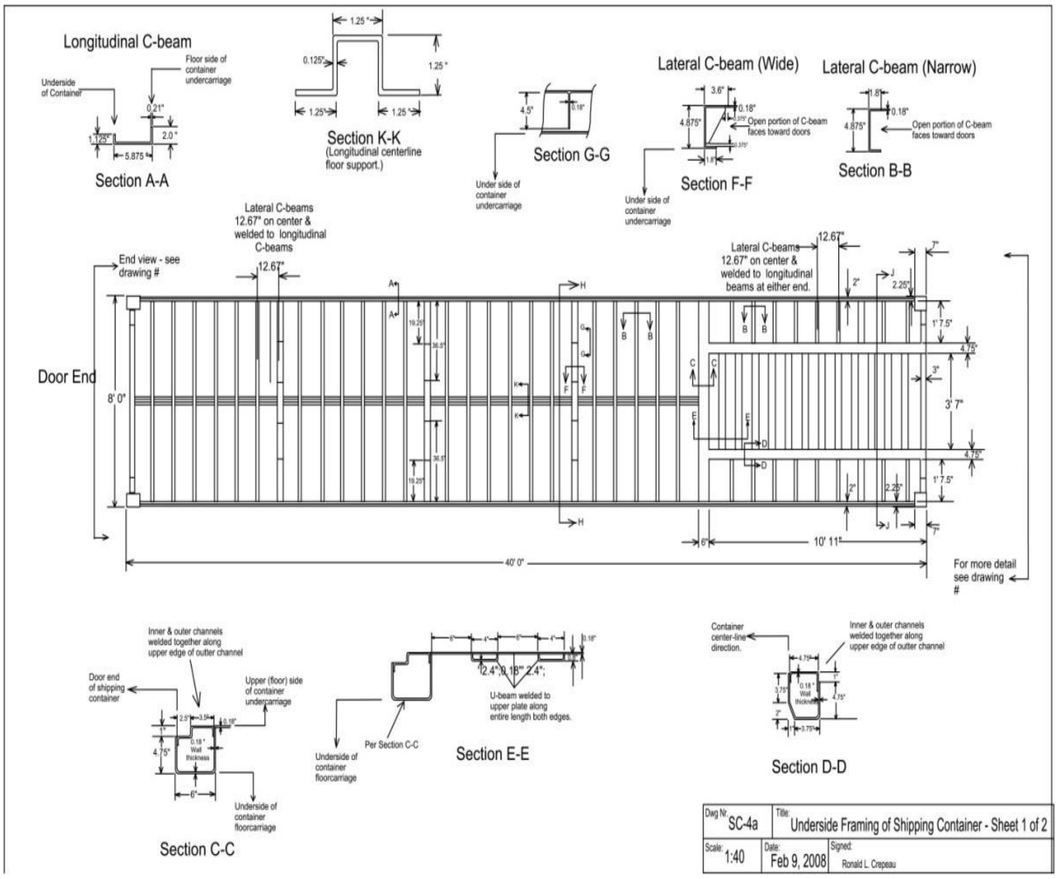


Figure 4.22: Floor Plan and Cross Sections of the Base Frame Structure of The 40' ISO Shipping Container (Crepeau R. 2008)

Roof Panel

The roof panel is constructed from 2mm die stamped steel sheet welded to the top side rails (figure 4.24). The corner of the roof panel is reinforced with 3mm steel plates for lifting purposes. The top side rails which form part of the side panels are made of square hollow section with dimensions of 60x60x3mm.

Side Walls

The side walls (figure 4.25) are constructed from a continuous corrugated sheet of 1.6mm thick at the intermediate area and with 2mm thick at both ends. The corrugated sheets are welded to the top side rails and the corner posts as well as to the base side rails.

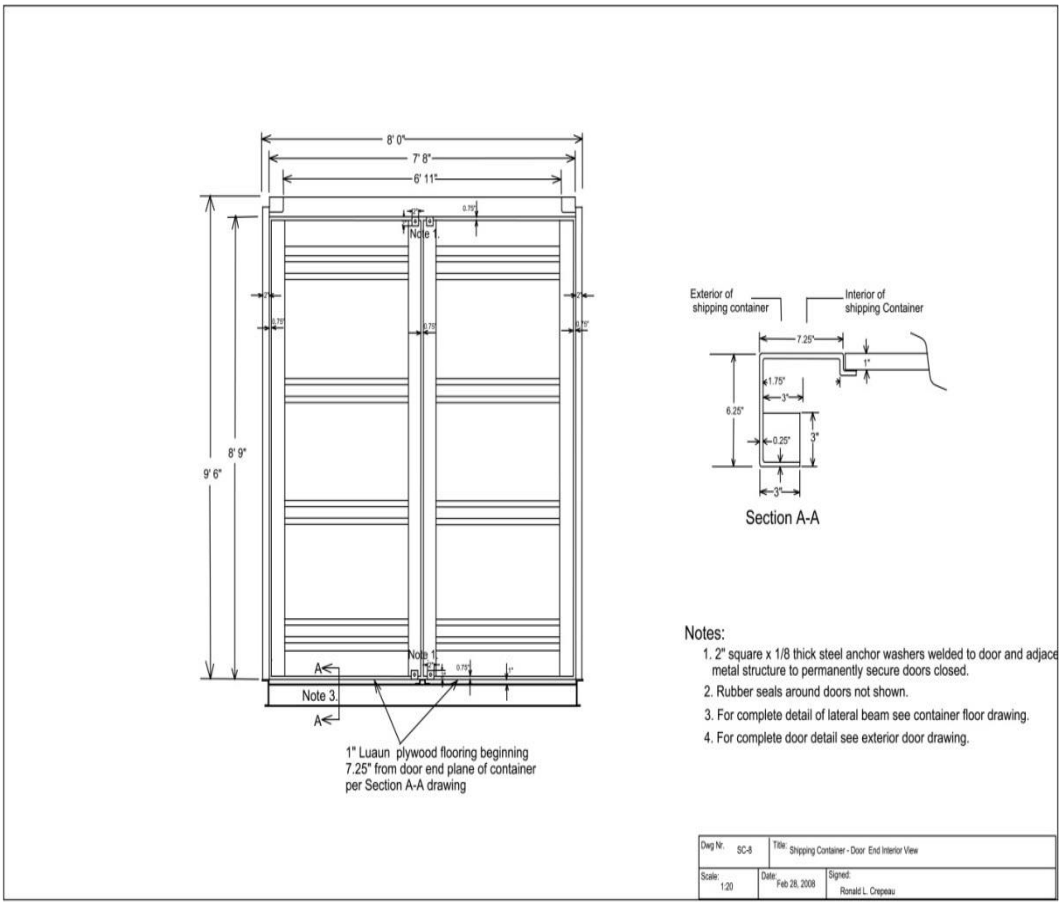


Figure 4.23: Façade and Cross Section Details of the Rear Side of the 40' ISO Shipping Container (Crepeau R 2008)

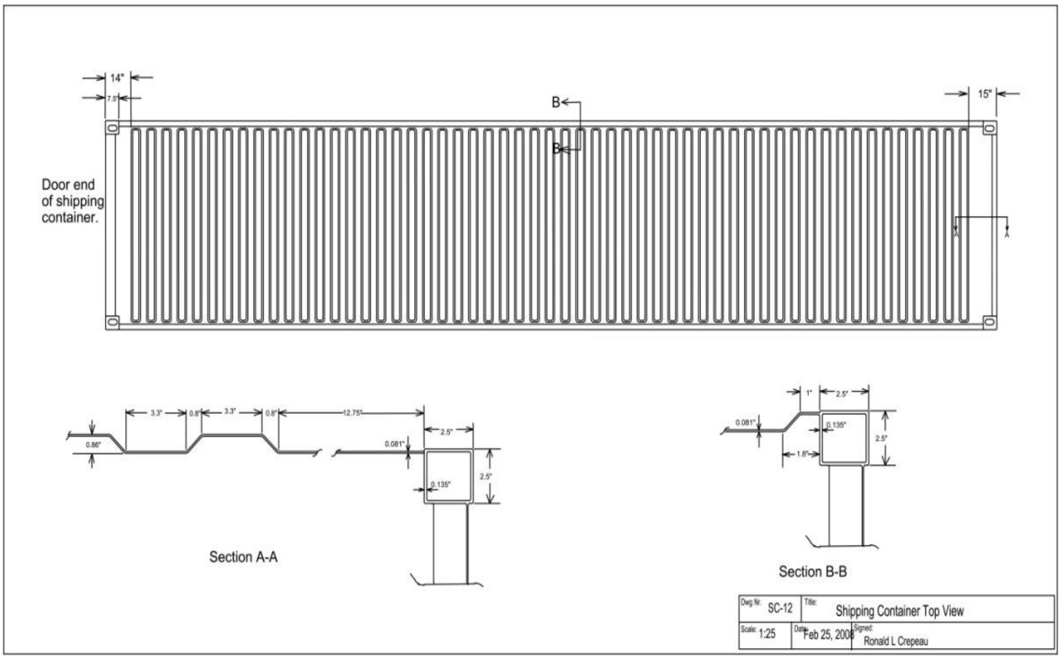


Figure 4.24: Roof Panel Details of 40' ISO Shipping Container (Crepeau R. 2008)

Front End Structure

The front end wall is composed of top and bottom rails, side posts, corner fittings and trapezium section front wall (figure 4.26). The bottom end rail is made of 4.0mm pressed open section steel while the top end rail is constructed of 60x60x3mm squared hollow section. Each of the corner posts are made of 6mm pressed open section steel in one piece to be strong enough to handle the stacking and racking forces. The front wall is made of 2mm thick vertically corrugated steel sheets welded together to form one piece. The corrugated sheet is continuously welded to the front rails and the corner posts.

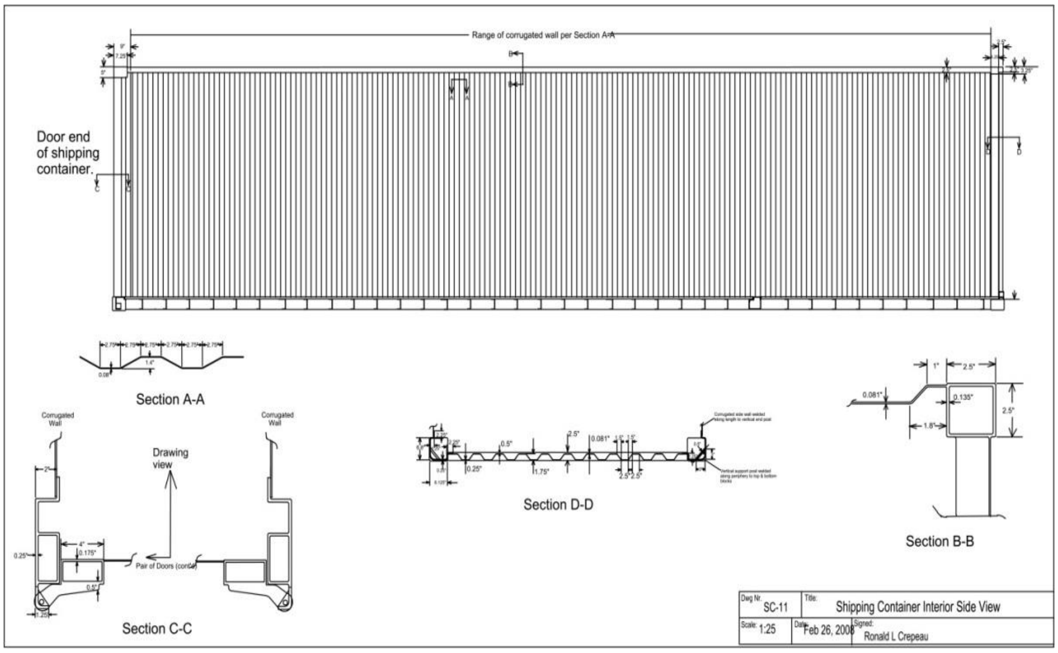


Figure 4.25: Side Wall Details of ISO 40’ Shipping Container (Crepeau R. 2008)

4.6.2 Shipping Containers Adaptation

Similar to the LGS option, 12 containers are put on top of each other on 4 floors (three containers per floor) to form the 4-storey building. All containers are welded together to be fixed in place and to achieve a structural integrity for the whole building. The walls and roofs are insulated with polystyrene boards for thermal insulation with the required thickness as per the U value calculation in appendix D.

Foundation

200mm thick concrete on grade slab will be used as a foundation for this option similar to the other previous options.

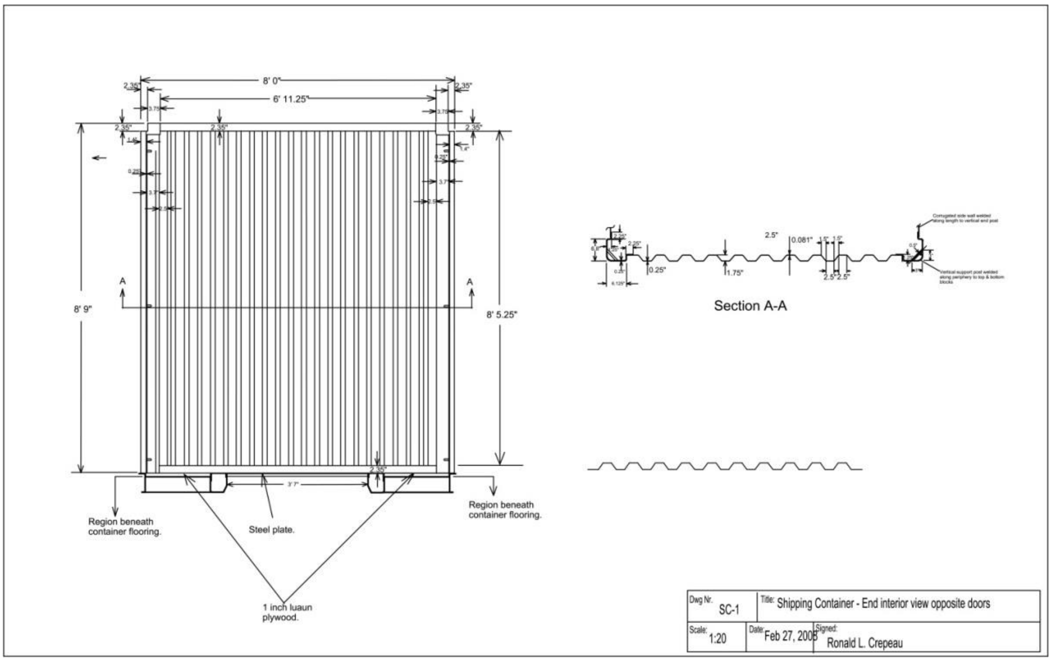


Figure 4.26: Front Side Details of ISO 40' Shipping Container (Crepeau R. 2008)

Walls Adaptation

All walls are insulated with 50mm layer of polystyrene boards for thermal insulation. A 12mm layer of gypsum boards are fixed on the top of the polystyrene to receive the internal finish of water based latex paint.

Roof

The top roof is insulated from inside with 75mm thick layer of polystyrene boards for thermal insulation. The containers as explained before are made of air tight corrugated sheets that are welded together and the inner face are sealed with silicon which are normally tested during the containers manufacturing process.

Table 4.8 shows the BOQ calculated from the architectural drawings and the table 4.9 shows the output BOQ from Athena software.

Table 4.8: B.O.Q of ISO 40' Shipping Container Calculated From the Architectural Drawings

COMPONENT	ASSEMBLY	WIDTH	THICKNESS	LENGTH	NUMBER				VOLUME	volume+CW	volume for 12 units	UOM	MATERIAL
GROUND FLOOR SLAP													
	ground floor slap	8.85	0.2	13.2	1				23.36	23.36	23.36	m3	CONVENTION CAST IN SITUE-25
	reinforced concrete								2.10	2.10	2.10	ton	REBAR, ROD, LIGHT SECTION
	water proof	8.85		13.2					116.82			m2	bitumen liquid applied
FLOOR	COMPONENT	CROSS SECTION		LENGTH	NUMBER OF BERLINS	VOLUME	PLOYWOOD9MM AREA	30GA SHEET	WEIGHT	QUANTITY		UNITS	ELEMENT
	BOTTOM SIDE BEAMS (A-A)	0.0012		11.515	2	0.027636			0.21860076	0.2186008	2.62320912	Tons	HOLLOW STRUCTURE STEEL
	BERLIN (23xB-B)	0.0009		2.26	23	0.046782			0.37004562	0.3700456	4.44054744	Tons	HOLLOW STRUCTURE STEEL
	BERLIN (3xF-F)	0.0011		2.26	3	0.007458			0.05899278	0.0589928	0.70791336	Tons	HOLLOW STRUCTURE STEEL
	BERLIN (16xB1-B1)	0.0009		0.4721	16	0.0067982			0.053774078	0.0537741	0.645288941	Tons	HOLLOW STRUCTURE STEEL
	BERLIN (2xF1-F1)	0.0011		0.4721	4	0.0020772			0.016430968	0.016431	0.197171621	Tons	HOLLOW STRUCTURE STEEL
	BERLIN (2xD-D)	0.0029		3.2246	2	0.0187027			0.147938199	0.1479382	1.775258386	Tons	HOLLOW STRUCTURE STEEL
	BERLIN (1xC-C)	0.0447		2.26	1	0.101022			0.79908402	0.799084	9.58900824	Tons	HOLLOW STRUCTURE STEEL
	PERLINS (1XE-E)	0.0018		1.0821	13	0.0253211			0.200290217	0.2002902	2.403482609	Tons	HOLLOW STRUCTURE STEEL
	PERLINS (1XK-K)	0.0005		8.3806	1	0.0041903			0.033145273	0.0331453	0.397743276	Tons	HOLLOW STRUCTURE STEEL
	PLAYWOOD	0.04068		11.677	1	0.4750204	26.39002			52.78004	633.36048	m2	PLYWOOD (9mm)
WALLS -SIDE 1+2													
	CORREGATED SHEETS	0.0003		2.66	168	0.134064		422.2488189	1.06044624	422.2488189	5066.985827	m2	METAL WALL CLADDING
	2X REAR SIDE COLUMNS	0.0008		2.6632	2	0.0042611			0.033705459	0.0337055	0.40446551	Tons	HOLLOW STRUCTURE STEEL
	2X FRONT SIDE COLUMNS	0.0031		2.6632	2	0.0165118			0.130608654	0.1306087	1.567303853	Tons	HOLLOW STRUCTURE STEEL
	POLYSTER BOARDS	12		2.6632	2	63.9168				63.9168	767.0016	M2	POLYSTER BOARD
BACK SIDE													
	CORRIGATED SHEET	0.0039		2.573	1	0.0100347		31.60535433	0.079374477	31.60535433	379.264252	M2	METAL WALL CLADDING
	POLYSTER BOARDS	2.35		2.6632	1	6.25852				6.25852	75.10224	M2	POLYSTER BOARD
FRONT SIDE DOOR													
	window	2.35		2.7	12						76.14	m2	double glazed window
ROOF	ROOF CORREGATED SHEET	0.0275		2.2865	1	0.0628788		198.0433071	0.497370913	198.0433071	2376.519685	M2	METAL ROOF CLADDING
	ROOF CORREGATED SHEET	0.000899		2.2865	1	0.0020556		6.474215748	0.016259507	6.47415748	77.68988976	M2	METAL ROOF CLADDING
	TOP LONG SIDE BEAMS(B-B)	0.0007		11.7195	2	0.0164073			0.129781743	0.1297817	1.557380916	tonnes	HOLLOW STRUCTURE STEEL
	TOP SHORT SIDE BEAMS(A-A)	0.0007		2.0975	2	0.0029365			0.023227715	0.0232277	0.27873258	tonnes	HOLLOW STRUCTURE STEEL
	POLYSTER BOARDS	2.35		12	1	28.2				28.2	338.4	M2	POLYSTER BOARD

Table 4.9: B.O.Q of ISO 40' Shipping Container as Per Athena Input Data Sheet

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	m2	1675.3	0	0	0	0	0	1675.3	13.5029	Tonnes
6 mil Polyethylene	m2	123.9227	0	0	123.9227	0	0	0	0.0186	Tonnes
Aluminum Window Frame	kg	215	0	0	0	0	0	215	0.215	Tonnes
Concrete Benchmark 3000 psi	m3	24.5184	0	0	24.5184	0	0	0	56.2356	Tonnes
Double Glazed No Coating Air	m2	103.0833	0	0	0	0	0	103.0833	1.6692	Tonnes
Extruded Polystyrene	m2 (25mm)	1241.1	0	0	0	0	0	1241.1	1.5266	Tonnes
FG Batt R11-15	m2 (25mm)	288.75	0	0	0	0	0	288.75	0.0904	Tonnes
Hollow Structural Steel	Tonnes	26.3762	0	0	0	0	0	26.3762	26.3762	Tonnes
Metal Roof Cladding - Residential (30 Ga.)	m2	2478.7517	0	0	0	0	0	2478.7517	8.7722	Tonnes
Metal Wall Cladding - Residential (30 Ga.)	m2	5470.8333	0	0	0	0	0	5470.8333	19.361	Tonnes
Small Dimension Softwood Lumber, kiln-dried	m3	1.5552	0	0	0	0	0	1.5552	0.6926	Tonnes
Softwood Plywood	m2 (9mm)	618.45	0	0	0	0	0	618.45	2.9216	Tonnes
Water Based Latex Paint	L	1890.06	0	0	0	0	0	1890.06	1.4175	Tonnes
Welded Wire Mesh / Ladder Wire	Tonnes	0.1056	0	0	0.1056	0	0	0	0.1056	Tonnes
TOTAL WEIGHT									**132.905**	Tonnes

CHAPTER 5

RESULTS AND DISCUSSIONS

5.0 Introduction

Interpretation is the last stage of the LCA as per ISO 14040. So, in this stage, and after running the life cycle inventory LCI and the life cycle analysis impact LCIA, the findings and the results are interpreted to identify the environmental impacts of the proposed studied options. In this chapter, the results for the LCA analysis for the four prefabricated systems will be discussed and compared to the conventional construction methodology. Athena will present the results side by side and in comparison to that for the convention construction methodology as the base case.

The results are categorized in the following sections:

- The impacts along the life cycle stages including the production, construction, occupation (use), end of building life and beyond building life.
- Resources use (materials) and land use (waste).
- Fossil fuel consumption and global warming potential.

5.1 Resources Use

In this section, all the used materials for the five construction systems will be discussed. All the systems vary in their used materials, volume of materials, their weight and the overall weight as well. Figure 5.1 and table 5.1 show a comparison between the different systems and their overall weight in absolute values. It is clear that some options use more materials than others. Concrete options either the base case or the pre-cast concrete (PCC) are remarkably heavier than other options. The lightest option is the light gauge steel LGS option. The comparison of the used materials for the five construction systems will be discussed in the next sections.

5.1.1 Base Case Model

The base case model uses cast in situ concrete for the structural elements of columns, beams and slabs. The external and internal walls are made of concrete blocks. The used materials for this option have been calculated as per the architecture and structural drawings and had been fed into Athena for assessment. After feeding Athena with the volume of the construction materials of the se model, Athena analyzes and calculates the basic natural materials that compose them. For example, concrete volume is analyzed and the mass of coarse aggregate, fine aggregates, limestone, water and iron ore that compose this volume of concrete are calculated. The following section will discuss the used resources in details.

Table 5.1: Overall Weight Comparison for the Four Options to the Base Case Model

OPTION	BUILDING OVERALL WEIGHT (TONNES)
BASE CASE-CONVENTIONAL CONSTRUCTION	626.3951
OPTION 1-PRECAST CONCRETE (PCC)	565.3273
OPTION 2-PRECAST GLASSFIBER REINFORCED CONCRETE (GRC)	177.9121
OPTION 3- LIGHT GAGE STEEL (LGS)	101.46
OPTION 4- ADABTED SHIPPING CONCRETE (ASC)	132.905

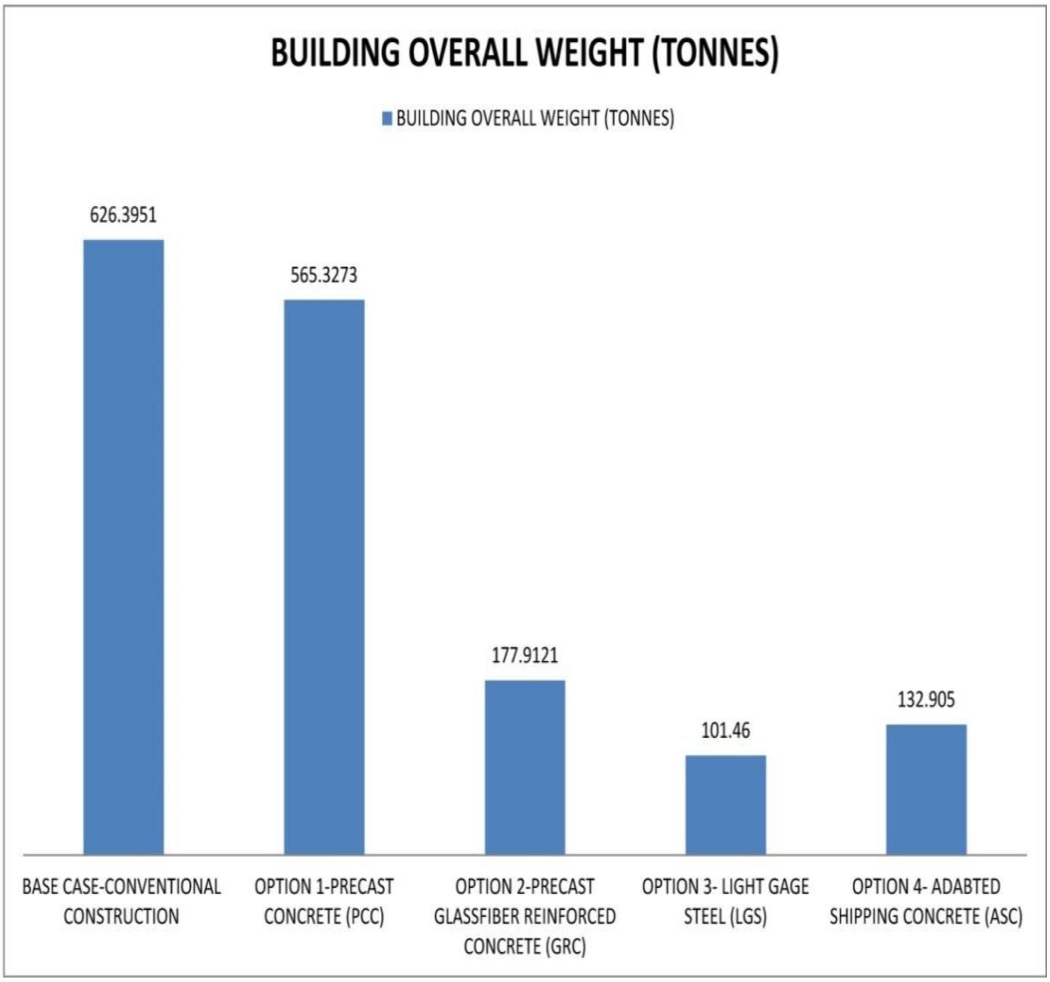


Figure 5.1: Overall Weight Comparison for the Four Options to the Base Case Model

Used Solid Materials

By analyzing Table 5.2 which shows the absolute values of the used resources through the lifecycle of the base case model, we can highlight the following notes:

- There are around 27 resources used for building the base case model. 6 solid materials have the highest contribution which is coal, coarse aggregate, ferrous scrap, Fine Aggregate, Gypsum, Iron Ore and Limestone.
- Water and crude oil have been analyzed separately
- The main three used resources are the fine aggregates with 46% of the used solid materials, coarse aggregate with 23% and Limestone with 16% during the production stage. Ferrous scrap is the main used resource for the steel that was used in concrete with ratio of 5% to the overall used materials.
- The materials used during the production stage form 94% compared to the 5% of the used materials during the preoccupation stage.
- The amount of coal material during the production stage is around 2% while its use during the occupation stage reaches 98%.
- The weight of the overall used solid resources during the production/construction stage (A) is 3.3E+5kg compared to 9.28E+05 kg of the overall used resources through the whole life cycle of the building. This form around 35.5% of the used solid materials. Figure 5.2 shows the used Resources in absolute value by life cycle stages (A to D).

Table 5.2: Base Case (Conventional Construction) -Resource Use Absolute Value Table by Life Cycle Stages (A to D)

		PRODUCT (A1 TO A3)	CONSTRUCTION PROCESS (A4 TO A5)	USE (B2, B4&B6)	END OF LIFE (C1 TO C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECT
Coal	kg	1.56E+04	9.08E+02	5.67E+05	1.21E+02	3.13E+03	5.86E+05
Coarse Aggregate	kg	7.17E+04	3.34E+03	1.24E+03	5.97E+00	0.00E+00	7.63E+04
Ferrous scrap	kg	1.45E+04	1.48E+02	1.76E+01	1.43E-03	0.00E+00	1.47E+04
Fine Aggregate	kg	1.43E+05	1.07E+04	1.17E+04	0.00E+00	0.00E+00	1.66E+05
Gypsum (Natural)	kg	1.27E+03	1.49E+02	1.70E-01	0.00E+00	0.00E+00	1.42E+03
Iron Ore	kg	2.46E+02	2.91E+01	6.94E+01	0.00E+00	5.98E+03	6.32E+03
Limestone	kg	5.02E+04	3.82E+03	3.55E+03	0.00E+00	-2.34E+02	5.74E+04

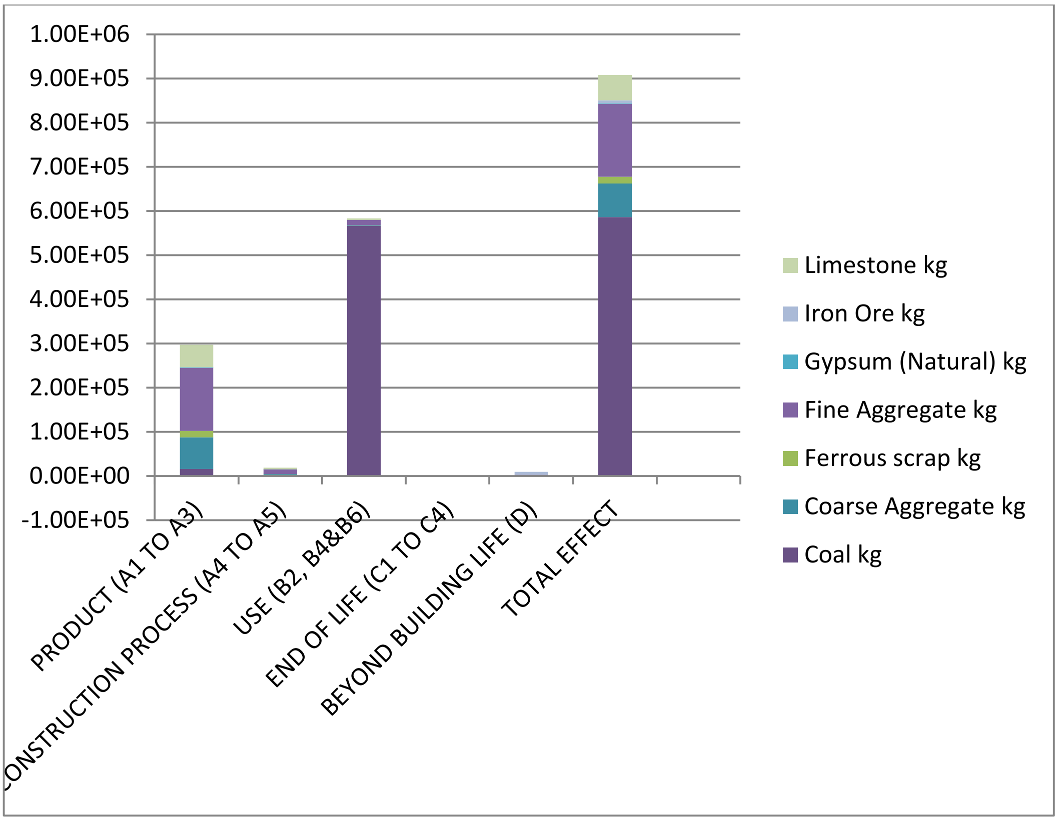


Figure 5.2 – Base Case (Conventional Construction) - Resource Use Absolute Value diagram By Life Cycle Stages (A to D)

Liquid Materials

Table 5.4 shows the absolute values of the used water and crude oil. It shows that 2.87E+05 Litters of water are consumed during the production stage (80% of the overall used water volume), while it is around 4% during the use stage and reaches 16% beyond the building life stage. The crude oil reaches around 3 times the amount of water during the construction stage while it is one third the amount used during the use stage. Amount of crude oil is around 10% of the overall water amount used along the lifecycle of the building. Table 5.3 and figure 5.3 show the absolute values of the used crude oil and water by lifecycle stages.

Table 5.3: Base Case (Conventional Construction) – A Brief of Resource Use Absolute Value Diagram by Life Cycle Stages (A to D)

		(A1 TO A5) stage
SOLID MATERIALS	KG	3.30E+05
CRUDE OIL	L	1.26E+04
WATER	L	2.87E+05

Table 5.4: Base Case (Conventional Construction) – Water, Crude Oil Use Absolute Value Diagram by Life Cycle Stages (A to D)

		PRODUCT (A1 TO A3)	CONSTRUCTION PROCESS (A4 TO A5)	USE (B2, B4&B6)	END OF LIFE (C1 TO C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECT
Crude Oil	L	7.34E+03	2.95E+03	2.38E+04	2.12E+03	-6.55E+01	3.62E+04
Crude Oil as feedstock	L	2.27E+03	6.47E+01	2.84E+03	0.00E+00	0.00E+00	5.18E+03
Water	L	2.79E+05	7.68E+03	1.51E+04	7.93E+01	5.52E+04	3.57E+05

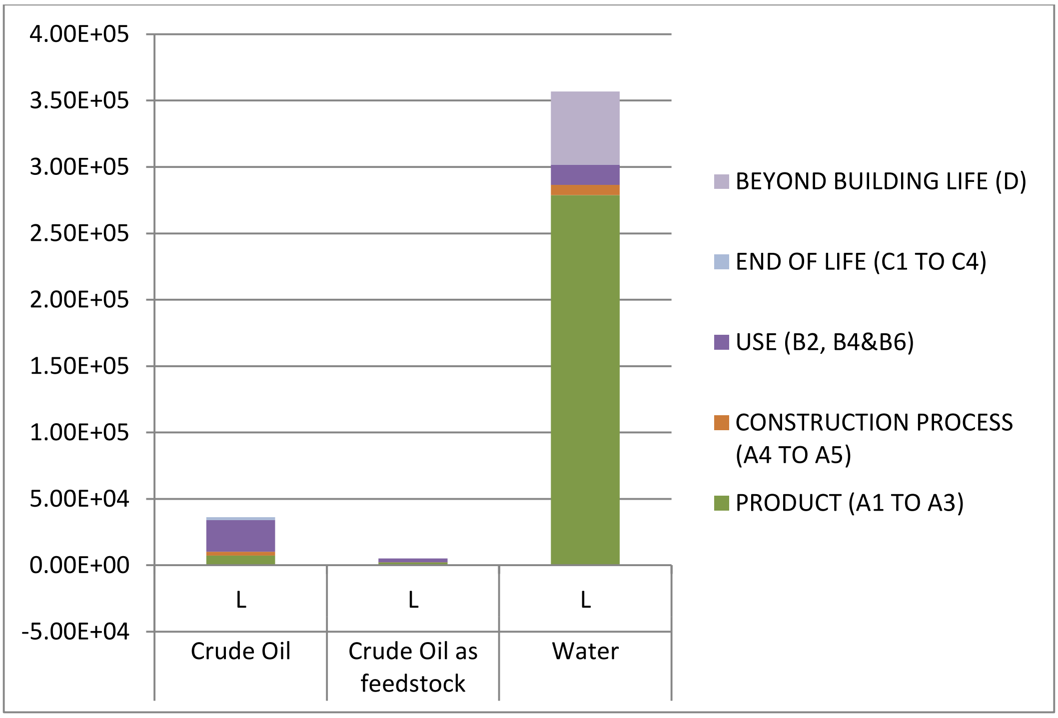


Figure 5.3: Base Case (Conventional Construction) – Water, Crude Oil Use Absolute Value Diagram by Life Cycle Stages (A to D)

5.1.2 Option1-Pre-Cast Concrete PCC

In PCC option, the volume of concrete has been increased as the block walls are replaced with pre-fabricated concrete panels. A comparison to the base case model has been conducted. The following sections will discuss these findings in details.

Used Solid Materials

Table 5.5 and figure 5.4 show the absolute values of the used solid materials by life cycle stages. It is clear that there is an increase in the used materials during product stage compared to the base case model. The coarse aggregate reached 1.36E+05 kg compared to 7.17E+04 kg in the base case with an increase of 189%. The fine aggregate increased to 1.92E+05 kg compared to 1.43E+05 kg with an increase of 134%. The limestone increased to 8.23E+04 kg versus 5.02E+04 kg in base case model with an increase of 163%. This increase refers to the increase in the amount of precast concrete walls which have replaced the block walls in the base case model. The overall solid resources increased to 4.69E+05 compared to 3.29E+05 kg in the base case with an increase of 143%.

Table 5.5: Option 1(PCC) Solid Resource Use Absolute Value Table by Life Cycle Stages (A to D)

		PRODUCT (A1 TO A3)	CONSTRUCTION PROCESS (A4&A5)	USE B2, B4 & B6)	END OF LIFE (C1 TO C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECT (A TO D)
Coal	kg	1.36E+04	4.83E+02	5.66E+05	9.56E+01	2.17E+03	5.83E+05
Coarse Aggregate	kg	1.36E+05	6.46E+03	4.63E+02	5.97E+00	0.00E+00	1.43E+05
Ferrous scrap	kg	1.01E+04	1.11E+02	1.76E+01	1.43E-03	0.00E+00	1.03E+04
Fine Aggregate	kg	1.92E+05	9.60E+03	0.00E+00	0.00E+00	0.00E+00	2.02E+05
Gypsum (Natural)	kg	1.40E+03	8.08E+01	0.00E+00	0.00E+00	0.00E+00	1.48E+03
Iron Ore	kg	5.33E+02	1.09E+01	1.36E+00	0.00E+00	4.15E+03	4.69E+03
Limestone	kg	8.23E+04	3.31E+03	5.35E+02	0.00E+00	-1.62E+02	8.60E+04

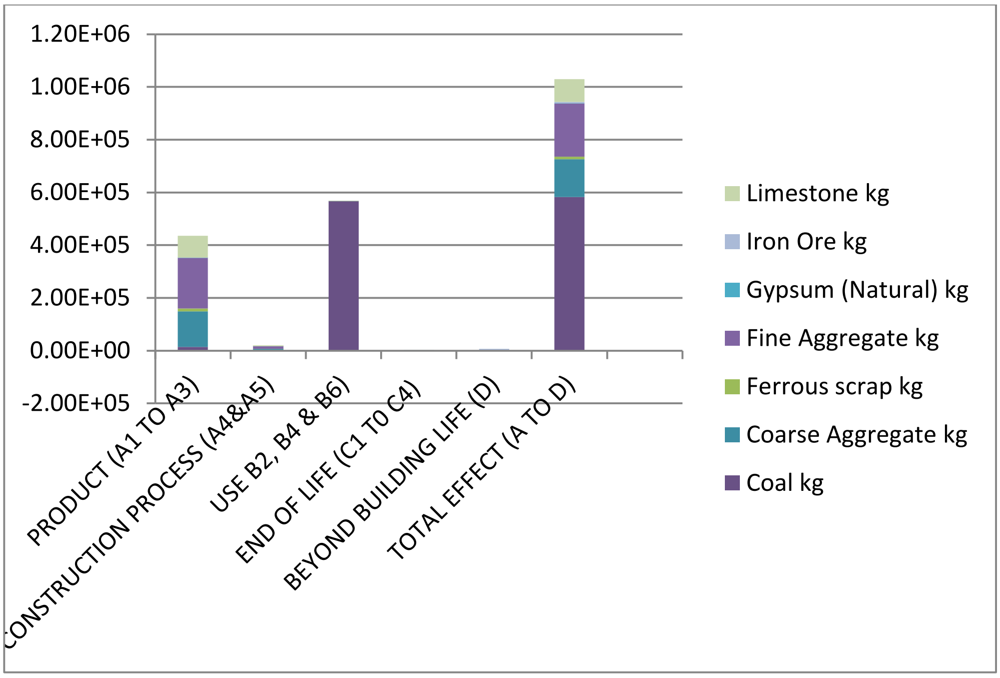


Figure 5.4: Option 1(PCC) Solid Resources Use Absolute Value Diagram by Life Cycle Stages (A to D)

Used Liquid Materials

Table 5.6 and figure 5.5 show the absolute values of the used crude oil and water. Table 5.7 shows that the water volume has increased from 2.87E+05 in the base case to 3.47E+05Litters with 120% increase. In contrary to the increase of the solid materials and the water volume, the crude oil has decreased from 1.26E+04 to 8.38E+03Liters with a reduction of 34%. Table 5.7 shows a brief comparison to the overall resources used during production/ construction stage (A). The reduction in the used crude oil could be explained in light of the manufacturing process and its energy savings.

Table 5.6: Option 1(PCC) Water, Crude Oil Use Absolute Value Diagram by Life Cycle Stages (A to D)

		PRODUCT (A1 TO A3)	CONSTRUCTION PROCESS (A4&A5)	USE B2, B4 & B6)	END OF LIFE (C1 TO C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECT (A TO D)
Crude Oil	L	4.87E+03	3.51E+03	2.32E+04	2.20E+03	-4.55E+01	3.38E+04
Crude Oil as feedstock	L	2.37E+03	6.61E+01	2.47E+03	0.00E+00	0.00E+00	4.91E+03
Water	L	3.39E+05	8.25E+03	1.25E+04	7.93E+01	3.83E+04	3.98E+05

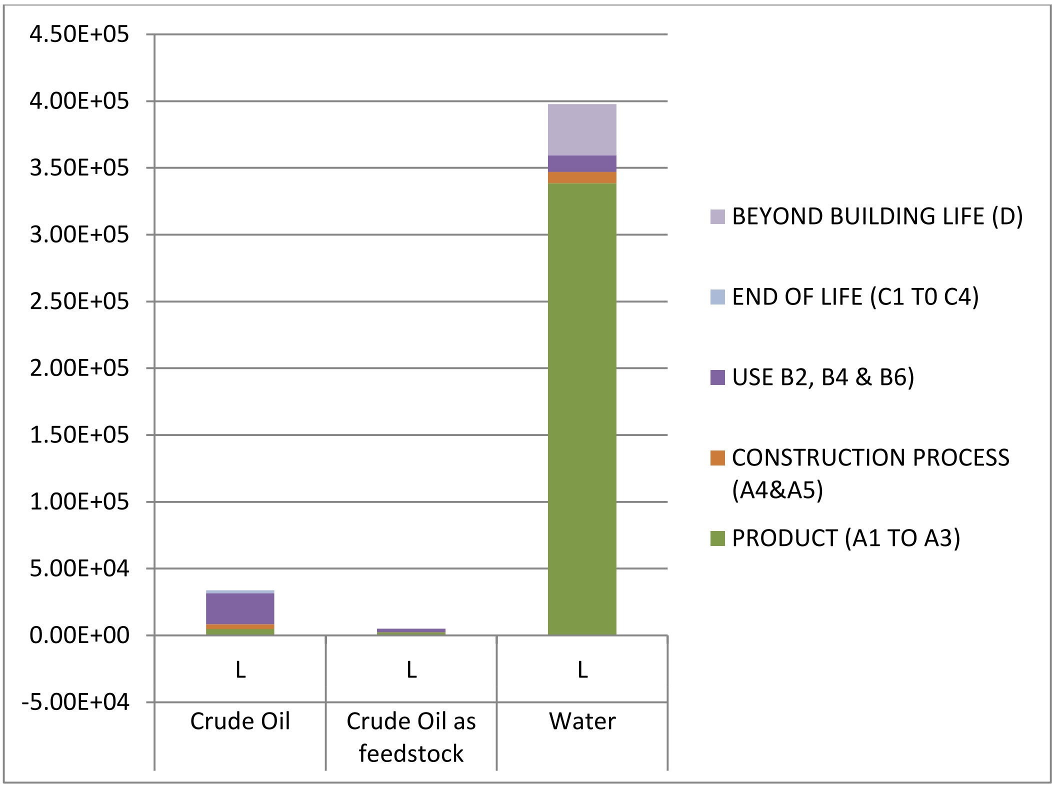


Figure 5.5: Option 1(PCC) Water, Crude Oil Use Absolute Value Diagram by Life Cycle Stages (A to D)

Table 5.7: Option 1(PCC) Used Resources Comparison with the Base Case Model

		(A1 TO A5) stage		
		BASE CASE MODEL	PCC	COMPARISON
SOLID MATERIALS	KG	3.29E+05	4.69E+05	143%
CRUDE OIL	L	1.26E+04	8.38E+03	66%
WATER	L	2.87E+05	3.47E+05	121%

5.1.3 Option 2 (Glass Reinforced Concrete GRC)

Used Solid Materials

ATHENA's results show that GRC option used much less resources compared to the base case model. However, the use of some materials increased remarkably. Coarse aggregate reduced to 40% and the natural Gypsum reduced to 63% compared to the base case. The fine aggregate, which form the main element in the GRC materials has been reduced to 42% and the limestone is almost the same. The ferrous scrap has been reduced to only 2% as GRC doesn't use steel in reinforcing; however the iron ore has been increased to 176% due to the fabrication process. Table 5.8 and figure 5.6 show the absolute values of the used solid resources.

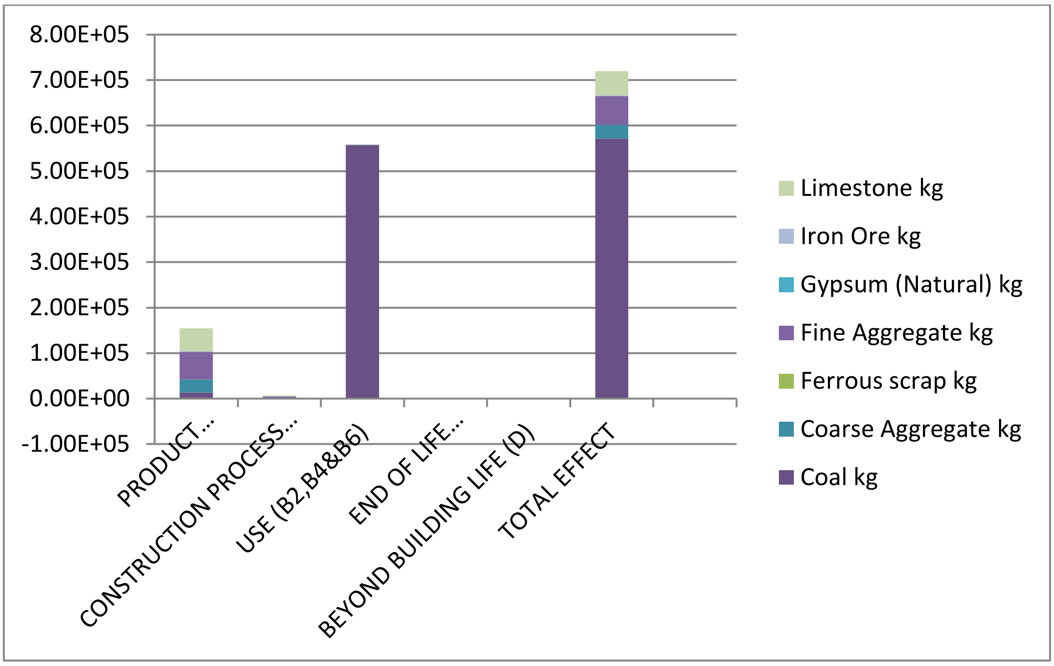


Figure 5.6: Option 2 (GRC) Resource Use Absolute Value Diagram by Life Cycle Stages (A to D)

Table 5.8: Option 2 (GRC) Resource Use Absolute Value Table by Life Cycle Stages (A to D)

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2,B4&B6)	END OF LIFE (C1 to C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECT
Coal	kg	1.34E+04	6.61E+02	5.57E+05	1.81E+01	3.76E+01	5.71E+05
Coarse Aggregate	kg	2.88E+04	1.11E+03	4.63E+02	5.97E+00	0.00E+00	3.03E+04
Ferrous scrap	kg	2.55E+02	6.15E+00	1.08E-02	1.43E-03	0.00E+00	2.61E+02
Fine Aggregate	kg	6.03E+04	3.01E+03	0.00E+00	0.00E+00	0.00E+00	6.33E+04
Gypsum (Natural)	kg	8.02E+02	8.01E+01	0.00E+00	0.00E+00	0.00E+00	8.82E+02
Iron Ore	kg	4.35E+02	2.03E+01	1.48E+00	0.00E+00	7.18E+01	5.28E+02
Limestone	kg	5.09E+04	2.54E+03	1.90E+02	0.00E+00	-2.81E+00	5.36E+04

Used liquid materials

This option is very efficient in water use; ATHENA results showed that the volume of used water is 37% of the base case. Similarly for the crude oil which is reduced to 35% during the production and construction stage compared to the base case as well. This overall reduction in the used resources could refer to the amount of materials which compose the building elements either for the walls or the slabs. Table 5.10 shows the used resources compared to the base case model.

Table 5.9: Option 2 (GRC) Water And Crude Oil Use Absolute Value Diagram by Life Cycle Stages (A to D)

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2,B4&B6)	END OF LIFE (C1 to C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECT
Crude Oil	L	3.41E+03	1.05E+03	2.27E+04	6.58E+02	-7.87E-01	2.78E+04
Crude Oil as feedstock	L	2.94E+03	1.02E+02	1.95E+03	0.00E+00	0.00E+00	4.99E+03
Water	L	1.01E+05	4.94E+03	5.57E+03	7.94E+01	6.63E+02	1.12E+05

Table 5.10: Option 2 (GRC) Used Resources Comparison with the Base Case Model

		(A1 TO A5) stage		
		BASE CASE MODEL	GRC	COMPARISON
SOLID MATERIALS	KG	3.29E+05	1.77E+05	54%
CRUDE OIL	L	1.26E+04	4.46E+03	35%
WATER	L	2.87E+05	1.06E+05	37%

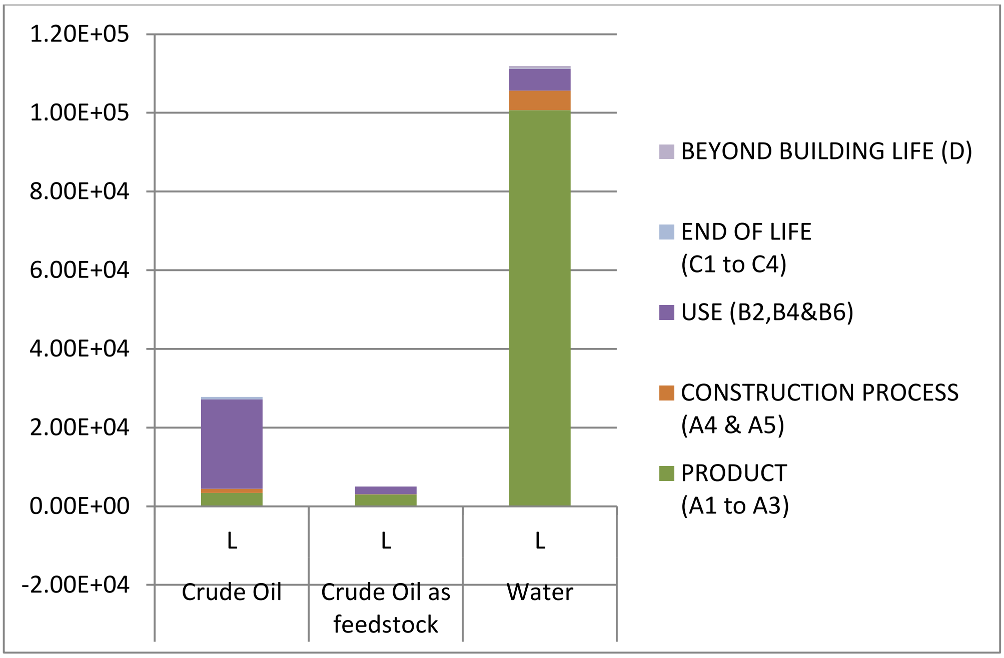


Figure 5.7: Option 2 (GRC) Water And Crude Oil Use Absolute Value Diagram by Life Cycle Stages (A to D)

5.1.4 <u>Option 3- Light Gauge Steel LGS</u>

Used Solid Materials

In the Light Gage Steel option, the overall used resources have been reduced majorly; however, the weight of iron ore and the gypsum materials have been multiplied several times as follows:

- Coarse aggregate has been reduced to 23%, the fine aggregate has been reduced to 16% and the limestone reduced to 22% of their weight compared to the base case model. This material is only used in the foundation of this option in contrary to the base case model which uses these resources for all of the main assemblies.
- Although the Ferrous scrap has been reduced to 45% of its weight in the base case model, The Iron ore weight has been increased more than 38 times its weight in the base case model. However, the analysis shows that beyond building life, two third of this quantity could be reused and reduces the overall effect to one third only.
- The gypsum material which is used in the wall assemblies has been increase 4 times compared to the base case model. Table 5.11 and (Figure

5.8) shows the absolute values of the used materials for LGS option by life cycle stages.

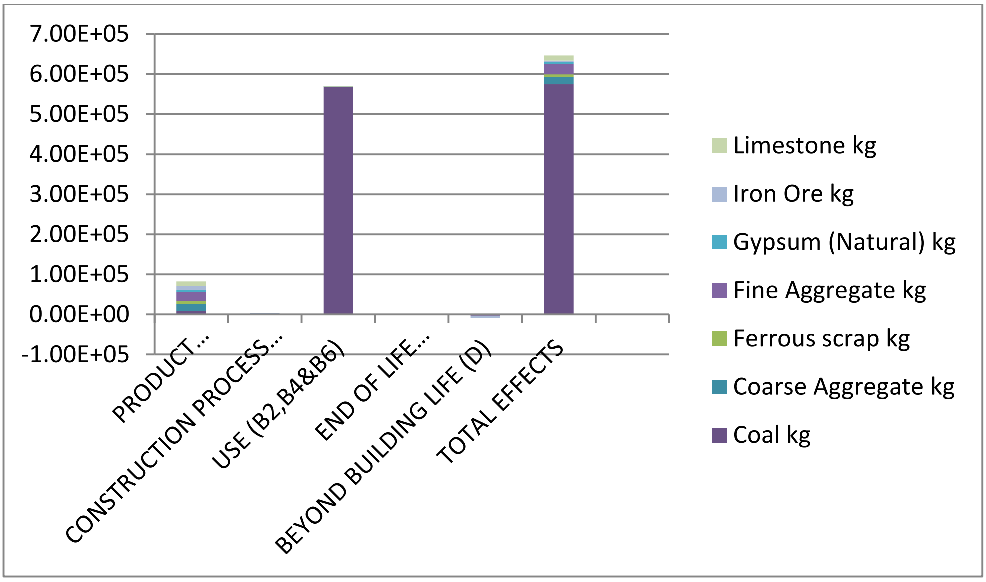


Figure 5.8: Option 3 (LGS) Resource Use Absolute Value Diagram by Life Cycle Stages (A to D)

Table 5.11: Option 3 (LGS) Solid Resource Use Absolute Value Table By Life Cycle Stages (A to D)

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2,B4&B6)	END OF LIFE (C1 to C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECTS
Coal	kg	9.05E+03	3.65E+02	5.68E+05	1.05E+02	-3.18E+03	5.75E+05
Coarse Aggregate	kg	1.70E+04	8.14E+02	4.63E+02	5.97E+00	0.00E+00	1.83E+04
Ferrous scrap	kg	6.59E+03	7.46E+01	1.76E+01	1.43E-03	0.00E+00	6.68E+03
Fine Aggregate	kg	2.39E+04	1.20E+03	0.00E+00	0.00E+00	0.00E+00	2.51E+04
Gypsum (Natural)	kg	5.36E+03	5.35E+02	0.00E+00	0.00E+00	0.00E+00	5.89E+03
Iron Ore	kg	9.37E+03	9.71E+01	1.36E+00	0.00E+00	-6.08E+03	3.39E+03
Limestone	kg	1.11E+04	6.84E+02	5.56E+02	0.00E+00	2.38E+02	1.26E+04

Used Liquid Materials

For the water use Table 5.12 shows the used crude oil and water. It is obvious that LGS manufacturing require higher volume of water. ATHENA analysis shows five times increase in water volume compared to the base case model. Volume of water used during product stage reached 1.69E+06 Littre compared to

2.87E+05 kg which are consumed during the manufacturing of steel and iron ore used in the production stage. Regarding the volume of crude oil use, it has been reduced to 55% of its volume compared to the base case model.

Table 5.12: Option 3 (LGS) Water And Crude Oil Use, Absolute Value Diagram by Life Cycle Stages (A to D)

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2,B4&B6)	END OF LIFE (C1 to C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECTS
Crude Oil	L	2.15E+03	5.12E+02	2.32E+04	4.64E+02	6.66E+01	2.64E+04
Crude Oil as feedstock	L	2.78E+03	1.04E+02	2.81E+03	0.00E+00	0.00E+00	5.69E+03
Water	L	1.62E+06	7.36E+04	1.25E+04	7.93E+01	-5.61E+04	1.65E+06

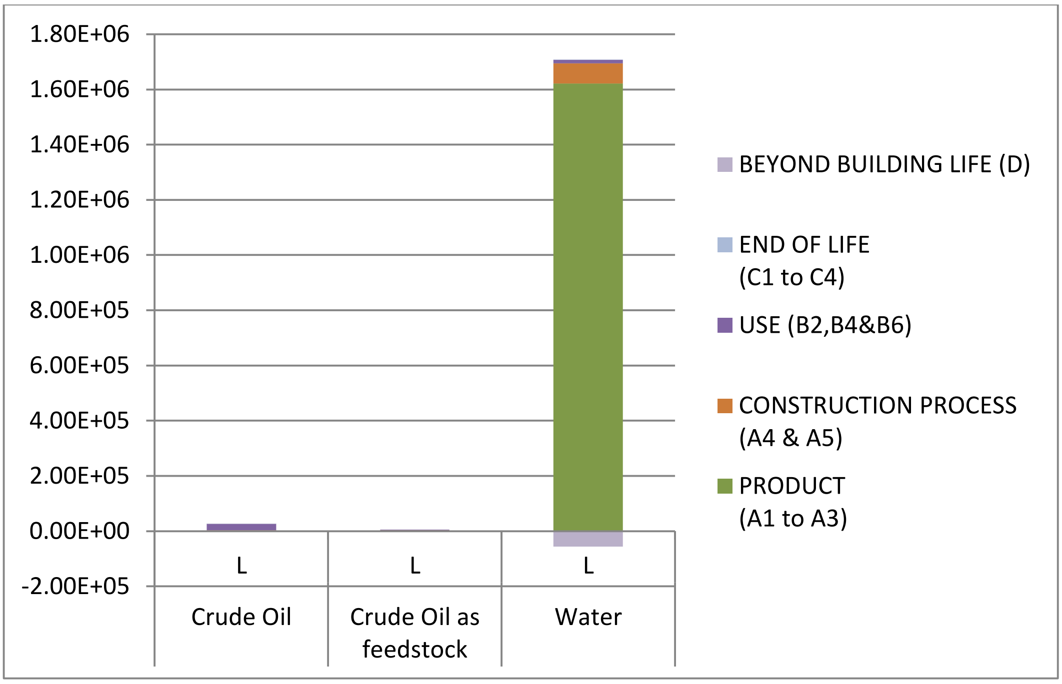


Figure 5.9: Option 3 (LGS) Water And Crude Oil Use Absolute Value Diagram by Life Cycle Stages (A to D)

Table 5.13: Option 3 (LGS) Used Resources Comparison with the Base Case Model

		(A1 TO A5) stage		
		BASE CASE MODEL	LGS	COMPARISON
SOLID MATERIALS	KG	3.29E+05	1.07E+05	33%
CRUDE OIL	L	1.26E+04	2.66E+03	21%
WATER	L	2.87E+05	1.69E+06	590%

5.1.5 Option 4-Adapted Shipping Containers ASC

Used Solid Materials

For the ASC option, and compared to the base case model, Athena's results show a clear decrease in the coarse aggregate, fine aggregate and limestone to 24%, 17% and 18% respectively. This reduction is expected due to the limitation of the concrete use to the foundation only. Gypsum material is increase almost three and half times for the internal sheathing layer used. The coal has been increased to almost 316% due to the steel production process. Although the Ferrous scrap has been increased by 250%, the major increase in the resources used is in the weight of the iron ore which has been moved from 246kg to more than 66 tons. This increase is also expected as the main used material for this module system is steel. Although it is a large increase of the steel resources, the reuse of the shipping containers beyond the building life could return almost two third of the initial used resources as indicated in Table 5.14 and figure 5.10 which show the absolute values of the used materials through its life cycle stages. Similarly, 42% of coal could be resumed beyond the building life as well.

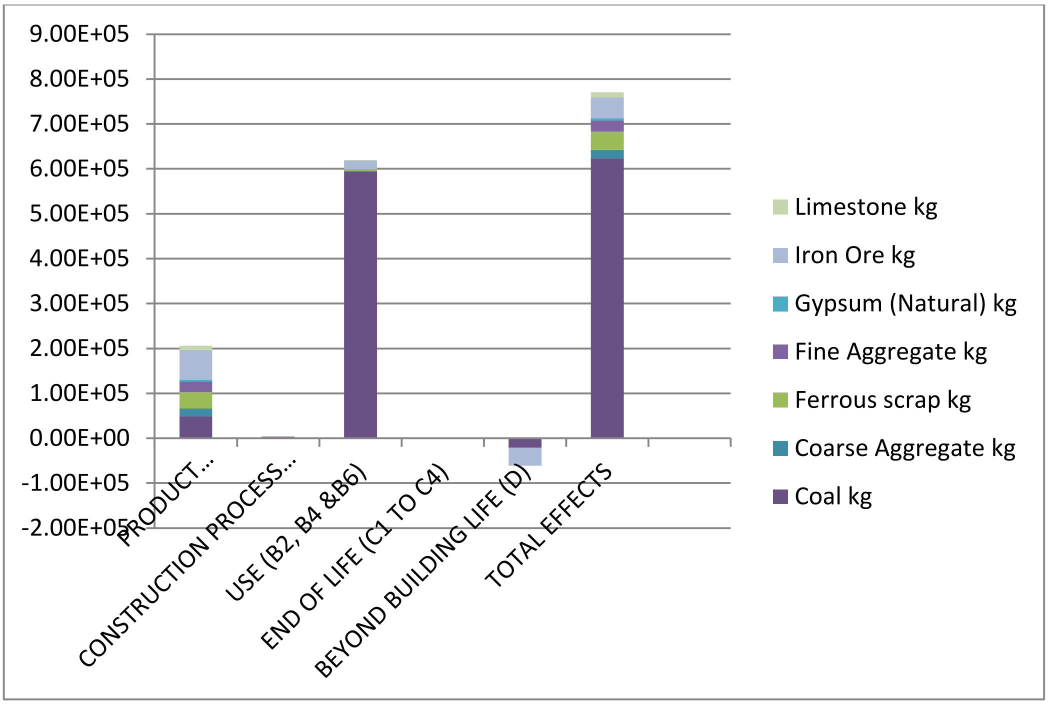


Figure 5.10: Option 4 (ASC) Solid Resource Use Absolute Value Diagram By Life Cycle Stages (A to D)

Table 5.14: Option 4 (ASC) Solid Resource Use Absolute Value Table by Life Cycle Stages (A to D)

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 &B6)	END OF LIFE (C1 TO C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECTS
Coal	kg	4.93E+04	6.07E+02	5.95E+05	4.33E+02	-2.10E+04	6.24E+05
Coarse Aggregate	kg	1.70E+04	8.14E+02	4.63E+02	5.97E+00	0.00E+00	1.83E+04
Ferrous scrap	kg	3.63E+04	3.64E+02	4.31E+03	1.43E-03	0.00E+00	4.09E+04
Fine Aggregate	kg	2.39E+04	1.20E+03	0.00E+00	0.00E+00	0.00E+00	2.51E+04
Gypsum (Natural)	kg	4.42E+03	4.42E+02	1.43E-05	0.00E+00	0.00E+00	4.86E+03
Iron Ore	kg	6.61E+04	6.62E+02	1.97E+04	0.00E+00	-4.02E+04	4.63E+04
Limestone	kg	9.12E+03	4.22E+02	2.46E+02	0.00E+00	1.57E+03	1.14E+04

Used Liquid Materials

For the volume of water, it has been increased 10 times compared to the base case model. It moved from 2.87E+05 litter to 2.91E+06 litter. For the same reason as in LGS option, the steel manufacturing consumes that volume of water. Table 5.15 shows the absolute values for the water and crude oil by life cycle stages (A to D).

For the crude oil and comparing to the base case, it has been reduced to 47%. It is clear that for GRC, LGS and ASC options, the reduction in the crude oil during the production stage is 55% to 60% due to the manufacturing process savings and reduction of used materials as well. Table 5.15 and figure 5.11 show the absolute values of the used water and crude oil during production and manufacturing stages.

Table 5.15: Option 4 (ASC) Water And Crude Oil Use Absolute Value Diagram by Life Cycle Stages (A to D)

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 &B6)	END OF LIFE (C1 TO C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECTS
Crude Oil	L	4.87E+03	1.03E+03	2.48E+04	7.45E+02	4.41E+02	3.19E+04
Crude Oil as feedstock	L	1.04E+03	5.05E+01	3.81E+02	0.00E+00	0.00E+00	1.47E+03
Water	L	2.83E+06	8.57E+04	3.86E+05	7.94E+01	-3.71E+05	2.93E+06

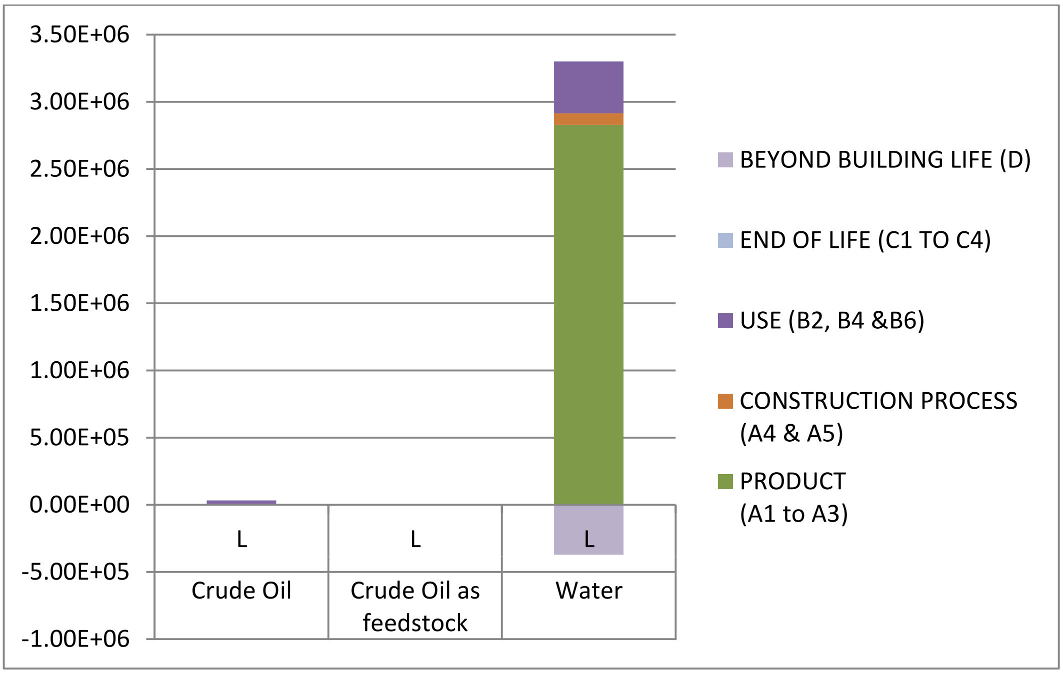


Figure 5.11: Option 4 (Adapted Shipping Containers ASC) Water and Crude Oil Use Absolute Value Diagram By Life Cycle Stages (A to D)

Table 5.16: Option 4 (ASC) Used Resources Comparison to the Base Case Model

		(A1 TO A5) stage		
		BASE CASE MODEL	ASC	COMPARISON
SOLID MATERIALS	KG	3.29E+05	2.41E+05	73%
CRUDE OIL	L	1.26E+04	5.90E+03	47%
WATER	L	2.87E+05	2.91E+06	1016%

5.1.6 Conclusions For The Options Comparison To The Base Case Model

Table 5.17 and figure 5.12 show a comparison between the used solid resources for the base case model and the four options during the product and construction stage (A). It is clear that the LGS option consumes the least mass of the used solid resources followed by the GRC option then the adapted shipping containers option. The mass of the used resources for the precast concrete option is higher than the base case model due to the larger amount of reinforced concrete. Table 5.17 and Figure 5.12 represent a comparison between the four options to the base case model during the production and construction stages only (A1 to A5) while table 5.18 and figure 5.13 show the total effect comparison during the whole life cycle (A to D).

Table 5.17: Product and Construction Used Materials Comparison

		PRODUCTION AND CONSTRUCTION STAGE (A1 TO A5)				
		BASE CASE	PCC	GRC	LGS	ASC
Coal	kg	1.65E+04	1.40E+04	1.40E+04	9.42E+03	4.99E+04
Coarse Aggregate	kg	7.50E+04	1.42E+05	2.99E+04	1.78E+04	1.78E+04
Ferrous scrap	kg	1.47E+04	1.02E+04	2.61E+02	6.66E+03	3.66E+04
Fine Aggregate	kg	1.54E+05	2.02E+05	6.33E+04	2.51E+04	2.51E+04
Gypsum (Natural)	kg	1.42E+03	1.48E+03	8.82E+02	5.89E+03	4.86E+03
Iron Ore	kg	2.75E+02	5.44E+02	4.55E+02	9.46E+03	6.68E+04
Limestone	kg	5.40E+04	8.56E+04	5.34E+04	1.18E+04	9.54E+03

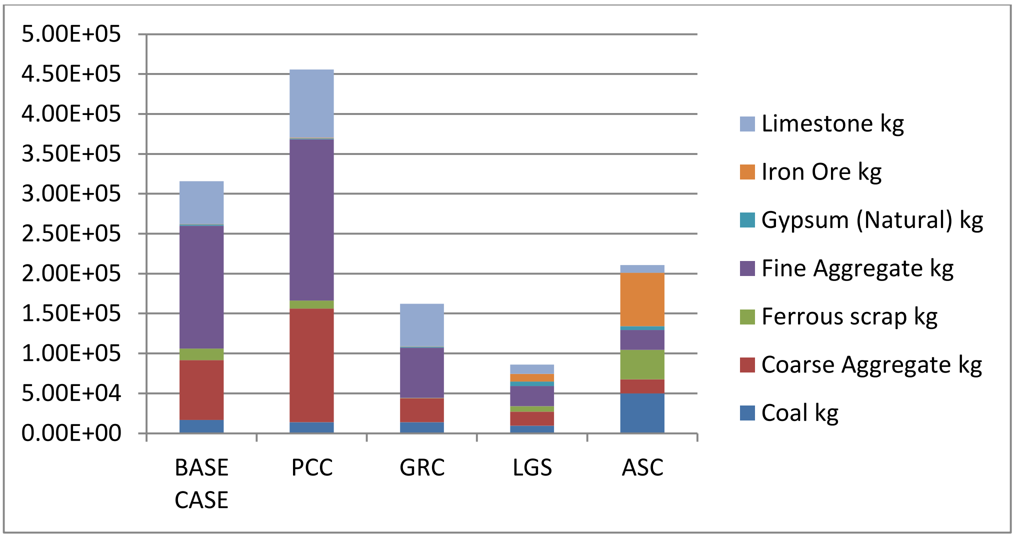


Figure 5.12: Product and Construction Materials Comparison

Table 5.18: Total Effect Used Materials Comparison

		LIFE CYCLE STAGES (A TO D)				
		BASE CASE	PCC	GRC	LGS	ASC
Coal	kg	5.86E+05	5.83E+05	5.71E+05	5.75E+05	6.24E+05
Coarse Aggregate	kg	7.63E+04	1.43E+05	3.03E+04	1.83E+04	1.83E+04
Ferrous scrap	kg	1.47E+04	1.03E+04	2.61E+02	6.68E+03	4.09E+04
Fine Aggregate	kg	1.66E+05	2.02E+05	6.33E+04	2.51E+04	2.51E+04
Gypsum (Natural)	kg	1.42E+03	1.48E+03	8.82E+02	5.89E+03	4.86E+03
Iron Ore	kg	6.32E+03	4.69E+03	5.28E+02	3.39E+03	4.63E+04
Limestone	kg	5.74E+04	8.60E+04	5.36E+04	1.26E+04	1.14E+04

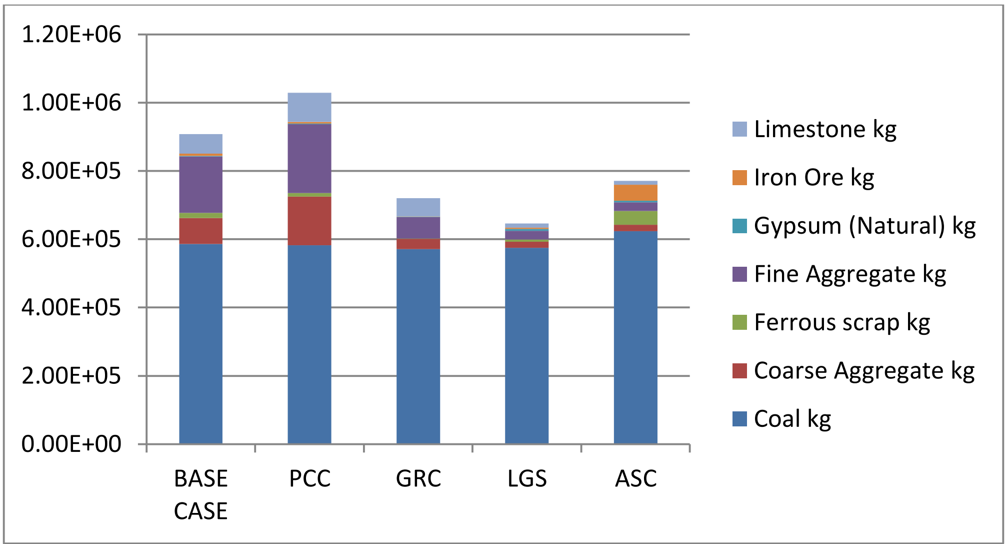


Figure 5.13: Total Effect for the Used Materials Comparison

5.1.7 Consumed CO2 Comparison

Regarding the amount of CO2 emissions during production and construction stages, it is increasing with the increase in manufacturing process. Accordingly, it is the highest in case of ASC option less in LGS option and lesser for the GRC option. It is almost the same between the base case and the precast concrete option.

Table 5.19: Product and Construction CO2 Comparison

		CARBON DIOXIDE IN AIR DURING STAGE A				
		BASE CASE	PCC	GRC	LGS	ASC
CARBON DIOXIDE IN AIR	kg	1.21E+03	1.17E+03	1.65E+03	8.28E+03	1.02E+04

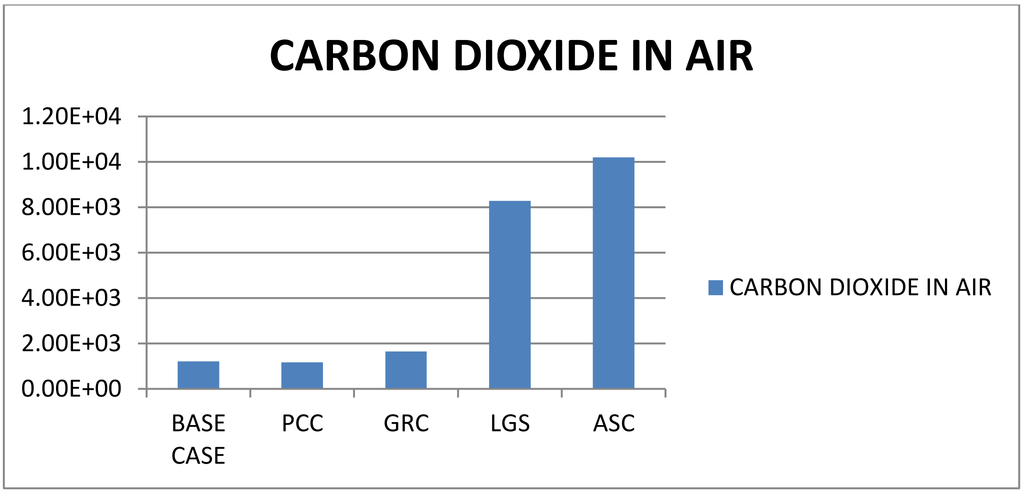


Figure 5.14: Product and Construction CO2 Comparison

5.1.8 Used Crude Oil Comparison

For the crude oil, it is related to the overall consumed materials. The relationship between the total consumed crude oil and its overall weight is almost the same. It is noticed that figure 5.15 for the crude oil consumption is so similar to figure 5.1 of the overall weigh comparison of the four options. This gives an indication to the relative proportion between the crude oil consumption during the pre-occupation stage of each option with its overall weight of its constructed materials. Table 5.20 presents a comparison of the absolute values between the all the construction systems.

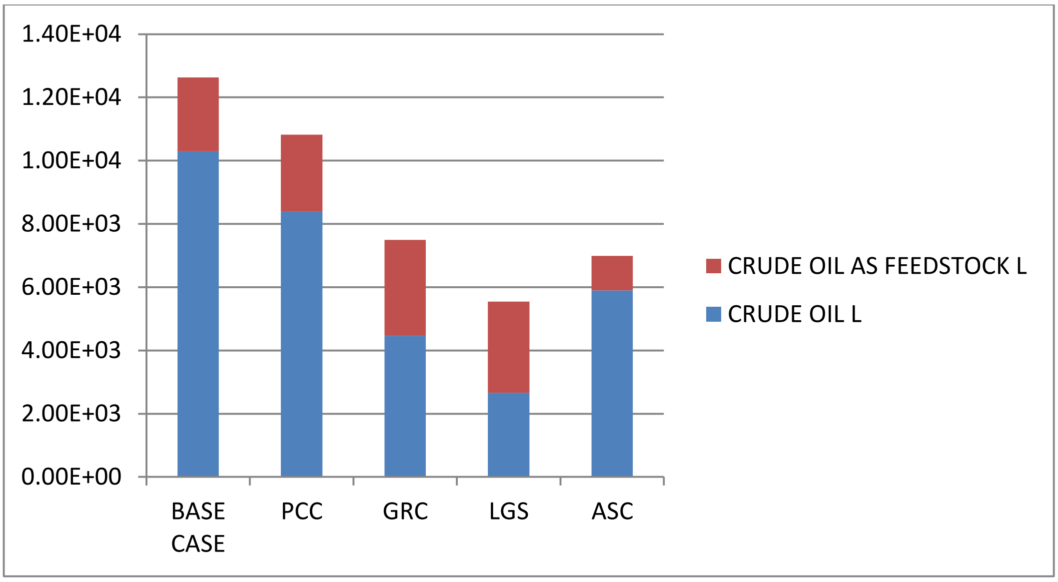


Figure 5.15: Product and Construction Crude Oil Consumption Comparison

Table 5.20: Product and Construction Crude Oil Consumption Comparison

		CRUDE OIL STAGE A				
		BASE CASE	PCC	GRC	LGS	ASC
CRUDE OIL	L	1.03E+04	8.38E+03	4.46E+03	2.66E+03	5.90E+03
CRUDE OIL AS FEEDSTOCK	L	2.33E+03	2.44E+03	3.04E+03	2.88E+03	1.09E+03

5.1.9 Used Water Comparison

For the water consumption, GRC option is the least in water consumption due to two main reasons, the used material which is free from steel manufacturing and the low use of resources. LGS and ASC options show a remarkable increase of water consumption due to the large amount of steel production. Table 5.21 and figure 5.16 show the comparison of the water consumption during production and construction stages between the five systems.

Table 5.21: Product and Construction Water Consumption Comparison

		WATER USAGE STAGE A				
		BASE CASE	PCC	GRC	LGS	ASC
WATER USAGE	L	2.87E+05	3.47E+05	1.06E+05	1.69E+06	2.91E+06

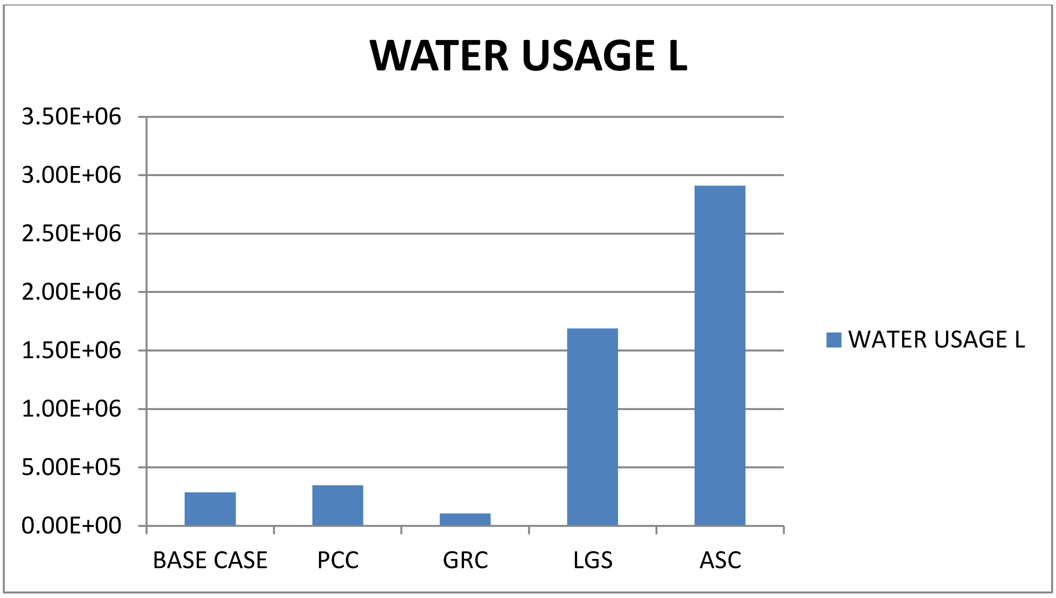


Figure 5.16: Product and Construction Water Consumption Comparison

Table 5.22: Overall Used Resources Comparison to the Base Case Model (Stage A)

		STAGE A (production and construction)				
		BASE CASE	PCC	GRC	LGS	ASC
SOLID MATERIALS	KG	3.29E+05	143%	54%	33%	73%
CRUDE OIL	L	1.26E+04	67%	35%	21%	47%
WATER	L	2.87E+05	121%	37%	589%	1014%

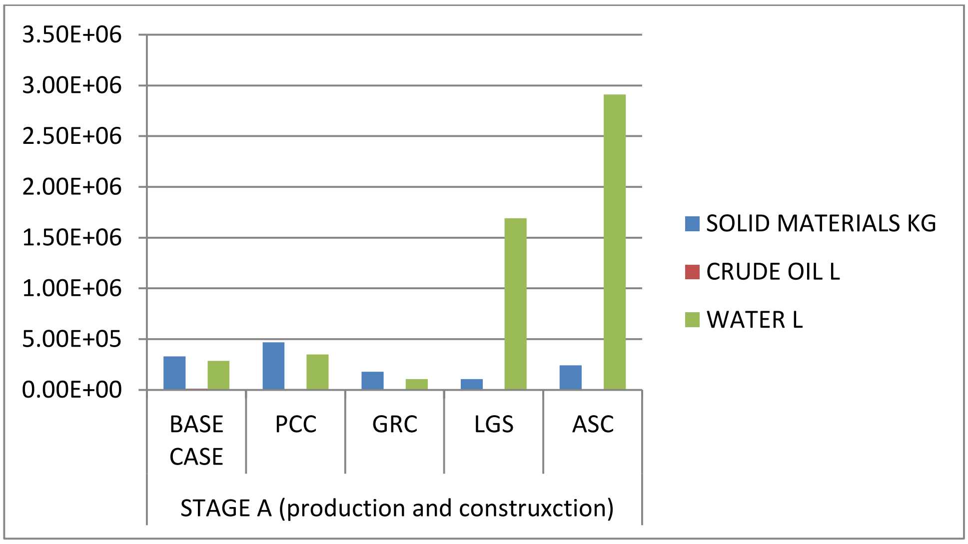


Figure 5.17: Overall Used Resources Comparison to the Base Case Model (Stage A)

Table 5.22 and figure 5.17 show a brief comparison of the four options in relation to the used resources in comparison to the base case model.

5.2 Land Emissions

5.2.1 Base Case Model

Studying figure 5.17, it is clear that the base case model produces its maximum waste during its operation and end of life stages. At the end of life stage and due to the lack of recyclability potential for the base case, 95% of its initial mass will be sent to landfill (3.14E+05 VS 3.3E+05 of its solid construction materials).

Table 5.23: Land Emissions Absolute Value Table by Life Cycle Stages (A to D) For the Base Case Model

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2,B4 & B6)	END OF LIFE (C1 TO C4)	BYOND BUILDING LIFE (D)	TOTAL EFFECT
Bark/Wood Waste	kg	3.84E+00	3.26E+03	3.04E+03	0.00E+00	0.00E+00	6.30E+03
Concrete Solid Waste	kg	6.33E+02	2.90E+04	5.31E+03	0.00E+00	0.00E+00	3.49E+04
Blast Furnace Dust	kg	4.95E+02	4.23E+01	3.58E+01	0.00E+00	0.00E+00	5.73E+02
Steel Waste	kg	2.47E-01	2.79E+01	2.07E+01	0.00E+00	0.00E+00	4.89E+01
Other Solid Waste	kg	3.22E+03	2.57E+02	1.45E+05	1.29E+02	0.00E+00	1.49E+05
Solid Waste to Landfill	kg	0.00E+00	0.00E+00	3.69E+04	2.77E+05	0.00E+00	3.14E+05

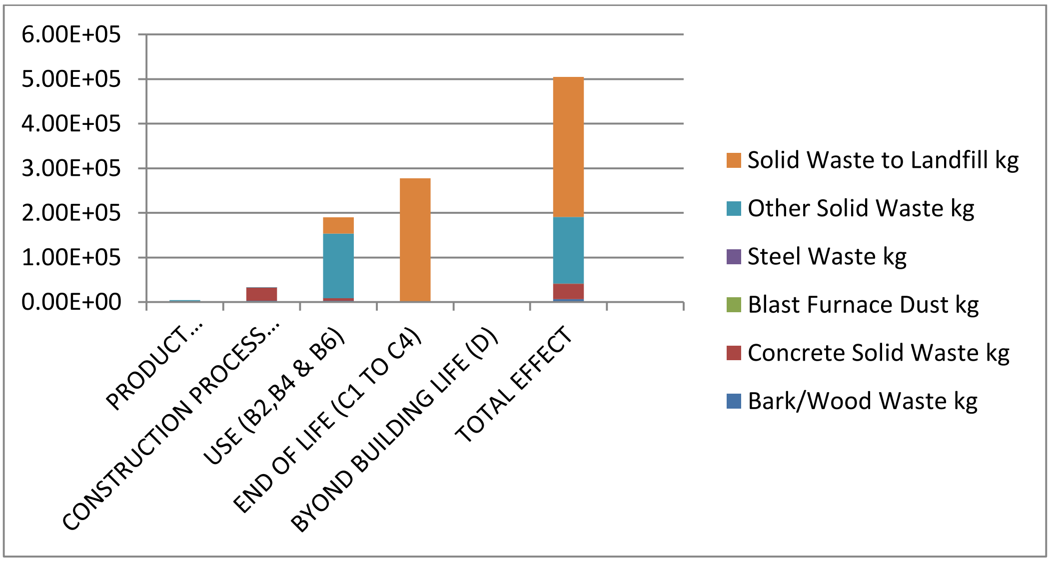


Figure 5.18: Land Emissions Absolute Value Table by Life Cycle Stages (A To D) For The Base Case Model

5.2.2 Pre-Cast Concrete PCC

Overall amount of waste is less compared to the base case model which is dropped from 5.05EE+05 kg to 3.82E+05 kg along the whole life cycle of the building. Figure 5.18, shows more waste during the precast production. The construction waste came down to only 29% compared to the base case model (from 3.26E+04 kg to 9.47E+03 kg). This reduction is due to the reduction of the concrete solid waste to 9.47+03 kg compared to 3.26+04 kg in case of the the conventional cast in situ methodology with a reduction of 71%. During the operation stage, the waste amount came down from 1.90E+05 to 1.50E+05 due to the reduction of maintenance materials and the manufactring replacement waste.

Table 5.24: Land Emissions Absolute Value Table by Life Cycle Stages (A to D) For the PCC Option

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2,B4 & B6)	END OF LIFE (C1 TO C4)	BYOND BUILDING LIFE (D)	TOTAL EFFECT
Bark/Wood Waste	kg	4.94E+01	1.23E+03	2.76E+00	0.00E+00	0.00E+00	1.28E+03
Concrete Solid Waste	kg	2.13E+03	8.08E+03	0.00E+00	0.00E+00	0.00E+00	1.02E+04
Blast Furnace Dust	kg	5.92E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.92E+01
Steel Waste	kg	4.91E-01	6.24E+01	0.00E+00	0.00E+00	0.00E+00	6.29E+01
Other Solid Waste	kg	2.18E+03	1.04E+02	1.45E+05	1.23E+02	0.00E+00	1.47E+05
Solid Waste to Landfill	kg	0.00E+00	0.00E+00	4.45E+03	2.18E+05	0.00E+00	2.23E+05

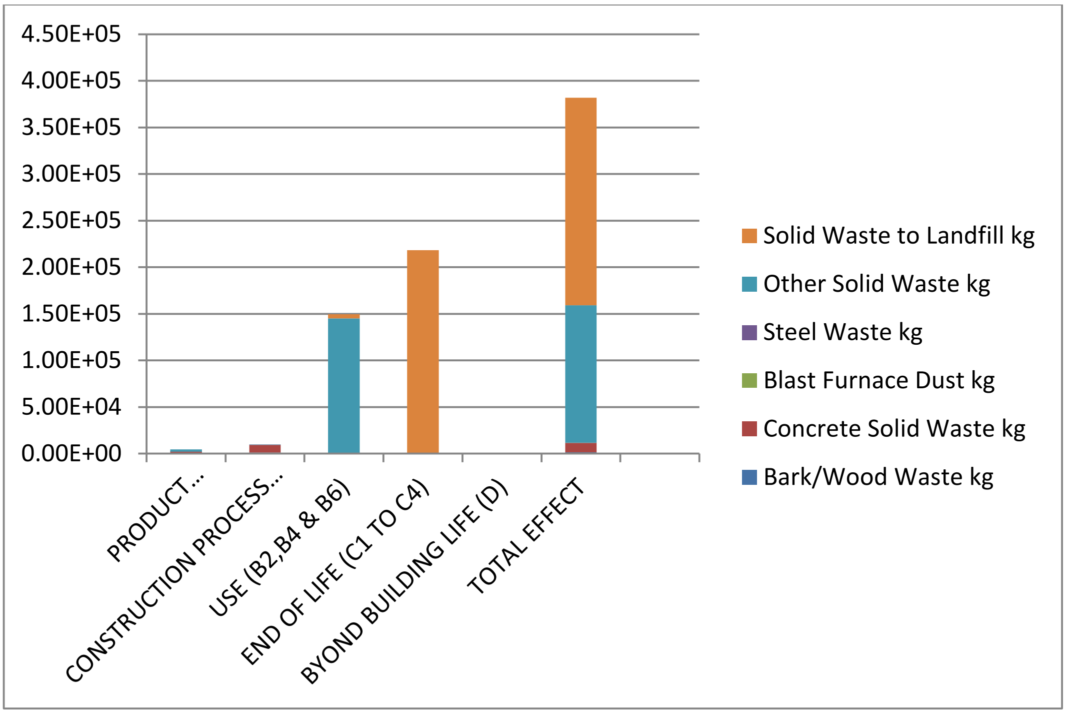


Figure 5.19: Land Emissions Absolute Value Table by Life Cycle Stages (A to D) For the PCC Option

5.2.3 Glass-fiber Reinforced Concrete GRC

Amount of waste in GRC option is much less compared to the base case model. Its overall waste came down to 2.32E+05 with a reduction of 54%. There is no Blast furnace dust waste at all as there is no use of steel rebar in this option. Compared to the base case model, waste during production came down to 62% and during construction to only 4.4% only. The amount of solid waste to the land fill at end of life stage is dropped from 2.77E+05 to 8.35E+04 with a reduction of 70% due to the reduction in the overall used material for this option.

Table 5.25: Land Emissions Absolute Value Table by Life Cycle Stages (A to D) For the GRC Option

		PRODUCT (A1 TO A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4& B6)	END OF LIFE (C1 TO C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECTS
Bark/Wood Waste	kg	6.40E+00	2.14E+02	0.00E+00	0.00E+00	0.00E+00	2.20E+02
Concrete Solid Waste	kg	2.33E+02	1.08E+03	0.00E+00	0.00E+00	0.00E+00	1.31E+03
Steel Waste	kg	7.23E-02	3.62E-03	0.00E+00	0.00E+00	0.00E+00	7.59E-02
Other Solid Waste	kg	2.49E+03	1.29E+02	1.42E+05	6.31E+01	0.00E+00	1.45E+05
Solid Waste to Landfill	kg	0.00E+00	0.00E+00	2.75E+03	8.35E+04	0.00E+00	8.63E+04

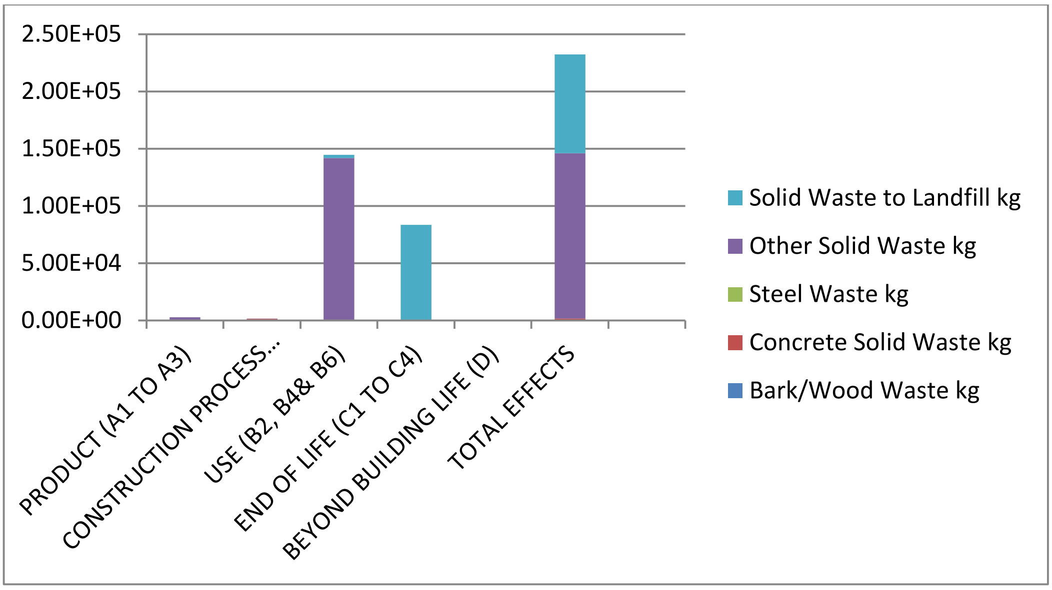


Figure 5.20: Land Emissions Absolute Value Table by Life Cycle Stages (A to D) For the GRC Option

5.2.4 Light Gauge Steel LGS

There is a similarity between this option and the GRC option in terms of the absence of the blast furnace dust and the amount of construction waste as well. However, the production waste is 1.4 times and the end of life waste is almost double that of the GRC option. In general, both options share almost the same overall amount of waste with 46% and 40% compared to the base case model for the GRC and LGS options respectively.

Table 5.26: Land Emissions Absolute Value Table by Life Cycle Stages (A to D) For the LGS Option

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2,B4 & B6)	END OF LIFE (C1 TO C4)	BYOND BUILDING LIFE (D)	TOTAL EFFECT
Bark/Wood Waste	kg	7.93E+01	2.17E+02	2.76E+00	0.00E+00	0.00E+00	2.99E+02
Concrete Solid Waste	kg	4.56E+02	1.09E+03	0.00E+00	0.00E+00	0.00E+00	1.55E+03
Steel Waste	kg	6.11E-02	2.37E+01	0.00E+00	0.00E+00	0.00E+00	2.38E+01
Other Solid Waste	kg	1.38E+03	1.26E+02	1.46E+05	7.95E+01	0.00E+00	1.47E+05
Solid Waste to Landfill	kg	0.00E+00	0.00E+00	4.98E+03	4.83E+04	0.00E+00	5.33E+04

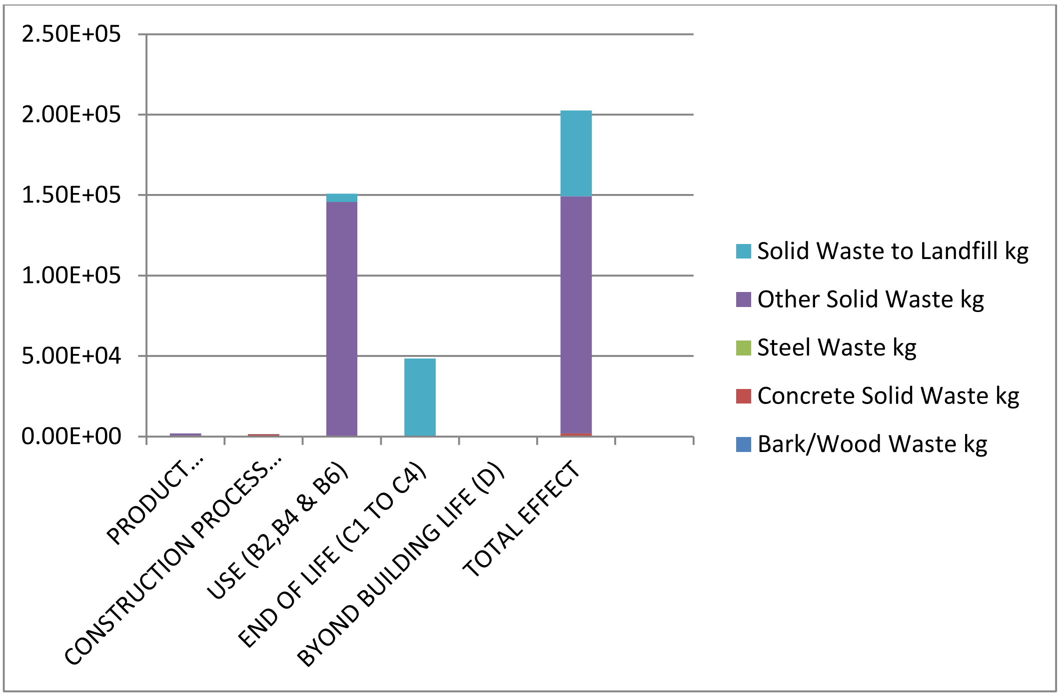


Figure 5.21: Land Emissions Absolute Value Table by Life Cycle Stages (A to D) For the LGS Option

5.2.5 Adapted Shipping Containers ASC

The ASC has the least amount of waste among all the 4 options. Compared to the base case model, its overall waste came down to only 38%, the end of life waste came down to 15% and the waste during the operation stage came down to 79%. The construction waste is similar to both previous options of GRC and LGS as 4% which came from foundation construction only.

Table 5.27: Land Emissions Absolute Value Table by Life Cycle Stages (A to D) for the ASC Option

		PRODUCT (A1 TO A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 & B6)	END OF LIFE (C1 TO C4)	BEYOND BUILDING LIFE (D)	TOTAL EFFECTS
Bark/Wood Waste	kg	8.18E+01	2.17E+02	0.00E+00	0.00E+00	0.00E+00	2.99E+02
Concrete Solid Waste	kg	2.99E-06	1.06E+03	0.00E+00	0.00E+00	0.00E+00	1.06E+03
Steel Waste	kg	6.11E-02	3.06E-03	0.00E+00	0.00E+00	0.00E+00	6.42E-02
Other Solid Waste	kg	1.23E+03	1.16E+02	1.48E+05	1.69E+02	0.00E+00	1.49E+05
Solid Waste to Landfill	kg	0.00E+00	0.00E+00	2.08E+03	4.01E+04	0.00E+00	4.22E+04

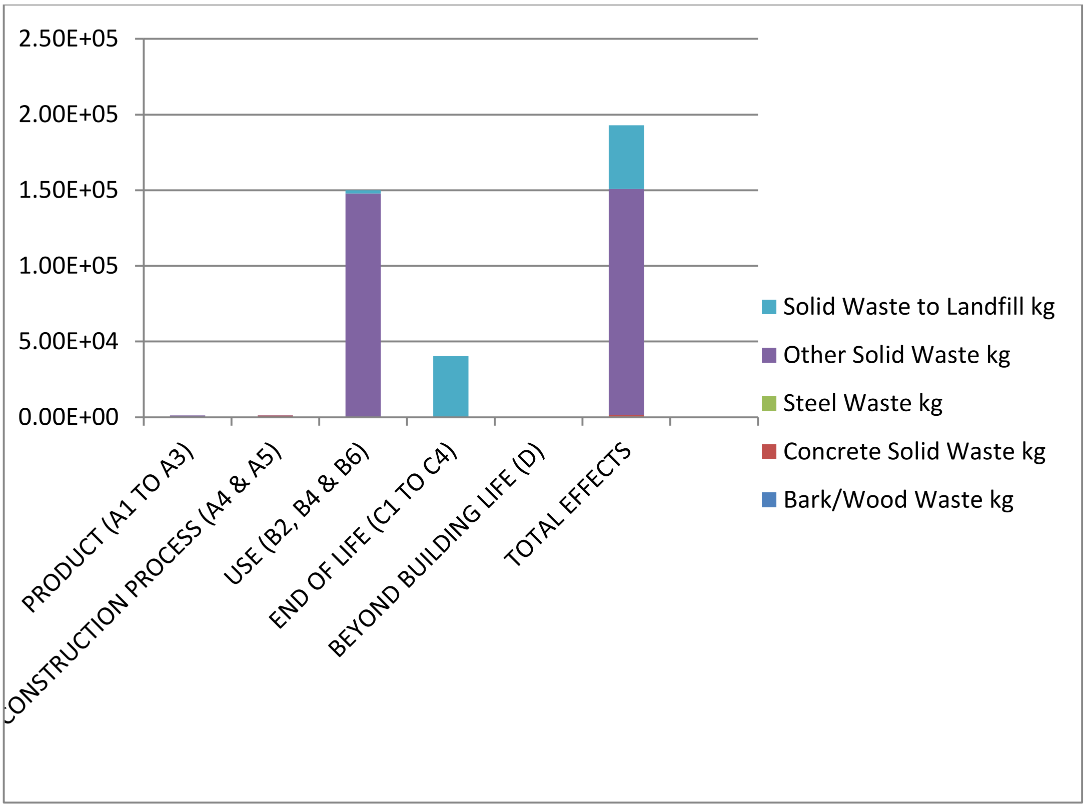


Figure 5.22: Land Emissions Absolute Value Table by Life Cycle Stages (A to D) for the ASC Option

5.2.6 Conclusions For The Options Comparison To The Base Case Model

Studying Table 5.28 and figure 5.23 which show the comparison between all the options for the absolute values of the land emissions along the lifecycle stages (A to D), it is clear that the base case produced the largest amount of waste followed by the pre-cast concrete PCC option. There is a reduction in the concrete waste for the PCC option due to the prefabrication process and due to the controlled environment in the production factory. The least mass of waste comes from ASC option followed by the LGS option due to the factory prefabrication process for both and due to its steel construction material which waste is always minimal.

Table 5.28: Land Emissions - Absolute Value Table (A to D) Comparison for the Four Options to the Base Case Model

		BASE CASE	PCC	GRC	LGS	ASC
Bark/Wood Waste	kg	6.30E+03	1.28E+03	2.20E+02	2.99E+02	2.99E+02
Concrete Solid Waste	kg	3.49E+04	1.02E+04	1.31E+03	1.55E+03	1.06E+03
Blast Furnace Dust	kg	5.73E+02	5.92E+01	0	0	0
Steel Waste	kg	4.89E+01	6.29E+01	7.59E-02	2.38E+01	6.42E-02
Other Solid Waste	kg	1.49E+05	1.47E+05	1.45E+05	1.47E+05	1.49E+05
Solid Waste to Landfill	kg	3.14E+05	2.23E+05	8.63E+04	5.33E+04	4.22E+04
total solide waste		5.05E+05	3.82E+05	2.32E+05	2.03E+05	1.93E+05
total in comparison to the Base Case		100%	76%	46%	40%	38%

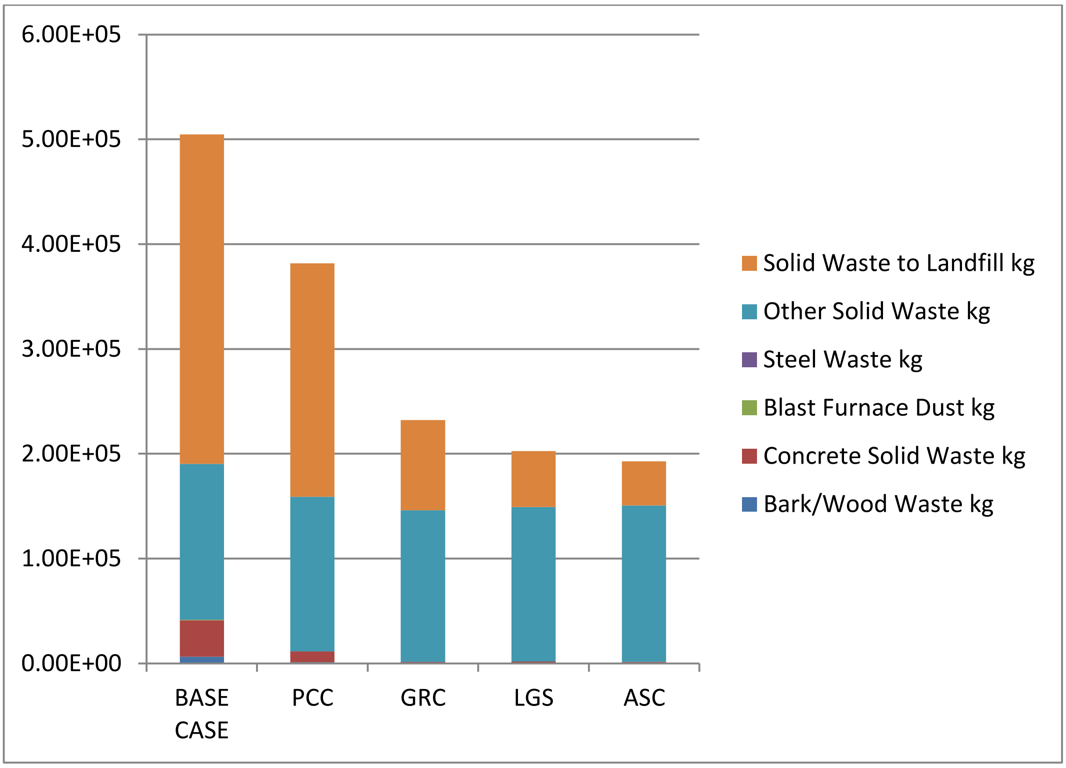


Figure 5.23: Land Emissions - Absolute Value Table (A to D) Comparison for The Four Options To The Base Case Model

The LGS option produces the second least mass of waste which confirms its efficient use of material. GRC came third due to its low amount of materials it used. The amount of the other solid waste which is produced during the building operation stage is almost the same for all the options. It is remarkable that the land emission diagram figure 5.22 matches with the overall weight comparison diagram figure 5.1 which indicates a direct relationship between the mass of produced waste of each option and its construction material mass.

5.3 Total Primary Energy Consumption (TPEC)

The TPEC is the amount of energy consumed during all the activities and processes to produce all the building components. TPEC is measured in mega joules MJ. In Egypt, the source of electricity for the majority of the substations is the fossil fuels. In the following sections, the TPEC will be studied along the different life cycle stages of each of the 5 construction systems.

5.3.1 Product Stage (A1 to A3)

Figure 5.24 shows a comparison for the TPEC by life cycle stage (embodied energy) without considering the operation energy consumption. The energy consumption for the base case model during the production stage reaches 1.00E+06 MJ. During the construction stage, the energy consumption is much less and reaches 1.26E+05MJ. The overall energy consumption during the pre-occupation stage is 1.13E+06MJ. The majority of the pre-occupation energy is consumed by the production of the construction materials not the construction activities which consume around 16.4% only of the total pre-occupation embodied energy. Compared to the overall area of the building (383.08m2), the embodied energy during production and construction stage is 2.95E+03MJ/m2. The preoccupation embodied energy is 79.6% of the total embodied energy excluding the operation energy. Considering the operation energy, the overall effect energy becomes 3.63E+07MJ and the percentage of the preoccupation energy becomes 3% only.

Table 5.29: Energy Consumption Absolute Value Table by Pre-Occupation Stage (A1 to A5)

		Manufacturing	Transport	**Total PRODUCT (A1 TO A3)**	Construction-Installation Process	Transport	**TOTAL CONSTRUCTION PROCESS**	**TOTAL EMBODIED ENERGY**
BASE CASE MODEL	MJ	1.21E+06	2.23E+04	**1.23E+06**	9.40E+04	7.55E+04	**1.70E+05**	**1.40E+06**
PCC	MJ	9.85E+05	2.95E+04	**1.01E+06**	1.10E+05	5.97E+04	**1.69E+05**	**1.18E+06**
GRC	MJ	1.22E+06	7.92E+03	**1.23E+06**	7.32E+04	2.21E+04	**9.53E+04**	**1.33E+06**
LGS	MJ	7.63E+05	1.02E+04	**7.73E+05**	3.87E+04	4.26E+04	**8.13E+04**	**8.54E+05**
ASC	MJ	2.77E+06	8.89E+03	**2.78E+06**	5.18E+04	1.13E+05	**1.65E+05**	**2.94E+06**

Compared to the base case model, the pre-cast concrete PCC option uses around 89% of energy during the production stage and it has almost the same overall construction energy consumption during the construction stage. Manufacturing energy during production stage is 9.85E+05MJ versus 1.21E+06 MJ for the base case with a reduction of 19%. However the transportation energy for the PCC during production (transporting the precast elements to the site) is 2.95E+04 MJ VS 2.23E+04 MJ in case of the base case with an increase of 30%. During construction, PCC installation requires more energy to run extra cranes and equipment to install the prefabricated elements. The installation energy for the PCC reached 1.10E+05MJ VS 9.40E+04MJ with an increase of 17%. Transportation for the base case during the construction is more with 26% for the larger number of workers transportation to and from the site. In total the embodied energy during the preoccupation stage (production + construction) for the PCC is 1.18E+06MJ VS 1.40E+06MJ for the base case model with a reduction of 16%.

For the Glass Reinforced Concrete GRC option, the production energy consumed the same energy as of the base case model with 1.23E+06 MJ. Although the production of the Glass fiber consumes more energy, the overall material mass is much less as has been discussed in the earlier section. The construction energy reached 9.53E+04 MJ (56% of the base case model energy consumption). The reduction in construction energy is due to the light weight of the prefabricated elements that don’t need special cranes or equipment for installation and the overall reduction of the construction process due to the prefabrication process. Transportation during manufacturing reached 7.92E+03 (with a reduction of 65% from the base case model production transportation energy). This reduction in transportation energy is due to the large reduction of volume and weight of the construction components. In total, the embodied energy during the pre-occupation stage is 1.33E+06 with a reduction of 5% from the base case model energy.

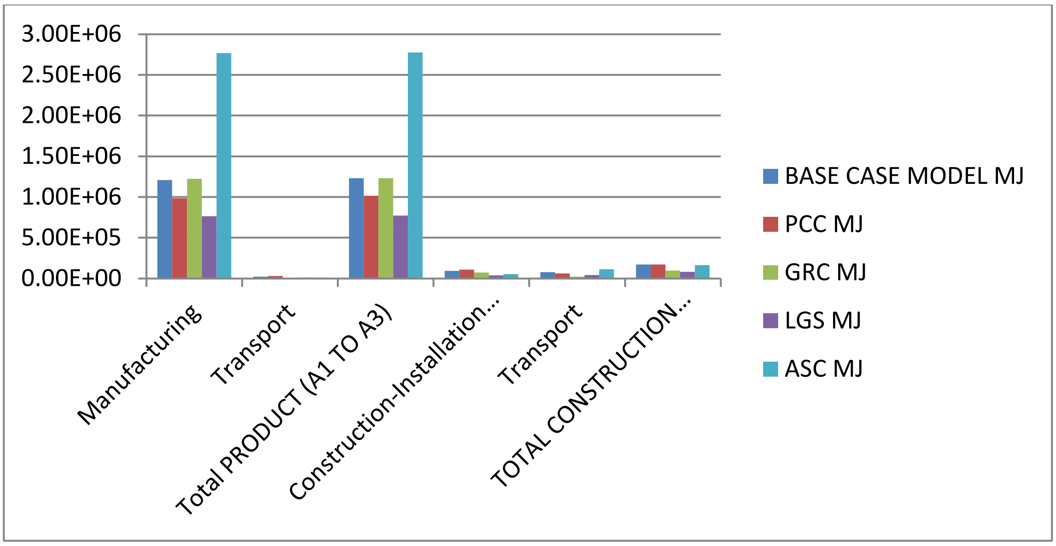


Figure 5.24: Energy Consumption Absolute Value Table by Pre-Occupation Stage (A1 to A5)

For the Light Gauge Steel LGS option, the production energy and the construction energy are 62.8% and 47.8% respectively compared to the same of the base case model with a decrease of 54% in transportation energy during manufacturing. This reduction of energy is due to the offsite manufacturing, the reduction of the material mass and due to the reduction of materials waste as well. Construction and installation energy is 41% of the base case model with a further reduction of transportation energy by 44%. The installation energy reduction is again due to the reduction of process on site as all the modules are constructed off site. The pre-occupation embodied energy is 8.54E+05 with a reduction of 39% of energy used by the base case model.

Regarding the Adapted Shipping Containers ASC, the production energy jumped 2.29 times the base case model. The production process of the steel sheets that compose the shipping containers is the main reason behind the remarkable increase in the production energy. The transportation during construction jumped to 150 % of the base case due to transporting the containers to the construction site. Installation energy is dropped by 45% due to the reduction of construction process on site. The production energy for the containers steel is behind the jump of the pre-occupation embodied energy to almost double compared to the base case model.

Although it is commonly known that the transportation of the prefabricated modular construction is the main item that contributes to the increase of its energy consumption, transportation energy during the pre-occupation stage for the LGS option is about 6% and for the ASC option is about 4% of its overall energy consumption compared to 7% for the base case model. This could be explained by the number of trips that a larger number of workers making in the conventional construction which offset the transportation of the modules over the heavy trucks.

5.3.2 USE Energy (B2, B4)

The use energy is the total energy consumed during the occupation stage of the building along its life time (50 years). This includes three main functions that consumes the energy; maintenance tasks (replacement manufacturing), transportation of the materials and components during these maintenance tasks and the operation energy. The base case model during the occupation stage consumes 3.03E+05MJ for maintenance. It is divided between replacement manufacturing energy which is 2.86E+05MJ and replacement transport which is 1.65E+04.MJ. Operation energy includes cooling, heating, water heating, lighting and all other operation energy that has been consumed during the life cycle of the building. Operation energy has been calculated by Athena as 3.49E+07MJ which forms 96% of the total energy consumption along the 50 years of the building life cycle. Maintenance energy compared to the overall energy during the occupation stage is less than 1%. The overall occupation energy including the maintenance and the operation energy is 3.52E+07MJ. Table 5.30 shows a comparison between the base case and the four options in their absolute values of the occupation energy consumption.

Table 5.30: Energy Consumption Absolute Value Table by Occupation Stage (B2, B4 & B6)

		Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total USE**
BASE CASE MODEL	MJ	2.86E+05	1.65E+04	3.49E+07	**3.52E+07**
PCC	MJ	2.12E+05	3.58E+03	3.49E+07	**3.51E+07**
GRC	MJ	1.42E+05	2.48E+03	3.45E+07	**3.46E+07**
LGS	MJ	2.33E+05	4.00E+03	3.50E+07	**3.53E+07**
ASC	MJ	7.41E+05	1.77E+04	3.57E+07	**3.64E+07**

For the PCC option, the overall occupation energy is slightly less than the base case model and it is 26% less for the maintenance energy. This could be explained that the buildings envelop for both provide the same thermal performance which makes the cooling and heating loads almost the same. On another hand, the durability of the precast walls reduces its maintenance and makes it more efficient maintenance wise. The precast panels either for the walls or the slabs are not plastered due to their fare face surfaces and this reduces the maintenance energy as well.

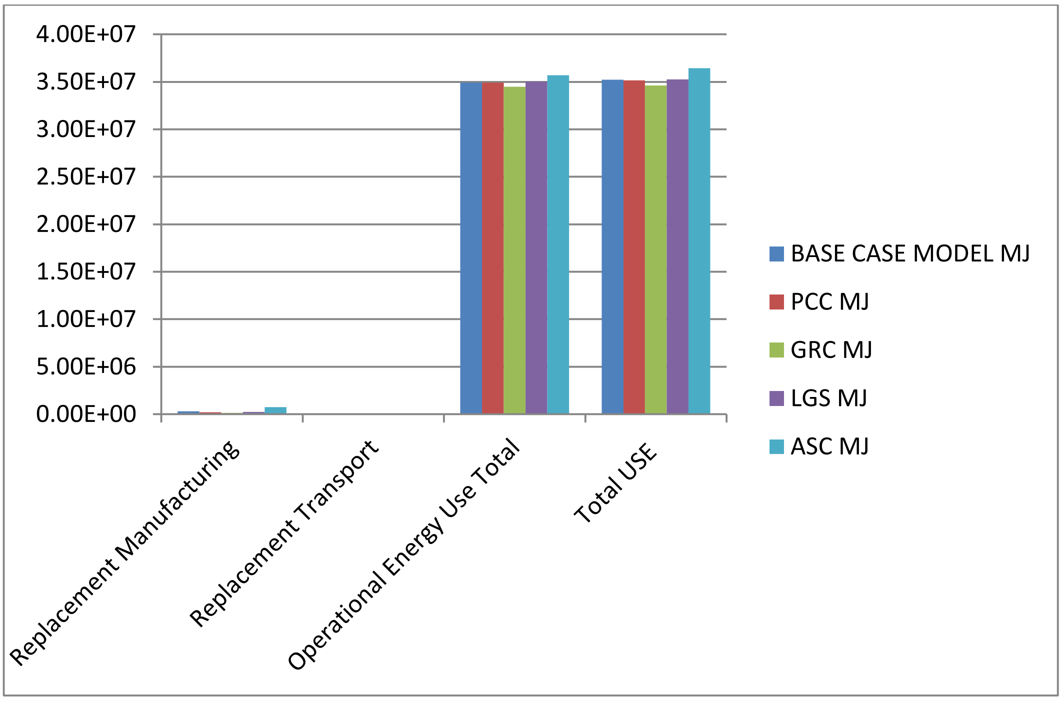


Figure 5.25: Energy Consumption Absolute Value Table By occupation stage (B2, B4 & B6)

For the GRC option, all the walls, slabs and floors are left unfinished relying on the fare face finish of the pre-fabricated panels. Accordingly the maintenance energy is dropped down to around 50% of the base case model besides the capital and the running cost saving as well. The operation energy is slightly less (1.2%) compared to the base case model. although all options share the same thickness of the thermal insulation layer, the high thermal insulation for the GRC cavity panels increases the efficiency of this option performance during the operation stage.

The maintenance energy for LGS option is still lower than the base case by 19% but much higher than in the GRC option. This reduction is referred to the reduction in the material mass for this option. The operation energy is slightly higher than the base case due to the possibility of air leakage of the system.

The 259% the increase in the maintenance energy for the ASC option with 259% compared to the base case refers to the high and frequent maintenance requirement for the steel buildings in general. Similarly, the operation energy is higher by 2.3% due to possibility of air leakage of the system similar to the LGS option.

5.3.3 End of Life & Beyond Building Life

In the end of life stage, Impact Estimator calculates the amount of energy required for demolition, de-construction, disposal and waste processing of the building and for the transportation of the deconstruction material to the landfill. However, in the beyond building life stage, the negative energy figures that are shown for LGS and ASC options refer to the energy gained through recycling or reusing the different parts of the building. Due to the relationship of these two stages, we will analyze their energy consumption results together. Table 5.31 shows the absolute values of the different options during these two stages.

Table 5.31: Energy Consumption Absolute Value by End of Life and Beyond Building Life Stages (C&D)

		De-construction, Demolition, Disposal & Waste Processing	Transport	**Total END OF LIFE**	BBL Material	BBL Transport	**Total BEYOND BUILDING LIFE**
BASE CASE MODEL	MJ	5.81E+04	3.36E+04	**9.17E+04**	2.94E+04	0.00E+00	**2.94E+04**
PCC	MJ	6.70E+04	2.64E+04	**9.34E+04**	2.04E+04	0.00E+00	**2.04E+04**
GRC	MJ	1.82E+04	1.01E+04	**2.83E+04**	3.53E+02	0.00E+00	**3.53E+02**
LGS	MJ	1.93E+04	5.86E+03	**2.52E+04**	-2.99E+04	0.00E+00	**-2.99E+04**
ASC	MJ	4.87E+04	4.87E+03	**5.35E+04**	-1.98E+05	0.00E+00	**-1.98E+05**

For the base case model, the total end of life energy is 9.17E+04 which is considered as 0.2% of its overall life cycle energy consumption. Demolition energy is around 63% of the total end of life consumed energy and transportation consumes around 37%. For the PCC option is higher by around 2% of this value. For GRC and LGS options and due to their overall reduced mass of materials used their end of life energy consumptions and compared to the base case model are 30% and 27% for the GRC and LGS options respectively. Compared to the base model, LGS option has 28% and GRC option has 16% of the used material mass (please refer to figure 5.1). This note highlights a relative relationship between the end of life consumed energy and the overall weight of the materials used in each option. For ASC, its end of life is around 58% compared to the base case model.

So, in general LGS option has the least end of life energy consumption among all the four options compared to the base case model followed by GRC options then the ASC option.

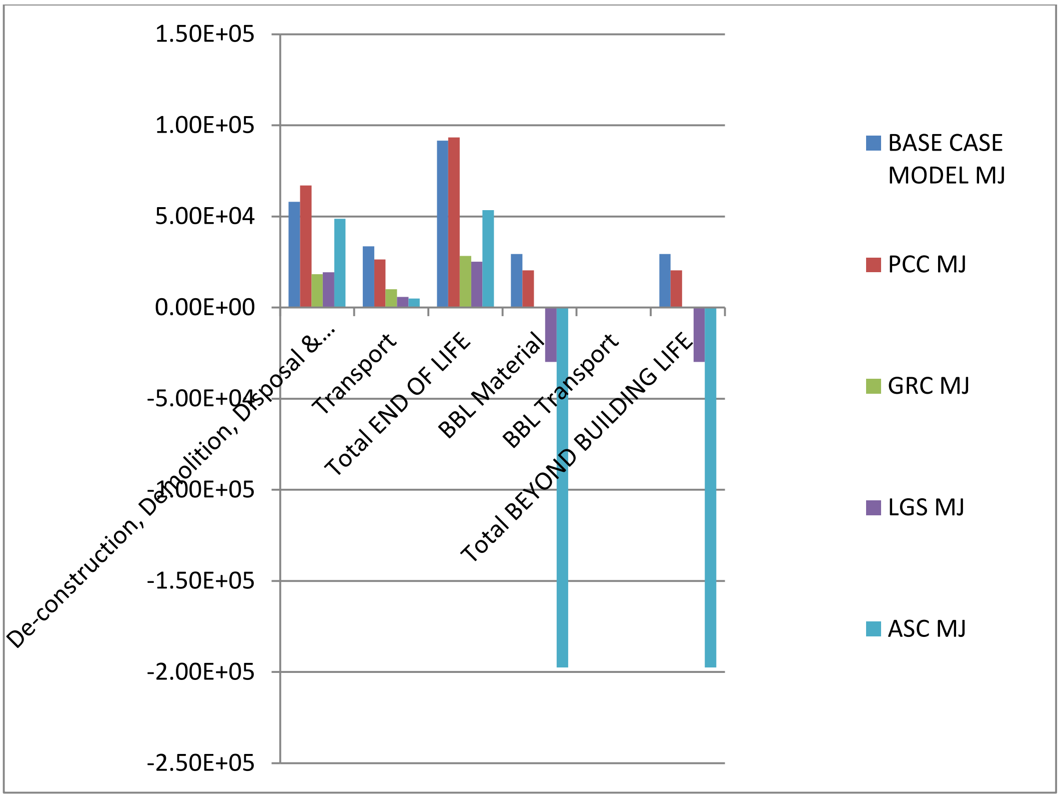


Figure 5.26: Energy Consumption Absolute Value by End of Life and Beyond Building Life Stages (C&D)

For the beyond of life energy, LGS and ASC options show negative energy calculated due to their reusability potential. For LGS option, the beyond of life energy is 3.8% of its production energy while it is 7.1% in case of the ASC option.

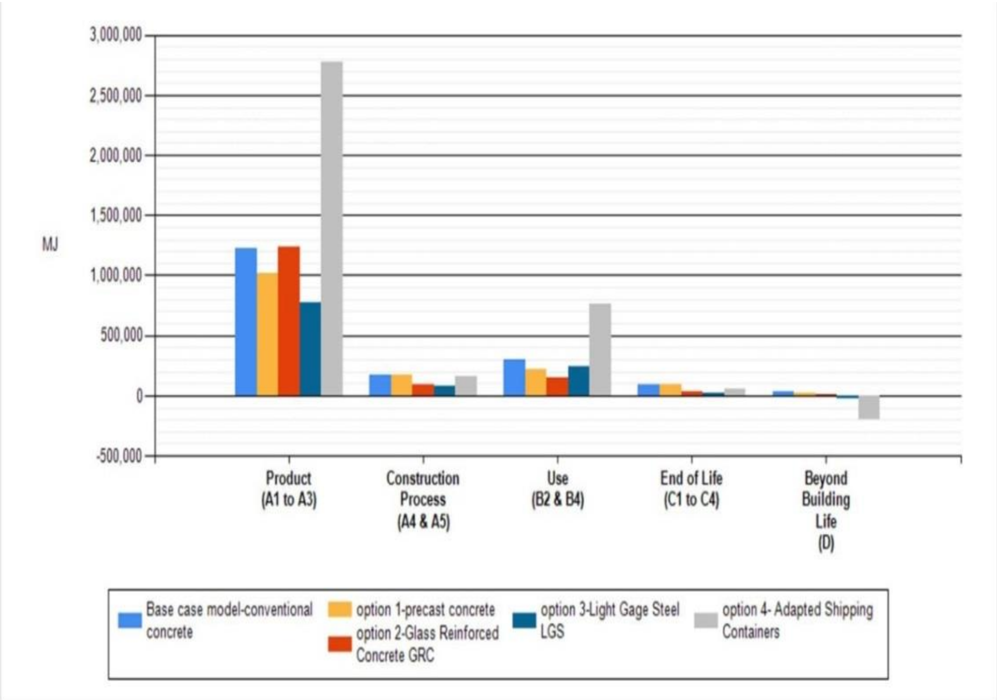
5.3.4 Total Effect

After analyzing the five different stages of the life cycle of each of the four options and by comparing their total effects of their embodied energy figure 5.27, it is clear that LGS option is the option with the least embodied energy with a saving of 40% compared to the base case model. If the operation energy is considered as in figure 5.28, GRC option becomes the least energy consuming option less than the LGS by 0.356%. ASC option has almost two times the embodied energy used by the base case model; however if after end of life energy is considered, this extra energy consumption could be reduced to 6% only as per figure 5.28 below.

One major factor that could not be considered in the Impact Estimator calculation is the reusability of the shipping containers as residential units after being used for10 to 20 years in the shipping industry. The proposed option here is based on the adaptation of used shipping containers and reconfiguring them to be used as residential spaces. Accordingly, a large portion of this embodied energy should be offseted to the first life of the containers. If we assume that the life time of the used containers as shipping components is 20 years and the life time of the containers as residential spaces is 50 years, 28.5% of the production energy should be deducted. Applying this correction measure, the production energy will become 1.98E+06MJ and the total embodied energy will be reduced to 2.76E+06MJ which is still 151% of the base case total embodied energy.

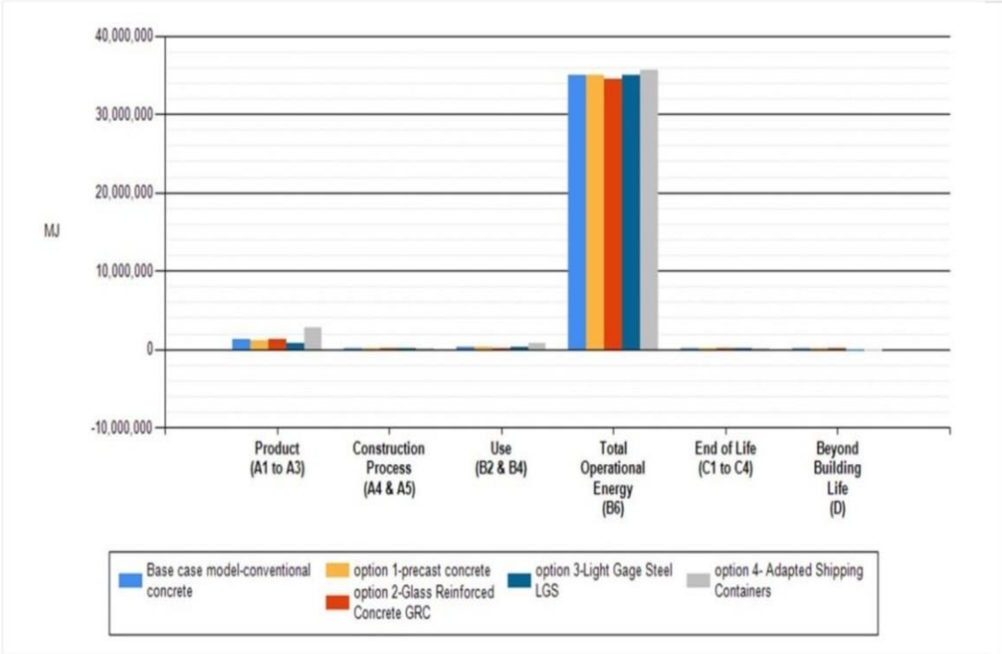
5.4 Global Warming Potential

Global warming potential (GWP) is also known as Green House Gases GHG emissions. It is one of the main environmental impact measures that all LCA researchers are looking after. It measures the equivalent amount of carbon contained in a mass of material (kg CO_2eq).



Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	End of Life (C1 to C4)	Beyond Building Life (D)	Total	COMPARISON TO THE BASE CASE MODEL
Base case model-conventional concrete	MJ	1.23E+06	1.70E+05	3.03E+05	9.17E+04	2.94E+04	**1.82E+06**	100%
option 1-precast concrete	MJ	1.01E+06	1.69E+05	2.16E+05	9.34E+04	2.04E+04	**1.51E+06**	83%
option 2-Glass Reinforced Concrete GRC	MJ	1.23E+06	9.53E+04	1.45E+05	2.83E+04	3.53E+02	**1.50E+06**	82%
option 3-Light Gage Steel LGS	MJ	7.73E+05	8.13E+04	2.37E+05	2.52E+04	-2.99E+04	**1.09E+06**	60%
option 4- Adapted Shipping Containers	MJ	2.78E+06	1.65E+05	7.59E+05	5.35E+04	-1.98E+05	**3.55E+06**	195%
Total	**MJ**	**7.02E+06**	**6.80E+05**	**1.66E+06**	**2.92E+05**	**-1.77E+05**	**9.48E+06**	

Figure 5.27: Comparison of Total Primary Energy by Life Cycle Stages (Embodied Effects) In MJ



Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total	comparison with the base case modle
Base case model-conventional concrete	MJ	1.23E+06	1.70E+05	3.03E+05	3.49E+07	9.17E+04	2.94E+04	**3.67E+07**	100.00%
option 1-precast concrete	MJ	1.01E+06	1.69E+05	2.16E+05	3.49E+07	9.34E+04	2.04E+04	**3.64E+07**	99.18%
option 2-Glass Reinforced Concrete GRC	MJ	1.23E+06	9.53E+04	1.45E+05	3.45E+07	2.83E+04	3.53E+02	**3.60E+07**	97.91%
option 3-Light Gage Steel LGS	MJ	7.73E+05	8.13E+04	2.37E+05	3.50E+07	2.52E+04	-2.99E+04	**3.61E+07**	98.27%
option 4- Adapted Shipping Containers	MJ	2.78E+06	1.65E+05	7.59E+05	3.57E+07	5.35E+04	-1.98E+05	**3.92E+07**	106.82%
Total	**MJ**	**7.02E+06**	**6.80E+05**	**1.66E+06**	**1.75E+08**	**2.92E+05**	**-1.77E+05**	**1.84E+08**	

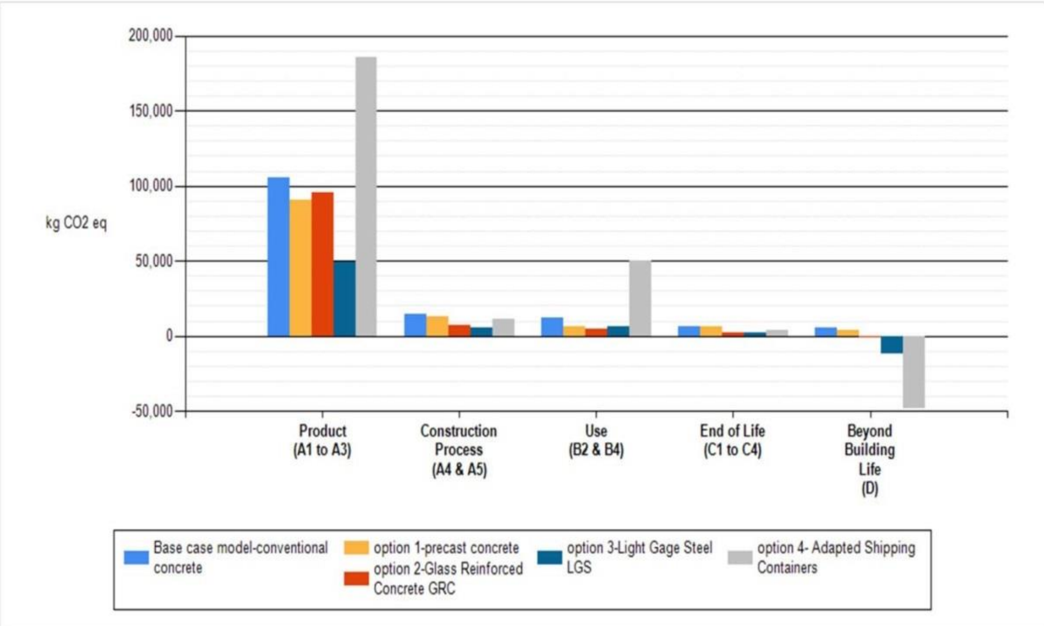
Figure 5.28: Comparison of Total Primary Energy by Life Cycle Stages in MJ

5.4.1 Pre-Occupation Stage

In the base case model, the overall embodied emissions is1.44E+05 kgCO2eq while its total embodied energy was 1.82E+06 MJ. This means that each MJ produces 0.08 kgCO2eq.

During the production process, 1.05E+05 kgCO2eq are produced equals to 73% of the total embodied emissions (excluding the operation emissions). The construction emissions are around 10% of the pre-occupation stage emissions. It is noted that production to construction emissions ratio is relative to the production to construction energy consumption. The total embodied emission is 1.44E+05kgCO2eq and 3.76E +02kgCO2eq/m2. For all the four options, their production and manufacturing GHG emissions are relative to their consumed energy as explained in the total primary energy section. However, the following points are noted:

- LGS option is the option with the least GHG emissions. Its pre-occupation emission compared to the base case model is 36%.
- PCC option is less than the base case by 17%.
- Although GRC option uses 54% of the solid resources that the base case consumes, it produces 86% emissions during its production and construction stage. This could be referred to the amount of emissions that 1kg of fiber glass produces compared to cement.
- ASC option produces 140% emissions compared to the base case model. This is due to the mass of steel used in this option and the amount of emissions produced compared to concrete.



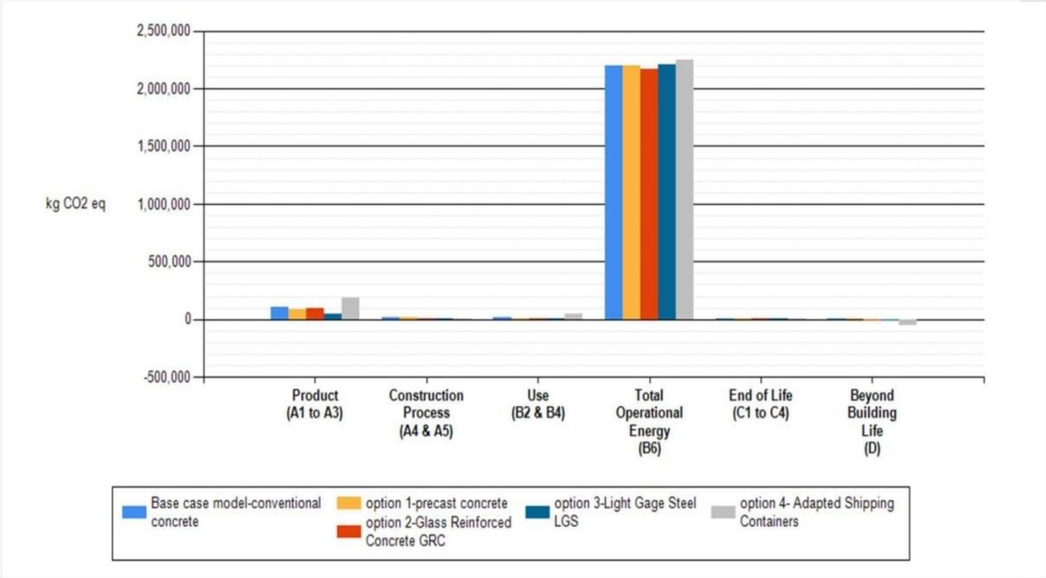
Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	End of Life (C1 to C4)	Beyond Building Life (D)	Total	COMPARISON TO THE BASE CASE MODEL
Base case model-conventional concrete	kg CO2 eq	1.05E+05	1.45E+04	1.23E+04	6.68E+03	5.65E+03	**1.44E+05**	100%
option 1-precast concrete	kg CO2 eq	9.05E+04	1.33E+04	6.36E+03	6.69E+03	3.67E+03	**1.20E+05**	83%
option 2-Glass Reinforced Concrete GRC	kg CO2 eq	9.58E+04	7.44E+03	4.46E+03	2.08E+03	-9.25E+02	**1.09E+05**	75%
option 3-Light Gage Steel LGS	kg CO2 eq	4.91E+04	5.85E+03	6.55E+03	1.80E+03	-1.16E+04	**5.17E+04**	36%
option 4- Adapted Shipping Containers	kg CO2 eq	1.85E+05	1.13E+04	4.99E+04	3.67E+03	-4.86E+04	**2.02E+05**	140%
Total	**kg CO2 eq**	**5.26E+05**	**5.23E+04**	**7.96E+04**	**2.09E+04**	**-5.18E+04**	**6.27E+05**	

Figure 5.29: Comparison of Global Warming Potential by Life Cycle Stage (Embodied Effects)

5.4.2 Occupancy Stage

During occupancy stage, Cooling, heating, water heating, lighting and all other operation activities for the base case produce around 2.20E+06 kgCO2eq. Figure 5.30 shows that the operation emissions are around 95% of the overall emission of the base case module and most of other studied options. GRC option has the least operation emissions which reach 2.17E+06 kgCO2eq while the ASC has higher operations emissions that reached 2.25E+06 kgCO2eq. The reduced operation emissions in case of the GRC option could be justified through its higher thermal resistance of its walls and roof panels forming its external envelop and helped in reducing the cooling and heating loads. In contrary to that and regarding ASC option, although the same layer of thermal insulation of 50mm extruded polystyrene within the walls and 75mm on top of the roof for all the options, its U value is relatively higher than the base case which leads to relatively higher cooling and heating loads.

For the maintenance processes of painting, components repairing or systems replacing, the base case module produces emissions of 1.23E+04 kgCO2eq. Among the four options, the GRC has the least maintenance emissions due to the absence of any internal or external finishes. The ASC has maintenance emissions equivalent to four times the base case which indicates the high maintenance cost of this steel option.



Project Name	Unit	Product (A1 to A3)	Construction Process (A4 & A5)	Use (B2 & B4)	Total Operational Energy (B6)	End of Life (C1 to C4)	Beyond Building Life (D)	Total	comparison to the base case model
Base case model-conventional concrete	kg CO2 eq	1.05E+05	1.45E+04	1.23E+04	2.20E+06	6.68E+03	5.65E+03	**2.34E+06**	100%
option 1-precast concrete	kg CO2 eq	9.05E+04	1.33E+04	6.36E+03	2.20E+06	6.69E+03	3.67E+03	**2.32E+06**	99%
option 2-Glass Reinforced Concrete GRC	kg CO2 eq	9.58E+04	7.44E+03	4.46E+03	2.17E+06	2.08E+03	-9.25E+02	**2.28E+06**	97%
option 3-Light Gage Steel LGS	kg CO2 eq	4.91E+04	5.85E+03	6.55E+03	2.21E+06	1.80E+03	-1.16E+04	**2.26E+06**	96%
option 4- Adapted Shipping Containers	kg CO2 eq	1.85E+05	1.13E+04	4.99E+04	2.25E+06	3.67E+03	-4.86E+04	**2.45E+06**	105%
Total	**kg CO2 eq**	**5.26E+05**	**5.23E+04**	**7.96E+04**	**1.10E+07**	**2.09E+04**	**-5.18E+04**	**1.17E+07**	

Figure 5.30: Comparison of Global Warming Potential by Life Cycle Stage with Operation Emissions

5.4.3 <u>Decommissioning Stage</u>

During end of life stage, the base case model and due to its demolition and transportation process produced 6.68E+03 kgCO2eq. It is clear that beyond the building life, its demolished materials could be recycled to be used as crashed recycled aggregate in the new concrete. For PCC option, almost the same case in end of life emissions, however its recycling emissions are almost two third compared to the base case. The reusability of some of the items, either the hollow core slabs or the precast walls could be the reason behind this reduction. GRC and LGS options share the least end of life emissions due to the high reusability portion. Looking beyond the building life for these two options, it shows negative emissions indicating the reusability consideration but with different percentages. In the GRC, it is -9.25E+02 kgCO2eq which is equal to 1% of its production emissions. For the LGS option, it offsets 23% of its production emissions through its reusability and recycling potentials. The production offsetting reached 26% for ASC option.

5.4.4 Total Emissions

LGS option has the least overall embodied emissions with 36% compared to the base case model while ASC option has the highest embodied emissions of 140% compared to the same base case model.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.0 Conclusions

Egypt is a developing country with many economic and social challenges and affordable housing is one of these issues. This research studies this topic and proposes prefabricated construction methodologies as an approach efficient housing solution. Many researches proofed the viability of introducing prefabrication into housing industry due to its many advantages which include high quality, low cost and time savings. It was clear through reviewing many literatures that there are many successful experiments in many developing countries that introduced prefabrication and modular construction systems to solve their shortage in housing supply.

This research focused on comparing different prefabricated and modular construction systems to the traditional conventional cast in situ construction methodology and assessing their environmental impact. It may seem irrelevant to focus on environmental not commercial impact for a developing country which cost of construction is the main criteria for selecting the preferable construction methodology. Although we did not run any commercial analysis for the assessed systems, it was clear that the most environmental systems are the systems that use less materials and accordingly less costly. Through this research and by running a life cycle assessment as a tool for comparison between the different prefabricated construction methodologies it was clear that the system that uses the least mass of the materials that have low embodied energy is the best environmental system. Accordingly, the cost of these systems will be less expensive due to its low mass of materials and low energy consumption during its production stage. With the introduction of prefabrication technology into the housing industry, it achieves fast construction due to its mass production and cost savings due to its economy of scale.

In this research, the following four prefabricated construction systems are compared to the conventional cast in situ and masonry construction methodology which was considered as the base case model:

1. Prefabricated Cast Concrete PCC

2. Glass Reinforced Concrete GRC
3. Light Gauge Steel LGS
4. Adapted Shipping Containers ASC

Through the analysis of the 4 prefabricated options and comparing them to the base case model, both LGS and GRC options showed lots of advantages in relation to the other options. Although ASC option showed great advantage in its reusability, it failed in many other areas due to its energy intensive manufacturing process. PCC option showed a close proximity to the conventional construction system regarding its performance in many areas due to the mass of the used concrete. The following conclusions highlight the areas where the best options have proved their better performance in:

Used resources:

- The weight of the LGS option is 16% of the base case model while the percentage in the GRC option is 28.4%.
- During the production and construction stages (stage A) LGS consumes 33% of the solid materials that the base case model consumes while GRC consumes around 54%.
- During the same stage, LGS consumes 21% of the crude oil while GRC consumes around 35% compared to the base case model.
- When it comes to the water consumption during stage A, GRC option becomes more competitive with 37% only while the LGS option consumes 589% of that amount that base case model consumes.

Land emissions (amount of waste):

- ASC option produced the least overall waste which reached 38% compared to the base case model.
- For the LGS option, the overall waste is less than GRC option as it came down to only 40% of the base case model.
- The overall waste for GRC option compared to the base case model came down to 46%. During production it was dropped to 62% and 4.4% only during construction. A large portion of the building with this option will

be recycled. Accordingly the land fill waste has been dropped to only 30% compared to the base case.

Total primary energy consumption TPEC:

- In comparison to the base case model, LGS had the least embodied energy with 60% while the GRC option consumed 82% with the exclusion of the operation energy. If the operation energy is considered, GRC comes the least energy consuming option lower than the LGS with 0.356%.
- ASC option has almost doubled the embodied energy of the base case model.
- The maintenance energy for the GRC is the least with 50% reduction compared to the base case model due to the elimination of the internal and external finishes relying on the natural finish of the GRC surfaces.

Global warming potential:

- LGS option is the option with the least GHG emissions. Its pre-occupation emission compared to the base case model is 36% followed by the GRC option with 75%.
- GRC option has the least operation GHG emissions.
- Although GRC option uses 54% of the solid resources that the base case consumes, it produces 86% emissions during its production and construction stage. This could be referred to the amount of emissions that 1kg of fiber glass produces compared to cement.
- GRC option has the least operation emissions with 96% of the emissions that the base case produces. This is because of its higher thermal resistance of its walls and roof panels which form its external envelop and help in reducing the cooling and heating loads.
- LGS and GRC options share the least end of life emissions with 96% and 97% respectively compared to the base case model due to the high reusability portion of both options.
- The reusability of LGS option beyond building life offset 23% of its production emissions while in case of GRC its reusability offsets 1% only.

- In all options besides the base case model, 95% of the overall environmental impact along their life time span happens during the occupation stage.

6.1 Recommendations

With these results, both GRC and LGS systems are recommended to be used as a better construction methodology that is more environmentally sustainable to be used for affordable housing. Both options consumed the least mass of materials and produced the least GHG. Both options proofed savings in energy consumption during production and construction stages as well as during the occupation stages. The reusability of both systems offsets good portion of their production energy as well. Although LGS consumed fewer materials, has less embodied energy and produces less mass of wastes and has larger amount of reused components, GRC consumed less amount of water and has the least operation and maintenance energy along its life time.

6.2 Future Research

- Due to the scope of this research, a case model building was designed with limited components to run the comparison between the different construction systems. Accordingly not all the building components have been tested in full details against each system. For example, the prefabricated staircase in LGS system has not been studied. A detailed comparison between the LGS system and GRC systems could be conducted in detail and existing case buildings to be studied.

- Although adapting shipping containers is normally considered as a solution for affordable houses, LCA proofed that ASC system has the highest embodied energy, produced the highest GHG emissions and consumed the highest amount of water during its production process. Accordingly, we recommend instead of its reuse, its steel could be recycled to manufacture LGS systems which will make it more efficient using recycled steel. So, one of the proposed future research is to assess the impact of using recycled steel of the shipping containers into LGS system to enhance its efficiency and reduce its cost for affordable houses.

- Run a commercial comparison between LGS and GRC systems based on some case studies in Egypt.

- Glass fiber is an energy intensive material that has a high embodied energy due to its manufacturing process. Some researchers studied replacing the glass fibers by other natural fibers for reinforcing the concrete. Accordingly and a proposal for the future researches we recommend to research the impact of replacing the glass fibers with natural fibers for the GRC option and to study the reduction in its environmental impact.

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APENDIX A

U VALUE CALCULATION FOR THE EXTERNAL ENVELOP FOR PCC OPTION

U value calculation for the Pre-cast Concrete (PCC) Option

Thermal transmittance U value (w/m2k) = 1/R value

Thermal Resistance R value (m2.k/w) = thickness (m)/thermal conductivity (m.k/w)

- R value for the roof = (70mm gravel+50mm foam concrete+50mm polystyrene+110mm hollow core concrete slab)
- The thermal conductivity values of Gravel, foam concrete, polystyrene and hollow core concrete slab are 0.7, 0.2, 0.03 and 0.258 m.k/w respectively (the engineering toolbox).
- R value for the roof = (.07/0.7)+(0.05/0.2)+(0.05/0.03)+(0.11/0.258) = 0.7+0.25+2.5+0.125= 2.5 m2k/w

U value for the roof=1/2.5=0.40 w/m2k less than 0.41w/m2k

- R value for the wall=(100mm concrete layer + 50mm extruded polystyrene board+75mm concrete layer)
- Thermal conductivity values for the concrete and polystyrene are 0.6 and 0.03 w/m2k respectively
- R value for the wall= (.1/.6)+(.05/.03)+(.075/.6)=0.16+0.16+0.1=1.96 m2k/w

U value for the wall =1/1.96=0.51w/m2k less than 0.98w/m2k

APENDIX B

U VALUE CALCULATION FOR THE EXTERNAL ENVELOP FOR GRC OPTION

U value calculation for the Glass Reinforced Concrete (GRC) Option

Thermal transmittance U value (w/m2k) = 1/R value

Thermal Resistance R value (m2.k/w) = thickness (m)/thermal conductivity (m.k/w)

- R value for the roof = (70mm gravel+50mm foam concrete+30mm GRC hollow slab+75mm polystyrene)
- The thermal conductivity values of Gravel, foam concrete, GRC hollow slab and polystyrene are 0.7, 0.2, 0.3 and 0.03m.k/w respectively (the engineering toolbox).
- R value for the roof = (.07/0.7)+(0.05/0.2)+(0.03/0.3)+(0.75/.03) = 0.1+0.25+0.1+2.5 = 2.95 m^2k/w

U value for the roof =1/2.95=0.338 w/m^2k less than 0.41w/m^2k

- R value for the wall = (30mm GRC sandwich panel+ 50mm extruded polystyrene board)
- Thermal conductivity values for the GRC panel and polystyrene are 0.3 and 0.03 w/m2k respectively
- R value for the wall= (.03/.3)+(.05/.03)=0.1+1.6=1.76 m^2k/w

U value for the wall =1/1.76=0.568 w/m^2k less than 0.98w/m^2k

APENDIX C

U VALUE CALCULATION FOR THE EXTERNAL ENVELOP FOR LGS OPTION

U value calculation for the Light Gauge Steel (LGS) Option

Thermal transmittance U value (w/m2k) = 1/R value

Thermal Resistance R value (m2.k/w) = thickness (m)/thermal conductivity (m.k/w)

- R value for the roof=(70mm gravel+75mm polystyrene+12mm fiber cement board+12mm gypsum board)
- The thermal conductivity values of Gravel, polystyrene, fiber cement boards and fiber glass boards are 0.7, 0.03, 0.17 and 0.17 m.k/w respectively (the Engineering toolbox)
- R for the roof = (.07/0.7)+(0.75/0.03)+(0.012/0.17)+(0.012/0.17) = 0.1+0.25+0.07+0.07= 2.75 m2k/w

Roof U value=1/2.75=0.364 w/m2k less than 0.41w/m2k

- R value for the wall=(12mm gypsum board + 50mm extruded polystyrene board+12mm fiber cement board)
- Thermal conductivity values for the gypsum, polystyrene and fiber cement board are 0.17, 0.03 and 0.17 w/m2k respectively
- R value for the wall = (.012/.17)+(.05/.03)+(.012/.17) = 0.07+1.6+0.07=1.96 m2k/w

U value for the wall =1/1.82=0.55w/m^{2}k less than 0.98w/m^{2}k

APENDIX D

U VALUE CALCULATION FOR THE EXTERNAL ENVELOP FOR ASC OPTION

U value calculation for the Adabted Shipping Container (ASC) Option

Thermal transmittance U value (w/m^2k) = 1/R value

Thermal Resistance R value (m2.k/w) = thickness (m)/thermal conductivity (m.k/w)

- R value for the roof=(75mm polystyrene+12mm gypsum board)
- The thermal conductivity values of polystyrene and gypsum boards are 0.03 and 0.17 m.k/w respectively (Engineering tool box).
- R for the roof= (0.012/0.17) + (0.75/0.03) =2.5+0.07= 2.57 m^2k/w

U value for the roof =1/2.57=0.39w/m^2k less than 0.41w/m^2k

- R value for the wall=(50mm extruded polystyrene board+12mm gypsum board)
- R value for the wall= (0.012/0.17)+(0.05/.03)=1.6+0.07=1.67 m^2k/w

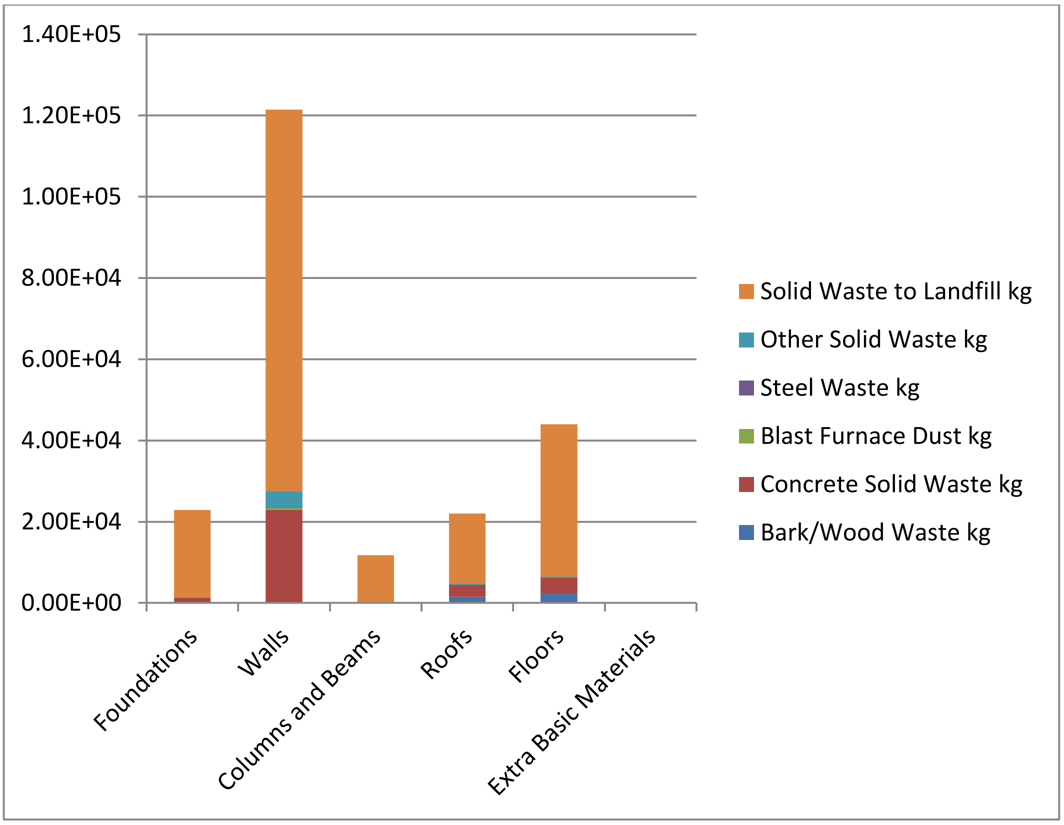
U value for the wall =1/1.67=0.57w/m^2k less than 0.98w/m^2k

APENDIX E

LAND EMISSIONS ABSOLUTE VALUES BY ASSEMBLY GROUPS BY (A to D) STAGES FOR THE BASE CASE

Table– Base Case - Land Emissions Absolute Value Table by Assembly Groups (A to D)

Emission	Unit	Foundations	Walls	Columns and Beams	Roofs	Floors	Extra Basic Materials	Total kg
Bark/Wood Waste	kg	2.13E+02	6.91E+00	0.00E+00	1.52E+03	2.28E+03	0.00E+00	**4.02E+03**
Concrete Solid Waste	kg	1.06E+03	2.30E+04	0.00E+00	2.90E+03	3.96E+03	0.00E+00	**3.09E+04**
Blast Furnace Dust	kg	0.00E+00	4.53E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**4.53E+02**
Steel Waste	kg	6.42E-02	7.24E+00	3.71E-02	1.04E+01	1.56E+01	0.00E+00	**3.33E+01**
Other Solid Waste	kg	1.34E+02	4.11E+03	7.58E+01	2.17E+02	2.32E+02	0.00E+00	**4.77E+03**
Solid Waste to Landfill	kg	2.15E+04	9.39E+04	1.17E+04	1.74E+04	3.75E+04	0.00E+00	**1.82E+05**



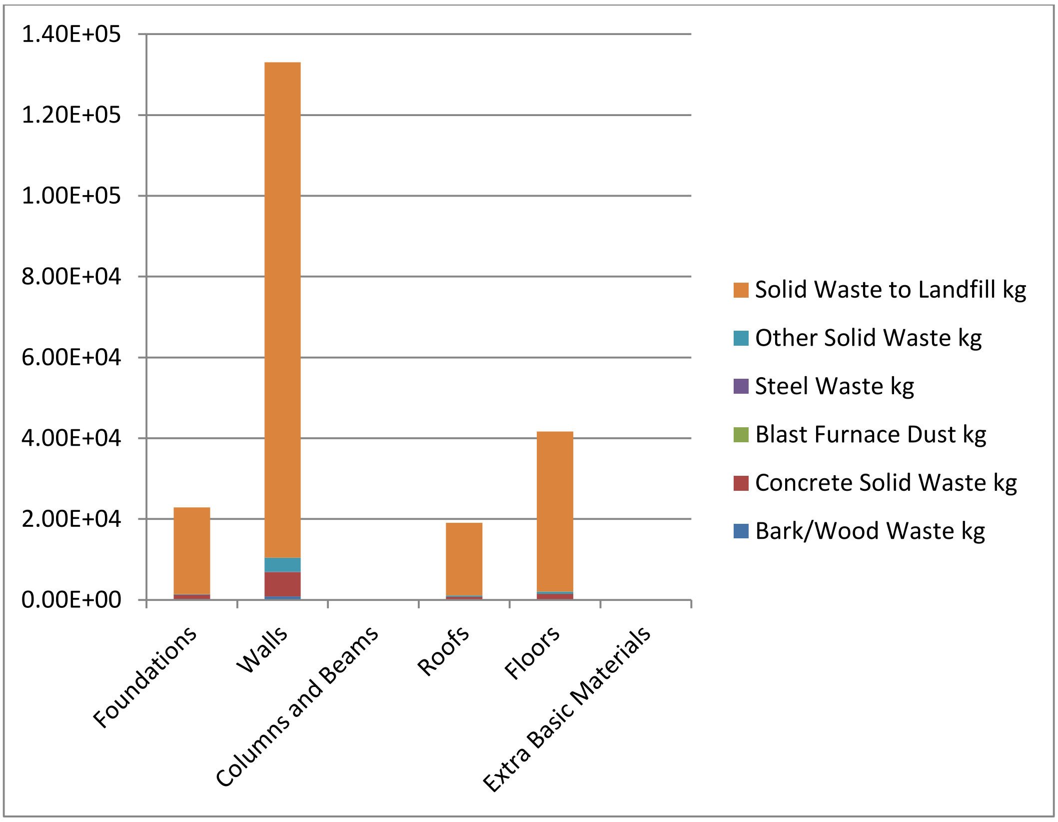
Base Case - Land Emissions Absolute Value By Assembly Groups (A to D)

APENDIX F

LAND EMISSIONS ABSOLUTE VALUES BY ASSEMBLY GROUPS BY (A to D) STAGES FOR PCC OPTION

OPTION 1 (PCC) Land Emissions Absolute Value Table by Assembly Groups (A to D)

Emission	Unit	Foundations	Walls	Columns and Beams	Roofs	Floors	Extra Basic Materials	Total kg
Bark/Wood Waste	kg	2.13E+02	8.77E+02	0.00E+00	1.14E+01	3.42E+01	0.00E+00	**1.14E+03**
Concrete Solid Waste	kg	1.06E+03	6.00E+03	0.00E+00	7.29E+02	1.42E+03	0.00E+00	**9.21E+03**
Blast Furnace Dust	kg	0.00E+00	0.00E+00	0.00E+00	1.48E+01	4.44E+01	0.00E+00	**5.92E+01**
Steel Waste	kg	6.42E-02	5.35E+01	0.00E+00	1.30E-02	3.91E-02	0.00E+00	**5.36E+01**
Other Solid Waste	kg	1.34E+02	3.50E+03	0.00E+00	3.23E+02	5.54E+02	0.00E+00	**4.51E+03**
Solid Waste to Landfill	kg	2.15E+04	1.23E+05	0.00E+00	1.80E+04	3.96E+04	0.00E+00	**2.02E+05**



OPTION 1 (PCC) Land Emissions Absolute Value Table by Assembly Groups (A to D)

APENDIX G

LAND EMISSIONS ABSOLUTE VALUES BY ASSEMBLY GROUPS BY (A to D) STAGES FOR LGS OPTION

Table – OPTION 3 (LGS) Land Emissions Absolute Value Table By Assembly Groups (A to D)

Emission	Unit	Foundations	Walls	Columns and Beams	Roofs	Floors	Extra Basic Materials	Total kg
Bark/Wood Waste	kg	2.13E+02	6.91E+00	0.00E+00	0.00E+00	6.34E+01	0.00E+00	**2.83E+02**
Concrete Solid Waste	kg	1.06E+03	5.52E+03	0.00E+00	2.58E+02	1.16E+03	0.00E+00	**7.99E+03**
Blast Furnace Dust	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Steel Waste	kg	6.42E-02	1.14E+01	1.49E+01	0.00E+00	0.00E+00	0.00E+00	**2.64E+01**
Other Solid Waste	kg	1.34E+02	1.16E+04	6.38E+01	1.55E+02	1.34E+03	0.00E+00	**1.33E+04**
Solid Waste to Landfill	kg	2.15E+04	3.21E+04	6.56E+01	4.89E+03	6.43E+03	0.00E+00	**6.49E+04**

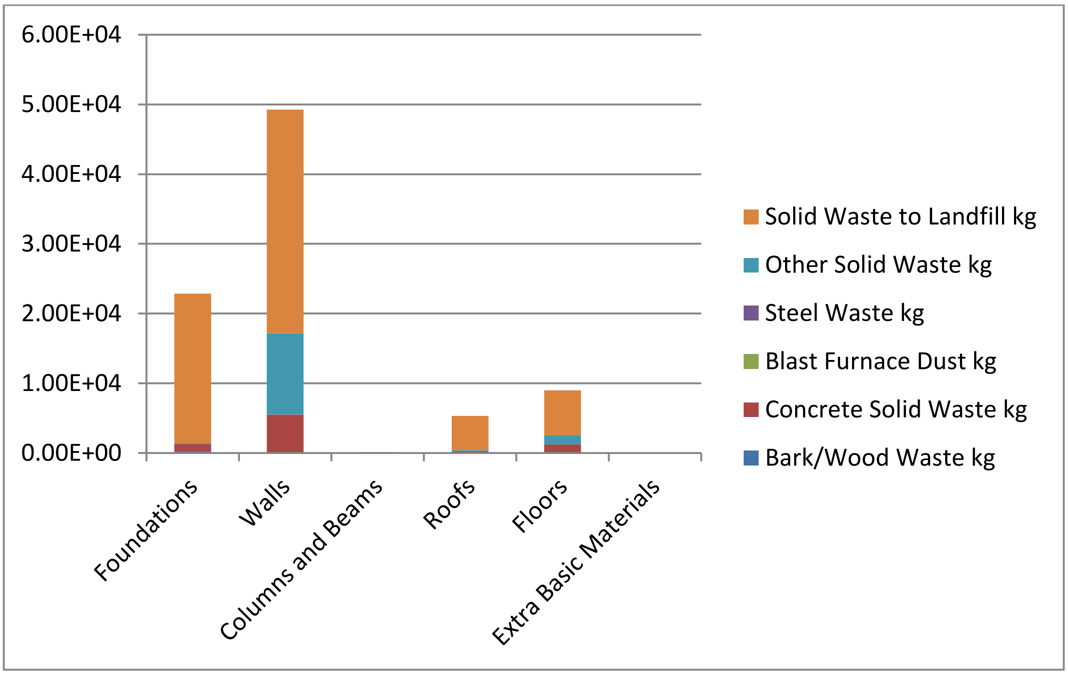


Figure – OPTION 3 (LGS) Land Emissions Absolute Value Table By Assembly Groups (A to D)