# A Comparative Evaluation of the Environmental Impact of Prefabrication versus Conventional Construction in UAE's Construction Industry

**الإنشاء بطرق مقارنة المسبق التصنيع لتكنولوجيا البيئية الآثار تقييم**

**المتحدة العربية الإمارات دولة في التقليدية**


**By**

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# ABSTRACT

This research undertook a comparative life cycle assessment (LCA) of the performance of the conventional construction method in relation to the use of a selected prefabrication method – precast concrete construction. Using a case study high-rise commercial building in Dubai, UAE, the aim of the study was to evaluate the differences in energy consumption and environmental impact profiles for both construction technologies throughout the 50-year lifespan of the building, in order to determine which of the two had lower environmental impacts and energy consumption demands; and would be a better-performing alternative for the UAE's construction industry. Using ATHENA Impact Estimator and eQUEST Energy Analysis tool, the case study building, The Binary, was simulated as 'Binary A' (the conventional concrete scenario) and 'Binary B' (the precast concrete scenario).

The results showed that, based on the 50-year lifespan, about 44% savings in embodied energy could be incurred from the use of precast concrete technology in relation to conventional construction of the same building. In addition, the precast concrete building had over 7% better performance during its occupancy phase than the conventional concrete building. Furthermore, the use of offsite constructed components produced 9% less GWP overall than from the use of on-site construction.

Therefore, precast concrete construction has the potential to improve the environmental performance of a high-rise structure by optimizing its embodied energy demand and reducing its operational energy requirements, in a more advantageous way than conventional concrete construction. Precast concrete construction also has the potential to contribute to UAE's Kyoto self-imposed target for GWP reduction. The results of this study bear significance in dealing with the lack of information on the LCA of commercial high-rise buildings in UAE. An awareness and understanding of the environmental impacts as presented by the LCA results could have a significant influence on the choice of building construction techniques in the future.

# الملخص


يعنى هذا البحث باجراء مقارنة تقييمية لدورة حياة بناء مبني بالطريقة التقليدية مقارنة بطريقة استخدام مواد مسبقة الصنع – تحديداً الخرسانة المسبقة الصب.

بدراسة حالة مبنى تجاري عالي الارتفاع، تهدف هذه الدراسة لتقييم الاختلاف في اسهلاك الطاقة والأثر البيئي بين طريقتي البناء لمقارنتين على مدى ٥٠ عام من عمر البناء لتحديد أي منهما ينجم عن الأداء الآقل استهلاكاً للطاقة والأقل تأثيراً على البيئة والأنسب أداءاً في مجال الانشاء في الامارات العربية المتحدة. تم تقييم مبنى "Binary" باستخدام برنامجين أحدهما ATHENA المقدر للأثر والآخر eQUEST لتقييم الطاقة. سميت الحالة التي تستخدم طرق البناء التقليدية Binary A والحالة التي تستخدم الخرسانة المسبقة الصب Binary B.

أظهرت النتائج و اعتماداً على عمر المبني على مدى ٥٠ عام أن استخدام الخرسانة المسبقة الصب أدت إلى خفض الطاقة المحتواة في المواد إلى حاولي ٤٤٪ مقارنة بالطريقة التقليدية للبناء. اضافة إلى ذلك، فإن فعالية استخدام الخرسانة المسبقة الصب أفضل بأكثر من ٧٪ من الطريقة التقليدية للبناء في مرحلة امتلاك واستخدام المبنى. أيضاً استخدام مكونات بناء من خارج الموقع انتج على معيار الاحتباس الحراري ٩٪ أقل من استخدام مكونات بناء محضرة في الموقع.

لذا، فإن لدى استخدام الخرسانة المسبقة الصب امكانية تحسين الأداء البيئي لمبنى عالي الارتفاع أفضل من الطرق التقليدية للبناء وذلك باختيار الحاجة الأمثل من الطاقة المكنونة في المواد وخفض الطاقة التشغيلية. كذلك فإن لدى استخدام الخرسانة المسبق الصب امكانية تحقيق الهدف الذي حددته الإمارات العربية المتحدة لنفسها في دورها لخفض معدل الاحتباس الحراري في اتفاق كيوتو. تبين هذه الدراسة أهمية الاهتمام بجمع معلومات عن العملية التقييمية لدورة حياة البناء التجاري في دولة الإمارات. تبين هذه الدراسة أيضاً أهمية الوعي وفهم التأثير البيئي لهذه النتائج وأثرها في تحديد طريقة البناء الأنسب في المستقبل.

# DEDICATION

To the future, sustainable in all things.

# ACKNOWLEDGMENT

Thank you Lord, for without You I wouldn’t even be here to do this.

Thank you, Prof. Bassam, for being an even better Supervisor than anyone could ever ask.

Thank you, the dearest of friends, who laughed, motivated, teased and encouraged me through this. “Disso” is finally complete!

Thank you, Mum and Dad, for your prayers and support, and for being the best parents ever!

Thank you, to my aunts and uncles who have threatened to ‘dis-uncle’ and ‘dis-aunty’ me if I don’t go ahead and get a Ph.D. I will think about it!

In everything and for everything, for the lessons on trust, casting cares, smart work and the thrills and displeasures of procrastination, Thank You.

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# CHAPTER 1

# INTRODUCTION

## 1.0 OVERVIEW

With the integration of sustainability into building systems and the alleviation of their negative environmental impacts, building construction has become more than a simple move from the drawing board to the construction site. Building design involves a plethora of factors; the ability to make intelligent design decisions and select the most suitable among construction alternatives is beneficial, especially in today's competitive construction market.

## 1.1 OUTLINE

Globally, buildings provide multi-functional purposes, from residential and official to commercial. The building industry is revered as the key contributor to the social and economic growth and development of any nation and plays a significant role in its sustainable development (Ramesh, Prakash and Shukla, 2010; United Nations Environment Programme, 2003). This impact is traceable to its direct and indirect relationship to other industries. In a detailed study on the economic impact of the construction sector, Balaban (2012) emphasises that the final product of any construction activity constitutes an assemblage of the component activities of other sectors of the economy, such as commerce, transportation and manufacturing sectors. An example of such an impact can be seen in Dubai, one of the most vibrant economies of the United Arab Emirates (UAE).

Meeting the construction needs requires the utilization of large amounts of energy and natural resources (Balaban, 2012). The construction industry consumes 60% of the earth's extracted raw materials, of which buildings consume 40% (Broun and Menzies, 2011); hence it is referred to as the '40% Industry'. Apart from basic construction processes, the manufacture and transportation of building materials is a significant consumer of energy (Thanoon, 2003). The United States Green Building Council (2003) data on the resource consumption levels of buildings in the United States shows 37% for total energy, 68% in electricity and 40% in terms of raw materials (Jaillon and Poon, 2010).

The dynamism of the construction industry is its strength as well its Achilles' heel, especially with the concerns raised regarding construction activities being one of the leading causes of environmental deterioration and greenhouse gas (GHG) emissions, and consequently, global climate change and adverse effects on human health. With the global consensus to preserve what is left of earth's natural resources with such mandates as the Kyoto Protocol, it has become vital for the construction industry to play its role in the mitigation of GHG emissions.

The growing awareness of this challenge has consequently increased the pressure exerted on professionals in the construction industry to improve the performance and status of the environment (Shen et al., 2005). As such, the need has arisen for a critical review and modification of traditional/conventional construction methods, manufacturing technologies and building functionality.

One such strategic modification is the industrialized buildings system (IBS), more commonly known as 'prefabrication'. Prefabrication has been recognized as a viable solution to the high demand placed on raw materials and resources, particularly in terms of waste production during the process of building design and construction, as well as at the end of a building's lifespan. An Israeli study carried out in 1984 to compare the economic benefits of traditional construction methods to prefabricated building systems indicated that the latter provided site labour savings of up to 70% while its incurred total construction cost was only 5-8% of that of the former. Similarly, labour savings are seen in the Singaporean construction industry where savings of close to 50% are achieved through the use of whole prefabrication methods. These examples are pointers to the immense positive benefits of prefabrication (Thanoon, 2003), in addition to reduced energy consumption, waste minimization, mitigation of GHG emission and overall negative environmental impacts.

An appraisal of building systems, their characteristics and the challenges they pose to the construction industry, especially in urban, fast-paced regions like the UAE, constitutes the background of this study.

## 1.2 TYPES OF BUILDING CONSTRUCTION SYSTEMS

There is no single system of building construction classification (as opinionated by Warswaski, 1999). The author believed that such a classification was relative to the user/producer and varied from one to another, usually based on the choice of construction technology. Based on this, it was asserted that four systems could be distinguished as determined by the main structural and enveloping materials of the building: timber, steel, cast in-situ concrete, and precast concrete systems. Warswaski (1999) also suggested that for further classification, the geometric configuration of the components of the building's mainframe could be used as follows: linear or skeletal system (beams and columns); planar panel) system; and three-dimensional (box).

Back in 1977, Majzub recommended the use of the relative weights of building components as the basis for the classification of building systems. The argument for this was that classification by weight significantly impacted the transportability, method of production and on-site erection of components. However, this system was found by Thanoon et al. (2003) to have one limitation: its inadequacy to categorise complex systems of two or more construction methods. They suggested that Majzub's system needed to be upgraded to incorporate recent advancements in building construction technology.

In a much later study by Abdul Kadir et al. (2006), two main types of building systems are proposed: Conventional Building system (CBS) and Industrial Buildings System (IBS). The CBS is sub-divided into two main components: the structural system and the non-structural system. The former consists of cast in-situ column-beam-slab-frames while the latter includes the use of brick and plaster as infill material. The IBS has various sub-categories as classified by different authors. One of such, the 'Badir-Razali' classification, originally done by Badir et al. (1998) for the Malaysian building construction industry has been the most broadly used. Under this classification, there are three main categories of IBS, namely: cast in-situ formwork system (table or tunnel formwork), prefabricated system and composite system.

On the other hand, three building classifications are proffered by Kok (2010) primarily based on their methods of construction: conventional, cast in-situ, and prefabrication construction methods. Furthermore, whereas Abdul Kadir et al. sub-categorised prefabrication and cast in-situ under IBS, Kok sub-lists IBS as a prefabrication method. Kok (2010) then defines CBS as the on-site prefabrication of a building's components using the methods of installation of timber or plywood formwork, steel reinforcement and in-situ casting. Cast in-situ construction method involves on-site implementation of formwork, a method that can be retrofitted for all types of building construction. Prefabrication method is defined as the process of manufacturing industrialized or precast construction components, offsite (in a factory), before delivery for erected on the actual construction site.

In carrying out the literature review, a note-worthy conflict in the classification of prefabrication was observed. Several definitions of prefabrication are clearly in favour of a system that consists entirely of offsite (factory-based) production of its components. However, Abdul Kadir et al. (2006) state that a fully prefabricated system could be one of two categories depending on the site of production: on-site or off-site (factory-produced). They argue that on- site prefabrication differs from the cast in-situ method. Here, the on-site system means that structural building components are cast in the site before being erected at the actual location. In their opinion, the on-site system also provides more advantage over the cast in-situ method.

Based on earlier works, three main classifications of building systems have been identified: conventional, cast in-situ and prefabricated building systems. They are expounded upon in the following sections.

### 1.2.1 CONVENTIONAL BUILDING SYSTEM (CBS)

In Kok's (2010) definition, CBS is the on-site prefabrication of a building's components using the methods of installation of timber or plywood formwork, steel reinforcement and in-situ casting. Abdul Kadir et al. (2006) break down CBS into two components: the structural and non-structural. The structural component includes column-beam-slab frames, which are cast in-situ. This component involves a four-step process. The timber formwork and scaffolding are erected; this is followed by the erection of the steel bars; the fresh concrete is poured into the formwork, and finally the formwork and scaffolding are dismantled. These operations are tiresome, labour-intensive, and demand considerable on-site coordination. The other, the non-structural component, comprises non-structural brick and plaster used for infill. The CBS has the advantages of ease of transportation of its wet trade; flexibility in terms of geometry of buildings; and easy adoption of last-minute changes. However, its downsides are in its 'exposed' production environment; extra time required for the drying of wet concrete; and the need for additional temporary works. Another issue is the high cost of time, labour, materials, transportation and low construction speed, especially because of the use of wooden formwork in the traditional method of construction (Kok, 2010).

### 1.2.2 CAST IN-SITU BUILDING SYSTEM

This construction system is one in which the formwork is implemented on the construction site. Technically, it is applicable to all kinds of building constructions. Cast in-situ is an improvisation of traditional formworks, aimed at the reduction and elimination of conventional on-site trades such as timber formwork, plastering and brickwork with aluminium, steel or fibreglass. This transition has proved to be cost-effective, thus making the cast in-situ method appropriate for constructions involving the repetitive use of formwork such as mass-produced housing units, as the usage is carried out with the least possible waste. This is an added edge over the traditional timber formwork method which can only be utilized twice or thrice. In addition, steel formwork provides ease of erection and dismantling, thus requiring low-skill labour. With careful planning, speed, precision, reduced overall cost and optimized productivity and durability of the prefabricated construction are achievable (Abdul Kadir et al., 2006; Kok, 2010).

### 1.2.3 PREFABRICATED SYSTEMS

The widely accepted definition of prefabrication is a process involving the manufacture of industrialized or precast construction components of various dimensions at a factory, before delivery to a construction site for assembly. However, as previously stated, the casting or manufacture of the structural elements could be carried out at the construction site before its actual erection. Therefore, a wholly prefabricated system primarily falls under two categories: off-site- and on-site prefabricated systems. The on-site system provided even greater time and cost savings and allows for larger quantities of mass-produced units than the cast in-situ system. Secondarily, a composite system exists which involves the casting of some elements of a structure on-site, while others are manufactured at the factory. This is referred to as the composite prefabricated system. Typically produced precast elements include in-filled walls, floor slabs, bathroom and staircase units, to be subsequently incorporated into the already cast in-situ columns, beams and the main units of the structure in question. Generally, prefabrication is a convenient construction system which allows flexibility in production as long as the required elements are delivered as scheduled. One of the major advantages of prefabrication is minimization of construction waste as well as time, labour and cost savings.

Although significantly less labour intensive and time consuming than CBS, studies show that it is yet to be fully embraced as the preferred system of building construction. Prefabrication and its significance to this study will be discussed in detail in the following chapter.

From several reviewed studies, a summary of the classification of building systems is as given in Figure 1.1.

## 1.3 PROBLEMS OF THE CONSTRUCTION INDUSTRY

The subject of construction as an environmentally unfriendly activity has become arguably redundant. The level of pollution generated by construction alone is overwhelming and has been worsened globally due to the rapid rate of urban development (Wei, 2006). The challenges faced by and imposed by the construction industry on the environment and human life have been identified as construction waste, GHG and carbon emissions, high energy and resource consumption rates, and the lack of technological advancement in the face of the fast-paced movement of other industrial sectors. These issues are discussed in detail in the following section.

### 1.3.1 STRUCTURES AND POLICIES

In a thesis on the precast concrete industry, Frondistou-Yantnas as far back as 1973 outlined some of the constraints of the construction industry. Chief among them were the economy of a nation, government and labour policies, and climatic conditions. The author stated that it was the response of the construction industry to these constraints that has set in motion a particular modus operandi which has guided the industry's path to efficiency and effectiveness. The structure of the

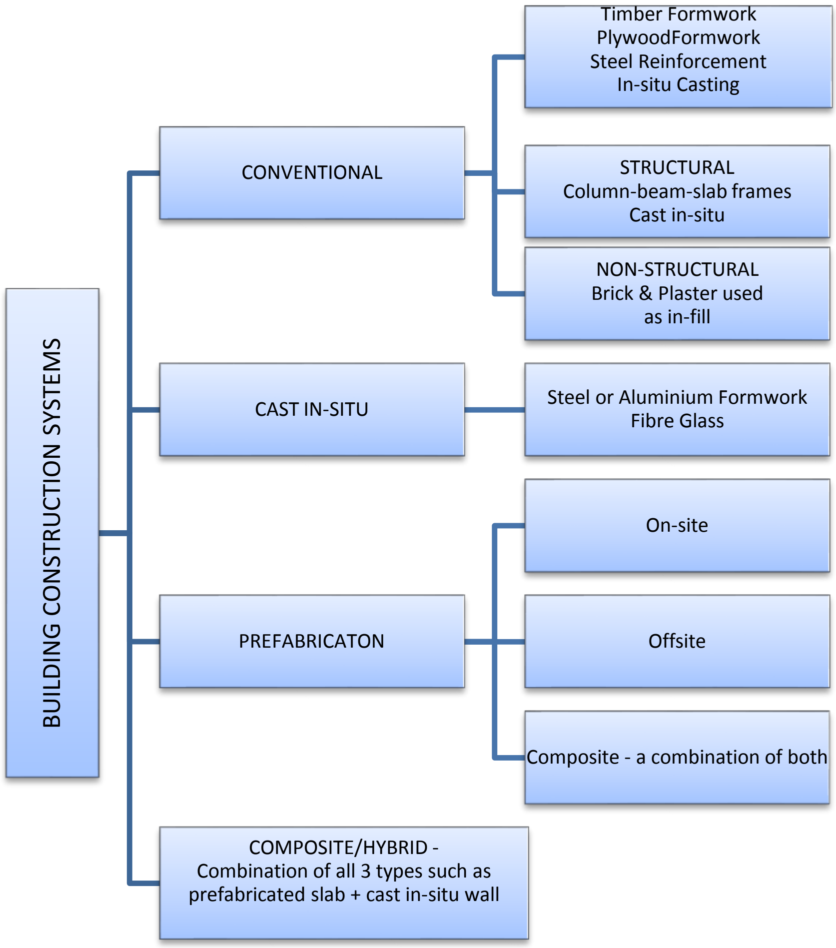



Figure 1.1: Classification of Building Construction Systems

construction industry, having significant bearings on the nation's growth, has affected government policies and ultimately, the nation's economy. With the unpredictability of any nation's economy, its governing policies as well as the changing climatic conditions in any given period, the construction industry has had to, and still has to cope with fluctuating demands in its effort to maximise flexibility. Thus, the construction industry has grown to become a characteristically fragmented industry. More so, there is a deficient working relationship that exists among the various participants of the construction process. Each sector looks to meet its inherent needs, disregarding the need for harmony required to effectively implement a complete construction process.

Although expediency is gained in the short-term, because it is acquired via this deficiency (fragmentation), it is paid for in the long-run. The long-term results are seen in the industry's enduring inadequacies, its increased difficulty in meeting the demands and specifications of more complex projects with the required standards and quality, and expectedly, high costs of construction.

### 1.3.2 LACK OF RESEARCH AND DEVELOPMENT

Another issue of major import is the patent lack of research and development in the construction industry. Although there has been a significant improvement in this regard over the last few years, the attempts are at best few and far between. Only in more recent times with the growing urgency to 'curb the excesses' of the industry have there been noticeable tracks on the path to sustainability in construction. Specifically apropos construction methods, the transition to the post-industrial age seems to be a perpetual struggle, set back by the industry's outright preference for the customary methods - the conventional construction systems - and its rather slow acceptance of industrial/factory-based building systems.

Unlike other industries of the economy that are quick to embrace technological advancements such as the manufacturing industry which has a constant influx of new products that improve productivity and product quality, the construction industry is set back by its snail-paced adoption of technology. As a result, where mass-customization of goods and services has enhanced and continuously so, the quality of work and life, especially from the beginning of the 21st century till date, the construction industry seems to be experiencing regression. It therefore goes without saying that the advantages provided by modern methods of construction such as cost, energy and time savings, improved quality and product durability, even better architecture, and ultimately sustainability, are yet to be properly harnessed by the construction industry.

### 1.3.3 ENVIRONMENTAL IMPACTS

As earlier stated, construction activities propagate environmental pollution which eventually causes climatic change that is fast becoming the bane of human existence. Overwhelming scientific evidence points to climate change as the gravest threat to humans by humans. Since the 18th century, precisely 1750, the concentration levels of GHG have increased considerably. The most notable of these atmospheric pollutants is carbon dioxide ($CO_2$). From that time till the present, $CO_2$ emissions from both the combustion of fossil fuels and the manufacture of cement, a prime construction material, have contributed to over 75% increase in atmospheric $CO_2$. The building and construction industry is principally responsible for these emissions globally, 25% of which is attributed to the energy use in buildings (Monahan and Powell, 2011). Figure 1.2 shows the total energy consumption of the US construction industry, the largest consumer of energy.

According to NOAA Mauna Loa $CO_2$ Data, $CO_2$ concentrations have increased from the mean monthly value of 315.71 in 1958 to the most recently recorded value of 396.18; a rise that has resulted in global warming. Climate scientists have

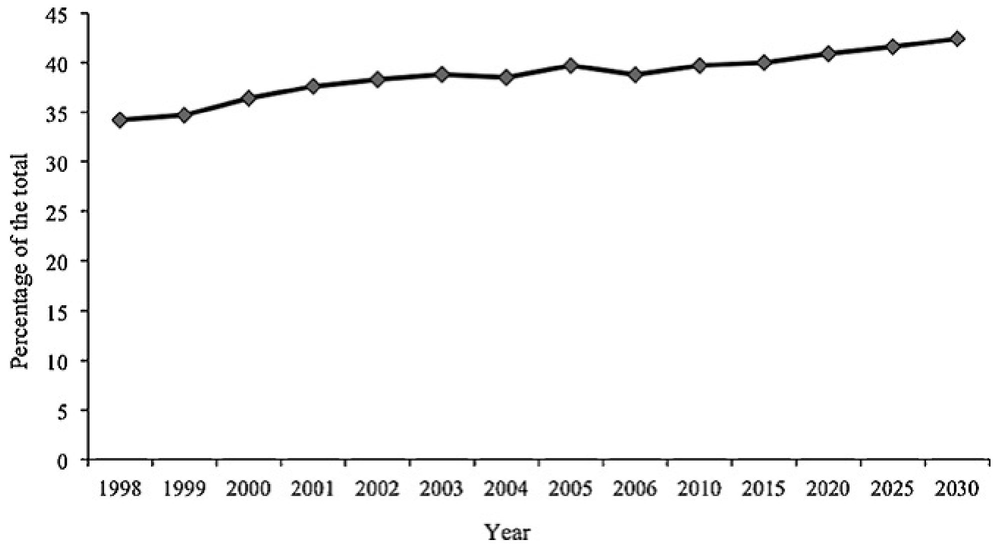



Figure 1.2: US energy consumption in the building sector as a percentage of the total (Dixit et al., 2010)

declared that there is very limited time - years and not decades - to balance $CO_2$ and other GHG (CO2now.org 2011). Hence, energy conservation has become a crucial factor in mitigating the consequential emission of carbon and GHG attributed to the buildings (Thanoon et al., 2003). Referred to in terms of $CO_2$, the energy and carbon emissions associated with a building's life cycle occur in three uniquely interdependent stages: construction, occupation and demolition. Although the occupational energy and emitted carbon are produced during the major part of a building's lifespan, the initial construction stage also contributes significant amounts of carbon emission to the carbon footprint of the building, which cannot be ignored.

As long as there is production, the extraction, refinement, manufacture, transportation and eventual use of raw materials, expend energy and create environmental impacts. Despite the fact that these impacts are considered 'hidden' or 'embodied' and are usually regarded as inconsequential to the overall amount of energy consumed during the design and construction of a building, the total embodied energy and carbon emissions are markedly influenced by the choice of construction materials and construction technology.

The energy associated with construction waste is another area of grave concern. In order to address the problem of embodied energy, it is important that the efficiency of construction and use of buildings be revised.

### 1.3.4 WASTE

Construction waste has been construed to be one of the major pollutants of the environment. Waste by definition is anything in excess of the minimum requirement of equipment, labour, time and materials essential for production, which should be eliminated for its lack of added value to the product in question (Pheng and Hui, 2010). In Wei's (2006) reference to Serpell and Ferguson (1998), waste is defined as the excess material resulting from human and industrial activities, with no additional worth. Another definition of waste is any:

> substance which constitutes a scrap material or an effluent or other unwanted surplus, arising from the application of any process, [and is required] to be disposed of as being broken, worn out, contaminated or otherwise spoiled. (Wei 2006, p.1).

More specifically, construction waste is defined as "the by-product generated and removed from construction, renovation and demolition workplaces or sites of building and civil engineering structure" (Tam et al. 2007, p. 1). Poon, Yu and Jaillon (2004) identify two main classes of building construction waste: structure waste and finishing waste. Structure waste refers to waste generated during the course of construction, such as abandoned timber plates/pieces, reinforcement bars and concrete fragments. Finishing waste, on the other hand, is waste produced during the finishing process of a building. An example of such could be excess cement mortar from screeding scattered all over the floors of a building. According to Bossink and Brouwers (1996), construction waste is classified according to the natural form of the material and the technology involved in its use. As such, the classes are concrete, mortar, roof tiles, sand lime bricks, piles, stone tablets and other fragments of wood and metal. Sources of waste are categorized under design inaccuracy, equipment handling error, material management, procurement and residual sources (Wei, 2006).

The impact of construction waste on the environment is borne on a global scale. For instance, 17% (70 million tonnes) of the total generated waste in the UK per year is solely from construction and demolition operations, making the construction industry the highest producer of controlled waste in the UK. This amount is estimated to be 24kg of waste per week per UK resident, four times as much as that generated by household activities. Similarly, in Australia, 44% of the 14million tonnes of waste reported annually is contributed by its building construction industry. Another instance is in Malaysia where 16000 tonnes of solid waste are produced daily. The country is reported to have over 200 landfills, and thrice that many illegal dumps; 80% of the landfills have been estimated to have a lifespan of just two years (Wei, 2006). Furthermore, in Dubai, UAE, 40000 tonnes of waste are generated daily, 30000 tonnes of which emanate from construction and demolition alone. According to the Dubai Municipality, landfills are clearly not sufficient as a solution to deal with its waste (Gulfnews, 2011).

In Wei (2006)'s extensive study on waste management, several causes of the high levels of waste encountered in the construction sector are analysed. One such cause is the poor attitude towards waste management which is blamed on the mind-set of operatives, for whom it is predetermined that waste generation is inevitable in construction, and minimization efforts are of non-priority. In addition, the cultural attitudes of the employees of any organization play a large role in their perception of waste management practices. Where such practices have been successfully implemented, there are higher chances of a positive attitude towards their constant implementation. On the other hand, the fear of diversity that has long held back the construction industry could be a major hindrance to the acceptance of new construction methods that will adopt waste management. This fear is particularly attributed to a severe lack of knowledge about the environment, although in Chan's (1998) opinion, the media's influence has bridged this gap. Another main cause of poor waste management is design changes, of which the belief is that constant changes in design details during construction due to insufficient knowledge, experience and miscommunication, play a major role in high levels of construction materials waste (Wei, 2006).

To summarize, the building construction industry is in dire need of sustainable development. According to Ramesh, Prakash and Shukla (2010), this kind of development is characterized by low-level environmental impacts and high-level socio-economic benefits. The realisation of sustainability in the building construction industry requires an adoption of strategies that include a reduction in energy demand, enhanced use of materials and resources, efficient waste management and subsequently, stabilization of carbon and GHG emissions. One recurring suggestion to the solution of the aforementioned challenges of the construction industry is the replacement of traditional construction methods with modern methods of construction (MMC), particularly prefabrication.

## 1.4 UAE'S CONSTRUCTION INDUSTRY

On the heels of oil and trade is the building and construction industry as the largest contributor to the UAE's gross domestic product (GDP), by 6% equivalent to twenty three billion dollars ($23 bn.); a contribution which was predicted would increase to between 10% and 11% by 2010 and 2011, respectively. The emergence of the construction industry dates back to the 1950s. During this time, the then ruler, Sheikh Sayed bin Maktum and his son Rashid embarked on the Dubai Creek Improvement Project, with the goal of transforming Dubai into a permanent coastal shipping haven. With the support of the then ruler of Abu Dhabi in the late 1950s, oil revenue generation increased significantly in the mid-1960s.This increase reflected itself in the rapid expansion of the construction industry during Sheikh Zayed bin Sultan Al Nayan's rule, with the endorsement of massive construction projects – schools, hospitals, roads and housing.

The construction industry began to expand at the end of the 1990s, with an average GDP contribution of 9%. According to the 2010 report by Market Research (2010a), this expansion continued up to the point where the UAE overtook Saudi Arabia as the GCC's biggest construction market in 2008. Data reports indicate that 20% of the Arabian construction industry is owed to the UAE.

As seen in Figure 1.3, this expansion peaked in 2005 at six hundred and twenty-four billion dirhams (624 bn. AED) and maintained that high pitch up until 2008 when the global economic recession caused a financial nosedive triggered by the huge debts incurred from the heavy investments that had been made by top construction companies in building projects which the y were unable to offset. This led to close to a 60% crash in the prices of property and rent. The following year Dubai began a fragile pick-up by restarting suspended projects and restructuring its market for investments. Thus, the construction industry despite the financial meltdown, recorded an almost 8% contribution to the UAE's GDP in 2009 (Market Research, 2010a, 2010b, 2011; Oryx Middle East, n.d.).

## 1.5 PROBLEM STATEMENT

The remarkable growth of the construction sector in the UAE, precisely in Dubai, raised global interest regarding the speed of architectural and structural achievements. However, the equally remarkable crash of the construction sector following the financial crises that hit globally in 2008, called for a strong review of the workings of the industry and its future outlook.

The estimated population growth from 6.5 billion recorded in 2005 to about 9 billion in 2035, is a clear indicator of the expected increase in construction

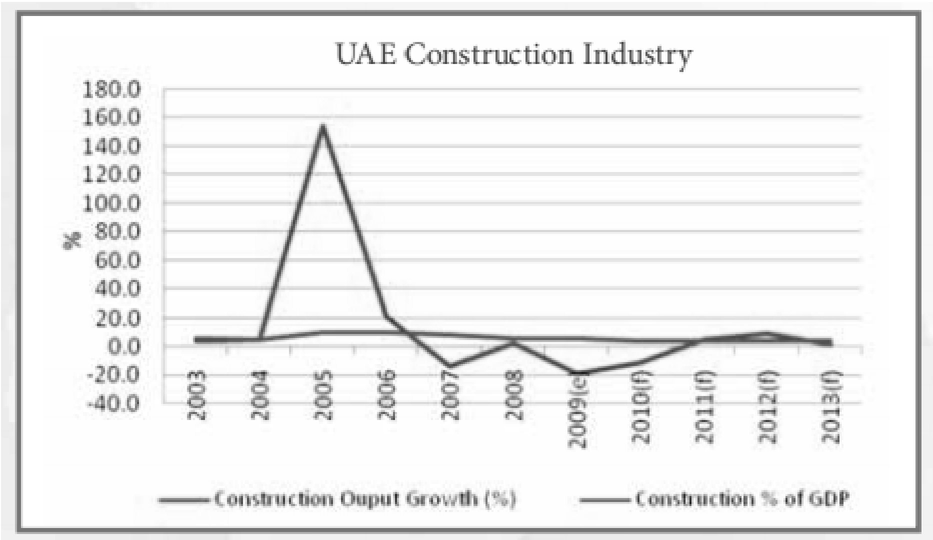



Figure1.3: The UAE's Construction Industry Growth trends from 2003 – 2013 (Oryx Middle East, n.d.).

activities in the coming years. To truly understand the extent of the impacts of the construction industry, Aye et al. (2011), discussed the importance of the consideration of the life cycle impacts of both the construction and operation of buildings. The problem with carrying out a life cycle analysis (LCA) of buildings, according to Dakwalea, Ralegaonkara and Mandavganec (2011), is that, by comparison to other products, buildings are more difficult to evaluate. Their stated reasons for this are the largeness in scale, complexity of materials and temporary dynamism as a result of the limited service lives of their components, as well as unpredictable user requirements. In addition, the slightly unique characteristics of each building means a lower degree of standardization in production processes than for most other manufactured products.

One suggestion is the strategy of a closed-loop system of material flows, that redirects deconstructed materials back into the system should be implemented. In other words, the design, construction and functionality of buildings should be fundamentally modified, that is, a deviation from the traditional/conventional methods of construction is inevitable (Schultman and Sunke, 2007). Another suggestion is that if the structural components of buildings are designed for durability and reusability, their life cycle environmental impacts could potentially be significantly reduced Aye et al., 2012). In order to effect this, it is important that innovativeness in the design of components at the initial stages of the building design process be considered. This has led to the proposed implementation of prefabrication of building components as one of the effective environmental impacts minimization strategies. Prefabrication of buildings has provided evidential advantages as pointed out by several authors. Chen, Okudan and Riley (2010b) stated that the benefits of prefabrication, besides an opportunity to improve the sustainable performance of construction projects, included shortened construction time; overall reduced costs; enhanced quality and durability; improved health and safety, conservation of materials and energy; less water consumption; less construction and demolition waste; and finally reduced environmental emissions.

Aye et al. (2012) stated that in addition to these numerous advantages, prefabrication has been proven to provide up to 52% savings in construction waste. However, authors Chen, Okudan and Riley (2010b) argued that despite the opportunity for sustainable building projects, prefabrication was implemented more on the basis of familiarity and personal preference than on rigorous data; hence, the deficiency in the choice of appropriate construction methods for construction projects.

## 1.6 MOTIVATION FOR STUDY

By nature, the activities of the construction industry while highly productive and beneficial, are environmentally unfriendly. The present global shift to sustain and protect what is left of the endangered environment has led to studies covering various aspects of GHG, energy savings and environmental protection as a whole. The pressure for expedited action has led to industries implementing measures to combat and control the hazards of pollution especially by the greatest contributor to environmental detriment, the construction industry. Waste, carbon emissions, vast consumption of natural resources and high energy consumptions are the motivating factors for this action.

In the race against time, the global movement for the reduction of carbon emission in the construction industries of the world, is geared towards the creation of environmentally responsible building technologies to meet the needs of humans and their immediate and future environment. In its industrial and economic boom, the UAE was known to generate about 11 million tonnes of construction waste. The current construction practices in the UAE were ill-equipped to assuage this seemingly worsening situation, the effects of which were only severed by the global economic recession of 2008.

The need has arisen therefore, to establish sustainable building strategies to mitigate the negative impacts of the UAE's construction industry, before its resurgence as per the pre-recession period. Several studies propagate prefabrication techniques in construction, as a significant contributor to positive environmental and economic impacts especially in highly commercialised regions like the UAE. To this end, a tailor-made prefabrication model is suggested to be the most appropriate means to alleviate the issues of waste generation and energy consumption and emission in the UAE's building construction industry.

# CHAPTER 2

# PREFABRICATION

## 2.0 PREFABRICATION: A RELEVANT DEFINITION

Prior to this research, it was the belief of the author of this work that prefabrication existed as a construction method on its own. However, it has been found that the term “Industrial Building System” has several related terms: modularization, prefabrication, preassembly and industrialization. The categorization of these terms will be discussed in detail in the sections below based on a thorough literature review of these terms and their scope of use. For the purpose of this research, prefabrication is considered as the main IBS under study, and the term will be used in reference to modern construction methods.

Several studies indicate that the definition of prefabrication is as widely varied as its terms of reference. Prefabrication could either be classified under IBS or modularization, or defined independently. In order to establish an understanding of the term and its relevance to this research, and allay the erroneous, an appropriate definition will be established based on previous related works. According to Haas et al. (2000), the various definitions which exist are subjective to time, industry and the purpose of the study as there is no organization monitoring the progression of these technologies, besides the Manufactured Housing Institute for the residential sector. In addition, several terms are used interchangeably in reference to prefabrication. The usage of these terms is predetermined by the user’s philosophy and understanding and also varies from country to country. The associated terms are defined briefly below, in order to gain an understanding of the fundamentals of prefabrication.

- ✓ **Modularization:** Modularization is defined as the off-site construction of a whole system prior to its transportation to the site of construction. The modules may often be required to be broken down into smaller sizes for ease of transportation. Modularization usually involves more than one trade.

- ✓ **Prefabrication:** This usually involves a single skill or trade and is generally defined as a production process, which normally takes place at a specialized factory where different materials are combined to form the component of an end-product. As long as the component is manufactured at a factory and is not a whole system, it is regarded as prefabricated.

- ✓ **Preassembly:** By definition, preassembly is the combination of various materials and prefabricated components at a separate facility before installation as a single unit. This installation is carried out similar to the process of modularization in which the manufactured components are assembled close to the site, followed by on-site installment. Commonly regarded as a combination of modularization and prefabrication, preassembly usually involves works form various crafts and parts of different systems.

- ✓ **Industrialization:** This term refers to an inclusion of all three aforementioned categories of offsite construction. Industrialization is based on the concept of manufacturing and is defined as the procurement of technology, equipment and facilities in order to increase productivity, reduce manual labour and improve production quality.

Kok (2010) identified several definitions of prefabrication from previous literature. One such definition states that a prefabricated home:

> is one having walls, partitions, floors, ceiling and roof composed of sections of panels varying in size which have been fabricated in a factory prior to erection on the building foundation. This is in contrast to the conventionally built home which is constructed piece by piece on the site. (pp. 15-16).

Another defines prefabrication as "… a manufacturing process taking place at a specialized facility, in which various materials are joined to form a components part of final installation" (p. 16); and finally a prefabricated building is one:

> [which] consists of elements that are manufactured or fabricated in a location (off site) which is not its final destination. They are transported to the site, and

> connected one to another to form a complete structure. Usually the elements are limited by size of transport vehicles and lifting equipment. (p. 16).

The prevailing definitions of prefabrication depend on the authors' perceptions. According to the definitions above, the general perception is that prefabrication is a process that primarily occurs in a factory or facility (factory); in other words, anywhere but on the actual site of construction. However, prefabrication is not limited to a factory or an offsite location. The manufacture of components can be carried out at the actual site of construction or in close proximity. It is important to note that this limited definition is revealed in the disparity in the categorization of the forms of IBS. For a complete definition of IBS, Thanoon et al. (2003) endorsed Junid's (1986) as the most comprehensive.

This expansive definition includes the balance between hardware and software components involved in the industrialised processes of the conception, planning, fabrication, transportation and on-site erection of the components of a building. Here, software relates to the overall system design and its complex processes from end-user requirements, through the layout of the manufacturing and assembly process, to the actual building framework; software components provide the layout for the development of industrialisation. On the other hand, hardware is categorized into three main groups: box system, panel system and frame (post and beam) system. The box systems involve the use of boxes (three-dimensional modules) for the fabrication of liveable units, capable of withstanding multi-directional loads due to their internal stability. The panel system distributes load through large wall and floor panels; while the framed systems are those that carry the load from beams and girders to the columns and the ground.

For simplification, IBS would be said to be a system that comprises prefabricated elements manufactured offsite and then transported to the on-site location for installation, or simply manufactured and installed on-site, thus eliminating the need for transportation. Kok (2010) cites IBS Road Map (2003) in which IBS is said to be a technique or process in which manufactured components are assembled and installed to form a whole structure in its predetermined location (Goodier and Gibb, 2007). Industrialization is often referred to in literatures as offsite production, prefabrication, automated construction, preassembly, and offsite manufacture.

## 2.1 HISTORY OF PREFABRICATION

Indeed the concept of prefabrication is not a modern one, albeit still under development. The industrialization of construction came about as a result of the need to shorten construction time, reduce cost and improve production performance. Meeting these needs provided strong motivation for ‘technological improvements’, which in Rosenfeld at al.’s definition by Sartori and Hestnes (2007) refers to the use of diverse tools, materials and equipment, and the adoption of modern methods of construction. According to Haas et al. (2000), the history of prefabrication, preassembly and generally industrialization of construction, is varied and complicated and therefore carries with it documentation difficulties. The history of prefabrication centres on the world wars, economic changes and housing industry boom.

Prefabrication is clearly rooted in the need for moveable/mobile dwellings. Historical records indicate that nomads such as the Arabs and Australian Aborigines first developed transportable architecture due to their wanderings in search of food and shelter, and also the need to exchange goods commercially. These required long hours of travel, meaning that only structures constructed with lightweight materials such as reed huts and tents could be built. Today, such structures are still in use, for instance the North American ‘tipis’ and Bedouins’ black tents. Prior to the 19th century, these structures were not regarded under the term ‘prefabricated structures’, rather they seemed to be isolated events, according to records which indicate that the first ever prefabricated building was a wooden house panelized in 1624 in Britain, and reassembled later on in the United States. One such isolated event is the famous “balloon frame” structure (shown schematically and typically in Figure 2.1).

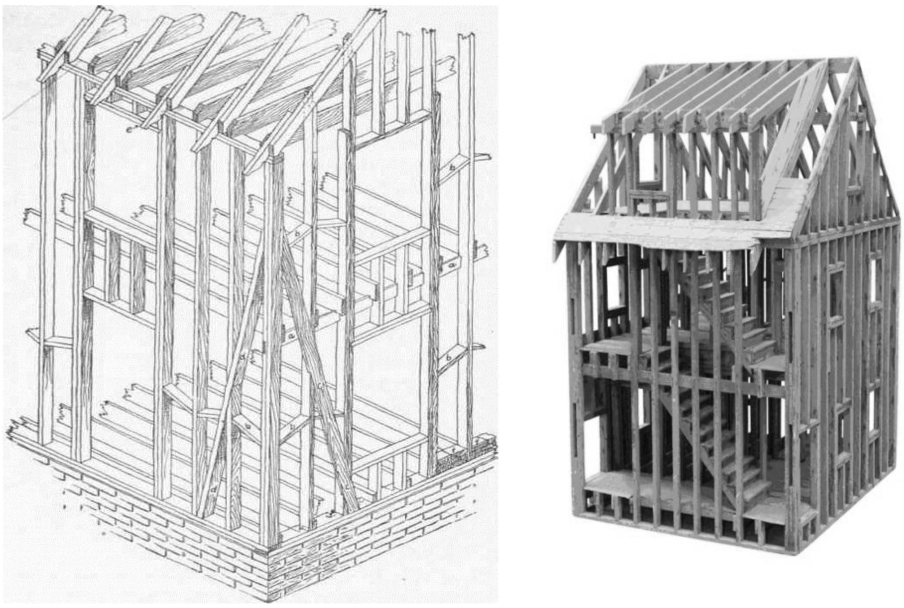


Figure 2.1: Schematic Representation of the Balloon Frame (left) (Chest of Books, 2011); Typical Balloon Frame House (right) (Deep Energy Retrofit, n.d.).

Yet, it was not until the late 1800s that carpenters achieved a break-through in considerable reduction of labour required for house construction. In 1851, during the Great Exhibition of Britain, a monumental building known as Crystal Palace was featured. The building, designed and supervised under construction by Joseph Paxton, featured cheap, light materials – wood, glass and iron. The construction involved the assembly of prefabricated components, which were based on specified dimensions that could be manufactured at optimum costs. After the exhibition, the palace was disassembled and moved to another location, Sydenham. The evolution of the balloon frame was eventually seen in the 19th century.

There are many other examples of early uses of prefabrication. Modern forms of prefabrication are dated back to 1905 according to Encyclopaedia Britannica (Haas et al. 2000). Prefabrication evolved from the 1920s as architects tried to apply the concept to provide architectural solutions to housing problems. Famous examples are Walter Gropius's Torten Housing Development in Germany and The Pessac by Le Corbusier (Figure 2.2), both designed circa 1926; and Villa Savoye by Le

Corbusier and Pierre Jeanneret of 1929 (Figure 2.3). In 1964, the English arrived in Massachusetts with a wooden panelized house which was to be used to house the fishing fleet in Cape Ann. Said house underwent subsequent disassembly, movement and reassembly severally. During this time, prescheduled procedures known today as the basis for modern mass production were introduced to home construction. Post-World War I, the US continued its experimentation with prefabrication while the Europeans advocated and developed it as part of their industrial development (Haas et al., 2000; Spunt, 2009).

Figure 2.2: Le Corbusier's Pessac (1926) (Mimoa, 2012).

As a means of supporting European nations in their colonial expansion, exported prefabricated houses met the urgent need for shelter, particularly as there was a shortage of local materials and labour suited to the tastes of the Europeans (Gibb,

Figure 2.3: Villa Savoye by Le Corbusier and Pierre Jeanneret (1929) (Architectural Record, 2012).

2001). The Second World War was the period during which prefabrication became vastly popular in the UK as a means of providing cheap, quickly built quality houses for its displaced citizens (Payne, Nguyen and Stodart, n.d.). The term MMC was developed with the intention of reflecting the technical improvements which have been achieved in prefabrication, ranging from on-site to offsite construction processes. From the 1980s, industrialization and prefabrication have taken precedence in public housing in such countries as Hong Kong and Singapore, and have achieved successful implementation in regions like Israel and Finland (Sartori and Hestnes, 2007).

After World War II, mass production was endorsed extensively for the reconstruction of cities. In Eastern Europe, the Closed System of prefabrication was used as prefabrication became more popularized. This system meant that the same factory manufactured all the required building elements and there was no form of interchangeability among systems. However, this production method became unacceptable in Western Europe as the people became more interested in variety and freedom of choice. Thus, prefabrication was slowly discarded. Conversely, prefabrication in the US was adapted not for the purpose of rebuilding the cities, but because the return of soldiers meant a lot of marriages, and thus an increased housing need. However, it took on a different paradigm for serial housing production referred to as 'kit-of-parts'. While Europe's closed system prevented interchangeability, the desire of builders in the United States for independence led to the evolution of the Open System. This system required considerable coordination for efficient integration of building components from different suppliers.

While the closed system reduced production costs (as each supplier was focused on one component), communication barriers jeopardized integration and cost control, and eventually monotony became extreme. In the 1960s, this led to the pursuit of new design and construction methods which would incorporate client involvement and allow urban diversity. One of the most influential solutions was John Habraken's 'Theory of Support' in the Netherlands. His theory stated that 'support' was different from 'infill', with the former being the rigid part (structure and infrastructure) of the building that households made a pact not to modify, while the latter was the flexible modifiable part of the building. The ability to customize to a certain degree caught the interest of the Portuguese government, who launched a similar program, the SAAL 2, to allow teams of architects and engineers coordinate with house owners to design and construct their houses. Thus, Alvaro Siza's design resulted in an estate which exhibited diversity with visual coherence, even in spite of several modifications over the years. So it was that Henry Ford's mass production gradually took a back seat to Toyota's lean production paradigm which aimed to reduce production cost and time by limiting waste through the application of the Just in Time (JIT) production method. JIT reduced storage requirements as production was on a demand-only basis. Thus, higher levels of customization were achieved and Toyota became the world's largest car manufacturer. From JIT, another paradigm, mass customization evolved. While other industries have adopted lean production and are gradually implementing mass customization, the building construction industry has been slow to adopt this new paradigm (Benros and Duarte, 2009).

The growth of prefabrication can be attributed to the housing sector of the construction industry, particularly as the refurbishment and housing needs of the post-war era saw the popularization of prefabricated housing. The growth even stimulated the establishment of the Prefabricated Home Manufacturers' Association in 1942. The function of this association was the dissemination of information, formation of industry standards, the study of the problems of distribution, improvement of manufacturing methods, studies on cost and accounting, and acting as a means of exchanging ideas. Despite this platform and the growing demand for prefabricated houses, prefabrication as a construction technology still did not evolve as the preferred method. In the 1960s, a program tagged 'Operation Breakthrough' was initiated by the US government as a means of providing jobs, cheap housing and an economic boost, on the foundation of prefabrication and modularization. The failure of this program was attributed to misguided goals, poor management and inappropriate execution. As a result, the 'image' of prework was tarnished before the public and became synonymous with failed housing projects. The introduction of prefabrication was in turn associated with the failure of 'Operation Breakthrough'; thus it suffered a backlash and ultimate downturn. The industrial revolution of the 1970s re-established prefabrication only briefly. Friedman (1992) in a study on prefabricated homes asserted that there seemed to be a growing trend in the consideration of modern home construction choices. First-time home-owners became open to new technologies and directions as the preconceived notion of prefabricated structures as cheap-looking and box-like began a rapid change. In the study, it was stated that the openness and acceptance by buyers and builders of the qualitative benefits of prefabricated homes has a lot to do with the change in manufacturers' approach: designs became attractive.

Prefabrication, modularization and IBS in general have not steadily grown over the years (as shown in Figure 2.4). Use has experienced fluctuations due to factors such as war, economic changes, and explosions in population, amongst other social and political factors. Besides these, Haas et al. (2000) believes that in the

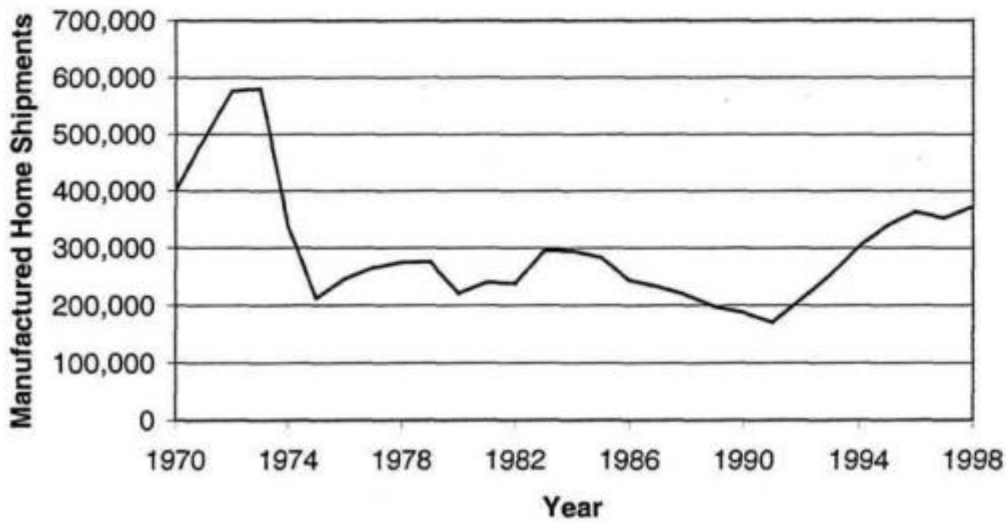



Figure 2.4: Shipments of Manufactured Homes over the Last 30 Years (Haas et al., 2000).

coming future, technological advancement may also have an impact, in addition to varying demand by the construction sector, with the housing industry bearing the greatest impact.

With the availability of advanced transportation and erection equipment, precast construction became feasible. In 1996, the highest recorded level of precasting was in Denmark since the inception of the 1960s legislation for modular coordination. Japan recorded Asia's highest with 15% precast construction and Singapore, 8% a figure it had hoped to increase to 20% by 2010 (Jaillon and Poon, 2008).

## 2.2 CLASSIFICATION OF IBS

Prefabrication is not a new concept. Its enlarging awareness is due to the increasing demand for better quality and performance of services and products in the construction industry. Buttressing this point, the Egan Report of 1998 stated the need for the construction industry to adopt a "culture of co-operation and greater innovation in procurement, design and construction" (p. 1) which would in turn provide outstanding client, contractor and societal benefits on the whole. In addition to its varying definitions, the classification of prefabrication varies even more widely. From studies of several literatures, a classification of prefabrication is as discussed in detail in the sections following (Rogan, Lawson and Bates-Brkljac, 2000).

### 2.2.1 CLASSIFICATION SYSTEMS REVIEWED

There is no single preferred classification of prefabrication. Several authors have classified prefabrication based on the techniques, processes and components of production. For instance, Friedman (1992) divides prefabrication systems based on their different methods of fabrication into components, modular and mobile houses. Kok (2010) gives a different, more general classification of the systems following Abdullah's (2009) categorisation is proposed: frame, panelised, cast in-situ formwork, modular and hybrid systems. The frame system involves structures whose beams and girders transfer loads to columns and the ground. The panelized system refers to a system in which load distribution is through the large floor and wall panels of the structure in question. Cast in-situ is as earlier explained, as the casting of concrete in formwork; modular, also referred to as the box system, utilizes three-dimensional modules (or boxes) with the inherent structural ability to withstand multi-directional loads. The hybrid system is a combination of any of the other systems.

Classification of prefabrication based on techniques includes:

- ✓ Standardization (established uniformity and modularization of components, processes and dimensions);
- ✓ Prefabrication (offsite or factory-based manufacturer of components); on-site fabrication (on-site or field factory manufacture of components);
- ✓ Preassembly (materials, equipment and prefabricated units assembled prior to installation);
- ✓ Modular buildings (components that enclose functional space and form part of the building structure;
- ✓ The building system (an entirely coordinated entity of synchronized components); mechanisation (substitution of manual labour with equipment and machines); and
- ✓ Automation (the use of programmable machines, such as robots, or computerised tools, for performing design and operation tasks) (Abdallah, 2007).

In Kok's (2010) opinion, all these classifications have a tendency to perplex clients in their choice of a construction method, and therefore proffers that the most appropriate system of classification would be more sensible if based on that which is obtainable per country. The author goes on to suggest an even simpler structural classification system put together based on what is most frequently implemented in the Malaysian construction industry. The grouping is as follows: Precast Concrete Framing, Panel and Box Systems; Steel Formwork Systems; Steel Framing Systems; Timber Framing Systems and the Blockwork Systems.

Gibb, as stated by Lessing, opinionated that standardization plays the foundational role for the expansion of IBS, through continuous upgrading, as is the case with other industrial sectors. Standardization in the technicality of building systems is closely related to pre-assembly and offsite production of building elements, from the manufacture of components to the production and on-site assembly of complex modular units. Standardization identifies four categories of pre-assembly. These categories are similar to the classification based on the degree of offsite production done by Goodier and Gibb (2007). They are as described as follows:

- ✓ Component manufacture – the components in this category are referred to as sub-assembled components, in that they are manufactured off-site and then incorporated into larger units on-site. They are never pre-assembled on-site. Examples of such units include doors, windows and light fixtures.
- ✓ Non-volumetric pre-assembly – this system comprises of units assembled at the factory or offsite, and some sub-assembly elements. They form a major part of the building/structure. Examples of these include wall panels, pipework assembly and structural sections.
- ✓ Volumetric pre-assembly – These items are usually installed on-site, contained in an independent skeletal frame. They include units such as toilet pods and modular lift shafts.
- ✓ Modular building – These are referred to as whole buildings. They are identical to the volumetric units; however they constitute the entire building. They could also be completed on-site. Examples include hotels, office blocks and modular residential units (Lessing, 2006).

A contemporary Danish study identifies two strategies for development: component and element strategy, and complete system strategy, both of which are at extremes. The former refers to the design of structures using components and elements centred on defined principles; while the latter denotes the use of complete system solution for a whole building based on stringent building concepts. In addition, the elements used per strategy are sub-divided into two: the open system in which the combination of components is flexible (for instance, different manufacturers' products can be combined together); and the closed system where the components in use are exclusive to that system.

The above categorization of prefabrication is illustrated in Figure 2.5.

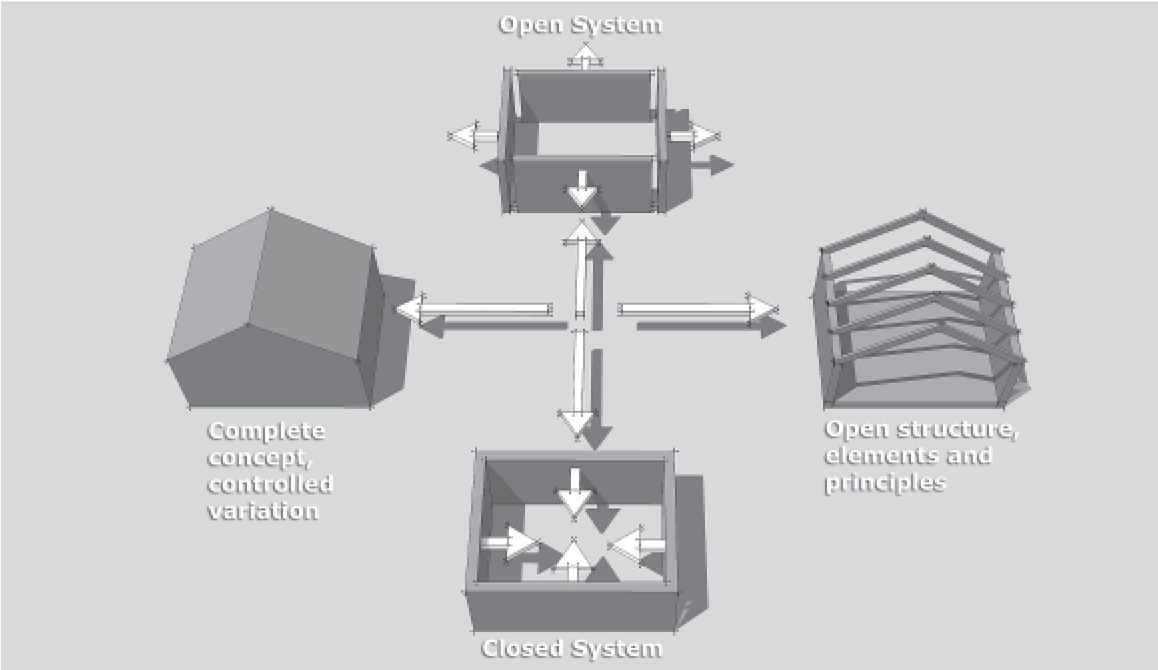



Figure 2.5: Diagram of the Categorization of Building Systems (Lessing, 20006).

## 2.3 TYPES OF PREFABRICATED BUILDING SYSTEMS

Precast systems are categorized according to the type of load-bearing structure. As such, there are four types of precast systems: large-panel systems; frame systems; slab-column systems with walls and mixed systems. These are discussed in the following sections:

### 2.3.1 LARGE-PANEL SYSTEMS

The vertical and horizontal connection of large floor and wall concrete panels in a multi-storeyed buildings, such that the panels form rooms by enclosing spaces in a box-like manner within the building, is referred to as the large-panel system. The panels resist gravitational loads and provide flexibility in the interior layout. Wall panels are usually the height of a single storey, while horizontal floor and roof panels span one- or two-way slabs. With proper joints, the horizontal panels transfer lateral loads to the walls. There are three possible configurations based on the wall layout:

- ✓ Cross-wall system: the gravity-resisting walls are placed in the short direction of the building
- ✓ Longitudinal-wall system: the gravity-resisting walls are longitudinally placed
- ✓ Two-way system: the placement of the walls is in both directions.

The advantage of this system is speedy construction, acoustic insulation, fire resistance and paint-ready surface finishing. It is suitable for residential apartments and hotels. Figure 2.6 illustrates this system.

Figure 2.6: Large-panel System Building in Brandenburg, Germany (Spremberg, 2011).

### 2.3.2 FRAME SYSTEMS

This system is better suited to buildings which require more flexibility, such as multi-level car parks, shopping malls, offices, industrial buildings and sports facilities. Precast frames can be constructed in two ways: spatial beam-column sub-assemblages and linear elements. The former construction allows the placement of connecting faces away from critical regions but are difficult to form, handle and assembly, and as such the use of linear elements (the placement of connecting faces at beam-column junctions) is preferred. Figure 2.7 shows a typical frame system in construction.

Figure 2.7: Precast Frame System in Construction (Sciroll, 2011 (left) and Precast Search, n.d. (right))

### 2.3.3 SLAB-COLUMN SYSTEMS WITH SHEAR WALLS

In this system, the slab-column structure is used to resist gravitational loads while shear walls are relied upon to sustain the effects of lateral loads. Two sub-systems in this category are:

- ✓ Lift-slab system with walls: this consists of precast columns (two-storeys high) and slabs are assembled using special joints (Figure 2.8).

- ✓ Prestressed slab-column system: in this system, continuity is achieved using two-directional horizontal prestressing.

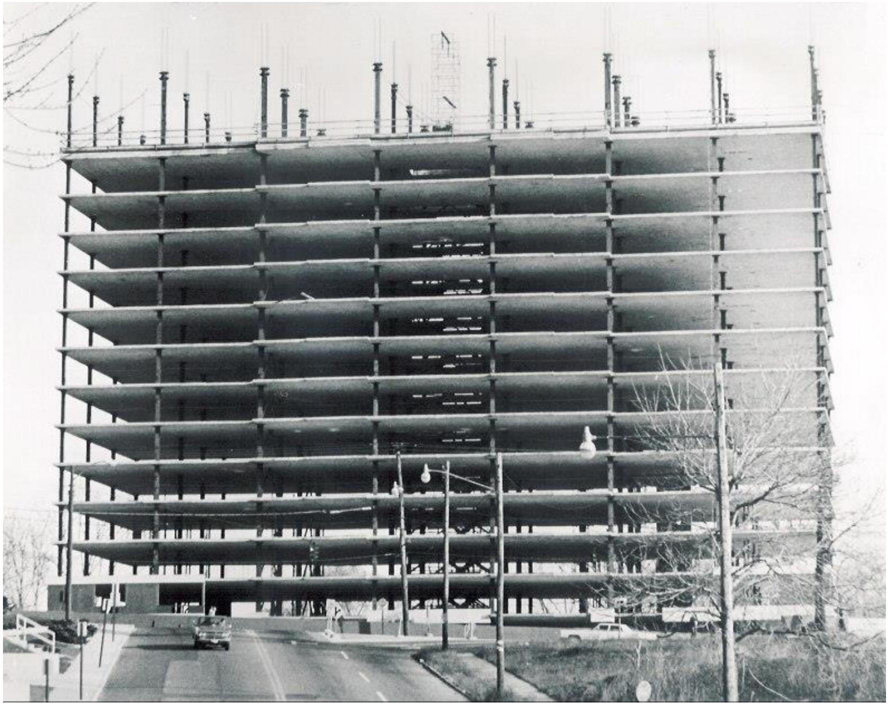


Figure 2.8: A Construction Using the Vaughtborg Lift-Slab System (Baumann Research and Development, 2004).

### 2.3.4 CELL SYSTEM

This system is used for specific parts of a building, such as bathroom, kitchen and stairs. The advantage of the cell system is speedy construction and high productivity, as the fittings and finishings are carried out at the factory (Building and Construction Authority, 2010).

## 2.4 PREFABRICATED COMPONENTS: MANUFACTURE AND ASSEMBLY PROCESS

The most commonly used prefabricated components are the precast concrete components. Examples are seen in Figure 2.9. Precast concrete is defined as concrete which is cast in one place, for intended use in another place, and is usually mobile. Most of the production of components is carried out in a specialist factory, except in cases where factors such as economy, geography, production scale and difficulty of access, require the components to be cast on or close to the construction site. Regardless of production location, the same managerial, supervisory and operational skills are employed. It should be noted that all references to precast components/systems/elements/units bear similarity in meaning to prefabricated components/systems/elements/units. This section is dedicated to all processes involved in the production of precast units, from design considerations through manufacturing to on-site delivery and assembly.

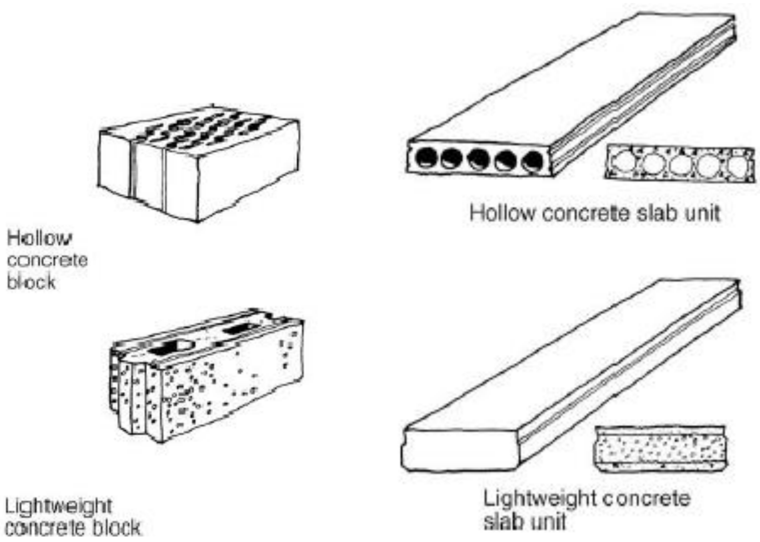



Figure 2.9: Types of Standard Precast Concrete Units for Floors and Walls (Bjørn, 2009).

The success of a prefabrication operation lies in the integration of all the concerned building professionals – architects, engineers, contractors, sub-contractors and clients. In order to achieve “total building performance”, these professionals must undergo a fundamental mind-set change from the conventional way of project execution. The conventional here being that consultants are more interested in the needs of clients, regulations, soundness of design and functionality while clients are more concerned with cost and final product; more so contractors’ main concern is the building process (Building and Construction Authority, 2006). The disciplinary differences between prefabrication and in-situ concrete are seen in the opportunities for mechanization and quality and output controls (Richardson, 2003).

The parts of a building to be prefabricated are grouped as follows: the building’s shell (which include its envelope and structural parts) and its finish works (which include doors and windows, exterior finish, insulation, electrical and plumbing elements). There are two main approaches to the prefabrication of heavyweight components: the planar partition approach and three-dimensional approach. The planar approach involves the prefabrication, transportation and on-site assembly of walls and floor slabs, while the three-dimensional approach refers to the partitioning of the building (interior finishes inclusive) into three-dimensional spatial units. Planar components could be of consistent modular room size. The elements of the room conform to its interior layout spaces and so their connecting joints are well-hidden – an architectural plus in houses and analogous buildings. The planar approach is the predominant approach as it gives more room for design flexibility, easier transportation and has no need for heavy lifting equipment.

### 2.4.1 PRECASTING DESIGN CONSIDERATIONS

Structurally, the difference between conventional construction and prefabrication is structural continuity. In the case of the former, continuity is inherent and flows naturally during the construction process. For the latter, conscious effort needs to be made to ensure this continuity begins with the connection of the precast elements; the connections act as bridges between the elements. Thus, safety and stability should be the watchwords at all stages of construction, in order to achieve a stable structural system. The successful implementation of the multi-disciplinary techniques of precasting requires careful planning and synchronization among the concerned disciplines (engineers, architects, general contractors and precast concrete specialist subcontractors), through all design stages.

The decision to use precasting in construction needs to be made at the earliest of design phases in order to allow for adequate coordination – lead-time to allow for factory set up of the precast elements should be sufficient. The precasting organization should be part of the decision-making process to ensure design practicality and simplify production. Design considerations are required to achieve high quality precast components. They include: dimension and shape of precast elements; concrete components; moulds; reinforcements; joints and connections; loads; lifting and handling devices; transportation systems and storage. Feasibility studies are required to assess the capacities of the available transportation systems and on-site storage space, to ensure adequacy. Compulsorily, the overall construction process must be properly established during the early design stages. The design requirements for the erection/assembly of the precast components must be done sequentially, with maximum tolerance. Product samples should be set up to test product characteristics and quality (both on-site and offsite) for conformity and standardization. Finally, and most importantly, last-minute design changes should be avoided as much as possible, as they inevitably lead to increased expenses (Baldwin et al., 2009; Building and Construction Authority, 2011).

### 2.4.2 DESIGN PROCEDURES

There are four phases of designs which must be undertaken by the structural engineer in the precast production process:

- ✓ Load assessment: load estimates and tables must be set up.
- ✓ Calculation model: this phase includes:
    - Definition of structural system
    - Description of potential load path

- Assessment of the stiffness of elements and joints
- Method of execution and load combinations

✓ Structural analysis: steps in this phase are:
- Determination of the elements and joints' loads
- Evaluation of the carrying capacity / strength of cross-sections, joints and materials
- Comparison of loads and resistances.

✓ Documentation: specification, shop and assembly drawings, and calculations.

The preceding steps are summarized in Table 2.1.

### 2.4.3 PRECAST CONSTRUCTION PROCEDURE

Conventional (cast in-situ) construction imposes many restraints that usually result in time penalties. The construction sequence begins from the foundations, followed by the supporting structure, from floor to floor, up to the roofing system and then final enclosure. This system usually entails a high level of erection and disassembling of formwork and falsework. Precasting reduces these requisites remarkably; decreasing time and affording the client earlier return on investment (ROI) as discussed in the advantages of prefabrication. Whereas with precasting, once the foundation is established, the frame construction process is easily carried out, and components are erected without framework or falsework, except in rare cases.

The structural concept behind precast components comprises:

✓ Conventional foundations (consisting of footings, rafts or piles)
✓ Cast in-situ ground reinforced concrete beam and slab system
✓ Precast concrete load-bearing walls

Table 2.1: Structural Design Procedure (Building and Construction Authority, 2010).

| PROCEDURES | ACTIONS |
|---|---|
| **1. Load Assessment** | Load Tables<br>Load Estimates |
| **2. Calculation Model** | Structural System<br>Load Path<br>Stiffness of Components and Joints<br>Execution Methods<br>Load Combinations<br>Calculations: Internal forces, Reactions |
| **3. Structural Analysis (Codes Of Practice)** | Designs:<br>Stresses<br>Deformations<br>Deflections |
| **4. Documentation** | Specifications<br>Calculations<br>Calculations<br>Drawings |

- ✓ Precast concrete non-load-bearing façade panels
- ✓ Precast concrete floor system: precast concrete walls with precast concrete slab system or precast concrete beams and slabs (with a composite in-situ top layer).

## FOUNDATIONS

The same foundation as used for conventional construction is used for precasting, the difference being the arrangement below the load-bearing walls and that used for the normal beam and column structural system. The aim is to have reasonably uniform support along the wall's length and reduce the effects of eccentricity should the walls be misaligned relative to the foundations. To achieve uniform support with a pile foundation, close spacing of the piles with a first storey capping beam is adopted, although uneconomical. The proffered solution is the designation of load- and non-load-bearing walls, locating the piles below the load-bearing areas, using the first storey beam not as a capping beam but as a means of dispersing the pile support along the wall, and finally grouping the piles to accommodate eccentricity.

## GROUND BEAMS AND SLAB SYSTEM

Precast construction is not cost effective or significantly advantageous over conventional beam and slab system for the construction of the first storey, based on the negligible cost of formwork construction and the significant extent of in-ground services. However conventional construction will be beneficial in allowing extra lead time for the production of precast elements, although there are possibilities to the use of precast system for ground beams and slab.

## PRECAST LOAD BEARING WALLS

Precast load-bearing walls are more economical in comparison to conventional wall, beam, column or infill system. They also provide better construction speed and eliminate wet trades. Besides designing the walls as simple concrete members, there are several factors to be considered in the design of the wall thickness, which include: joint details between panels, connection details for supported slabs and beams, fire assessment and sound transmission, and future services which could reduce the available concrete area. The recommended wall thickness is 180mm based on characteristic building layouts and regulations.

## PRECAST NON-LOAD BEARING FAÇADE PANELS

The non-load bearing façade components are usually the wall panels at the front and rear elevations of a structure. For support, any of the following is implemented: connection of the main load-bearing walls to the façade panel which is designed for self-support; or connection of the façade panel to the floor slab or beam which is designed to support the wall. Typical designs are for vertical loads due to self-weight and horizontal loads due to wind forces, where applicable. 120mm is the recommended wall thickness to allow insertion of windows and window profiles around the window's boundary.

**PRECAST FLOOR SYSTEM**

There are two kinds of systems for precast flooring: Prestressed Plank and Half-Slab Floor System, and Precast beams and precast slabs. Both systems adopt structural in-situ toppings. The former consists of prestressed planks spanning the load-bearing walls. The latter comprises reinforced concrete half-beams which span between load-bearing walls and half-slabs which span between beams. This system bears structural similarity to the conventional reinforced concrete design.

### 2.4.4 CONSTRUCTION PROCESS

Once the design procedure for the components is completed, each component has to undergo the following processes as outlined by Chan and Hu (2001):

1. Concrete mixing and movement from the mixing point to the mould;
2. Setting of moulds: the moulds are cleaned and oiled and the side frames are fastened;
3. Placement of fixtures, reinforcements, electrical components and such as will form part of the components;
4. Casting: the concrete is poured, compacted and levelled;
5. Curing; naturally or artificially (by heating);
6. De-moulding: the side frames are stripped and the components are taken out;

7. Finishing, patching and repairing of the components;
8. Placement of the finished components in the stockyard for delivery strength; and
9. Transportation of the components to the assembly site.

### 2.4.5 TRANSPORTATION AND DELIVERY

The cost savings achieved by prefabrication are usually partially offset by transportation costs from the factory to the project site. In addition, road transportation regulations in certain countries may also pose as a barrier to the transportation of heavy prefabricated panels. Such limitations ought to be given serious consideration prior to the adoption of prefabrication (Abdallah 2007). It is of the essence that the delivery program is in sync with the erection cycle. As much as possible, elements should be delivered into position directly from the transportation. The usual process involves direct placement of the elements into the structure without turning or on-site storage. Where on-site storage space is limited, considerations for offsite storage can be made; therefore additional incurred costs should be accounted for. However, site-stored elements are susceptible to damage and repetitive handling from site stacking.

### 2.4.6 HANDLING AND ERECTION

The erection and assembly of precast panels require heavy equipment such as cranes, especially in the case of high-rise buildings. Such costs and operations need to be given consideration in the case of implementation of prefabrication (Abdallah, 2007). A specialist team generally carries out erection and assembly of precast components. The main operations are the offloading, handling, installation of the components, lining and levelling of the cladding elements, jointing and subsequent waterproofing of the whole structure.

The on-site lifting equipment and attachments must be similar to those obtainable at the factory. Where necessary, specialized equipment have to be designed for circumstances such as lack of headroom or access to already erected components. In the event of on-site storage due to delay in delivery, appropriate stillages and racks are needed to prevent damage to the precast elements. It is paramount that personnel are assigned responsibility for the structural integrity of all fittings, connections and weather-tightness where cladding is involved. In short, names of persons responsible for all erection operations need to be published where quality assurance firms are employed.

## 2.5 CLASSIFICATION OF PREFABRICATED COMPONENTS

Girmscheid and Kröcher (2007) indicate that the manufactured products of prefabricated companies are of two categories. The first group comprises supplier components such as balustrade elements and staircases, as well as supports built into otherwise traditionally constructed buildings by contractors. The implication of these products is the late involvement of the prefabrication companies in the construction process. For the other group, entire buildings inclusive of their load-bearing structures and elements for room-building are prefabricated by precast concrete factories. Unlike the first group, the relevant planning specialists or prefabricated components manufacturers are involved as early as the planning stage.

### 2.5.1 PRECAST CONCRETE SLABS

Figure 2.10 shows the common precast concrete slabs, ranging from the simple solid flat slab to the double tee slab.

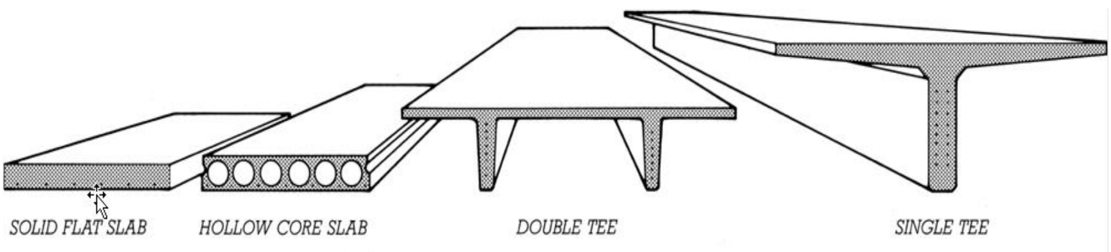


Figure 2.10: Precast Concrete Slabs (Bethlehem Construction, 2012).

### 2.5.2 PRECAST CONCRETE BEAMS AND GIRDERS

There are different kinds of precast concrete beams and girders, which serve as load-bearing support. These include the rectangular beam, L-shaped beam and inverted 'T' beam, as shown in Figure 2.11.

### 2.5.3 PRECAST CONCRETE COLUMNS

Precast concrete columns providing aesthetical value and structural support to a building are shown in Figure 2.12.

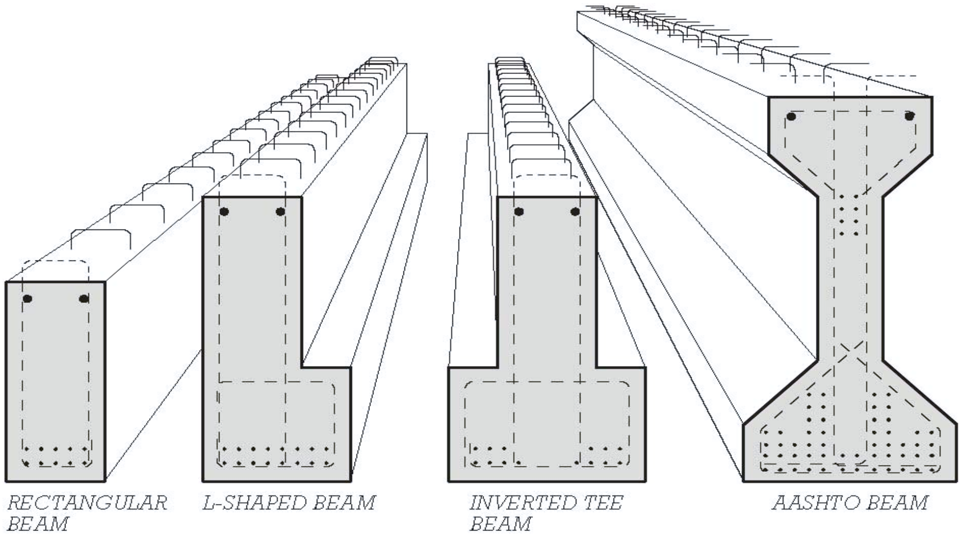



Figure 2.11: Precast Concrete Beams and Girders (Bethlehem Construction, 2012).

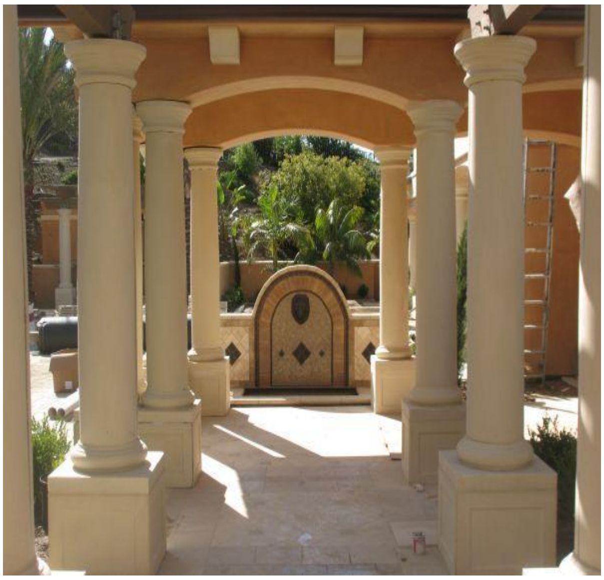


Figure 2.12: Precast Concrete Columns (Bethlehem Construction, 2012).

### 2.5.4 PRECAST CONCRETE WALLS

Figures 2.13 and 2.14 depict samples of precast concrete walls.

Figure 2.13: Precast Concrete Walls (Bethlehem Construction, 2012).

Figure 2.14: Precast Concrete Walls (Insulating Concrete, 2012).

### 2.5.5 PRECAST CONCRETE STAIRS

One of the most commonly used precast concrete units is the precast concrete stairs. Typical examples are given in Figure 2.15.

Figure 2.15: Precast Concrete Stairs (Precast Concrete Steps, 2012 (left); The Step Guys, 2012 (right)).

### 2.5.6 PRECAST KITCHEN AND BATHROOM UNITS

Precast concrete bathroom units (Figure 2.16) and kitchen units (Figure 2.17) are equally commonly used, both in conventionally constructed and prefabricated housing units.

Figure 2.16: Precast bathroom unit (Florida Homebuyer, 2010).

## 2.6 SEMI-PREFABRICATED CONSTRUCTION

Mwamila and Karumuna (1999) studied model buildings constructed with semi-prefabricated technology. They defined this technology as the partial application of prefabrication to the technique of concrete construction. That is, a full building is constructed using both prefabrication components and in-situ concrete. The

Figure 2.17: Precast Kitchen Unit (Florida Homebuyer, 2010).

purpose of this is to exploit the advantages of both construction systems. Semi-prefabricated construction involves the on-site production of small-sized prefabricated elements/components, which are then either manually- or machine-assembled. Auxiliary supports are not usually required due to the self-supporting nature of most of these elements. According to the authors, semi-prefabrication provides one significant advantage – the maximization of construction outputs from available resource inputs, simply referred to as optimization, in terms of construction speed, economy and quality.

## 2.7 PARADIGMS OF PREFABRICATION

The idea of learning from other industries to improve the construction industry's performance is not newHenry Ford exploited the advantages which manufacturing provided over the production of scattered craft. Said advantages included: the opportunity for better management control; economies of scale (that is, cost per unit experienced a quicker drop than rise in production cost with increase in the volume of processed materials); and technical potentials for the development and deployment of capital equipment. Ford's invention of mass production together with the implementation of scientific management meant that standardised products manufactured from substitutable parts could be more easily produced in large volumes. The development of the construction industry was strengthened on three principles: standardisation, prefabrication and systems building. Standardization was the most essential requirement for factory-based production. Components specifications were scientifically examined in order to categorize by modules each attribute or function of the component such as performance, installation and tolerance. Bricks were the first housing component to be manufactured to standard in factories using the batch production method and later on, volume method, long before the existence of Ford's production system.

Certain manufacturing and production concepts are based on the principles guiding the efficiency in production processes and customer satisfaction. Some of these concepts include the Just in Time (JIT), the popular concept developed by the then Chief Executive Officer of Toyota Corporation; Lean Production, Supply Chain Management and Automation. Over the years, the construction industry has built interest in these concepts and their application to construction processes in order to enhance productivity and maximise efficiency, advantages enjoyed by the manufacturing industry. The JIT system is a management philosophy utilised in manufacturing industries, involving the right quantity and quality in the right place at the right time. Wei (2006) adds that it is only the 28 parts needed at the right quality at the right place and time are produced and delivered cost effectively, with the use of the minimum required materials, human resources, equipment and facilities.

Lean Production for the most part is based on the underlying principles of the JIT system also referred to as the Toyota Production System (TPS). It embodies the following principles: teamwork; efficiency in the use of resources and waste elimination; communication; and constant improvement. Lean Production paradigm is the ‘pull’ system which means that materials are replaced only upon consumption and stocks are filled up only on demand. Production of goods or services is not carried out until there is a consumer demand downstream. Several organizations are focussing on the implementation of lean principles in the construction industry such as the Lean Construction Institute, the International Group for Lean Construction as well as the recently founded Swedish Lean Forum Bygg. The following sections describe in detail these production paradigms and concepts and their relevance to prefabrication (Lessing, 2006).

Automation in prefabrication could range from the use of construction robots, manufacturing planning and cost estimation, integration of building systems via expert systems, the development of software for design, estimation and accounting for manufacturing firms to the use of CAD/CAM software such as was done by Herkommer and Bley (1996) and virtual prototyping, as used by Li et al. (2011).

## 2.8 PREFABRICATION – ADVANTAGES AND DISADVANTAGES

### 2.8.1 ADVANTAGES OF PREFABRICATION

Generally, the advantages of prefabrication are tied to the reduction of construction costs of projects. As time and labour are saved while productivity is increased, cost savings are achieved. Several authors such as Polat (2010) and Pheng and Hui (2010) endorse the implementation of prefabrication based on the results of research and studies carried out to determine the true benefits of prefabrication over traditional construction methods. Based on seven case studies carried out on houses, hotels, hospitals and other buildings of different functionalities, Rogan, Lawson and Bates-Brkljac (2000) found the following benefits provided by prefabrication in comparison to conventional construction: improved quality  reduced ‘call backs’); increased construction time by 50%; waste reductions of 70%; up to 10% savings in project capital costs, and the advantage of JIT delivery to the site.

As far back as 1985, Deb studied the 'Holopan System' of construction, a system involving the use of simple prefabrication. After a thorough study, the economic and technical specifications of the components were arrived at that would meet the requirements of low-income earners, and subsequently middle- and high-income earners and were found to be satisfactory. Other authors studied the various applications of prefabrication such as the Footbridge in Mongkok, the Hunghom Bypass and the Cambridge Office Building by Chan, Chan and Kung (2004), Kok (2012) in military bunkers, and Rogan, Lawson and Bates-Brkljac (2000) in social housing construction. Their collective conclusions presented the advantages of prefabrication to be short build times; superior quality (by pre-design and quality control); low weight (prefabricated construction is 70% less than the weight of traditional masonry construction); environmentally less sensitive (less waste and less disruptions of installations); usability on infill sites (such as rooftop-extensions); reduction of labour requirement; safer construction; cheaper professional fees (standardisation means simpler and less specialized design input needs) and the much-needed economies of scale. These advantages are discussed further.

#### 2.8.1.1 OVERALL COST REDUCTION

The primary advantage of prefabrication recognized by many researchers is the overall reduction of project cost as compared to the conventional method of construction. According to Haas et al. (2000), this could be attributed to several factors. If more work is carried out offsite than on-site, then the risk of costly delays due to weather and harsh on-site conditions would be avoided. The need for local labour, which is mostly incompetent or expensive, would be significantly reduced. In addition, worker congestion and on-site complication could be avoided, allowing for increased productivity and reduced costs.

Cost savings from the use of prefabrication are the reduction on the need for site preliminaries and quicker return on investments (ROI) to the client, loss of profitability in the case of extension of existing facilities, and construction schedule predictability. Site preliminaries are typically estimated to range between 8% and 15% of the overall construction cost. It is known that prefabrication provides 50% savings in time which in turn leads to a beneficial proporrionate savings in the cost of these preliminaries. Although dependent on the type of operation, at the least, the client earns savings on the charged interest on land cost and mean construction cost over the shortened construction time. At the most, the client benefits from the early earning potential of the structure due to early operation. In the case of existing buildings such as recreational facilities, clients tend to experience heavy loss. The saved construction time means that commensurate savings are achieved (Rogan, Lawson and Bates-Brkljac, 2000).

Additionally, Huanga, Chen and Sun (2004), showed that the time taken to erect formworks for a reinforced concrete building project amounts to a third of the total concrete cost or 15% in terms of the overall construction cost. By replacing traditional formwork construction with prefabricated form sets, cost is effectively optimized as the form sets could be reused within the same project or between projects, also minimizing material loss. Another instance of cost savings is the use of the BIG CANOPY (BC) to virtually construct the earlier mentioned Westpoint building, which reduced almost 1% of the total project cost (about 312,000 Euros) (Gassel, 2005).

In their report on the unpublished cost analysis of Hong Kong's Housing Authority, Baldwin et al. (2009) stated that by including manufacturing and material costs, offsite and on-site inspection costs, and erection costs of prefabricated components, the cost of prefabrication is between 25% and 35% more than the cost of traditional construction. However, prefabrication becomes more competitive when the following are considered: 30% production savings which results in less labour requirements on-site; savings in materials as a result of reduced formwork and falsework needs; and optimised use of reinforcement in factory production which eliminates on-site concrete dumping. Precast floor slabs save 28% and 45% while precast prestressed concrete beams save 60% and 65%, of the quantities of concrete and steel required, respectively, for cast-in-situ construction.

Another aspect of cost savings is economies of scale. Factory production and products pre-testing of typical units, such as those for bedrooms and bathrooms, offer the benefits of speed and quality. Design is greatly improved upon, more investments are made in the production, stringent quality assurance measures are implemented variation in design is provided at optimal costs, and waste is reduced as design repetition is avoided. However, Rogan, Lawson and Bates-Brkljac (2000) debate that conversely, prefabrication may result in the over-engineering of structures due to the requirements for hoisting and conveyance. Also, standardization may in actuality oppose the supposed economy of scale due to the need for efficiency in production.

#### 2.8.1.2 TIME SAVINGS

Time is a critical resource in all construction activities. Time provides competitive advantage as the ability to deliver products faster than competitors means higher job consideration value of contractors. The adoption of JIT philosophy provides this advantage; speed and efficiency have become associated with prefabrication and the industrialisation of buildings. The production and delivery of the right quantities of products and the right quality for offsite casting and on-site assembly at just the right time enhances the productive, buildable and logistical edge for building contractors. It was observed by Clarke and Wall (2000) that the construction speed for the prefabricated residences in Netherlands was four times that of the traditionally-built houses in UK and nearly three times that of Germany's concrete-framed flats (Chan, Chan and Kung, 2004).

Implementing prefabrication shortens on-site construction period considerably, which in effect means a decreased construction schedule, an advantage to contractors and project owners working with compressed schedules. As opposed to the conventional methods where construction activities are performed in an austerely linear order, prefabrication allows for multiple activities to be carried out simultaneously in different locations, thereby lessening the duration of construction

(Girmscheid and Kröcher, 2007; Haas et al., 2000; Rogan, Lawson and Bates-Brkljac, 2000). The speed of construction that prefabrication provides ranges between 5% and 10% of the total cost of construction measured in terms of time saved on site, compared to the traditional construction method.

With regards to the construction of formwork, the use of traditionally constructed formwork is highly time-consuming. This is because in addition to the number of mandatory man hours required for the erection of these formworks, it is necessary to put in more hours in order to further finish the concrete surfaces after stripping. However with the use of modular formwork systems, there is less need for further finishing due to the smoothness of the surface of the formwork, the time required for erection is considerably shortened and skilled labour is saved (Huanga, Chen and Sun, 2004).

In comparing the advantages and risks of construction systems, Gassel's (2005) earlier mentioned Westpoint building was constructed in reality the conventional way, while a virtual construction was carried out using the BC construction system. The results of the study showed that the BC saved 13% of the entire construction period that was implemented for the traditional method.

#### 2.8.1.3 SAFE AND CONTROLLED CONSTRUCTION ENVIRONMENT

The construction environment is generally considered unclean, unsafe, untidy, hazardous, vulnerable and accident-prone due to the carelessness of construction workers and a lack of safety and health awareness (Kok, 2010). One of the major causes of causalities on-site is the construction of the false work required for the erection of formwork. On the other hand, modular formwork has higher strength and hence the task of pouring concrete is considerably less risky, and so the safety of workers is more assured Huanga, Chen and Sun (2004).

One notable achievement which prefabrication provides is a safer and more productive working environment. There is a significant improvement in the overall project safety as a result of less risk of worker accidents, thus saving on the set-back of potentially lost time due to the prevalent severity of the working conditions of on-site jobs. Job conditions are not dictated by the weather, therefire, work progresses uninterrupted and productivity level remains high, providing a truly considerable advantage over traditional construction (Haas et al., 2000). Chan, Chan and Kung (2004) assert the use of prefabrication in recent times in the construction industry, as it has been seen to boost site safety by providing a cleaner, tidier work environment. Kok (2010) speaks for prefabrication in relation to the advantage it provides construction stakeholders - a better more controlled, more organized environment which enhances health, safety and welfare.

#### 2.8.1.4 QUALITY IMPROVEMENT

Prefabrication provides better quality of work than is obtainable through on-site construction. This is attributed to the controlled working conditions in the production factory, the repetitions of processes and activities as well as the use of automated equipment (Haas et al. 2000).

According to Rogan, Lawson and Bates-Brkljac (2000), since quality is a highly critical issue to clients in their concern for the post-construction operation of their finished buildings, the implementation of prefabrication system means pre-installation trials of products can be carried out to ensure quality and client satisfaction, especially with regards to high-service units such as elevators, plant rooms and kitchens. The need for the ‘call-backs’ cost (usually 1-2%) that is usually included in the bill of quantities of conventional construction procedures is reduced considerably. Standardization of modularisation of components is more enhanced (Polat, 2010).

#### 2.8.1.5 ENVIRONMENTAL IMPACT

With less need for field labour and on-site activities, the impact of construction on the environment is positively reduced. This advantage is especially significant considering the negative environmental impacts associated with the construction industry, which are particularly attributed to the traditional construction processes (Haas et al., 2000).

Rogan, Lawson and Bates-Brkljac (2000) give detailed benefits of the application of prefabrication to the construction of buildings in terms of construction operation, building use and subsequent re-use. Prefabrication saves the environment when compared to traditional construction methods. In terms of operation, energy used for product manufacture, construction and service operations is comparatively lesser. These advantages are part of the benefits of speedy construction which prefabrication provides, in that shorter construction period means less environmental impact.

Mainly, there is greater efficiency and economy in the use of materials than can be achieved with conventional construction. More so, factory production means waste is substantially reduced, and the need for landfill is lessened by about 30% of that of conventional construction, as well as the environmental damage due to on-site packaging and use of materials. Installation of modules on-site is fast and quiet, requiring no storage or the use of noisy equipment. Schedule for delivery and installation of modular units can be programmed to avoid traffic and site working constraints, and even delivery of a large number of small quantities of materials is reduced. This advantage includes the reusability and relocatability of modular components. There is less noise pollution and other environmental nuisances to nearby buildings since the main construction operations are carried out elsewhere, in a factory.

With regards to the use of the buildings, high performance is an important benefit of prefabricated construction. For instance, prefabricated buildings particularly steel buildings, are more thermally efficient meaning less energy requirement and therefore reduced carbon emissions; provide better acoustics; have a more ‘solid’ feel and require marginal maintenance.

As seen in later sections in this study, prefabrication provides immense energy saving benefits in comparison to conventional construction. The production of precast concrete components requires far less cement per volume of concrete for similar cast-in-place productions, due to enhanced quality control measures. Aye et al. (2012), Monahan and Powell (2011) and several others carried out comparative studies on the embodied energy and carbon contents of traditional and prefabrication processes. It was found that prefabrication provided energy savings by as much as 17% of $CO_2$ emissions and 32% of embodied energy. According to the Parliamentary Office of Science and Technology (2003), prefabricated houses generally require less heating energy as a result of increased insulation levels in their walls and roofs, and also less air leakage, due to the manner of construction of the prefabricated building components. As a result of this advantage, builders are embracing prefabrication more and more because of anticipated enforced stringency in building regulations in the UK.

Finally, prefabricated buildings are much easier to expand or reduce, than traditionally constructed buildings. At reasonable prices, they are also much easier to relocate, affording lower energy costs for their dismantling, reduced long-term use of scarce resources, and importantly, no material wastage.

#### 2.8.1.6 WASTE REDUCTION

It is a known fact that the construction industry is one of the main generators of waste and a huge percentage is attributed to on-site concreting. In order to achieve a significant reduction of waste, it is therefore paramount to limit on-site concreting processes during construction. Prefabrication and precasting provide significant opportunities for the reduction of waste of resources in construction. Precasting has been said to encourage waste minimization in the construction industry through design innovation. Less timber formwork, less wet trades on-site, reduced water pollution, from construction activities and general improvement in waste management and disposal increase environmental merits. Factory production ensures a cleaner, safer setting for works resulting in more economic use of materials. Similarly, precasting improves quality of components thereby standardization is ensured and the occurrence of waste is minimized (Baldwin et al., 2009; Chen, Okudan and Riley, 2010).

Construction waste and its environmental impact have become a major source of public concern, particularly in countries such as Hong Kong where there are no more sites available for use as landfill. According to Tam et al. (2005), excessive construction waste is as a result of wet-trade construction such as plastering, bricklaying and in-situ concrete works. Their stated reasons for these wastes are inconsistency in design, poor workmanship, installed losses, in-transport damage, cutting and over-ordering, all of which can be effectively mitigated by the adoption of prefabrication (Chan, Chan and Kung, 2004).

The result of a study on the waste reduction value of prefabrication showed a 56% construction waste reduction, in addition to 20% saving on construction time, and over 40% reduction in water consumption. Albeit a ground-breaking study on the innovative use of precast procedures, these records were obtained from the study of only one building sample (Jaillon and Poon, 2011).

In terms of waste recycling, Jaillon and Poon (2011) and Chan, Chan and Kung (2004) disagree that waste is defined only to include the residues of delivered used in built works while excluding excess materials that could be reused in construction projects, as was opinionated by Tam et al. (2005). The authors advocate the use of prefabrication for effective waste reduction as it encourages the recycling of construction waste and thereby promotes environmental safety and sustainability.
In spite of the highly praised advantage of waste reduction and minimization provided by prefabrication, Dubois and Gadde (2002) argue that prefabrication is not as much a waste saver as it is said to be. Their argument is that prefabrication, in fact, causes waste due to overproduction. Pheng and Hui (2010) suggest that production at the point of use - that is only when required - will eliminate this problem. The application of JIT will greatly minimise the waste resulting from

mismanagement of prefabrication techniques in building construction further, albeit marginally.

### 2.8.1.8 INNOVATION AND INDUSTRIALIZATION

According to Dubois and Gadde (2002), the process of learning and innovation is hardly a success in the traditional construction industry because “each house is treated as a pilot model for a design that never had any runs” (p. 14). Innovation in construction is said to be the process of generating new ideas for new components with intrinsic functional, economic and technological values. The need for innovation has been pressed upon building professionals as a result of the requirements for increased quality of buildings, tight schedules, safety and the regulations for environmental protection. As such, more and more contractors are embracing prefabrication of building components. Prefabrication is associated with better product delivery in terms of mass production, factory conditions, offsite production, standardization, innovative technology and equipment. Prefabrication has become much more than just the industrialization of buildings and building technologies. It is “reengineering, industrialization, concurrent engineering and value-adding” (Chan, Chan and Kung, 2004, p.7).

To summarize, Tam et al. (2007) carried out a survey on the significance of the benefits of the adoption of prefabrication. The results of the survey showed that according to its participants, ‘‘better supervision on improving the quality of prefabricated products’’ was regarded as the most significant benefit of better supervision because of the pre-installation trials and inspection of the products. This was followed by early standardization of design layouts and overall cost reductions as second and third in significance, and time savings and the fourth in the rank of benefits of prefabrication.

Polat (2010) states that precast concrete technology can contribute to sustainability when incorporated in the construction industry based on the advantages discussed as the replacement of the traditional cast in-situ technique.

### 2.8.2 DISADVANTAGES OF PREFABRICATION

In spite of the praise-worthiness of prefabrication as a preferable construction method, it poses a certain disadvantage which has rendered it disagreeable as implied by several authors. This single disadvantage is cost. The cost competitiveness of prefabrication in comparison to other systems is seen at the initial mass production stage, where initial cost of form-making is high. However, once constructed, every additional component becomes much cheaper. The higher costs are also incurred from shipping, engineering and installation of the prefabricated components, particularly when steel frames are used (West, 2011).The cost savings in production may be belied by the cost of transportation of manufactured components, particularly in the case of large modularized sections that must be conveyed over long distances. Size therefore becomes a constraint to the method of transportation which implies cost and schedule considerations. As a result, certain engineering aspects need to be pre-approved before construction is fully implemented, such as finalization of design work and wide-range planning, as well as interference analysis.

Although this may cause limitations in the flexibility of prework - as a result of the difficulty associated with design modifications once the project has begun - Haas et al. (2000) argue that it could be beneficial in the sense of better scope control and an overall improved project performance. However, Kok (2010) debates that the uncertainties of the impending cost may affect the performance of the project and as such for construction industries such as Malaysian construction industry, prefabrication is uncommon as developers are not convinced about its ability to meet their aesthetic and other design conditions.

Prefabricated houses are more affordable than traditional houses, as the controlled factory environment means production is carried out at a faster pace, meaning less time is required, materials are saved and labour is reduced. All of this translates to less cost. However, the initial/upfront cost demanded by the prefabricated manufacturers is seen to be quite high and as such the cost advantage of prefabrication is reduced. Another aspect of cost ineffectiveness is in the use of non-standard units due to client requirements, which may actually increase production costs Rogan, Lawson and Bates-Brkljac (2000).

## 2.9 CONSTRAINTS TO THE ADOPTION OF PREFABRICATION

Wei (2006) endorses prefabrication as one of the means of effective waste management. Blismas et al. (2005) state that according to the Egan Report supply-chain partnerships, standardization and prefabrication were said to play major roles in the improvement of construction processes. In spite of these and the aforementioned advantages of prefabrication, certain constraints to its successful application have been identified by numerous reports such as those of Lovell and Smith (2010) and Blismas et al. (2005). The former talks about the paradox of prefabrication which is discussed in the Chapter 3 of the study. Gibb (2001) referred to several of these constraints as the 'myths and legends' of prefabrication. Expounding on the causes of these constraints, Blismas et al. (2005) based on Egan (1998), associate the following negative characteristics with the construction industry: disjointedness, underachievement, work at low profitability, almost non-existent capital investment in training and research and development (R&D), and in general, a low-level performance satisfaction of clients.

Tam et al. (2007) analysed the hindrances to the adoption of prefabrication in Hong Kong and discovered ten factors responsible for this: design inflexibility; higher initial construction cost; more time consumption during initial design stages; lack of background research information; lack of experienced contractors; limited space for prefabricated components; inconsideration of the advantages of on-site conventional construction methods; possible leakage problems during joining of prefabricated components; lack of demand for prefabricated building components; aesthetic building monotones. Among all these constraints, design flexibility ranked as the worst constraint, while cost ranked fourth. This is unlike other studies in which the perceived higher construction cost was said to be the main reason for the low level of implementation of prefabrication.

### 2.9.1 COST

The widely-held perspective on prefabrication as a higher cost of construction than conventional methods of construction, particularly in the UK was studied extensively by Pan and Sidwell (2011). The authors observed that prefabrication, like every other innovative technology, is trapped under the caption of ‘high investment cost. These perceptions on the higher costs of prefabrication seem to be deeply rooted in the mentality of construction professionals. In their study, they observed that the most critical constraint is seen as the higher cost, in addition to the lack of public data and information which has been identified as the most inhibiting factor to the increased use of prefabrication. The general belief is that innovative technology in the construction industry is cost-intensive with indefinite returns, and due to the peculiar nature of the construction industry, is a poor competitor for direct profits associated with conventional construction methods. The cost-effective argument against prefabrication is based on the indicated 7-10% increase in construction cost according to industry sources, in spite of the stated advantage of reduced costs that prefabrication is said to provide in the UK. The reason for said higher costs is difficult to determine due to the commercial confidentiality of most projects’ financial information, and also because of the widely varied costs of traditional masonry.

The greatest cost constraints of prefabrication can be summarised into the following four factors: the opacity of the concept of cost as a barrier; the resultant real or perceived grater cost of implementing prefabrication and offsite technologies as compared to traditional construction methods; the absence of data and information of offsite construction cost; scarcity of data on the cost reduction and increased cost effectiveness of prefabrication. Prefabrication appears more expensive than traditional construction because these cost factors are e hidden in the preliminaries, and softer issues as health and safety are either implicit or disregarded. Using a simple cost basis, prefabrication is deemed to appear more expensive, while a more holistic approach exposes its benefits which are not easily monetized. These cost factors are the reason for the reluctance expressed by builders and developers to adopt prefabrication in spite of the cost-unrelated and life cycle cost benefits. Thus, cost evaluation comparison systems are inadequate (Blismas et al., 2005; Pan and Sidwell, 2011).

The authors carried out a study in which they successfully dispelled this myth by proving that the use of precast concrete of medium to high-rise buildings provided cost savings that ranged between 11% and 32%. In addition, the adoption, development and innovation of cross-wall technology continuously saved on costs, up to 25% in apartment buildings as well as improved cost effectiveness in high rise buildings. They however propose that sustenance of the cost reduction benefits of prefabrication is neither automatic nor just a result of long-term use, but requires organisations to be committed and continuously explore offsite technologies, along with their supply chains, otherwise the myth would eventually become a reality.

Wing and Atkin (n.d.) in their paper argue that it is not really practicable to compare the cost of prefabrication with conventional construction. They assert that if considered on an elemental basis, prefabrication would come across as being a more expensive technology than the conventional method. For instance, the cost of factory set-up must be included in the overall cost, whereas for on-site, similar costs are sometimes ‘lost’ in the contractor’s preliminaries. Also, the economies of scale that should follow cost savings are not realised because the manufacturer has to wait on orders from the general contractors and the only savings are those obtained from bulk purchases. Tender prices may not actually reflect the actual costs because in line with a free market economy, manufacturers and suppliers seek the maximum sustainable market price. As such, comparison of prefabrication with conventional construction is hindered.

A study observed that in spite of the awareness of quality improvement and reduced snagging as the advantages of prefabrication, these advantages were hardly included in projects costings and as such many projects were still either deliberately or not, judged purely on their initial cost. Furthermore from survey results, the biggest barrier to the adoption of prefabrication was the belief that it was more expensive than implementing conventional construction methods, even though perversely, a large number of respondents agreed that one advantage of using prefabrication was its reduced initial cost as well as whole life cost. It was presumed that most suppliers preferred to sell the idea of prefabrication to clients based on factors such as improvement in construction speed and quality rather than cost reduction It is concluded therefore that the choice of any construction method is cost-based rather than value-based (Blismas et al., 2005; Goodier and Gibb, 2007).

### 2.9.2 INFLUENCE OF TRADITIONAL CULTURE

Höök and Stehn (2008) point out interestingly that in applying lean principles to construction, the scarcity of error proofing, maintenance of equipment and standardisation of floor works in the industrialised building system implemented in Sweden shows that the prefabrication is clearly still influenced by a production culture bearing the marks of traditional construction techniques, despite its similarities to manufacturing. Their opinion is that the mentality that construction professionals bring from the traditional background into the industrialised system is a constraint and thus the application of lean construction principles needs careful implementation. They agree however that this mentality is not entirely a constraint; the traditional culture brings to the table flexible teams that take responsibility for themselves, is important for lean culture. Therefore, retaining certain aspects of the traditional construction culture seems beneficial to the application of lean principles in construction. The authors note that although it is stated that lean principles are applicable to just about any industry; it has met certain resistances in the construction industry as a result of the traditional mentality and the variability of players in the construction industry, when compared to the manufacturing industry.

There are no formal criteria backing the decision to implement prefabrication in building projects, besides the simple and holistic evaluation methods that consider labour, transportation and materials costs when comparing construction methods (Chen, Okudan and Riley, 2010). These methods are deemed anecdotal as they do not take into account long-term issues such as environmental impact, energy consumption and life cycle costs. Arguably, recent studies on the advantages of prefabrication carry out extensive life cycle and environmental analyses of the impacts of prefabrication. However, Chen, Okudan and Riley (2010) argue that prefabrication is not always the only suitable available option for consideration for a construction project, there may be several other viable choices depending on the type of project. They further argue that prefabrication is not necessarily always a better option than conventional construction methods, pointing out that precast technology could be disadvantageous in terms of such problems as delays in production and erection schedule and significant cost overruns. They propose that holistic criteria are needed to truly determine the appropriateness of any construction method and also the stimulation of the use of prefabrication for a particular building project.

### 2.9.3 STANDARD EQUALS BORING

“Standardization means standard (and therefore boring) buildings” was one of the most popular topics during the CIRIA Research (Gibb, 2001). Standardised buildings have been dismissed as being aesthetically faulty such as the McDonald’s Drive-Thru, a fact which is unsubstantiated considering the business point for which the modular buildings were constructed to begin with. Classic examples of buildings whose standardised components were used to produce effective customised solutions include the Charles Eames house and the Georgian residential design style. These buildings may be deemed boring in the architectural sense but then aesthetic is clearly is a subjective issue, and as Gibb (2001) points out the these are houses people aspire to own, and ‘boring’ is further from their minds than anything else. The argument here is that although the individual components are standardised, the building as a whole should be a representation of customization, that it must provide variation.

Perhaps the fear of presenting a standardised product which clients may misinterpret as boring is the reason suppliers downplay the standardisation of their products in order to make clients think they are in fact purchasing products specially designed for their projects. Gibb (1999) established that these modern specification turn out to be mere adaptations from earlier projects. Gibb (2001) concludes that by focusing on design excellence, standardisation and pre-assembly could produce buildings that are innovative and exciting, and certainly not boring.

Additionally, one impeding criterion of the increased use of prefabrication is the bad image attached to buildings constructed with precast concrete elements (Girmscheid and Kröcher, 2007). The highly negative influence of the post-war perception of prefabricated houses on house buyers poses a strong resistance to any construction innovation that presents houses in a different way than what a 'traditional' house is supposed to look like, including prefabrication. This resistance to change and the negative image of prefabrication is also seen among industry professionals in the UK where the refusal to accept innovation has proven to be a huge set back (Goodier and Gibb, 2007). According to Friedman and Cammalleri (1993), despite the much improved standard of quality provided by prefabrication, the general public still views prefabricated houses with a negative eye. Though the reasons for this remain varied, one fact remains: people would rather watch their houses built from scratch than delivered by truck. Pheng and Hui (2010) in support of this asserted that the client would rather not have his building looking like every other person's building. In order to please the client, the builder is ready to sacrifice buildability for aesthetics and uniqueness of the building.

The FutureHomes project was believed to signify the arrival of a fully factory-based housing approach that took full advantage of the digital technologies of today. The authors noted that by incorporating visualisation and mass-customization, it was hoped that the greatest apprehension – the association of factory-based housing with styles that lacked taste and were unable to express custom or culture – would be avoided (Wing and Atkin, 2002).

### 2.9.4 EARLY PLANNING AND DECISION-MAKING

One of the drawbacks to the implementation of prefabrication includes the late decision for its use. Final decisions have to be made early on in the planning process which means adequate attention is required; however, architects see this more as a challenge than a constraint (Girmscheid and Kröcher, 2007). In support of this early planning requirement as a constraint, Wong (2003) asserts that tighter coordination is required for the structural design, planning, procurement and approval stages of construction.

Goodier and Gibb (2007) identified longer lead-in times as a significant setback, to contractors in particular, because the use of prefabrication could mean delay in on-site project commencement. One comment was that to minimize lead-in times meant that prefabrication needed to be integrated right from the beginning of design and a better coordination was required to reduce costs as well. This would require the integration of and education on supply chain as well as design flexibility. Cooperation amongst professionals would be necessary at the earliest stages of the project in order to ensure proper integration of prefabrication into the building design; however as affirmed by the authors, cooperation amongst concrete prefabrication companies is complex and lacking.

Process, according to Blismas et al. (2005) is one of the main constraints of prefabrication. Clients and designers are unable to 'freeze' the design and specification of the project at an early enough stage for the manufacturing process to commence concurrently with other works in order to achieve delivery when required. Conversely, with traditional construction, clients and designers are free to make changes during the construction phase. It is noted that changes to the design of a project, regardless of the construction methods, affects its efficiency; however, these effects are more apparent in prefabrication. Therefore clients and designers must be forced to conclude all design processes early enough in order to benefit from prefabrication. This will in turn dismiss the implication that prefabrication lacks the ability to meet short project timescales. The difficulty in modifying components once produced even upon the discovery of errors, meaning the need for rework, time delays and extra costs (Li et al., 2011).

### 2.9.5 KNOWLEDGE GAP

One of the difficulties of the application of prefabrication is the know-how required for the use of standardised components to manufacture houses that are both aesthetically and functionally pleasing to the client (Pheng and Hui, 2010). Architects and planners perceive the attainment of this knowledge as tedious (Girmscheid and Kröcher, 2007).

Goodier and Gibb (2007) carried out a survey to determine the barriers to prefabrication. They basically note that there is a discrepancy or gap in the understanding and knowledge of prefabrication. Apparently, this knowledge gap - customers believing they are aware on one hand and suppliers believing that they are not – is often a cause of frustration for suppliers, most of whom assert that there is a general lack of understanding of the advantages of prefabrication in all aspects of the construction industry, and that customers see prefabrication as 'grey, volumetric modular boxes'. Further frustration results from customers who regularly utilise precast concrete without any awareness or appreciation of this as a form of prefabrication, and hence its full benefits. It was suggested that an improvement in communication, education and experience would bring clients, designers and suppliers closer together, and bridge the knowledge gap.

Blismas et al. (2005) opinionated that when viewed holistically, knowledge was the one constraint that had the biggest influence on all the other constraints of prefabrication. The limited experience of project teams in handling prefabrication is a hindrance to its widespread application. For instance, with experience in prefabrication, more options for its use could be considered for implementation during construction projects; product and process reuse would be more easily determined based on knowledge and experience gained form earlier prefabrication projects.

Because contractors are used to submitting tenders for conventional construction projects, the same methods are applied for prefabrication projects. The issue here is that unlike the case for conventional works where design can be changed during the erection of the structure, prefabrication requires conclusive design and planning before execution, and the decision to include the use of prefabricated units in projects usually comes at a much later execution phase. Thus, tenders for conventional on-site works prevent the widespread use of prefabricated units. Construction professionals need to be made aware that tenders for prefabricated units are more beneficial than those for conventional works. Girmscheid and Kröcher (2007) suggested the founding of an industrial institution to bridge knowledge gaps and provide decision-making aids, innovative performance parameters and elimination of the strict requirement of a certain number of prefabricated elements to be produced at a given time for a project.

Chan, Chan and Kung (2004) advocated for not just the acquisition of knowledge but also its proper management in order to achieve competitive advantage and improved performance among contractors. They state that to manage knowledge is to identify, optimise and actively manage intellectual assets for value creation, increased productivity and sustained competitive advantage. They propose that proper knowledge management can proffer solutions to the issues of the construction industry via knowledge-based strategies, organizations, project management, innovation, product improvement and customer satisfaction as well as intellectual capital (market, structural and customer assets).

### 2.9.6 OTHER CONSTRAINTS

In Hong Kong, practical constraints to the adoption of prefabrication were outlined by Wong (2003) to include the need for large workspaces to handle precast elements, which in Hong Kong's overcrowded urban environment, proved difficult; this congested state of the environment is the reason for the difficulty in access and delivery of heavy precast elements to the work site. In addition, where large numbers of precast components are structurally utilised, quality assurance becomes a critical issue and there are more demands for planning and management. Burdorf, Govaert and Elder (1991) report that the prefabricated concrete industry is said to be well-known for its ergonomic problems, particularly the risk of low-back pain. The pain is associated with activities such as monotonous tasks, stooped work postures, whole-body vibrations and sudden maximal physical effort. Li et al. (2011) also report on the risk of accidents associated with the installation of heavy prefabricated components.  Because the minimization of such risks through the introduction of new safety technologies is not yet a given, they are simply avoided by employment of only skilled workers and careful monitoring.

Blismas et al. (2005) further suggest that a broader understanding of the constraints is required, arguing that although prefabrication can contribute to change in the industry, it itself depends on change in order to be widely adopted. During a thorough research carried out for the development of the Client's Guide and Toolkit for Standardisation and Pre-Assembly 2, a set of data was developed from the results of an in-depth survey to determine the constraints of prefabrication. From the data, a higher-level model of the constraints to the adoption of prefabrication was developed. The constraints which were perceived as the greatest inhibitors of prefabrication utilisation were tested and confirmed. The results are outlined in Table 2.2.

Table 2.2: Constraints to the implementation of Prefabrication
(Blismas et al., 2005)

**TABLE 1** List of drivers and constraints

| | DRIVERS | | CONSTRAINTS |
|---|---|---|---|
| | **Cost drivers** | | **Site constraints** |
| D1 | Ensuring project cost certainty | C1 | Restricted site layout or space |
| D2 | Minimizing non-construction costs | C2 | Multi-trade interfaces in restricted work areas |
| D3 | Minimizing construction costs | C3 | Limited or very expensive available skilled on-site labour |
| D4 | Minimizing overall lifecycle costs | C4 | A problem transporting manufactured products to site |
| | **Time drivers** | C5 | Live working environment limits site operation |
| D5 | Ensuring project completion date is certain | C6 | Limitation to movement of OSP units around site |
| D6 | Minimizing on-site duration | C7 | Site restricted by external parties |
| D7 | Minimizing overall project time | | **Process constraints** |
| | **Quality drivers** | C8 | Short overall project timescales |
| D8 | Achieving high quality | C9 | Unable to freeze design early enough to suit OSP |
| D9 | Achieving predictability of quality | C10 | Limited capacity of suppliers |
| D10 | Achieving performance predictability throughout the lifecycle of the facility | C11 | Not possible for follow-on projects to use the same processes |
| | **Health and safety driver** | C12 | No opportunity for component repeatability on this or future projects |
| D11 | Reducing health and safety risks | | |
| | **Sustainability drivers** | | **Procurement constraints** |
| D12 | Reducing environmental impact during construction | C13 | Project team members have no previous experience of OSP |
| D13 | Maximizing environmental performance throughout the lifecycle | C14 | Obliged to work with a particular supply chain |
| D14 | Implementing Respect for People principles | C15 | Not willing to commit to a single point supplier |
| | | C16 | Obliged to accept lowest cost rather than best value |
| | | C17 | Key decisions already made preclude OSP approach |
| | | C18 | Limited expertise in off-site inspection |
| | | C19 | Early construction/manufacturing expertise and advice unavailable |
| | | C20 | Obliged to accept element costing based on SMM |

Polat (2010) in a study to evaluate the factors mitigating the implementation of prefabrication in Turkey as compared to other European countries, discovered that even in a highly technologically advanced country like the USA, prefabrication was still at a low level of use in construction despite its significant advantages. The study compared the situation in both countries and it was observed that each country had prevailing factors accounting for this. Through a survey it was revealed that size and load restricted transportation; in addition, poor communication lack of qualified contractors with specialisation in precast concrete systems were the three main factors mitigating the extensive use of prefabrication in the USA. On the other hand, the respondents in Turkey revealed a lack of communication as well as a lack of structural engineers and contractors with specialisation in precast concrete systems, as the barriers to the extensive use of prefabrication in Turkey. Thus, Polat (2010) demonstrated the perspectives of prefabrication from the developing and the developed country, and suggested the need to recognize the peculiarity of the each country in relation to its level of usage of prefabricated technology in construction, and that solutions should be found in the same way.

In conclusion, inadequate attention is being paid to the exploration of the broader issues – economic, environmental and social – affecting prefabrication. The irony of this situation, as aptly put by Blismas et al. 2005 is that “the very environment and culture [prefabrication] has been promoted as being able to change, is itself inhibiting [the] adoption and success” of prefabrication (Blismas et al. 2005, p. 81). The likelihood of prefabrication effecting any changes in the construction industry for its advancement remains very low except a conducive environment for its successful implementation is created.

# CHAPTER 3

# LITERATURE REVIEW

## 3.0 INTRODUCTION

Two outstanding construction systems – Conventional Construction and Prefabrication - have been studied. This research aimed to evaluate the performance of both construction methods in order to determine the more suitable method for application the UAE's construction industry. To this end, the earlier works of many other authors on the comparisons between conventional construction and prefabrication are reviewed herein. Within this section, conventional construction may be referred to as 'conventional', 'traditional' or 'masonry' construction; while any reference to 'precast' or 'prefabrication' or 'offsite' construction is made to prefabrication.

The dynamic and conservative nature of the construction industry poses challenges to the adoption of innovative construction technologies. The conventional method of construction which has become a locked-in force in the construction industry has been seen to impose limits to the advancement of the construction industry as a whole. While its uniqueness may have been a beneficial characteristic once upon a time, the trends in technology which have lent a hand in the globalization of the industrial sectors of the world, have somewhat displaced the relevance of this construction method, and unavoidably the stringent nature of the construction industry.

Prefabrication, on the other hand, is still being viewed as some kind of philosophy. Over the decades, it has gone through the vicious cycle of rejection, scepticism and acceptance, while still playing a key role in the development of the construction industry, owing to its conventionally-bound intransigent nature. It would seem that prefabrication is fighting a losing battle as far as gaining ground in the construction industry is concerned. Generally, institutional structures (involving planning, design, engineering and tenders) are customized for a wide-range conventional construction application. This has been the norm for many years. As such, it is difficult to initiate any opportunity to implement changes in the preferences, beliefs and actions of multiple institutions, based on the complexity of the lock-down of conventional construction (Table 3.1). According to some traditional builders in the UK, it is believed that if structures have been built in a certain way, then there is no need for any change that will reduce profits. Yet, it has been argued that prefabrication must be embraced and conventional construction relegated - altogether eliminated in some opinions – if the construction industry is to eventually be at par with other major industries such as manufacturing.

There are notable struggles between prefabrication and conventional construction particularly because of their categorical differences. As a result of these differences, ensuing challenges are encountered in the acceptance and adoption of prefabrication as a preferred or alternative method of construction. Highlighting these differences in both construction methods and the challenges encountered by this inertia of change, several authors have undertaken detailed comparative studies of both conventional and prefabricated construction.

This literature review is the foundation for the determination of the implementation of prefabrication as a more suitable alternative to traditional construction methods in the construction industry of the UAE, and also the preferment of strategies that will facilitate the achievement of a more sustainable construction environment in the UAE. It is important to note that there was no available literature on the comparison between traditional construction and prefabrication in the UAE, as such all analyses are based on the reviewed works from other parts of the world, particularly the UK, for which extensive work on this subject has been carried out. A wide variety of such works relating to the performance comparisons of both construction systems in terms of their waste reduction levels, productivity improvement, energy savings, and eventual sustainability, is summarily reviewed hereon.

## 3.1 CONVENTIONAL CONSTRUCTION AND PREFABRICATION: THE JOSTLE

Lovell and Smith (2010) pointed out that the preference of the people in a particular region played a significant role in their choice of construction methods. In the UK for instance, the preference was for masonry-constructed style houses, as the tendency was towards aesthetically aged houses, a choice that had been ‘locked-in’ by the deep-rooted prevalence of masonry in building construction. The validity of this was abetted by the fact that prefabrication, because of its principal application as temporary works, had come to be perceived as a transient construction method in the building industry. Friedman and Cammalleri (1993) attributed the reluctance by traditional builders to embrace changes in the construction industry and the acceptance of modern construction methods to the fear of interrupting the familiar age-long process and inevitably complicating its traditional methods. Bordieus regarded this conflict of preference between both construction methods - prefabrication and conventional construction (termed ‘assemblages’) - as a ‘jostle’. In the opinion of Lovell and Smith (2010), the dominance of the traditional construction method (masonry) over prefabrication in the UK’s house building industry was paradoxical in view of the former’s disadvantages over the latter: higher cost, lack of flexibility and inefficiency, and of course unsustainability.

Conversely, Friedman and Cammalleri (1993) argued that in spite of the conservative nature of the housing construction industry, its traditional methods had efficiently established a construction technique for building production. The reluctance to accept any deviation to this method was understandable given that builders were sceptical about interrupting and complicating their building construction traditions. Applying changes to this set system was difficult yet not impossible. However, the authors asserted that the interests of builders should be given priority before any study of prefabricated building systems was undertaken.

Chiang, Tang and Wong (2008) had an interesting view of prefabrication. They stated that prefabrication was no more than the by-product of a successful cost leadership scheme. According to their study, prefabrication was neither effective nor competitive, and as such had failed ‘Barney’s Test’ which stated that in order to be a sustainable source of competitive advantage, a system had to be rare, expensive to imitate, an asset to clients, and non-interchangeable. They opinionated that while prefabrication was necessary for Hong Kong's public housing sector, it was insufficient as per effectiveness and competition. What distinguished the leaders in the public housing construction was not the application of prefabrication regardless of its mandatory requirement, but the need for cost effectiveness, which led to mass production, as the build-up of the market share increased the need for efficient contractors.

Lovell and Smith's (2010) viewpoint on the jostle between prefabrication and conventional construction bears significance because it takes into consideration the salient mix of social, cultural, technological and institutional factors which impede the implementation of prefabrication. Friedman and Cammalleri (1993) noted the same, stating that consideration had to be given to the practical, marketable and economic characteristics of the systems in question which would be determinant of their acceptance in the construction industry. Lovell and Smith (2010) then provided an enlightening perspective that encapsulated the largely differing characteristics of both methods. For instance, one key characteristic of conventional construction, in this case masonry, was that construction activities could commence and end with limited notice because of its limited invested costs and the ease with which a large part of the workforce could be laid off. The conventional construction assemblage had been well-equipped over time to handle such short-and long-term fluctuations. In contrast, prefabrication assemblage required the employment of a fully trained workforce in factories, and regardless of the regularity of construction projects, payment of employees was voluntary. Thus, once investment was made in a prefabrication factory, manufacturers had to produce a minimum number of prefabricated homes annually in order to break even, since the initial set-up was high (in the UK for instance, it could cost up to thirteen million pounds (£13m) and certain expenditures such as the cost of utilities were fixed, regardless of factory output.

Another instance is the result of an interview with the operations manager of a steel-framed prefabricated company on the prejudice against prefabrication. The interviewee asserted that the logic of lenders regarding prefabrication was that if the housing components were all bought and bolted on-site as against being bolted in a factory and delivered in a truck, they would be more than happy to invest in a prefabricated factory. In addition, the lifespan of prefabrication is maximised at sixty years, whereas masonry dwellings have a proven lifespan of one hundred years, a technical characteristic of conventional construction which legislations have incorporated for a very long time. Thus, it was concluded that apparently the acceptance of prefabrication would be expedited upon proof of a lifetime possibility of hundred years. According to the authors, such perceptions showed the level of interconnectivity of the technical, material and social aspects of prefabrication and conventional construction, and emphasized the difficulties in making changes in the current state of the construction industry where one assemblage had apparently achieved a 'lock-down' and enjoyed predominance over all other technologies.

In another angle regarding the jostle between traditional construction and prefabrication, Callon postulated the 'Theory of Agencement' in the construction industry (as given in Table 3.1). Agencement herein referred to construction methods and their contents, active characteristics or quality (by which they remain constant or change). This theory implied that whole systems of building construction changed progressively (as a result of continuous jostling) or drastically (as fundamentally different construction methods were thrown together). These agencements comprised the jostling that occurred not just between construction methods, but also within these methods themselves. The outcome of this is a hybrid of construction methods which has blurred the boundaries of both methods. Although this hybrid might seem like a good idea to promote the co-existence of prefabrication with the traditional method, in practicality, it is only a variant of traditional construction and as such results are not as satisfactory as expected.

Table 3.1: The Agencement Lock-In of Conventional Construction by Stakeholders of the Construction Industry (Lovell and Smith, 2010).

| Type of organisation | How they have acted to reinforce the masonry *agencement* relative to prefabrication |
|---|---|
| Planners | • Often require prefabricated houses or flats to resemble traditional masonry dwellings (Edge, 2002).<br>• The planning process favours masonry technologies, where last minute changes to design and layout can be made, rather than prefabrication, which requires 'design freeze' at an earlier stage (Gorgolewski, et al., 2001).<br>• "The nature of the UK planning system may operate against the introduction of alternative construction techniques by increasing delays and uncertainty… In other cases, planning committees are reluctant to embrace off-site manufacture [prefabrication] as they have a perception that this method produces identical, poor quality homes with a short life span". (Barker 2003, p. 10). |
| Mortgage lenders | • Some mortgage companies have refused to lend money on prefabricated homes due to concerns about their durability, ease of repair, and market appeal. One major mortgage provider lists 800 non-standard building systems. It will not lend on a third of these, and will lend only with restrictions on a further 30% (The Housing Forum, 2001).<br>• Heavily influenced by historical experience with prefabrication (Council of Mortgage Lenders, 2003 pers.comm.). |
| Building insurers | • It is expensive, costing up to one hundred thousand pounds, and time-consuming (twelve months minimum), to gain accreditation for a new prefabrication technology.<br>• In contrast, accreditation is not required for masonry construction, as it is judged to have proven durability.<br>• There is a backlog of prefabricated technologies awaiting accreditation, and there are currently only two registered accreditors in the UK (the BBA and BRE Certification). Some manufacturers are therefore gaining accreditation from overseas.<br>• The Council of Mortgage Lenders and Building Research Establishment have responded to these issues by launching in 2006 a new certification standard – LPS 2020, which is intended to meet the concerns of lenders, insurers and other stakeholders about prefabrication (BRE Certification Ltd., 2006). |
| Surveyors | • Surveyors may rate a prefabricated building as higher risk, simply because they know less about the technologies used.<br>• Cited alongside mortgage lenders as one of the most conservative stakeholders in their attitude to prefabrication (The Housing Forum, 2001). |
| Building contractors | • There are too few trained prefabrication erectors, thus leading to difficulties with construction on-site, and negatively affecting the quality of the prefabricated housing product (Ross, 2002; Richards, 2003 pers.comm.).<br>• An international comparative study revealed the importance of skilled workers erecting prefabricated dwellings (Clarke and Wall, 2000).<br>• Certified courses on prefabricated construction are yet to be established in the UK. |

Technical issues arise because many conventionally built homes are constructed individually (and as such have minor inconsistencies); it is difficult to combine masonry with more sophisticated construction technologies such as prefabrication. The concern here is that building contractors are now suppliers of prefabricated dwellings, understandably as a result of the uncertainty of adopting a new technology of construction; unfortunately, they are inexperienced in prefabricated buildings. The technical issues associated with conventional construction would most likely be peculiar to one individual structure, and are unlikely to be spread across several individually-built structures at the same time. However, the systemic failure of mass-produced buildings is that if one is defective, then all others are likely to be equally defective. This theory has stemmed from past negative experiences with prefabricated houses, and is one of the reasons for the negative attitudes from the construction industry and clients towards the adoption of prefabrication.

Lessons learned, the UK adopted a hybrid strategy to nullify these negative perceptions of prefabrication: the construction of prefabricated homes with brick cladding in order to give the homes a concrete-built appearance, according to Brinkley (2001), Edge (2002) and Smit (2002). The ideal alternative, it was argued, would be to use the technologies of prefabrication to construct structures that had a completely different appearance. A mandate was given to England and Wales by the government, to construct 255 of new publicly-funded social houses with prefabrication. In addition, the government advocated for the replacement of the term ‘prefabrication’ with ‘modern methods of construction’ in referring to factory-based construction in order to curb the stigmatization of prefabrication (Figure 3.1).

According to the UK government:

> prefabrication, at least as far as house-building in [the UK] is concerned, is a term that implies criticism, because of its connections with temporary housing in the past. It is in the interests of the [UK’s] building industry to avoid using the term ‘prefabrication’. (Lovell and Smith 2010, p. 465).

Such laudable efforts are however ineffective, if the fundamental (and otherwise) aspects of the reasons for this jostle are not tackled. It is also paramount to recognize the materiality and sociality - how the hybrid combinations of social, cultural, economic, technical, political and institutional factors constitute the costs, prices and values - of conventional construction and prefabrication (Lovell and Smith 2010).

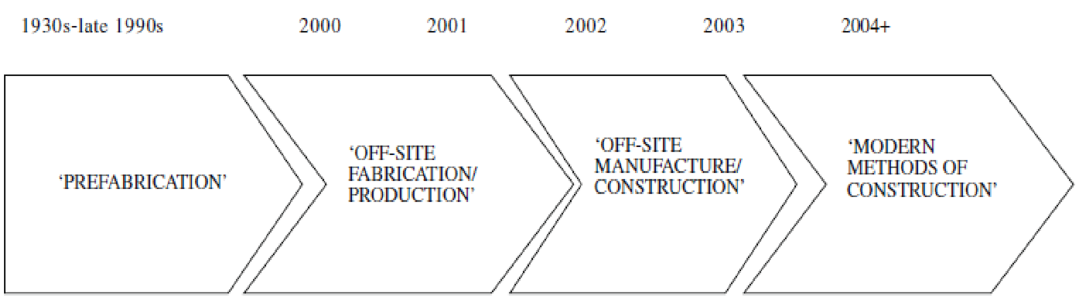


Figure 3.1: The UK Government's Attempt to Stifle Negative Perceptions on Prefabrication (Lovell and Smith, 2010)

However, Chen, Okudan and Riley (2010) observed that there was no existing list of performance criteria based on these factors (social, economic, political and technical) for the selection of an 'appropriate' construction method for concrete buildings. Using the triple bottom line of sustainability, they carried out a thorough exploration and comparison of prefabrication and conventional construction, in order to be able to ensure a clear distinction between both methods by the selected criteria. An illustration is given in Table 3.2 in which construction time as an economic criterion, was expansively compared under both methods.

In the table, the positive and negative sides of each construction method based on construction time were compared, followed by a quantification of both differences. The same format was used to compare all the differences. In total, seven latent factors (via factor analysis) were used to determine the fundamental structure of the criteria used to select a construction method for concrete buildings. The seven factors were: long term cost, constructability, quality, first cost (economic factors); impact on health and community (social factors); environmental impact (environmental factor). The authors argued strongly that, beyond the immediate selection of prefabrication as the preferred method of construction was the need to determine based on selected criteria, its absolute suitability and significant advantage over conventional construction methods. To do this required the identification of holistic criteria which would assist construction practitioners in making a choice.

Table 3.2: Sample Comparison between Precast (Prefabrication) and On-Site (Conventional) Construction /Cast-In-Place Construction Method (Chen, Okudan and Riley, 2010).

| Factors | Precast/Prefabrication | Positive/ Negative | On-Site/Cast-in-place | Positive/ Negative | Quantification of differences |
|---|---|---|---|---|---|
| *Economic criteria* | | | | | |
| Construction time | Reduction of construction time | | Time consuming | | |
| | 1. Prefabrication and site preparation can occur simultaneously, and the erection process is fast; | √ | 1. All construction occurs on site, and one work cannot start until the previous work is completed; | × | 1. Construction time for prefabrication is less than half of on-site construction [29]. |
| | 2. Independent of adverse weather which has almost no impact on the schedule of the prefabrication manufacturing; | √ | 2. The construction process can be easily delayed by adverse weather or scheduling conflicts; | × | 2. Up to 70% time saving can be achieved when compared in-situ construction [30]. |
| | 3. Prefabrication usually has a greater potential for automation (e.g., digital fabrication) and intelligent management systems; | √ | 3. Most on-site construction procedures heavily depend on manual methods; | × | 3. Average reduction in construction time can achieve 20% when compared with on-site construction [16]. |
| | 4. Workers in a prefabrication plant are able to be more proficiently experienced at specific tasks; | √ | 4. Most of workers on site are temporary, and their craft and technical skills are more variable; | × | |
| | 5. Precast beams and slabs eliminate field forming and shoring requirements; | √ | 5. Formwork and shoring installation are necessary for on-site construction; | × | |
| | 6. Less finish works (e.g., external wall finishes, laying tiles and plastering) is required to be completed on-site. | √ | 6. All finish works need to be finished on site. | × | |

Note: positive for project goals: √; negative for project goals: ×.

Similar to Chan, Chan and Kung (2004) and other researchers, they asserted that time and cost were the most important criteria, yet added the increasing importance of environmental concerns and social awareness. Traditionally, clients make their choice based on cost of construction. The authors noted a change in the trend of clients' criteria of selection from 'first cost' and 'quality' to the inclusion of 'long-term cost'. Contractors made decisions based on 'constructability' while architectural engineers aptly favoured 'architectural impact'. Chen, Okudan and Riley (2010) opinionated in the conclusion of their research that the two most significant characteristics of sustainability were 'impact on health and community' and 'environmental impact', and were now given growing consideration by all project participants.

## 3.2 CONVENTIONAL CONSTRUCTION AND PREFABRICATION: PERFORMANCE COMPARISONS

The discovery of the defects of precast reinforced concrete (PRC) housing in the UK began in the 1980s. A fire outbreak had occurred in the precast concrete column and panel system of a 1940s house and it was during the refurbishment that it was discovered that there were cracks at the bases of a significant portion of the structural columns. The Building Research Establishment (BRE) investigated the upon further investigation discovered that the defects were a result of low reinforcement cover, alkalinity of the concrete (carbonation) and high cast-in chloride content in the concrete. About the same time, an engineer investigating the cause of dampness of the flat roof of another house discovered cracks in a significant proportion of the PRC roof units. These findings led to the realization that several other PRC houses could be having similar problems and further investigation was carried out on 17 other PRC system built pre-1960 houses which at the time constituted about 98% (170,000 houses) of the UK's PRC housing stock. Also, it was deemed necessary to provide technical information and guidelines for engineers and building owners to determine the structural condition and possible future performance and maintenance of houses.

While engineering solutions were sought, the PRC components were removed and replaced with conventionally constructed walls, or alternatively retained, but became structurally redundant via load transfer to newly built load-bearing masonry walls. However many building owners raised concerns about the cost effectiveness of such major works, and proposed that the PRC components be retained while being maintained in a dry, stable environment. To answer this question, the BRE with keen interest in the effects of over-cladding, undertook research to observe the environmental conditions of the structural components of two precast houses, before and after cladding. From the first set of results, the researchers were able to identify high- and low-risk areas of corrosion of precast concrete components. The expected results were that cladding would increase the habitability as well as life expectancy of these houses. Unfortunately, as at the time of the report the research was still on-going and follow-up reports were not available (Reeves 1997).

Wong (2003) observed practical constraints of prefabrication in Hong Kong's construction industry. They included: tighter schedule requirements for coordination procedures for all processes from planning and design to approval; advanced production of prefabricated units means more time needed in order to meet the demand prior to on-site assembly; more inputs for planning and management; heavy precast components require careful handling and assembly and risk the safety of workers, their installation requires careful planning and equipment provisions, their storage and pre-installation need extra space; complications in installation especially with large numbers of precast members such as with high altitudes, congested on-site floor layouts and so on; and defects due to errors in handling of members that will eventually pose maintenance problems.

However in Wei's (2006) thesis on the comparison of the material wastage levels of both conventional construction methods and prefabrication, prefabrication was seen to provide several advantages in Hong Kong's construction industry. Wei outlined the advantages provided by conventional construction to include flexibility in terms of geometry, easy transportation of wet trades, allowance for last-minute structural changes and uniformity of the structure. Contrarily, conventionality in construction meant longer drying times for the wet trades, 'unsafe' production environments and the need for more temporary works. Prefabrication was found to provide benefits in terms of good quality of production, speed of assembly and erection. Concurrently, it was disadvantageous in its need for detailed design and complications in connection detailing. Nevertheless, it was proven to produce far less waste than conventional construction. A case study of a low-cost public housing project in Hong Kong was seen to provide a waste reduction in the range of 30 – 40% from the use of precast elements in construction. The result was based on the elimination of wet trades which had been observed to be the highest contributor to on-site construction waste.

Abdul Kadir et al. (2006) undertook a statistical comparison between conventional building system and IBS. With a focus on the structural cost (reason being the high labour demand for structural work), the bases for comparison were the construction cost, size of labour, productivity and cycle time. The statistical results showed that IBS provided up to 70% in labour savings, as it required less construction trades than conventional construction. In addition, the greatest difference between the conventional construction and IBS could be seen in the cycle time factor (76% more savings in the latter than the former). This could be translated to savings in the cost of equipment, labour and construction time, achievable through efficiency in site management. Nevertheless, there was no significant difference between the structural costs of conventional construction and IBS. As such, contractors in Malaysia saw no motivation for the consideration of IBS for housing construction. Furthermore, the conventional methods had been in practice for decades and therefore in their argument, the adoption of a new building system was nothing short of an uphill task.

In the same vein, Tam, Deng and Zeng (2002) investigated the impact of different construction techniques on the production performance of high-rise public buildings in Hong Kong. The investigated techniques were traditional timber formwork for floor slabs (Scheme 1); semi-precast slabs with similar inputs as scheme 1 (Scheme 2); and increasing plant input based on scheme 2 (Scheme 3). It was observed that construction time could be shortened from eight days to four, while reducing the need for labour which was already in short supply in Hong Kong. Interestingly, it was seen that construction cost could potentially increase. That is, a shorter time from eight to six days could reduce costs; however, further reduction from six days to four would increase labour and cost requirements. The findings showed that Scheme 2 was most advantageous of all based on the economies of labour and cost. Scheme 3 would provide construction speed and was the most preferred as there was an urgent need for housing in Hong Kong. It was concluded that the adoption of a construction technique would depend less on its economic benefits and more on the local needs and characteristics.

A summary of Friedman's (1992) comparative study of the costs of homes (in terms of cost per square foot, quality and production time) constructed by both conventional means and prefabrication, revealed the following. Firstly, per square foot of a conventionally constructed home cost an average of $7.46 less than the cheapest prefabricated option available. Secondly, depending on the time of year and management, production time might be longer or shorter. In particular, findings showed that prefabrication had a 10 – 15 day advantage over conventional construction. Friedman argued that contrary to indications from other authors' works which included quality improvement as one of the main benefits of prefabrication, there was no strong evidence to show that in comparison to conventionally constructed homes, prefabricated homes were of better quality. The author supported this by stating that the slight improvement in the quality of prefabricated homes was simply attributable to the techniques and equipment used for transportation of the modularised homes to their final point of erection.

The above findings were supported by the results of a survey of fifteen Canadian home manufacturers. The survey results lent insight into factory and investment conditions of prefabricated homes. For instance, factories required high capital investments, large number of permanent staff and a minimum production volume in order to break even, which was difficult to achieve due to the cyclical nature of production conditions in the construction industry. At best, 250 housing units were produced annually. Contrariwise, conventional construction required only a handful of permanent employees, meaning lower costs of operation as per salary. Several advantages of prefabrication were dismissed. One of such was that the mass production of manufactured housing units did not provide as much in cost savings and time reduction as was the general school of thought. According to Friedman (1993), the repetitive production of similar housing units was non-existent as the factories surveyed asserted their willingness to customise single housing units. This meant that time and thought were required for the production of each unit as opposed to mindless mass production. In addition, union regulations demanded that union members handled the final assembly of manufactured houses. Their high wage requirements (as much as those of trained subcontractors) meant that potential cost savings were significantly reduced. Having asserted the importance of the inherent benefits of prefabrication (such as a quality-controlled production environment and less risk of on-site vandalism) to certain builders, Friedman (1993) recommended strategies to reduce the cost of prefabrication to increase its appeal. These included breaching knowledge gaps, production of cheaper housing units, and exploitation of new markets. It was believed by the author that such strategies would close the gap in costs between conventional construction and prefabrication and make the latter more appealing to conventional builders.

One of the issues of providing low cost housing in the urban areas of developing countries is the availability of practical alternative construction methods. Scott and Sridurangkatum (1980) sought to compare four different construction methods in Thailand, each with its own prefabrication and mechanization: the traditional construction method; the concrete block bearing wall (CBBW); prefabricated panel (PP) and prefabricated beam-column (PBC) methods, both of which had never been used at that time for construction activities in Thailand. The comparisons were based on structural design, engineering and economic analyses. The engineering analysis was carried out using the basic architectural and design form for low-income housing. The economic assessment took into consideration all aspects of cost, which included labour, equipment (on-site and factory costs and formwork (including system development for prefabrication), transportation (for prefabrication alone), materials, general expenses and overhead costs. According to research results, observation was that traditional construction was the most expensive, followed by CBB and PBC, with PP being the cheapest. As per materials, cost was almost the same for all four methods. With regards to construction time, the construction of 100 units of housing would take ten months for the traditional method, six for both CBBW and PBC, and five for PP. It would appear that based on the construction cost and time, PP was most suitable. However, its implementation would require technical know-how, high investment, and organizational and managerial skills. The authors hoped that with time, Thailand's construction industry would evolve such that the prefabricated panel construction method could be applied, and effectively. With similar interests in panelised construction as an innovative prefabrication technology, Friedman and Cammalleri (1993) examined the quality of prefabricated wall systems in relation to the energy efficiency of homes. In their study, the evaluation of the quality of prefabricated wall systems could be based on three interconnected characteristics; craftsmanship, durability and technical performance.

Compared to conventionally constructed panel systems, the authors believed that prefabricated wall systems performed better for the most part. For example, as a result of the remarkable fittings of the joints in prefabricated panels, excellent insulation was achievable and the simplicity of the panel design allowed for better highly commendable performance overall. The drawback though was that prefabricated panels were susceptible to delamination and ridging at the joints. Still, the prefabricated panels were not subjected to defective workmanship as was the issue with conventional panels (except those constructed with distinctive techniques). The relatively straightforward production techniques of prefabricated panels ensured that technical performance levels were consistent. On the other hand, conventional construction had the benefit of durability; although the variability in craftsmanship as well as the materials' high susceptibility to damage from poor storage was undesirable.

Lesniak, Grodzki and Winiarski (1975) asserted that prefabrication was developed to meet growing global housing demands. With the trend towards flexibility in construction systems, which allowed for architectural and functional freedom while limiting the number of component types, more opportunities for automation in design and construction were made possible. System building, that is the use of computerization, enhances design automation better than individually designed buildings. As prefabrication is the preferred method of mass housing construction, additional costs are incurred from computerization. The application of system building would place restrictions on design, thus curtailing flexibility and ensuring that the automated design system would be kept within practicable limits. Although this was not always the desired case, Lesniak, Grodzki and Winiarski (1975) pointed out that no automated design system regardless of flexibility was without imposed limits, such as dimensions of components, standardization of joints, and so on; deviations would inevitably result in cost increases. A good example is in the mass production of automobiles such that manufacturers have been able to reduce the cost of an average by as much as 16 times that of an average house produced by artisans.

However, there were two key issues that automated building design faced within the context of existing construction systems. The first was the generation of building layout plans that satisfied functionality and building regulations, whilst remaining within imposed building system constraints. The other was the generation of variant schemes within the limits of the layout for the structural design and the selection of applicable components, including cladding. The authors in their work sought to evaluate a small design system which would aid in the generation of layout plans and building sections within an existing construction system, without the need to develop a large, generic system of building from scratch. They studied two sample small systems ASY - an automated design and layout optimization system for flats and building sections - and BOSY- an automated design system for precast frame buildings construction. The time and cost of such systems was observed to be less than required for the development of a whole new building system.

Conventional construction of mass housing follows a set procedure: design of a limited number of house types, followed by repetition based on market demand. This is because individual house designs require too much information processing and also, mass production reduces cost. Thus, clients are not privy to tailor-made housing. Existing technology provided solutions via a design system, a building system and a computer system. However, the solutions were lacking in that there was as yet no link between the design and fabrication systems. Similar to Lesniak, Grodzki and Winiarski (1975), Benros and Duarte (2009) aimed to solve this problem by proffering innovative design, construction and information technology for mass housing customization, as well as refining the end results of the framework for easy client customization at no cost. Baldwin et al. (2009) analysed traditional construction methods and precasting. Their study aimed to evaluate the potential of precast concrete technology to minimize on-site construction waste, as it was categorically stated that on-site concreting was a major contributor to construction waste. However, they noted that more than just the application of precasting as an alternative construction technique, it was important to optimize the design phase of any project. The authors through information requirements modelling and the use of Design Structure Matrix (DSM) showed how designers could model and understand the impacts of design decisions for more effective decision-making.

In spite of the cost savings which could be achieved on the whole via the use of prefabrication in construction, Girmscheid and Kröcher (2007) observed in their study that project tenders in Switzerland were still being made with consideration for only conventional construction. Also, the consideration for prefabrication was only given when the need arose, usually at the late phase of the project's execution. In their opinion, this was the reason prefabrication still took a backseat to conventional construction. Expounding on this, the authors opinionated that because planning services were only carried out during erection of the structure as was the traditional method, it would be difficult to include those services for prefabrication due to their requirement as early as the planning stage of the project. They proposed that in order for this to change, tenders and working drawings should be restructured to include options for prefabrication as a method of construction, rather than as a last resort, which would automatically hinder the extensive application of prefabricated units to structures. More so, architects, engineers and contractors and such need awareness of the importance of tenders suitable for the application of prefabrication, such as overall cost savings.

Girmscheid and Kröcher (2007) then postulated the institution of a knowledge platform which would close knowledge gaps concerning precast concrete construction, aid in decision-making on the more suitable form of construction, eliminate prejudices against prefabrication and provide innovative performance parameters (such as quality, functionality and sustainability) of construction elements. In addition, the platform would serve as the interface between manufacturers of prefabricated units and manufacturers. Chiang, Tang and Wong (2008) in support of this blamed the lack of innovation as the root cause of the current issues facing the construction industry. According to the authors, the issues of immobility and unpredictable demand could be solved by prefabrication. The controlled factory production environment ensures higher quality of produced units, improved efficiency and subsequently enlarged market share, thus solving the problem of unexpected demand; while the use of modular components eliminates the problem of mobility.

Despite the seeming advantages of prefabrication over conventional construction, Friedman and Cammalleri (1993) opinionated that it remained to be seen whether prefabrication would be accepted by builders, as any innovation in technology only gains support when it gets the attention of the buyer of said innovation. The selling points of prefabricated systems are the higher quality and better energy efficiency at equal or lower prices than conventional construction methods, although these vary with the configuration of the prefabricated units. Marginal savings were not regarded as enough incentive for builders or first-time home purchasers to switch construction technologies, for example, the case of prefabrication of panel system instead of conventional methods. In support of this, Chiang, Tang and Wong (2008) stated that by itself, prefabrication held no competitive cost advantage over conventional construction. It could be termed 'an agent of innovation in the process of cost leadership'.

As such, Friedman and Cammalleri (1993) suggested that prefabrication technologies could be considered for integration as part of the operational processes of traditional construction, as long as they did not interfere with the traditional routine. Simpler management tasks, for instance, could be integrated in construction practices. By this, prefabrication might gradually gain acceptance. The authors assert that to achieve this both builders and buyers would need to be educated on the potential energy, materials, time, and eventually the total overhead cost savings, that prefabricated components could provide. They stated the need to emphasise the simplification of construction activities and reduced managerial stress.

## 3.3 ENERGY SAVINGS AND THE CARBON FOOTPRINT WIPE-OUT

Studies showed that the occupational energy of a building could be 10 to 15 times higher than its initial construction energy. This fact regardless, Gartner and Smith (1976) found it worthwhile to compare building construction systems in terms of their energy use, because of the possibility of significant energy savings upon the identification and subsequent elimination of wasteful construction methods. The authors employed two methods, the statistical and input-output analysis methods, to evaluate the energy costs of housing construction. Four different construction methods were evaluated:

- Type 1 - Traditional brick and block construction of houses and bungalows, with loadbearing outer walls, timber framed pitched roofs and timber joisted upper floors.
- Type 2 - Rationalised-traditional construction of houses and bungalows, with loadbearing cross walls of brick and/or block and with lightweight infills to outer panels; floors and roofs same as Type 1.
- Type 3 – Buildings with brick and block vertical loadbearing elements, pitched timber framed roof structures and reinforced concrete floor slabs, considered typical for 2-5 storey constructions (flats and maisonettes).
- Type 4 - Reinforced concrete vertical load-bearing elements and floor and roof slabs, representing medium and high-rise construction (flats and maisonettes).

The results indicated large differences in material energy input levels for types 1, 2 and 3; however, their values still fell lower than for type 4 (at least 40% of the energy requirement is attributed to steel reinforcement). Furthermore, bricks and blocks had the greatest variation in energy demand. For instance, the use of fletton bricks would require half as much energy as the use of non-fletton bricks. Since non-fletton bricks were available locally and therefore preferred, Gartner and Smith (1976) suggested that the transportation energy demands ought to be included in the analysis. However, the authors purposely refrained from factoring transportation energy, based on reviewed literature which showed that transportation contributed than 10% to the total construction needs. In addition, attaching a mean distance to building materials meant each material would have its own specific transport distance which would vary appreciably from one site to another. Conversely, the high cost of transporting less energy intensive materials could partially be the reason high energy intensive materials were preferred in certain localities. The input-output analysis on the other hand, evaluated the overall primary energy demand per pound (£) of each material. The prices of building materials are generally an approximate reflection of their relative energy requirements, such that a price-performance selection would afford a tolerably low total energy requirement for the building. Noteworthy, the choice of high energy-intensive and costly materials could be based understandably on aesthetics. It was conclusively suggested that further savings on cost and energy by the reduction of on-site waste of building materials was possible.

Cole (1999) evaluated in detail the energy and GHG emissions related to the on-site construction of selected alternative steel, concrete and wooden structural systems, primarily to determine the proportions of embodied energy and GHG emissions represented by their construction processes, and the significant differences between them, if any. Interestingly, Cole included the transportation of construction workers to and from the construction site as part of the environmental audit, an otherwise ignored aspect of the construction process as opposed to the work done by Gartner and Smith (1976).

The inclusion of this aspect corrects the erroneousness that the construction process alone constitutes 7-10% of the embodied energy (an assumption made by Gartner and Smith (1976) based on their review of previous works), and that steel and timber constructions are associated with high embodied energy levels, while that of concrete is low. Given, the manufacture of materials demands energy and equipment; however, embodied energy and GHG levels vary with construction systems, and actual construction is considerably labour intensive. The higher the labour intensity, the greater the need for transportation of workers. Thus, it represents the highest portion of construction energy for many structural systems and when considered analytically, increases the initial embodied energy of construction than is the current assumption. Based on study results (and assuming worker transportation is ignored), steel assembly made up 2-5% and wood 6-16% of the initial embodied energy, both ranges still lower than that of concrete (11-25%). For GHG emissions, construction represented higher energy levels with concrete still leading at 15-25%, followed by 8-20% for wood and steel with 3-6%. Cole's (1999) results are summarized in Figures 3.2 and 3.3.

Aye et al. (2012) carried out a study on three different construction methods of an eight-storey multi-residential building – conventional concrete construction, prefabricated timber and prefabricated steel construction. The aim of their study was to assess these methods in order to determine the environmental benefits of modularised prefabrication using an innovative hybrid approach (a combination of both process analysis and input-output analysis) to assess the embodied energy. Study results showed that at least 32% of the required total primary energy was attributed to embodied energy, thus showing the importance of the embodied energy of a building, particularly in light of recent developments in building efficiency performance. Their study indicated that the use of prefabricated steel provided over 50% reduction in weighted raw materials' consumption. In spite of this significant advantage, prefabricated steel was reported to containing as much as 50% higher embodied energy than concrete construction. However, the authors argued that this could be countered by the waste reduction benefits of the reusability and adaptability of steel, thus providing over 80% saving in the

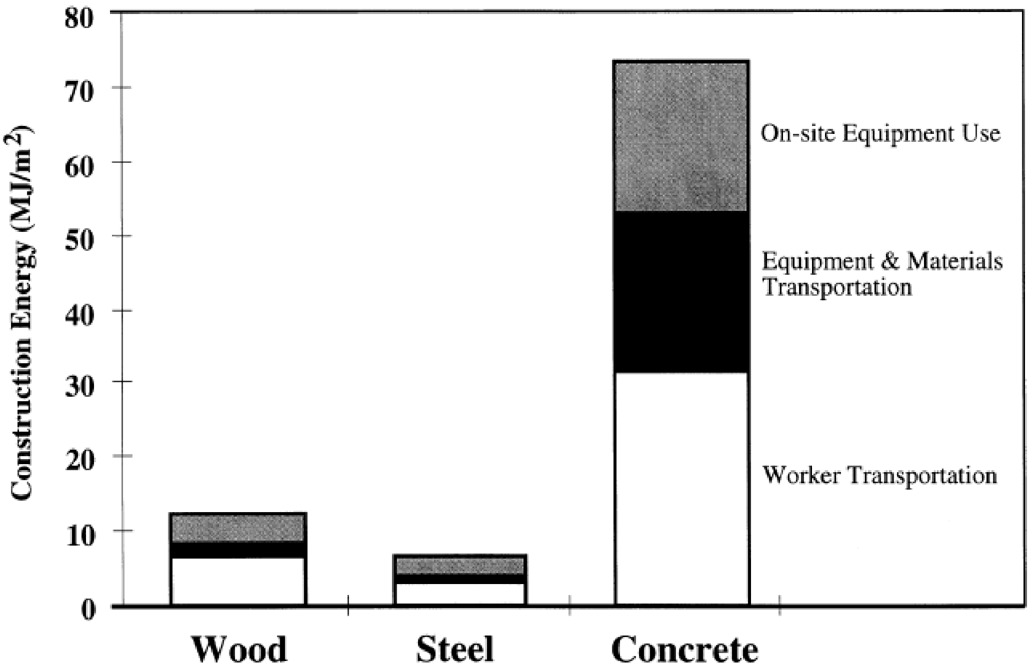


Figure 3.2: Average Construction Energy for Wood, Steel and Concrete Assemblies
(Cole, 1999).

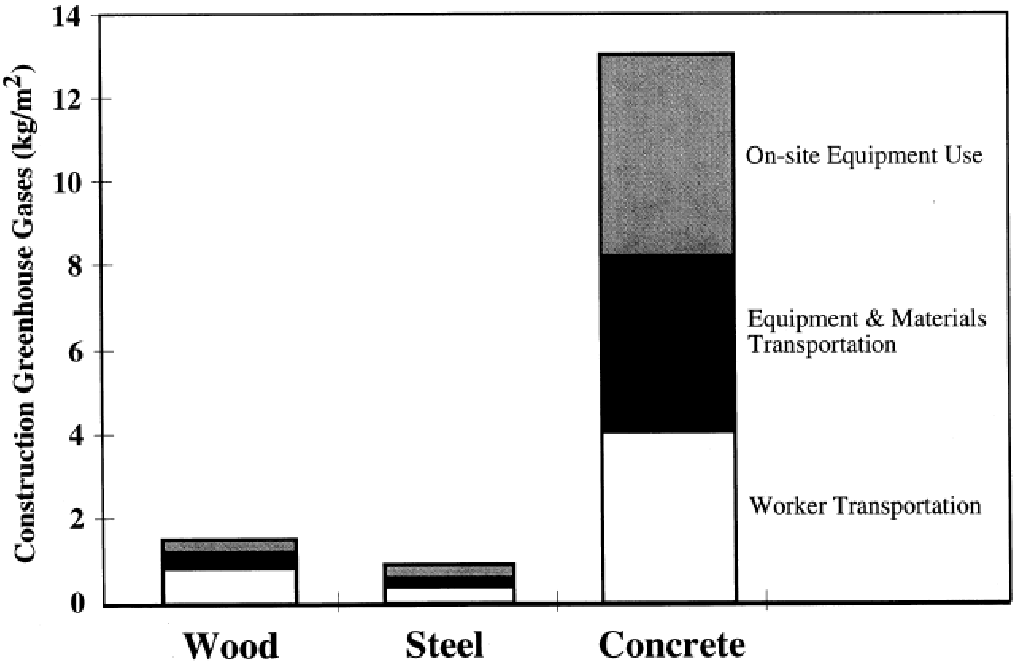



Figure 3.3: Average Construction Greenhouse Gas Emissions for Wood, Steel and Concrete Assemblies (Cole, 1999)

embodied energy of the steel. Furthermore, if designed initially to include adaptability and reusability, prefabricated steel could potentially provide even higher environmental performance than timber and concrete construction methods.

López-Mesa et al. (2009) compared the environmental impacts of two slab systems in Spain: one, the more common concrete-based, one-way spanning slab used in residential buildings and the other, the hollow-core slab floor with increasing popularity except in residences. A LCA using the EPS 2000 method was carried out. Results showed that precast concrete floors (PCF) had a 12.2% lower environmental impact than cast in-situ floors (CIF). This showed that PCF were more beneficial than CIF, besides the already established advantages of high quality and installation speed. A cost analysis was also carried out and the results showed that PCF cost approximately 18% more than the CIF for the functional units in question. López-Mesa et al. (2009) asserted that this was the probable reason for the unpopularity of PCF in residential constructions, in spite of its apparent advantages. The authors suggested further studies to determine the number of floors from which PCF would have a vantage point over CIF.

Monahan and Powell (2011) compared a house constructed with traditional masonry to that using panellised timber frame construction. Their results indicated that embodied carbon was 34% less in the latter than in the former method for the same house. This was principally due to the replacement of brick and blocks with softwood timber, a material of lower embodied carbon. Timber also replaced traditional brick as the material for the building envelope which led to an additional 24% savings in carbon. Furthermore, the use of timber frame meant less structural weight and reduced the need for sub-structural support, and consequently, the foundation materials. Again, this translated to the reduced need for high carbon-embodied materials – concrete and reinforced steel - as it was noted that half of the materials that emitted carbon came from the construction of the substructure, foundation and ground floor of the building (concrete generated 236% carbon). Another factor responsible for the reduced carbon embodiment in the case study house was the effective volume production related to prefabrication. The manufacture of the timber frame produced only 4% of waste-related carbon, a significant low compared to the on-site 14% contribution. This attested to the fact that offsite manufacturing reduced the occurrence of waste relative to on-site manufacturing. It was still noted that much of the carbon emission was due to the substructure; however, the collected waste data was insufficient to quantify the amount of waste generated on-site.

Despite the carbon savings results of their study, the authors stated that further research was required to effectively compare the efficiency in resources prefabrication was said to provide with that of traditional construction. Monahan and Powell (2011) recommended that further carbon savings could be achieved for the overall structure via increased prefabrication, selection of sustainable materials and on-site waste reduction measures. In addition, a systemic lifetime practice was required. They opinionated that decision-making on the basis of embodied carbon alone could be counterproductive and misguiding, in the long run. For instance, in spite of the high embodied carbon content of concrete, it is useful in construction and also to reduce the occupational energy requirements if judiciously employed in a structure. The authors concluded that carbon consequences could not be totally eliminated in the UK's house building programmes despite its zero carbon aspirations. They estimated a range of 110 to 167 $MtCO_2$ (megatonnes of $CO_2$), depending on the ration of timber prefabrication to traditional masonry construction, and also the agenda of sustainable construction, from design to occupation, and demolition of a building.

In a recent study, Chau et al. (2012) applied the Monte Carlo method to probabilistically generate the distribution profile of the carbon emission levels of the superstructure of a high-rise concrete office building, based on the material use data of thirteen of such buildings in Hong Kong. It was reported that the relocation of prefabrication yards in a certain part of Hong Kong for cheaper labour and cost could have an impact on the carbon footprint as a result of increased need for transportation from factory to assembly sites. In order to determine whether or not prefabrication produced less carbon emissions than on-site construction, both embodied and transportation energies were taken into account based on the assumption of 50 – 80% use of prefabricated materials for the office building. First, the researchers determined the building elements with the highest $CO_2$ levels which were found to be the external walls, upper floors and suspended ceilings. Based on the high-energy elements, the next step focused on impact of the use of different materials. This was followed by a study on the impact of importation of construction materials from neighbouring regions, retaining the existing structural and non-structural elements of the office, reuse of resources, recycling construction wastes, and prefabrication.

The results showed that the most effective way to reduce carbon emissions and lower embodied energy was by maintaining the building's structural and non-structural elements. Retaining the external walls, beams and columns (15-30% of the building) reduced 17% of $CO_2$ emissions. Waste recycling lowered emissions by almost 6% and reuse of resources by only 3.2%, however, it reduced the need for landfill. Regional importation of construction materials showed no reduction in carbon emission levels, rather importation from further locations provided as much as 9% carbon savings. This result was attributed to the fact that the further countries (Germany and Korea) had cleaner fuel sources than regional suppliers (China). Contrary to expectations, the use of prefabrication slabs, partitioning walls and facades actually increased the $CO_2$ emission levels by 5%. However, the authors proposed that this increase should be measured against the advantages provided by prefabrication in terms of increased construction speed, reduced material waste and improved product quality.

Synthetic fibres provide improved performance of traditional mouldable construction materials, such as are used in fibre-reinforced plastic (FRP) materials, which became used as workable substitutes for traditional construction materials, primarily due to their structural superiority. A prefabricated interlocking fibreglass composite panel system was newly introduced for the construction of building envelopes and was seen to have outstanding advantages such as construction speed, corrosion resistance, lower maintenance needs and electromagnetic transparency. As a result of low-level information on this system, Abdou, Murali and Morsi (1996) carried out a test of two commercial FRP panels, 25mm and 75mm thick and compared them with conventional building envelopes, in order to determine the more energy-efficient panel system by measuring their thermal characteristics, R-values particularly. One of the results showed that the thermal resistance of the 25mm FRP was more than twice that of a 150mm concrete masonry wall. With higher thermal values, FRP was encouraged as a way of achieving greater energy efficiency.

## 3.4 <u>CONVENTIONAL CONSTRUCTION AND PREFABRICATION: GLOBAL VIEWS</u>

Thanoon et al. (2003) compared prefabrication with conventional construction as regards the construction industry in Malaysia and found that the former beneficially presides over the latter in terms of sizeable cost savings, non-interruptions due to weather conditions, reduced labour requirements, and greater speed in construction, leading to earlier occupation thus saving on capital expenditures/payments on interests. Furthermore, prefabrication provides architectural flexibility, thereby reducing design monotony, and overall allows for different systems in construction with different prefabrication methodologies. The advanced technologies and stringent quality control measures involved in prefabrication also ensure higher quality of manufactured components than would be obtained with conventional construction. Yet, prefabrication is not without its shortcomings.

Thanoon et al. (2003) outlined ten of these, some of which have already been discussed in earlier sections. The others include lack of scientific backing to substantiate claims as to the advantages of prefabrication over traditional construction methods; the emphases on standardization and repetition have led to monotony in construction without technical proficiency and adequate quality control, hence the deterioration and dilapidation of buildings over time. This could be traced to the lack of assessment criteria, which has been deemed the most detrimental limitation to the successful adoption of prefabrication in Malaysia's construction industry and a setback to the intense marketing strategies which go as far back as the 1980s. Despite the aforementioned flexibility of design, prefabrication is said to be inflexible with regards to necessitated changes in design of prefabricated units over their lifespans. The authors also noted that the limitation of knowledge gap was partially due to the fact that Malaysian university students were not acquainted with the rudiments of prefabrication as a construction technology, hence these students went into the workforce only empowered with knowledge of conventional construction methods. The fact that breaching this gap would require huge investments was another hindrance to the uptake of prefabrication as an alternative construction technology.

The Parliamentary Office of Science and Technology (2003) pointed out that while the UK government was eager to implement prefabrication in house-building, on-going research was still being carried out to assess its benefits. Some issues with prefabrication were observed, such as planning and building regulations, cost of prefabrication, quality of prefabricated houses, environmental benefits and public approval. The Office observed that despite house builders' claims that prefabrication was cheaper than conventional, industry resources indicated a 7-10% increase in construction cost. The authors asserted that this could be a result of the fixed costs of factory operations, as opposed to on-site costs which were incurred only during actual construction. They, however, argued that such claims could not be verified due to the confidentiality of financial information of projects. They also argued that if prefabrication reduced construction time, it therefore followed that construction cost savings should be achieved. With regards to industry capacity, the shortage of skilled labour for factories of prefabricated units is a big issue in the UK. There is uncertainty as to exactly how much skilled labour is required for prefabrication in comparison to conventional construction. Thus, there is a limit to the number of manufactured houses which can be produced at any given time. The researchers noted that it was the lack of qualified labour rather than the use of defective materials that led to the production of low-quality housing in the 20th century. The UK government at the time of research was undertaking the training of over 2000 workers via the Construction Industry Training Board (referred to as CITB Construction Skills).

The environmental benefits of prefabrication are promoted by the UK government and bodies such as the Building Research Establishment (BRE) who found from research that prefabricated houses were actually more energy efficient than traditionally constructed houses, although there was no significant evidence of transportation and waste reductions. Determining the actual energy efficiency of prefabricated units was complex because of the difficulty of attributing energy savings to just the implementation of prefabrication alone. This was in spite of the fact that prefabrication was known to save heating energy due to the increased wall and roof insulation it provided. In terms of waste, although the likelihood was high, research was yet to actually confirm reductions as it had been observed that these reductions had been achieved as a result of changes in on-site practices. More so, the energy target was believed to have been met mainly through the use of an efficient combined heat and power (CHP) generator. With regards to transportation savings, it was said that this was subject to the distance from the factory to the site of erection, although the number or required trips to a building site may actually be reduced. Traditionally constructed homes in the UK are allocated as high as £2,000 for the repair of defects. Although prefabricated units means less defects (such as reduced defects in construction materials because of less exposure to poor weather conditions), if any prefabricated house is found to be defective, chances of replication of the defect in similarly prefabricated houses are high. Accreditation systems for prefabricated housing units exist, but these cost as high as £100,000, can take as long as a year, and are not applied by all manufacturers of prefabricated units. From a survey, low market demand and public perception of prefabrication were the two main reasons for the limitations of prefabrication in the UK. This was mainly attributable to historical concerns on prefabricated housing.

Planning requirements do not include prefabrication as a construction type. Planning and building regulations in the UK's construction industry are expected to undergo reforms to make prefabrication an alternative construction method and easier to implement. For instance, amendments to the energy saving requirements and structural integrity of houses might reduce the cost of prefabricated units compared to traditional masonry houses and make them more acceptable to house builders. The controlled environment of a factory is a lot less risky to construction workers than the exposed vulnerable on-site environment, thus the health and safety of workers is deemed much higher, and is encouraged by The Health and Safety Executive Health, regulators of construction safety in the UK, to reduce construction workers' mortality, recorded at 100 per annum at the time.

Takada (1990) observed that Japan owed the growth of its construction industry to the continuous growth of other industries. However, the state of many construction sites indicated the construction industry seemed to struggle to meet rapidly growing demands. As a result of the labour-intensiveness of the industry, the struggle was attributed to labour shortage. Admittedly an age-long issue of the construction industry, it was still without solution. Several schools of thought proposed that rather than be considered problematic, labour shortage was an opportunity for the construction industry to reform its labour-intensive characteristic. A way of doing this was the application of innovative technologies to construction processes, so as to entirely revolutionize the construction industry. One such method as proposed by Takada (1990) was the integrated construction system (ICS) which had hitherto been employed effectively in dealing with labour shortages. The author noted that while such studies had been previously carried out on other construction processes, precisely the comparison of traditional construction with prefabrication, ICS selects subsystems regardless of traditional or modern construction procedures, thus affording a wider range of selection. This was beneficial in that such a system would be applicable across many construction sites, and with improvement could serve as a complete system: the ICS. Takada (1990) went on to evaluate in-situ, half-precast and precast concrete procedures and the present state and future possibilities of ICS, as well as propose an optimized plan for improved ICS procedures in Japan.

Polat (2010) compared the application levels of prefabrication in the construction industries of the United States and Turkey. The author observed that while it was understandable that prefabrication was not widely implemented in Turkey as it was a developing country, it was rather fascinating that the same position of prefabrication in Turkey could be seen in the United States. Via survey, it was discovered that the factors responsible for this in both countries were significantly different from each other. In America, the top three factors were transportation restrictions (regarding load and size), poor communication among stakeholders and lack of qualified specialised contractors of precast concrete systems. In Turkey, lack of communication, lack of specialised structural engineers and lack of specialised contractors in precast concrete were ranked top three. Polat (2010) observed that typical issues such as lack of specialisation, poor management, low use of advanced technology, and poor level of standardization could be seen in both developing and industrialised countries alike. In spite of this, the author concluded that for prefabrication to be effectively implemented, it was important for the manufacturers and users of precast concrete to recognize that the uniqueness of the constraints varies from country to country, and to understand the prevailing limiting factors in their country, in order to provide immediate solutions to these constraints.

Oral, Mustikoglu and Erdis (2003) aimed to determine the feasibility of the application of JIT to the Turkish prefabrication sector. Their review of JIT in other developing countries revealed that the high costs of imported technology, high inflation rates, few suppliers, low labour costs and the government's lack of stringency on quality, were some of the barriers to the implementation of JIT. Specifically, uncertainty of demand and issues in the macro-economy ranked as the top barriers to JIT in prefabrication. It was observed that contrary to most developing countries, Turkey's market for construction materials was competitive both locally and internationally. Contrary to reviewed literature, the authors observed that inflation had an insignificant influence on the companies' inventory policies. As supply conditions with regards to materials quality proved satisfactory. It was noted however that the fear of risks was the predominant cultural value affecting organizational sub-cultures in developing countries. The authors then proposed that in order to successfully implement JIT and other advanced systems in prefabrication, training programs relating to both local and organizational culture should be implemented.

Girmscheid and Kröcher (2007) spoke of developing a business model that would enhance the expansion of the Swiss prefabrication market for the construction industry, based on the creation of an awareness of prefabrication and its advantages. They noted that the market was currently on a low level compared to their European counterparts and that majority of sales came from imports from the international market for prefab concrete elements.

Scheer et al. (n.d.) observed that a lean flow of materials was essential to achieving a production characterised by high quality, reduced waste, and synchronization, where the exact quantity was produced at the exact time of need. Their study involved an investigation of Southern Brazil's largest prefabricated components manufacturing company, in order to obtain the information technology (IT) required for a lean material flow, with a focus on information flow and process transparency within the design office, factory and construction site. The study aimed to provide solutions for the improvement of integration in the process of automation in order to ensure transparency of information flow. It was suggested that since each aspect of the market required particular systems for its needs, firms such as the one under study were in need of IT strategies for the development of said systems. Each system was to define the software, hardware and transmission means to be employed and establish managerial guidelines for the IT developer, such as amount of capital required, seed of transmission and necessities of the systems. The case study factory showed that adequate information flow at the right time was necessary among the technical/engineering department, commercial department, production and assembly teams, and the consumers. Otherwise, excess supply would arise leading to unwanted increase in cost. To avoid this and ensure full transparency, the authors suggested that IT solutions be effected alongside visual management strategies such as visual controls.

Improper planning and poor managerial decisions are partially responsible for the drawbacks of precasting. The effect of this is seen in inefficient utilisation and overstocking of resources. Dawood and Neale (1993) developed a computer-based model for capacity planning of precast concrete building products in order to facilitate the decision-making processes for production managers and enable them better explore available options. The model, a factory simulator, provided the function of planning automation and testing managerial strategies for effectiveness prior to production, using various factory and market characteristics – demand patterns, shift patterns and performance measures. The results showed that managerial performance relied highly on demand conditions and shift patterns.

According to Tam (2002), traditional construction practices had been criticized by Hong Kong's construction industry and its citizens for poor quality performance and safety records. As such, prefabrication had been strongly encouraged for improved safety, enhanced quality and the elimination of site malpractices via the provision of a safer, cleaner and more controlled construction environment (factory). In addition, under factory conditions, waste was reduced and recycled, leading to the industry's sustainability. Nevertheless, prefabrication had its downsides, one of which was design monotony which architects and town planners were opposed to. Also, there were concerns about the connection and jointing (tightness due to water and weather) issues associated with Hong Kong's high-rise buildings, which constrained the widespread adoption of prefabrication. Besides these, one major concern was the effect of prefabrication on the labour market. At the time of the study, Hong Kong's construction industry was characterized by high labour intensity, with the industry recruiting young school leavers and also absorbing low technology labour during the shift of manufacturing industries to more suitable regions in the country, thus diminishing social pressures.

The transition to prefabrication from traditional on-site construction was reported in Tam's (2002) study to affect local labour consumption by a 43% reduction. Although the author asserted the possibility of exaggeration in the figure as some minor trades (such as marble laying, scaffolding and project management) were unaccounted for in the model. In spite of this negativity, the author notes that following global trends, the move to prefabrication for public housing construction was inevitable, and if ignored, the competitiveness of Hong Kong's construction industry would suffer in terms of time, productivity, quality and safety.

The permanency of a production plant offers greater technological proficiency, more satisfactory working environment, more efficient production, and more rigorous enforcement of control measures, than offered by a fluctuating unsystematic and exposed working site environment. Therefore, the prefabrication and on-site assembly of building components promise much better performance as well as more economic efficiency in the use of resources than on-site construction of the same components would (Retik and Warszawski, 1994).

## 3.5 AIM AND OBJECTIVES

This research involves a comparison of the energy consumption levels of various existing construction processes in the building industry of Dubai (Reddy and Jagadish, 2003). Its primary focus is on two major construction methods: the conventional/traditional construction method (referred to in this work as 'on-site') and the prefabrication method (herein referred to as 'prefab'). The main aim of this research is an evaluation and comparison of the total embodied energy and consequential carbon emissions of these two construction methods as determined by their respective life cycle analysis. The results of this analysis will determine whether prefabrication is indeed a more environmentally and otherwise, beneficial improvement over the UAE's traditional method of construction. The outcome of this research will aid in the selection of a more appropriate construction method to meet the global targets of reduced carbon footprint of the construction industry as well as energy conservation and sustainable construction practices in the UAE's building and construction industry (Chen, Okudan and Riley, 2010).

In order to achieve this aim, the study objectives are as follows:

- ✓ An extensive literature review of construction systems, along with prefabrication, its definition, types, advantages and limitations, and industry challenges to its implementation;
- ✓ A global view of the current status of prefabrication;
- ✓ A case study of a traditionally constructed high-rise building in Dubai by implementation of a LCA framework, in order to quantify its embodied energy and carbon emissions over its lifespan, based on the traditional construction method;
- ✓ A simulation of the same building with the prefabrication construction method in order to evaluate its embodied energy and carbon emissions;
- ✓ A detailed comparison of the results of the LCA of both construction methods;

- ✓ A detailed analysis of the results of the evaluation in order to determine the advantages of prefabrication over the UAE's traditional construction method;
- ✓ A proposal of an efficient tailor-made prefabrication model based on the results analyses, best suited to the construction industry in the UAE.

# CHAPTER 4

# METHODOLOGY

## 4.0 INTRODUCTION

In order to investigate the role of prefabrication in waste reduction and mitigation of carbon emissions in comparison to existing conventional construction methods, several methodologies have been employed by different authors. There are two general kinds of research methods: qualitative and quantitative. Both are applicable to a research of this nature as both have strengths and weaknesses that are complementary to one another. The main difference between both methods is that while quantitative involves the transformation of obtained data into tangible quantities (numbers, tables and figures), qualitative research is concerned with the personal interpretation of information by the researcher without quantification or transformation into numbers.

Whatever method of research is chosen, it is always best to base this choice on the aim of the study and the most appropriate approach to achieving said aim. Majority of the existing studies carried out their researches using a combination of methodologies. To determine which of these methods would be most appropriate for this research in fulfilment of its aim and objectives, the prevailing methodologies were evaluated.

## 4.1 CASE STUDY RESEARCH METHOD

Girmscheid and Kröcher (2007) define a case study as "an empirical inquiry that investigates a contemporary phenomenon within a real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (p. 31). Case studies are applicable to complex investigations whose aim is the description and analysis of certain components in complex, holistic and qualitative terms. Case studies are usually carried out within a certain time frame and require limited system of focus (people, relationships and components) of interest to the researcher.

Case study is carried out more commonly through observations, interviews and the study of documents, with the researcher being the tool for data collection and analysis. For the success of a case study, the researcher is required to be empathetic, a good communicator and be able to register as much information as possible.

Case study methodology is used in the areas of prefabrication to test the validity of a proposed application of prefabrication/prefabrication components to a building project/projects. These projects range from small to medium to large scale. Selected buildings are investigated for their construction methods – prefab or conventional. Selection criteria are determined based on the aim and scope of the project. For instance, Jaillon and Poon (2008) conducted case studies on seven recently constructed high-rise buildings, either by prefabrication or by conventional construction. The criteria for building selection included the size of the project, type and height of the building and the year of completion. For data collection, the researchers first carried out literature reviews, followed by a questionnaire survey and finally face-to-face interviews were conducted with the architects, contractors, engineers, manufacturers of precast elements as well as the project clients. Furthermore, site observations were carried out at one precast manufacturing plant and six construction sites. Also, drawings and project documentations of all seven buildings were collected. By doing this, the authors comprehensively carried out all the aspects of a case study: interviews, observations and documentation.

Another similar research involved the case study of seven buildings, carried out by Rogan, Lawson and Bates-Brkljac (2000) in which they examined the practical use of modular construction, by comparing its benefits to those of traditional construction methods. Their case study methodology involved interviews and questionnaires with the projects' designers and contractors. The seven buildings researched covered a wide range – a hotel and hotel extension, a hospital, a residential building, a retail building, an educational building and a student hostel, all in the UK. The case studies were used to demonstrate the process of value assessment as applied to the choice of modular construction for various types of buildings.

It is apparent from the afore-mentioned examples that the successful application of case study to a research involves at least two or more aspects of case study, particularly including the use of interviews and questionnaires.

## 4.2 INTERVIEW RESEARCH METHOD

Interviews are used in order to obtain information which cannot be gotten through observation; and the choice of interview depends on the aim of the research. This methodology has been used to obtain information on the several perspectives of prefabrication as an alternative construction technology. One relevant study which applied interview method of research is discussed next.

In Malaysia, a pilot construction project had been built in 2007 consisting of five bunkers followed by four others in 2008. It was observed that the same problems which had been encountered in the first phase, regarding safety, cost, time and security, had been replicated in the second phase of construction. In order to determine the feasibility of implementing prefabrication as a construction method for the RMAF Planning and Development Department, Kok (2010) carried out a comparison of the cost effectiveness with regards to quality, cost and time, of prefabrication and conventional construction. Although there was no readily available guideline or benchmark for cost effectiveness comparisons, the author decided to focus on information gathered via site visits, review of the scopes of existing works, interviews and literature review. Site visits to bunker construction sites were carried out and physical construction data were recorded for comparison with existing drawing designs and specifications. The next step involved interviews carried out to identify the perceptions of cost effectiveness of the construction methods from those involved in all stages of the construction, from planning through procurement to implementation. According to Kok, the decision to carry out interviews instead of questionnaire surveys was made because face-to-face interviews with respondents created a better atmosphere for the respondents to aptly understand the purpose and importance of the interview. Based on the results of the documentation and interviews, the author was able to carry out a proper cost effectiveness comparison of prefabrication and conventional construction.

## 4.3 QUESTIONNAIRES AS A RESEARCH METHODOLOGY

Questionnaires are a qualitative methodology which could be used alone for research on prefabrication and the appropriateness of its application to construction projects.

In order to establish a framework for, and a description of the processes of the concept of IBS, Lessing (2006) chose a qualitative method in order to be actively involved in the investigation of the IBS environment of several companies. By doing this, the author was established as an important tool in the study. The author asserted that his pre-understanding and previous experiences were some of the factors that affected the study to some extent. This is usually the case with the questionnaire methodology. The application of questionnaires is presented in the following examples.

Tam et al. (2007) applied a questionnaire survey in Hong Kong in order to reveal the advantages, disadvantages and further developments of prefabrication on construction sites. Their questionnaires were sent out to two hundred parties – consultants, developers, government departments, main- and sub-contractors. The authors used seven benefits of prefabrication to conduct their survey: the freezing of design at the early stage for improved implementation of prefabrication; overall reduction of construction costs; shorter construction time; better supervision for improved product quality; minimised waste generation; integrity of building design and construction, and building aesthetics. The benefits of implementing prefabrication have varying degrees of significance to the construction industry. Tam et al. (2007) therefore aimed to identify the levels of recognition of these benefits. Their survey entailed each respondent to judge the levels of significance of the seven benefits based on a Likert Scale of 1 – 5, with 1 being 'least significant' and 5 representing 'extremely significant'. In addition to this, the authors used an alternative approach (employing statistical means) to determine the relative levels of significance of the benefits in question.

Haas et al.'s (2005) study had three main objectives. The first was the determination of the impact of prefabrication and pre-assembly (PAP) on the construction workforce in the USA. The second was a documentation of current trends regarding the area and volume of PAP activities in the construction industry. The final objective was an investigation of the utilisation of PAP in the construction industry – who performed what task in the project. Due to insufficient records and those unavailable due to confidentiality, expert judgement and assessment were used to quantify overall trends over the previous fifteen years. The first step the researchers used was an extensive literature review of developments, which had occurred during the twentieth century, and research, which had been conducted over the last four decades. The next step was a series of formal interviews of leading professionals at junior, middle and upper management levels in prominent construction companies to obtain further information. The third step – a survey – was based on the results of the literature review and personal interviews. Professionals at the management level and above of over fifty construction organisations and companies were involved in the survey.

## 4.4 SIMULATION AND DESIGN TOOLS

With reference to construction activities, Stouffs, Krishnamurti and Oppenheim (1994) defined simulation as the "computational modelling of a process described by the activity network of construction tasks, the spatial description of each robot action, and an accompanying representation of the evolving building at each state in time" (p.1).

The primary advantage of simulation is the practical user feedback on a particular system. As thorough investigations of the effects of design and construction decisions can be carried out before actual erection, the user is saved the need to commit time and resources to procurement. In addition, the user is able to explore alternatives design systems and aptly determine the correctness and efficiency of a system (Birgisson, 2009). Thus, the user is able to select that which provided the optimum value in terms of functionality and resource requirements. This aspect of simulation is critical, because changes to the design and construction process once construction has begun are known to be very expensive. Upon the creation of a final valid model, policies and operational procedures can be experimented with, at no further costs and without interruptions of the real system (Birgisson, 2009).

This follows Stouffs, Krishnamurti and Oppenheim's (1994) assertion that simulations aid in the determination of the feasibility of construction activities and the maintenance of a continuous measure of construction cost and time. A simulation can be used to provide a detailed study of alternative construction plans and use of resources. One of the main applications of simulation is in task scheduling and planning of construction activities to enhance productivity. When applied in this way, simulation involves a three-step process: identifying the input, which usually consists of the task plan/scheduling process; creating a scheduling process (more commonly as a separate step; and finally the output, which identifies the most efficient scheduling of tasks.

The authors carried out a simulation to demonstrate the effectiveness of robotic task-planning in construction projects, using RUBICON, a rule-based simulator, for a typical Japanese precast concrete residential building. First, a building construction task plan was created in which the construction elements and processes (referred to as a task schedule) were described (input). Then, the tasks were individually translated into robot motion plans (by rule-based descriptions) which reflected the mobile capabilities and limitations of the robots, to avoid collisions (scheduling process). Considerations were made in the simulation for the roles of each robot in construction, its relation to the environment (site), human labour, and other construction robots. The output was a graphical simulation of the entire construction process, with visual representations of the robots' actions according to the task plans.

The simulation provided several advantages to the project planning engineer, including the recognition of unfeasible tasks and task inefficiencies, the study of alternative task plans, resources and robot types. RUBICON provided results such as the total time, number of robot agents and amount of human labour involved in the project. An illustration is seen in Figure 4.1. . RUBICON was used to demonstrate the effects of alternation of task sequences on types of robot paths and construction productivity, in a task such as floor-by-floor versus staircase-by-staircase construction.

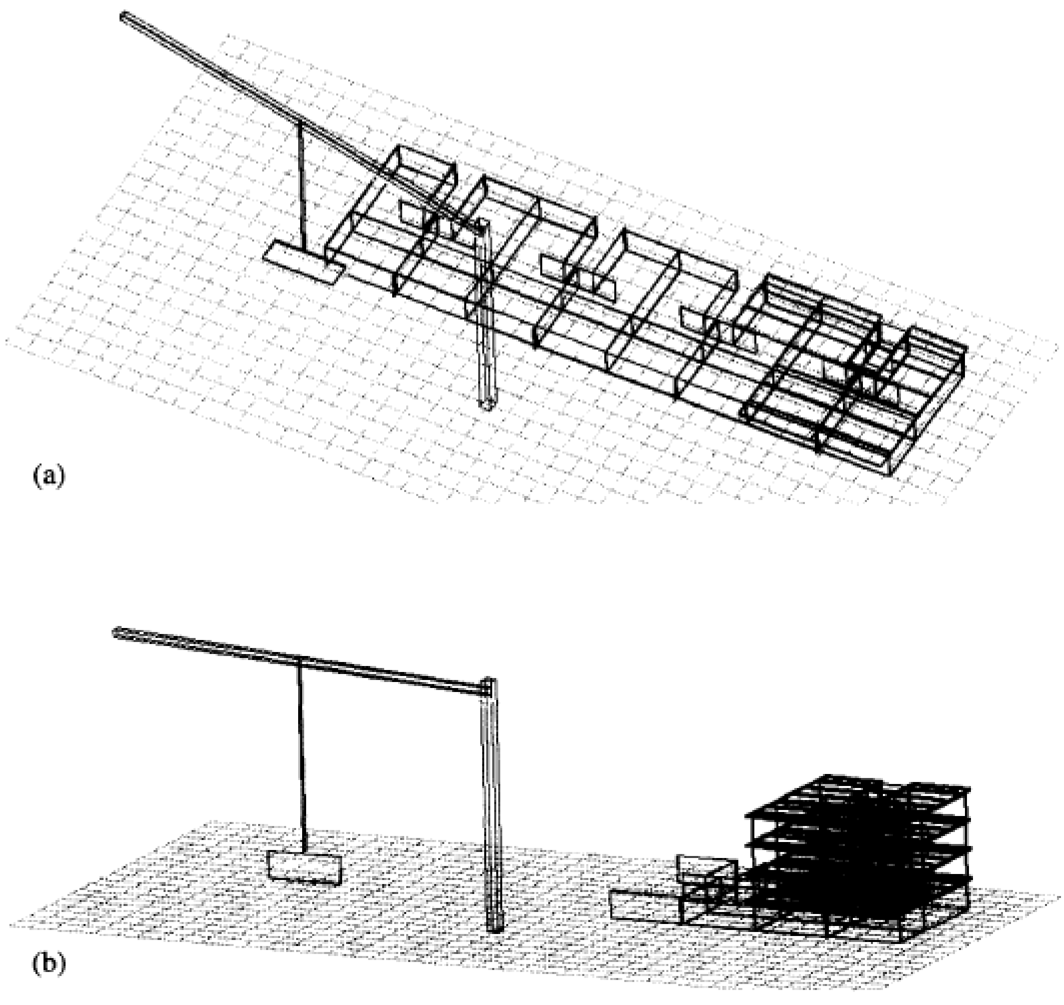



Figure 4.1: Task Sequencing: Floor-by-floor (a) versus staircase-by-staircase (b) (Stouffs, Krishnamurti and Oppenheim, 1994)

Huanga, Chen and Sun (2004) advocated for the use of simulation techniques in their research on the study of different form reuse schemes for the adoption of modular formwork systems (with a focus on gang forming as opposed to handset forming systems) in building construction. The objective of the study was to gain a better understanding of the different form construction schemes and through simulation, better plans for the prefabrication of multi-storey multi-building projects. According to their study, computer simulation was the most suitable method for their research because it was a valuable management tool well equipped for studies of resource-driven construction processes. The use of computer simulation provided alternative solutions for the improvement of such processes via simulation and evaluation, which were far cheaper to carry out than actual real-life operations.

In order to analyse the balance between site and factory operations, as well as the optimum level of prefabrication for designing houses, software tools which investigate the interactions and interdependencies between the components of a complex system are employed. For their research on the investigation of modules and sub-systems, Wing and Atkin (n.d.) preferred the use of the Dependency Structure Analysis (DSA), a systems analysis tool. They pointed out that one benefit of this modelling approach was that any change in an element was automatically reflected in the rest of the model, thereby preserving the integrity of the data. In addition, various arrangements could be tested and optimised within the process. Besides the creation of the house model, provision was made for a simulation of its construction processes, which allowed for an examination of the time, cost and quality parameters. The software provided a list of components in an expansive library from which its user could select and view components three-dimensionally and decide on its addition to the house design using techniques of collision detection and constraint-based modelling, for easy interaction. As components are added to the design, the user would be able to view the total cost of the components. Following the design, the user would then proceed to the construction environment where the construction process was simulated by animation, with the inclusion of virtual site equipment such as a tower crane. The results of the simulation would enable the user determine optimum construction processes and the most suitable construction method applicable to a particular project.

As mentioned earlier, the apparent advantages of simulation are the ease of testing different construction scenarios in a controlled environment without the added task of physical construction. Simulation provides a simplification of the direct relationships between the environmental parameters of the construction site and the construction processes. Visualization of the output allows for easy evaluation and analysis of results. The downside is that all elements of the design must be completed before an actual simulation is carried out (Donn, 2004).

Simulation answers “how”, “why” and “what-if” questions of all aspects of a simulated construction activity. For instance, “what if a process is omitted and replaced with another?” Since simulation by itself is a complex theory, and when added to the dynamism of the construction industry, simulating construction processes involves a high degree of random tests. Birgisson (2009) according to Banks (2000) argues that because of the high level of randomness of variables, it is difficult to truly determine whether the outputs are due to systematic interrelationships or should be attributed to randomness. However, Lesniak, Grodzki and Winiarski (1975) argue that practical implementations means the imposition of restrictions on the design of prefabricate construction systems, thus keeping the size of automatic design systems within practical limits. Although undesirable, they buttressed that regardless of the degree of flexibility, certain standardisations cannot be dispensed with, at least not without incurring extra costs.

Furthermore, simulation allows for time manipulations. Time can be compressed or expanded depending on the investigation in order to thoroughly investigate a process. Simulations can be carried out limitless number of times to ensure the accuracy of results. However, the simulation process can be time consuming, relative to the simulation programme and level of thoroughness and detail required. More so, simulation requires a certain level of knowledge of simulation concepts and a considerable amount of time is required to gain this knowledge.

Csoknyai (2007) argues that the use of simulation tools has a better advantage than simplified methods because more accurate results are obtainable and there are further possibilities for the application of the tools such as parametric studies, statistical analysis and justification of new methods. The author however asserts that although these tools are widely available in the market, the use of simulation requires high level of technical skills and working time; thus they are better suited for specific tasks which cannot be carried out using simpler methods.

## 4.5 DECISION MODELS

A model, by Warswski's (1985) definition is "an artificial device which represents certain characteristics of a system under examination" (p. 3).

Warszawski (1985) examined three kinds of tools involved in decision-making processes for construction management. Firstly, the author looked at analogue models, which could range from simple tools (such as charts, graphs and diagrams) to advanced ones (flowcharts and networks). These are used to graphically represent a project's main attributes and how they affect budge and schedule. This was followed by mathematical models, otherwise referred to as optimization models. As earlier mentioned, these models are used to determine cost- optimized solutions to construction problems by manipulating the attributes of a particular project. Thirdly, expert models were examined. Considered the most complex of all decision tools, these involve the manipulation of normative data (such as prices, equipment, capacity etc.), use of algorithms, and also the application of unstructured decision rules based on the opinions of experts.

### 4.5.1 MATHEMATICAL MODEL METHOD

Mathematical models are only applicable when they truly reflect all the relationships critical to the problem in the system under investigation and given that all data required for their compilation are readily available. The main strength of this method is its basis on the thorough analysis of available data which results in the provision of an optimal solution to the problem at hand. Conversely, the main weakness is that this method is totally dependent on quantitative data to represent relationships amongst system functions and constraints. This limitation is particularly disadvantageous in large real-life applications, because it is not feasible to gather all the data required for a full representation of the system being investigated.

In addition, the decision maker may have a strong influence on the final solution, in as much as the solution might be measured by more than one factor (cost and time, quality and cost, etc.), based on preference, experience and so on. Furthermore, where the data is not deterministic, the models may underperform such that it might be impossible to optimise solutions objectively and quantitatively, as the expected outcomes might be subjectively selected. Lastly, there are strong temptations to use abstracts and simplify results in large systems that require rigorous study, leading to invalid and unreliable solutions.

Mathematical models are usually used in conjunction with experimentation in order to validate the results. The following paragraphs give reviews of different mathematical models applied in the precast construction research.

Bljuger (1976) developed mathematical models for the classification and an analysis of the deformability characteristics of the then commonly available vertical wall joint types in multi-storeyed structures. The values obtained were recommended for use in elastic and elasto-plastic design of multi-storey structures.

Hsieh (1997) developed a conceptual model for comparing subcontractor-contractor relationships in prefab and traditional methods. For their research which included a literature review of the difficulties (unfriendliness) faced by general contractors during the consideration of prefabrication, the aim of the model was to compare the conditions for selection of prefabrication as a construction method with emphasis on two specific areas: a comparison of the cost structure of structural construction when prefabrication in implemented; and an examination of the risk-sharing nature in sub-contracting. They supported their mathematical model with interviews of two project managers in order to support the development of their conclusions.

Zenunović and Folić (2012) compared the results of both experimental and mathematical methods of two types of reinforced concrete (RC) connections: the precast slab and monolithic wall (Type 1), and monolithic slab and wall elements (Type 2). Three specimens per type were examined. The results of the experiment were used to develop the mathematical models which in turn were based on matrix formulated displacement, and used to describe the assembly (structural mechanism) of precast slabs and monolithic walls. The model was used to define the method of displacement application, together with the modification of the stiffness matrix by introducing the yielding of joints. The authors asserted that the accuracy of the calculations were dependent on the model, one of the afore-mentioned limitations of the use of mathematical models.

### 4.5.2 ALGORITHMS

Scheduling of construction activities is regarded as gruesome task. In order to solve this problem for planners and building managers, Artificial Intelligence (AI) and Operations Research (OR) have been used. Although known for its provision of optimal solutions, due to the difficulty in the real-life application of OR, it has been used in conjunction with heuristic methods. AI on the other hand, explicitly represents all the constraints of an operation, even though the information provided is no completely verified. One form of AI is Generic Algorithm (GA). GA's are defined as "algorithms based on the mechanism of natural selection and develop a solution of the previous optimization problem" (Catallo, 2004, p. 8).

GA's have been widely used over time to beat the limitations of mathematical models (Chan and Hu 2001).

For precast production scheduling, Chan and Hu (2001) used GA to solve a modified flow shop scheduling model (FSSM) for specialized production in a precast concrete factory. By distinguishing between normal and off-normal working times, and categorizing operations into pre-emptive and non-pre-emptive tasks, the proposed model able to model current industry situations more accurately. The procedure followed the same steps from initialization through selection to termination as outlined earlier.

De Albuquerque, El Debs and Melo (2012) presented a study of the Decision Support System for Precast Floors (DSSPF), a design optimisation tool using GA, for the design of an integrated structural precast floor. The study took into consideration the cost impact for all stages of the construction such as transportation, manufacturing and erection. As per usual with mathematical models, the verification of the results of the GA was carried out by comparison to the result of an existing design, using a case study of the Commercial Carvalho. The results indicated the reliability of the DSSPF as a design optimization tool.

## 4.6 EXPERIMENTATION

Reeves's (1997) paper summarized the report of a field experiment in which several local authorities in the UK decided to overclad precast concrete buildings as it was believed that overcladding would improve the habitability of the buildings as well as improve their life expectancy. The Building Research Establishment (BRE) undertook a monitoring of the environmental conditions of two of such houses. To carry out this research, sensors were installed in a number of components within the houses to measure temperature, atmospheric oxygen content and relative humidity and oxygen content. The monitoring system was linked to a datalogger for the duration of the experiment. The results revealed the precast concrete components susceptible to low- and high-level corrosion. The authors however suggested the use of laboratory experiments to supplement the results from the field.

Cassagnabère et al. (2010) carried out an experimental study on the replacement materials for clinker content in cement for the precast concrete industry. The experiment involved an investigation of composed cements and combinations of clinker and mineral admixtures (silica fume, metakaolin, limestone and siliceous filters) in order to evaluate the compressive strength of cement-based materials on days 1 and 28 of the steam curing process.

## 4.7 LIFECYCLE ASSESSMENT (LCA) METHOD

LCA is employed as one of the main techniques of a cradle-to-grave (extraction, processing, manufacturing of raw materials; transportation, distribution, use, re-use, maintenance, recycling and eventual disposal) quantification and evaluation of the environmental impacts of a product, a process, or services. LCA involves an assessment of the impact of the use and release of energy and materials to the environment; and an identification and evaluation of ways to improve upon these impacts. This assessment framework is usually carried out based on International Standards (ISO 14040) which defines LCA as

> a technique for assessing the potential environmental aspects associated with a product (or service) by compiling an inventory of relevant inputs and outputs, evaluating the potential environmental impacts associated with these inputs and outputs, and interpreting the results of the inventory and impact phases in relation to the objectives of the study. (Asif, Muneer and Kelley 2007, p.2).

There are four main interactive stages of a complete LCA framework (Figure 4.2): goal, scope and definition (or planning); inventory analysis (LCI); impact assessment (LCIA); and improvement analysis (or interpretation). Stage one involves a definition of the scope of the study, which includes a definition of the goals/objectives of the functional unit of the LCA framework, amount of detail, boundaries of the study, and the allocation of environmental burdens. This phase depends on the subject and purpose of the study and varies considerably depending on the particular LCA. The second stage, LCI, is a compiled inventory of the input and output data in reference to the product or system (raw materials, energy, air emissions, water-borne effluents and solid wastes) being studied. This phase is an iterative one as data is constantly updated as more information is obtained regarding the system under study. Stage three, the LCIA uses the results of stage two, the LCI to evaluate the importance of possible environmental impacts of the product or system, and provides information for stage four. The final stage is the interpretation or improvement analysis phase. It involves a summary of the LCIA results (or the results of an LCI in a partial LCA) as a basis for improvements on the environmental burdens put in place by the product or system under study, through an objective view of its entire life-cycle (as defined in the first stage) and an assessment of the impacts of such changes on the environment (Asif, Muneer and Kelley, 2007; Monahan and Powell, 2011).

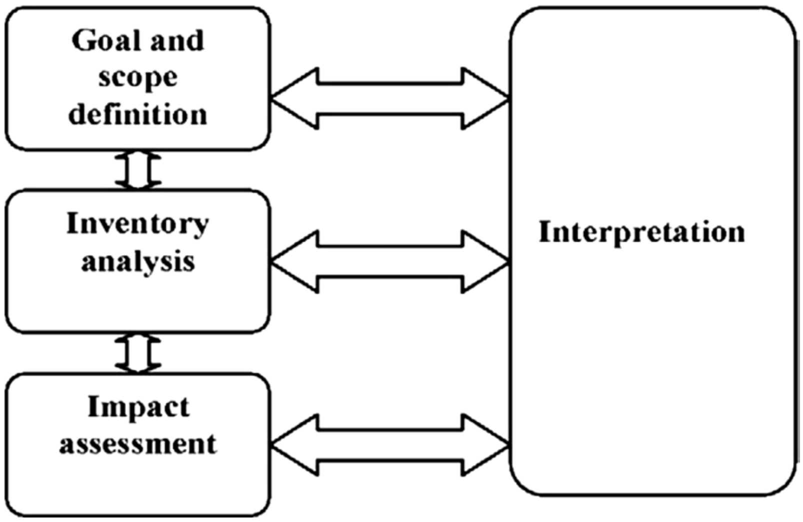



Figure 4.2: ISO 14042's LCA Steps (Menoufi et al., 2012)

The standardization of LCA was implemented by the Society of Environmental Toxicology and Chemistry (SETAC) whose technical guidelines for the proper use of LCA have become the most widely used. One very important step in this includes an often ignored component, the Lifecycle Improvement Analysis. This step is defined as the process of reducing the environmental burden linked with the use and release of raw materials and energy into the environment throughout the lifecycle of a product.

According to multiple reviewed literature related to this study, LCA is the most prominently used methodology. Several examples of studies involving the application of LCA in the evaluation of environmental impacts in relation to the precast industry are reviewed as follows.

Asif, Muneer and Kelley (2007) carried out an assessment of eight different construction materials: concrete, glass, timber, aluminium, slat, plasterboard and damp course. Of the eight, the five that were deemed more significant in terms of their embodied energy and characteristic environmental impact were more thoroughly investigated: concrete, timber, aluminium, glass and ceramic tiles. The study involved a LCA of a three-bedroom semi-detached house in Scotland. An investigation of the inventory reports along with direct observations and interviews of the contractors and local housing association personnel, were the methods used to quantify the materials under study.

Bribián, Capilla and Usón (2011) carried out a comprehensive literature review on numerous studies involving the use of LCA for investigating the embodied energy of construction materials. The study followed the methodological standards defined in ISO 14040:2006 and ISO 14044:2006. The aim of the study of different building materials was to evaluate their energy and environmental specifications, analyse the possibilities for their improvement, and provide materials selection guidelines. Upon consideration of the present energy and environmental issues facing Europe, the impact categories selected for analysis in the study were based on the 20-20-20 targets requirements. The categories included: primary energy demand using the Cumulative Energy Demand (CED) method; Global Warming Potential (GWP) based on the Intergovernmental Panel on Climate Change (IPPC) 2007 methodology; and water demand.

The authors selected one kilogram (kg) of material as the functional unit. The stages considered included: material manufacture (from the supply of raw materials through transportation of the factory and manufacturing processes); product transportation to the building site (a 20-28 tonne lorry travelling an average of 100km and a sensitivity assessment for other means of transportation); building construction and demolition, and final product disposal for all the stages analysed, the Ecoinvent Version 2.0 database (2007) inventories were used for the European averages, to which country-specific characteristics (manufacturing technology, energy mix and so on) were adapted. For the LCA study, the SimaPro Version 7.1.8, was the selected software tool. With regards to final disposal, building demolition and the most prevalent disposal methods were taken into account. The authors concluded that in comparison to other LCA studies, theirs was observed to show 20 to 30% more impact. They asserted that this significant difference was justified by the wide-ranging limits which their study considered in addition to other LCA-related hypotheses (such as requirements for data quality, energy-mix, useful life and so on). Following this, they suggested the importance of upgrading existing inventory databases of construction materials to match the dynamics of the construction industry in each country.

Gustavsson and Joelsson (2010) carried out a comparative analysis of the primary energy use and carbon emissions for the construction (conventional and low-energy methods) and operation of five different residential buildings, from a life-cycle perspective. They integrated previous detailed studies on construction, operation and supply systems in order to identify possibilities of improving life-cycle energy efficiency and the reduction of carbon emissions. It was here noted that the energy use in the building production stage was dependent upon the choice of construction material. The authors asserted the several phases of a LCA: materials production, on-site construction, operation, disassembly and waste management, while stating that the complexity of a LCA was due to the long lifespan, the many stakeholders involved and the dynamism of each building. Their primary focus was a detailed study of the production and operation stages from a primary energy perspective. The authors however argued that they excluded the energy used for on-site construction of the buildings in the production phase because unlike in other studies, it only accounted for a small portion of the life-cycle energy in their studies.

Rossi, Marique and Reiter (2012) presented a paper on the comparative analysis of the LCA of a residential building using tow construction methods in Belgium and a steel frame house in Belgium, Portugal and Sweden. Their study first of all compared two different structural systems for the house in Belgium – traditional masonry and steel frame systems. Their selected functional unit was a reference house designed based on the typical construction methods of detached Belgian houses. Notwithstanding the building traditions which vary from country to country, the same reference house was used in all three regions with a focus on climate, materials and energy mix for the purpose of analyses.

They selected as their databases the one included in the Building for Environmental and Economic Sustainability (BEES) software as well as the database published by the Centre de Resources Henri Tudor (CRTI). According to the authors, it was noteworthy that their results obtained using the basic LCA tool were compared with the University of Bath's Inventory of Carbon & Energy database and the EcoInvent database, in order to assess the confidence level of their database and for the purpose of verification.

In Cole's (1999) work, different constructive solutions were tested for to determine the most sustainable with the least operational energy demand. To do this, a LCA was carried out on seven experimental cubicles (two precast, two alveolar brick and three conventional brick cubicles) in Spain. The LCA was implemented using Eco-Indicator 99 (EI99), for its easy recognition of the relative differences between the cubicles, and engrossed a wide variety of substances with different processing strategies. Under controlled temperatures, thermal performance measurements were conducted for the entire system. The LCA focused on the impact assessment of the required embodied energy for manufacturing and disposal, via a comparative analysis of the effect of different building, insulating and phase change materials.

López-Mesa et al. (2009) reported on a study of the environmental impacts of two slab systems, a concrete-based one-way spanning slab and the second, a hollow core slab floor. The study was carried out by applying the EPS 2000 method of LCA, taking into account the local construction practices. To buttress the environmental analysis, a cost analysis was undertaken. While results showed the superior environmental performance of the precast concrete floor over the in-situ cast floor, the reverse was the case in terms of cost as the former was revealed to be more expensive than the latter. The authors asserted that this was a probable reason for the still preferred use of the latter over the former as a floor construction alternative.

Based on studies, LCA provides several outstanding benefits. This methodology assists in two key areas:

- ✓ The identification, estimation/quantification and impact assessment of a particular product, system or process on the environment; particularly.
- ✓ Comparisons between viable technologies and their alternatives in order to determine the most optimal solution in terms of environmental friendliness.

In addition to the above, LCA has the potential to structure a flow of quantitative information between different stakeholders (industry, customers, researchers, governmental agents, local communities and other groups). It can be used internally within an industry for process improvement, technology selection and reporting, and externally to support marketing, and to inform different stakeholder groups. Finally, it must be noted that with the help of LCA, producers take better decisions pertaining to environmental protection.

As with every research methodology, the use of LCA is not without its disadvantages as given:

LCA is known to be time-consuming and costly due to its data-intensive nature. The more comprehensive the data required, the more time and money involved in the LCA, especially because of the need for expertise in impact assessment and improvement scenarios. Where data is not available or accurate, it invariably affects the accuracy of data and the final results of the study.

Assumptions made for LCA studies tend towards subjectivity in relation to data sources, the determination of system boundaries and methods of assessment. The issue lies in the complexity of LCA methods, inclusive of data intensity and boundary selection details. The effect of this is seen in the conflicts which arise in decision-making by stakeholders.

Again, data availability is a sensitive issue. Researchers have to deal with outdated data sources, and the outright impracticality of collecting data for every single input being investigated. Most studies are carried out using unpublished existing databases, which while time-saving, may mean that they are no available for peer review. This poses the problem of validity of information and final results.

According to LeVan (1995), these limitations coupled with the current trend of making LCA the sole environmental impact assessment method have resulted in a lack of confidence in the results of LCA studies. More so, the abuse of LCA methods by advertising strategies which claim that one alternative is "more environmentally friendly than its competitor" has turned LCA into just another marketing ploy.

## 4.8 SELECTED RESEARCH METHODOLOGY: LCA

The aim of this study was to comparatively analyse and evaluate prefabrication and conventional construction method currently applied in the UAE's construction industry, using a selected high-rise building in Dubai, representative of typically constructed buildings in the UAE, in order to determine the more optimized construction solution for carbon emissions mitigation, waste reduction and energy conservation. Following the evaluation of the benefits and limitations of the commonly applied methodologies to relatable researches, the LCA was found to be the most appropriate method to achieve the aim and objectives of this work.

The outlined advantages of LCA, coupled with its apparent preference by other researchers influenced the selection of this methodology for the purpose of this study. With the LCA as the primary study methodology, an exhaustive literature review was carried out in order to lend credence to the results of this study. The justification for its selection is further discussed.

Manufacturers in particular have applied LCA for the following reasons: the identification of components, processes and systems which are the major contributors of environmental impacts; the comparison of alternative options in a specific process that could minimize these impacts; and the provision of a guide for long-term strategic planning with regards to trends in the design of products and the materials involved in their production.

According to policymakers, LCA is most useful as an aid in the development of long-term policies regarding the uses of materials, conservation of resources and the reduction of environmental risks associated with the materials and processes of a product throughout its lifecycle. In addition, LCA is beneficial in the evaluation of the effects of reduced utilisation of resources and alternative waste management methods. Lastly, it provides with information on the resource features of materials and products.

The most significant application of the LCA that influenced its selection as a tool for this research is its function as a comparative tool. LCAs can be used to comparatively evaluate the impacts associated with the use of a product or the processes of its production. The comparison of competing products or processes serves as a guide for consumers and manufacturers to make choices among options, as well as provide information for decision makers in policy-making and development of regulations. With regards to this study, the conventional construction process is compared with the process of prefabrication in the UAE, in order to evaluate the more viable construction alternative with the primary aim of carbon mitigation and energy and resource conservation. In addition, analysts can make use of the results of this research to determine the ramifications of technological changes and policy evaluations and adaptations. It is hoped that the results of the LCA would provide a basis for further research to boost the growth and development of the UAE's construction industry.

Additionally, considerations were made given time limitations. The time taken to understand the rudiments of selected LCA software was calculated to be the least in comparison to the time required for the development of a mathematical or simulation model. Furthermore, mathematical models were used by researchers to carry out technical analyses of the structural behaviour of precast concrete. Since this research was more concerned about generic construction methods, the development of a mathematical model was not required; hence the use of the mathematical model methodology was impractical.

In spite of the aforementioned difficulties in the use of LCA, it is still a highly valuable tool. The need for information on resources, energy and emissions requirements for construction technologies cannot be eliminated, especially as construction has been determined to be a major contributor to the current deterioration of the human environment. LCA tools meet this critical need in the identification of areas within lifecycles that need to have reductions in environmental impacts and a guide for improvement of and sustainability in design to suit the environment.

In order to sufficiently achieve the aim of this research, a detailed methodology was needed to be applied in order to obtain as much relevant information as possible. A detailed literature review on the construction industry was carried out, in addition to the history of prefabrication, its advantages and limitations, as well as current status of the construction industry. It was observed that there was very limited literature on the construction industry in the UAE, specifically related to prefabrication and its applications.

## 4.9 LCA: CONCEPT AND FRAMEWORK

For a full appreciation of this methodology, the abridged steps of the LCA earlier outlined have been expatiated upon in the following sections, as was implemented in this research.

As indicated in section 4.1.7, a LCA is conducted in the following stages: definition of goal and scope, inventory analysis, impact assessment and interpretation. In addition, an improvement analysis is recommended by SECTA. These steps are detailed here on.

### 4.9.1 STEP ONE: GOAL AND SCOPE DEFINITION

The first stage of LCA involves the definition of the goal and scope of the study. The goal of the study must clearly present its aim, future use of the study's results, and the stakeholders to which the study is focused. The scope requires that the system and its boundaries must be examined – including a study of the system's alternatives; the functional unit and unit of calculation must be identified; the impact categories, applied methodology, and all necessary assumptions and limitations must be determined.

#### 4.9.1.1 SYSTEM

Firstly, a reference system for this study is defined. In this context, a system is "the set of different processes or subsystems connected to each other that, acting at the same time, make a specific function in the life cycle of a product or process" (Stone n.d.). The function of the system is to provide a record of the inputs (raw materials, energy, fuel) and outputs (environmental emissions), as well as the totality of the environmental impacts of all processes/products. According to Stone (n.d.), the system is seen as a box which encloses all the analyzed process and marks its boundaries. The author insists that the scope should clearly describe the study's depth and the possible achievements within the limitations of the study. A typical system should include the breakdown of the lifecycle into subsystems (each linked to the next) comprising the acquisition of inputs (raw material, energy, fuel) and outputs (environmental emissions), production, transportation, recycling and final disposal.

Following the definition of the system in the study, the next step is the identification of its subsystems.

#### 4.9.1.2 SYSTEM BOUNDARIES

Boundaries comprise the market in which the substitution occurs (geographically, temporally and in relation to the consumer) as well as the product's alternatives (determined by the goal of the study). This stage of the LCA involves the selection of the sequential processes (subsystems) that form the system studied in this research, as earlier defined.

The boundaries typically considered are outlined:

- ✓ Boundaries between nature and technology: the starting point of a lifecycle is the extraction of raw materials and energy from nature and it ends with the generation of waste and/or heat.
- ✓ Geography: The natural geography (climate, transportation, landscape, etc.); administration (standardization, subsidies, legislation, etc.) and consumer culture, make up geographical boundaries. Geography is crucial to LCA studies, as the above listed factors vary from one region to another. More so, the susceptibility of ecosystems to environmental impacts is regionally influenced.
- ✓ Time: It is important to define the boundary of time. LCAs are essentially carried out for the evaluation of current impacts and the prediction of future scenarios.
- ✓ Boundaries between the present life cycle and life cycles of related technical systems: As a result of the interrelation of most activities, they must be studied in isolation from each other. An example is the comparison between the current technologies used for the manufacture of a product in comparison to more environmentally friendly technologies.

#### 4.9.1.3 FUNCTIONAL UNIT (FU)

Another critical aspect of an LCA study is the definition of the FU, as it profoundly impacts the result of the study. The FU is a quantified measure of the function of the system under study and constitutes the reference point for all the inputs and outputs involved in the system. The reference unit provides the basis of, and ensures the possibility of, comparison of the LCA results of two different systems (products or processes) (Dantes, 2006; Weidema et al., 2004), in this case, traditional construction versus prefabrication.

The FU gives a description of the product's properties which are required for the product under study to be substituted. In turn, the properties are dictated by the requisites of the market in which the product is to be sold. Depending on their relevance, the properties could be divided into two groups:

- **Obligatory properties:** properties which the product must possess for it to be given consideration as a relevant alternative. They are those properties which are included in the definition of the FU. They typically comprise national and international regulations. For instance, in the comparison of alternative wall types for a building, the determinant property of the material consumption will be a function of the specific wall type which, will in turn depend on the choice of material or type of construction. Thus, one particular determinant property for all walls in comparison cannot be identified; however, each individual wall will have its own determining property. It could be acoustics for one and durability for another.
- **Positioning properties:** these are not compulsory, but are seen as a bonus to the consumer if available. As such, they increase the consumer's favourability relative to other products with similar obligatory properties (Weidema et al., 2004).

Care has to be taken in the choice of the FU as ambiguity is one of the major sources of error in a LCA.

#### 4.9.1.4 REFERENCE FLOW (CALCULATION UNIT)

The reference flow is the unit of calculation to which all the inputs and the outputs of the system will be referred. It is defined as the quantified amount of the product (inclusive of parts) required for the delivery of system performance as defined by the functional unit. The function of the reference flow is the translation of abstract functional units into specific product flows for each system under comparison in order to ensure an equivalent base for all the alternatives in consideration. This ensures that the impacts of the alternative substitutions are clearly defined. It is paramount to take into account the determining properties (obligatory, position and market-irrelevant) and ensure that a relative measure is determined of the possible extent of substitution of alternatives. This should in turn be related to the functional unit.

### 4.9.2 STEP TWO: LIFE CYCLE INVENTORY ANALYSIS (LCI)

This step is considered the most developed of all the steps of the LCA and consists of the computations of material and energy for the system under study. It concerns the repetitive process of recording every datum going in or out of the system; that is input (such as raw materials, water and fuels) and output (such as wastes, by-products, pollutants and so on) generated throughout the system based on the FU.

The LCI involves two phases: data collection and calculation process. These are usually carried out using dedicated LCA software (Dantes, 2006).

#### 4.9.2.1 DATA COLLECTION

According to Stone (n.d.), the data collection process is the basis of the LCI. The difficulties in this process are the limited availability of data and cost factors, and the need for detailed knowledge of each procedure for proper description of the quantitative and qualitative input and output, as well as accurately express the selected data in terms of the calculation unit. Data sources usually include published technical and scientific data, LCA software-embedded and commercially available databases, site- or company-specific measurements, engineering calculations based on the chemistry and technology of processes, expert estimates and conjectural material and energy balances (Stone, n.d.; Tan, 2005). Dantes (2006) asserts that data gathering is time consuming for most of the LCA, hence it is recommended that data be collected from existing sources, but care must be taken to ensure that the data are representative, thus the quality of data is crucial.

To gain an appropriate perspective on the results of the LCI, it is necessary for certain data quality requirements to be met (Tan, 2005). These include: time-related parameters (age of the data), technological parameters, geographical parameters, statistical uncertainty and data gaps, uniformity and reproduction of the methods of data collection, and the accuracy and totality of the data (Dante, n.d.; Tan, 2005). It also follows that data must be validated and linked with the FU for proper collection of results. In addition, data has to be sufficiently documented to be reusable.

#### 4.9.2.2 CALCULATION PROCEDURES

Following data collection is the inventory results calculation based on the gathered data. These calculations are carried out according to the assumptions made and methodology appropriated in step one: definition of the goal and scope of the study. All the inputs for the operation of subsystem are used in the calculation of the mass balance related to all the subsystems, as well as to approximate the outputs of all the subsystems and the system as a whole. One critical process in calculation phase is the allocation of flows (such as air and water emissions). Since most technical systems produce more than one product, the material, energy and environmental flows must be related to the different products. Dantes (2006) recommends that these allocations be made as follows:

- To begin with, allocation should be prevented as much as possible
- Where allocations cannot be avoided, inputs and outputs should be properly linked with the different functions of the system such that the underlying relationships between these parts are reflected.
- Again where physical relationships cannot be defined, other existing relationships should be used as the bases for allocations.

### 4.9.3 STEP THREE: LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Stone (n.d.) explains that the LCIA process is a "a technical, quantitative and/or qualitative process to characterize and assess the effects of the environmental burdens identified in the [LCI] stage in order to understand their environmental importance and to estimate the possible environmental impacts which are related to the recorded inputs and outputs" (p.1.). This stage of the LCA helps to identify improvement strategies, for the comparison between different systems using specific indicators, and to localize environmental issues which supplementary data could be obtained using other techniques to provide information for decision makers. The ISO 14040 mandates that the LCIA be carried out in the following three stages:

#### 4.9.3.1 CLASSIFICATION

This step involves the selection of impact categories based on existing inventory and cause-effect relationships, and the assignment of individual inventory data to these impact categories. An instance is the assignation of $CO_2$ to global warming. Classification is very important to the final result of a LCA. It deals with environmental impacts alone, and is not concerned with economic or social impacts. Examples of common impact categories include global warming, ozone depletion, waste generation and effect on human health.

#### 4.9.3.2 CHARACTERIZATION

This step answers the question "how does each pollutant contribute to different environmental impacts"? It deals with the quantification and possibly, the summation of the impacts within each impact category, using characterization models or factors. An example is GWP model measured in $CO_2$ equivalent. Characterization can be taken a step further by normalization. This means that the impact category results are calculated relative to external references or benchmarks. An example of a benchmark could be the mean global per capita environmental impact, which is used to even the scores of the environmental impact to a common measurable unit. Grouping of results (referred to as the environmental profile) is carried out for the appraisal of alternative technologies and system optimization.

Stone (n.d.) asserts that the following must be taken into consideration during characterization:

- Assumptions should be the lowest which can be possibly made;
- Impact categories, indicators and characterization factors must meet global legislations and policies;
- Impact categories must be a summary of environmental emissions or resource consumption of the system under investigation;
- The selected indicators must be environmentally apposite.

#### 4.9.3.3 VALUATION

This is the last stage of the LCIA. It involves the weighting of alternative technologies so as to gain insight into their total environmental impact, in order to select the most suitable environmental option. Unless one alternative displays a marked superiority over others, the final choice will be made on the basis of trade-offs. While the use of weighted averaging aids in valuation, this subject has been surrounded by controversy regarding techniques of weighting and valuation appropriation, and is still a subject of research.

### 4.9.4 STEP FOUR: INTERPRETATION

This is the final stage of the LCA and concerns the processing of all the information obtained throughout the previous stages of the LCA – from identification through evaluation to presentation. The aim of interpretation is to analyse results (from LCI AND LCIA) and to make unbiased conclusions and recommendations, based on the goal and scope of the study defined in stage one of the LCA. The final output should be the improvement models targeted at the reduction of environmental impacts of a system. ISO 14040 recommends a critical peer review, the results of which should be publicized.

## 4.10 BENEFITS OF LCA TO THE STUDY

The use of LCA software provided the following benefits in the comparison of prefabrication and the conventional construction method:

- The ability to determine at an early stage the strategic risks and the possibilities for environmental optimisation of prefabrication;
- The identification of the measure and significance of each step involved in the prefabrication and conventional construction processes to determine which was the cause of greater environmental burden in the UAE;
- The provision of more detailed information on the environmental impacts of conventional construction processes - through the calculation and evaluation of the levels of carbon emission, energy consumption and waste generation - to justify the need for a holistic environmental solution to the issues of waste and GHG emissions plaguing the UAE's construction industry, and also to improve communication on such need to construction stakeholders;
- The identification of the most efficient method of construction for the UAE and its optimal application to the construction industry in the UAE through a proposed prefabrication model.

# CHAPTER 5

# LCA COMPUTER MODELLING

## 5.0 LCA: DETAILED APPLICATION

As a reminder, the aim of this study was the comparative assessment of two construction methods applicable in the construction of a high-rise commercial building in the UAE, in order to determine the more suitable method of construction that would provide a lower environmental impact and energy emission. The method of application of the LCA to this study is expatiated upon in the following sections.

### 5.1 STEP ONE: DEFINITION OF GOAL AND SCOPE OF STUDY

This step involved a comprehensive description of the system, its boundaries, the reference unit and the functional unit which made up the parameters of the LCA methodology. The goal of this study was a thorough investigation and comparative evaluation of the environmental impacts of the overall lifecycle of two different construction scenarios for a typical commercial building: conventional (concrete masonry unit) and prefabrication (precast concrete) systems. Considering the evolving contemporary nature of high-rise buildings in the UAE, a modern multipurpose commercial high-rise building located in the UAE's most commercial emirate, Dubai, was selected as the case study building.

The purpose of this research was to determine the more environmentally friendly construction method (the one with less negative environmental impact) for the UAE. It is expected that the results of this study would provide useful information on the importance and influence of construction systems, from the lifecycle perspective. The results of the study are aimed at the UAE construction industry's decision makers, stakeholders and practicing construction professionals. It is hoped that the information provided by this research serves as a useful guide for further research, and eventually, the development of a UAE-specific LCA database and model, as is obtained in US and Europe.

The scope of this study was limited to one representative commercial high-rise building and was defined by the following parameters: the system, system boundary, reference unit and functional unit, as well as the assumptions and limitations of the study, detailed hereon. It was seen that the goal of this study could be achieved well within the construed limitations according to Dantes (2006). Assumptions and limitations are detailed in later sections.

### 5.1.1 SYSTEM: CASE STUDY BUILDING

Firstly, a reference system for this study was defined. The system in this context was defined as all the processes involved in the construction of a high-rise commercial building in order to provide the function of a high-rise commercial building. The function of said building is to provide shelter and spaces for the undertaking of various forms of commercial activities for profitmaking and user-defined goals.

A typical system comprises all the phases involved in the construction, operation and demolition of a building. The system of this research essentially constituted the construction techniques being comparatively analyzed, which were the UAE's cast-in-place construction (the conventional) and precasting (the alternative). Both techniques have been extensively reviewed in Chapters 2 and 3 of this study.

This section provides a detailed description of the selected building for the study. It was imperative for the chosen building to be a representative of the commercial high-rise building situation obtainable in the UAE. To this end, the representative building was chosen based on the following criteria:

- Location: Every city is zoned into commercial districts and residential districts. It was imperative for the building to be located in a commercial district.
- Building function: The selected building was required to provide the functions of a commercial building. A building is said to be commercial if 50% or more of its space is dedicated to commercial purposes. Commercial

purposes generally include the provision of offices and retail spaces (Business Dictionary, 2012).

- Building type: One important characteristic was the nature of the building. As the focus of this study was on high-rise buildings, it simply followed that a high-rise building had to be selected. A high-rise building is defined by Emporis (2012) as a multi-storey structure with an architectural height range of 35 – 100 metres, or 12 – 39 floors, regardless of the height.

In light of those criteria, firstly the commercial district was selected. Dubai was chosen as the representative city for the UAE based on its reputation as the commercial core of the region. Within Dubai, there exist several commercial and business districts, one of the most prominent being the famous Business Bay district. Business Bay was designed for the creation of a "central business district (CBD) and regional business capital". In fact, its primary purpose was to position Dubai as the business capital of the Middle East, similar to Manhattan in the United States. This positioning was significant to the choice of building function as 'commercial'. Business Bay is known for its provision of prime commercial spaces (Dubai Properties Group, 2012). With a land area grossing 80 million square feet (7.4million $m^2$) of prime commercial, residential, medical and educational units, Business Bay undoubtedly offered endless possibilities in the selection of a representative commercial building.

Dubai has become well-known for its ultra-modern and contemporary architecture, with such famous buildings as the Burj Khalifa and the Burj Al Arab. One feature of the city's present-day architecture is the substantial number of high-rise buildings constructed over the past decade in Business Bay and other areas of the city. High-rise buildings have become Dubai's architectural trademark. Thus, a high-rise building was deemed the 'right' type of building for this study. Finally, the conventional construction method in Dubai is the cast-in-situ concrete technique. Statistically, the selected building would be conventionally constructed.

The building, referred to as "The Binary" (Appendix A shows a rendered image) is located in the Business Bay district of Dubai, UAE and is currently under construction. The information herein is as obtained from the architectural, structural, mechanical and electrical drawings, as well as the Bill of Quantities, made available by the building's Consultants and Contractors.

The Binary, as its name implies, is a 2-in-1 building. Summarily, the first part is a make-up of: 3 Basements + Ground floor + 4 Podiums + 24-Storey Commercial Building + Roof deck. The second part comprises the Podium Roof and Landscaping. The Podium facade is a combination of curtain wall and aluminum horizontal fins. The tower facade is fully covered curtain wall with a combination of a double glazed vision glass and spandrel glass, treated with aluminum vertical fins on one side of the tower and horizontal fin on the other. The basements are to serve mainly as car parks and utility services requirements (including the generator room, substation, building maintenance services (BMS), the security room, main telecommunication and server Information Technology (IT) Rooms).

The Ground Floor includes the main lobby and retail units while the Podiums function as offices and parking spaces. The rest of the building constitutes 24 storeys mostly used as office spaces, with the topmost floor serving as the mechanical floor, above which is the roof deck. The podium roof provides landscaping and such amenities as restaurants, gymnasiums, lounges and tranquility spaces.

The focus of the study was the substructure (foundations and basements) and superstructure (ground floor, podiums, main building and roofs) of the building. Details of the analysis were limited to the floors, walls, beams-and-columns systems and roofs of the building; the building's landscaping was excluded.

For the analysis, The Binary was estimated to have a gross floor area of approximately 49,000$m^2$ and an overall height of 128.45m. Relevant floor plans and elevations are provided in Appendices B – E.

### 5.1.2 SYSTEM BOUNDARIES

Each subsystem was selected subjective to the availability of data and examined in detail. It was critical to the study for the subsystems to be accurately determined and kept stable throughout the research. Furthermore, it was ensured that every impact relevant to the study was included. The totality of the subsystems was equal to an addition of every subsystem, given mass and energy balances from all inputs and outputs, in order for a correct estimation of the total environmental impact of both construction techniques to be made. The subsystems were identified as all the phases of the building's lifecycle, from the extraction of the materials used for its construction, through its production, operation and eventual disposal or end-of-life. Thus, the system boundaries were successfully defined. A simplified description of the system boundaries for The Binary is illustrated in Figure 5.1.

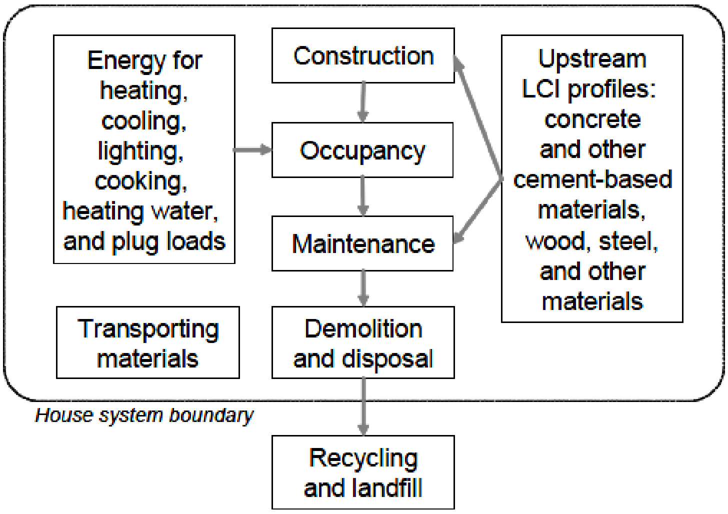



Figure 5.1: LCA System Boundary (Marceau and VanGeem, 2008).

System boundaries are divided into three phases: pre-occupancy, occupancy and post-occupancy phases (Ooteghem and Xu, 2012) and include all the associated energy consumptions. The components of each phase with regards to this study are given as follows:

- The pre-occupancy phase involves every aspect leading up to the building's construction and just before its operation. The stages include:
  - The extraction and refinement of resources from various sources, fabrication of materials and on-site construction, inclusive of waste generation.
  - Transportation from sites of extraction of materials to industries, and eventually, the building site, inclusive of the type and quantity of fuel consumption.
  - Assembly (on- and off-site), considering the energy consumption levels of construction equipment and waste generation during assembly.
- The occupancy phase basically involves all the materials and processes of the building's operation, renovation and maintenance throughout its lifespan. For this study, it comprised the overall service life for the Heating, Ventilation and Air Conditioning (HVAC) (otherwise referred to as the cooling loads), lighting loads, painting, roof repair, and so on.
- The post-occupancy phase refers to all the stages of the end-of-life of the building, that is, the energy required for the demolition and disposal of the building (incineration, landfill and recycling) after its 50-year lifespan. It also includes the amount of waste generated and the energy consumed by the machinery used during these activities. It must be noted that this study was limited by the lack of data on recycling stage; as such those, as well as the transportation details on landfill, were excluded from the analysis. However, Aye et al. (2012), and Stephan, Crawford and de Myttenaere (2012), according to Crowther (1999), argue that the energy associated with the post-occupancy phase is less than 1% of the building's lifecycle energy demand and is thus considered insignificant.

### 5.1.3 <u>REFERENCE UNIT</u>

When two or more systems are under comparison, one system is used as the reference or basis of comparison for the systems in order to carry out a proper evaluation and analysis. For this study, the reference essentially comprised the predefined/existing building parameters, that is, the typical construction scenario (concrete masonry) of a commercial high-rise building in the UAE. Thus, the reference unit was defined as the whole existing high-rise building, The Binary, constructed with cast-in-place concrete. The impact assessment was made by comparing the alternative scenario, precasting, to the conventional method.

### 5.1.4 FUNCTIONAL UNIT (FU)

The definition of the FU is considered a highly critical aspect of an LCA and is tied in with the selected reference unit of the study. One of the most widely used definitions of the FU for the LCA of a building is one square metre ($1m^2$) of living space, with an assumption of a building lifespan of 50 years, as was implemented by Ortiz-Rodríguez, Castells and Sonnemann (2010), Ooteghem and Xu (2012) and several others. Deviations to this include 30- and 75-year lifespans (Heede and Belie, 2012).

Therefore, the FU of this LCA was taken to be “$1m^2$ of the building area based on a projected lifespan of 50 years”.

### 5.1.5 DUBAI: GEOGRAPHY AND CLIMATE

Located in the North-eastern region of the United Arab Emirates (UAE) and the second largest emirate, Dubai is geographically positioned 25° 15' 8" North, 55° 16' 48" East. The climate of Dubai is primarily classified as hot arid climate.
Generally, hot arid climates are marked by intense solar radiation, which is further amplified by reflected radiation from the barren light-coloured desert topography. The sky is typically cloudless most of the year; this is punctured by haze and dust storms due to convection currents caused by the intense heat and the air close to the ground. Relative humidity varies with air temperature.

Dubai is characterized by long periods of heat and short cool months. In Dubai, the weather is extremely hot and sunny most of the year, with temperatures averaging lows to highs of 30°C to 40°C and occasional extremes. Summers are usually dry and windy; however the peak summer months (June to September) are characterized by intense humidity, sometimes as high as 90%, owing to the sea breezes on the east coast, thus causing very high levels of stress and discomfort. During the short much cooler winter periods, diurnal temperatures are at an average of 25°C, and a lot less closer to the coast (12°C - 15°C) where the humidity ranges between 50% and 60%. Dubai experiences short, sporadic periods of rainfall of about five days per Annum, mostly during the winter, stamped by occasional thunderstorms (Dubai Airports, 2010; Dubai, n.d.).

Naturally, the climate of Dubai influences its building construction and operation techniques.

## 5.2 STEP TWO: LIFE CYCLE INVENTORY ANALYSIS (LCI)

The two-step LCI processes, data collection and calculation, are carried out with the aid of LCA software. Some software were investigated for application to this study: BEES, ATHENA Impact Estimator, SimaPro and Gabi. The last two are only commercially available and were not within means for this study. BEES provides LCA data and reports for products and assemblies, and has a limited range of choices. For instance, BEES only considers choices between alternative cement types for the construction of a building's foundation. On the other hand, ATHENA allows the user to input assembly type (foundation), sub-assembly (envelope, insulation) and provides the option for user customization. More so, BEES considers the United States as an entire region, whereas ATHENA is region-specific, based on localized system boundaries within the US and Canada. This implied that a city that best represented the UAE's energy and building characteristics and data could be selected for the simulation.

Thus, by virtue of flexibility and its more comprehensive user interface, ATHENA was considered more suitable for this study. An overview of ATHENA is discussed in the following section.

### 5.2.1 ATHENA: OVERVIEW

ATHENA is the only available tool for the LCA for the North American continent. The tool is applicable in two ways; as an 'EcoCalculator', for a quick snapshot of the carbon footprint of a building, and as an 'Impact Estimator' (IE), a decision support tool, specifically for a more advanced LCA. ATHENA IE provides the environmental implications of various design options or material mixes, from which the user can make trade-offs. One advantage of the IE is that it allows the user up to 5 design scenarios from a set of selected impact measures. The user can select a baseline design and proceed to compare alternatives that enhance environmental performance.

ATHENA's LCI databases are derived from the Athena Sustainable Materials Institute, a core sustainability research institute, and developed in accordance with the ISO 14040 and ISO 14044 standards. The latest version of ATHENA Impact Estimator, Version 4.2.0140 was implemented in this study.

One limitation of ATHENA is that it does not calculate the whole building operation energy data. However, the tool provides the option to enter the operation energy information (which would be gotten from an energy simulation tool). The selected energy tool for this operation was "eQUEST".

### 5.2.2 EQUEST: OVERVIEW

In order to determine the operational energy of the building, estimation had to be made considering it was a building under construction. The simulation tool used to calculate the building's operational energy of the building was eQUEST, acronym for The Quick Energy Simulation Tool. This software utilizes DOE-2 simulation engine, and the latest version 3.64 was used for the analysis.

### 5.2.3 DATA COLLECTION AND CALCULATION PROCESS

This stage of the LCA is an inventory of all the inputs of the processes and assemblies associated with the entire construction process. These include the extraction of raw materials, processing, manufacturing of assemblies, transportation, construction, maintenance, repair, and end-of-life impacts of the whole building. The building and its components comprise infinite materials which must be thoroughly accounted for, in order to achieve accuracy. The complex task of this process was simplified by ATHENA. With the exception of offsite manufacture of precast concrete components, both scenarios under consideration share the same basic processes and therefore, similar inputs. The entire flow of processes from the extraction of raw materials up to land, air and water emissions, in terms of energy, are discussed in further detail, in later sections.

All the data inputs for ATHENA simulation were obtained from the architectural, structural, mechanical and electrical drawings and design specifications, as well as the Bill of Quantities provided by the Contractors.

#### 5.2.3.1 MATERIAL CONSIDERATIONS

All inputs from the materials (extraction, processing, manufacture, transportation and assembly) right up to before the occupancy stage of the building, produce energy which is referred to as the 'embodied energy' or the 'primary' energy. The building's envelope and structure are defined, and different assemblies are developed based on the building's structure. Building assemblies include foundations, walls, roofs, beam – and – column systems and floors, each assembly with its own sub-assembly. All material inputs for this study were calculated from the Binary's elevations and specifications. Each material has its own set of physical characteristics, which make up its LCI, and this information was provided by ATHENA, which served as a tool for the compilation of the data for the LCA. For materials absent in the database or which did not meet the requirements, customization options were available to an assembly of materials.

#### 5.2.3.2 GEOGRAPHIC CONSIDERATIONS

The geographic considerations for data collection are discussed in detail:

a. **TRANSPORTATION**

Geographic location plays a vital role in the results of the LCA. The influence of climatic, commercial and environmental factors, is significant in the contribution of the carbon emissions of a particular location. ATHENA takes into consideration the origin of every construction product, whether imported or locally produced. It is beneficial to note that political boundaries are not regarded because the flow of materials is the basis for regional designation. Transportation includes the movement of all materials to the building. Transportation includes the importation of materials, movement of materials from sites of extraction to manufacturing industries, and from industries to construction sites, and accounts for the type and quantity of fuel involved in the applied mode of transportation, throughout its lifespan, and to the landfill upon its end-of-life period. The assumption is that all materials are transported by road by diesel-powered trucks. According to Marceau and VanGeem (2008), the energy associated with return trips are excluded because trucks deliver to more than one destination and return to their bases empty, in order to avoid overestimation of the transportation energy. For the simulation software ATHENA, the typical source of each product, mode of transportation and distance of travel are the parameters for the development of transportation profiles. The software assumes a manufacture of imported products from North America.

## b. ELECTRICITY GENERATION AND CONSUMPTION

Further assumption is the production of electricity – self-produced or imported. In addition to this is the source – oil, coal, hydropower, natural gas, etc. The global emissions generated by electricity from the manufacture of building materials and components, as well as from the building's construction, operation and maintenance, are the considered parameters. As ATHENA is limited to the North American regions, the area closest to the UAE's in terms of transportation structure and electricity generation was selected for the simulation. From studies of global energy reports (International Energy Agency 2009, 2011; The World Bank 2012; United States Environmental Protection Agency 2012), the city of California in USA was seen to have the closest relationship to the UAE, in terms of transportation emission values over the past few years. Therefore, for the analysis, the region of Los Angeles was selected as the "Project Location", to fulfil one of the required parameters for the LCA (ATHENA, 19). This decision is supported by the software's developers' note that region is not to be based on climate in order to achieve accuracy in the analysis; rather the transportation factor should be given preference. The influence of climate is accounted for in the operational energy calculation aspect of the LCA.

## c. CONSTRUCTION CONSIDERATIONS: ON-SITE AND OFFSITE

Besides the contribution of transportation, the energy associated with the construction and assembly of the structural and non-structural components on the building site, including human labour, are considered to have effects on the LCA results. The major energy-emitting activity is said to be excavation in particular (Marceau and VanGeem, 2008). For offsite construction, all the energy associated with the production processes such as the use of factory machinery is taken into account. For both on- and off-site constructions, the land, air and water emissions linked with all construction activities are borne in mind. An example as cited by ATHENA is in the pouring of cast-in-situ concrete for a wall assembly. First, the formwork assembly, the placement of the reinforcement bars, the pouring of concrete, the use of forklifts or cranes, and the use of other construction equipment such as concrete mixers, and their associated energies are included. In addition to these are waste from concrete pouring, form spillage, loss of material and dumping of left-over concrete.

### d. OCCUPANCY CONSIDERATIONS

The basic function of the building, occupancy patterns and schedule of activities and all the associated energies make up these considerations. In order to ensure validity of results, the same occupancy configurations and characteristics were assumed when the alternative scenario, precasting, replaced the initial cast-in-situ scenario. As such, both operational scenarios have similar air infiltration patterns, HVAC systems, schedules of operation for lighting and cooling. The selected cooling system was the chilled water coil system; no heating was required because of the predominantly hot, humid climate in UAE. Identical efficiencies were assumed (95%). Consideration was also given to the peak cooling loads. Temperature set points were selected to range from 18 - 24°C. The chilled water system control and schedule were set for the average 8-hour daily operation for weekdays and turned off during weekends. Daylighting controls were assumed; water services such as water required for utilities and hot water needs were not included in the analysis. It was assumed that they would be the same for both conventional and precast concrete building scenarios. ASHRAE Standard 90.1 was the selected jurisdiction for cooling profiles, including air infiltration, humidity rates and so on (Marceau and VanGeem, 2008).

The sum of all the energy values from the building occupancy and operation defines its operational energy. EQuest provided the analysis and values for both scenarios under comparison.

### e. REPAIR, MAINTENANCE AND RENOVATION (RMR) CONSIDERATIONS

As the building ages, it becomes susceptible to factors like weather exposure and wear and tear. The effects under this consideration include the use of materials, mode of transportation, the frequency, and energy consumption of RMR activities. More so, the service life of each material and component, as well as the incurred waste and disposal are considered. These are dependent on the building, its location, occupancy type, function and lifespan. The lifespan is determined in ATHENA, and the software calculates the LCA on the assumption that materials and components for RMR are the same as those used in the building's construction. Although this has a low probability, the assumption avoids the need for technological forecasting, which would build on uncertainty. ATHENA also assumes that where the service life of an RMR material or component exceeds the building's remaining lifespan, then the difference is documented. For instance, a 25-year lifespan door installed 25 years to the end of a building's lifespan will be credited with only half of the environmental impact of the door (ATHENA, 2012).

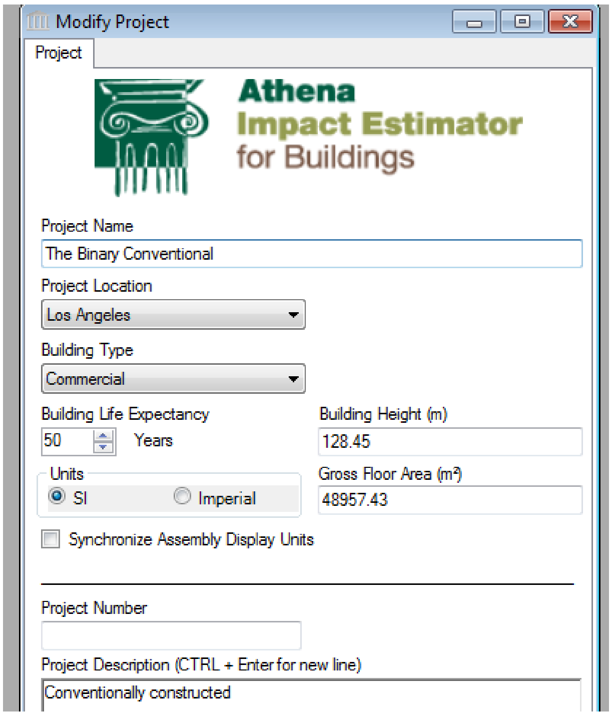
### f. END-OF-LIFE CONSIDERATIONS

Marceau and VanGeem (2008) asserted that the demolition and disposal energy of a building at the end of its useful life was less than the energy involved in its excavation; that is it took more energy to construct than to demolish. As mentioned earlier, the demolition and disposal energy is less than 1%, a highly insignificant contributor to the overall lifecycle energy of the building. There was no data available for this consideration in the study; more so, ATHENA acknowledges the difficulty in forecasting the technological situation 50 years from the time of the building's construction. Thus, a basic algorithm is used to determine the building's final disposition at the end of its useful life. This is done by first estimating the amount of energy required for demolishing all the various kinds of structural material, followed by a calculation of the bill of materials in order to determine their final disposition and then landfill. One assumption is that landfilled waste remains landfilled while recycled or re-used materials remain the same and are integrated in their next use. Another consideration is the transportation to landfill sites and its related emissions, assuming typical distances.

#### 5.2.3.3 BUILDING PROJECT PARAMETERS

The cradle-to-grave LCI is given by ATHENA for the selected lifespan of a building. As information in input, the software determines the bill of materials and applies the region-specific LCI for the all the processes from extraction of raw materials, transportation and assembly to maintenance, demolition and disposal. The Binary was modelled as accurately as possible, using all the available data from the architectural and structural drawings. As seen in Figure 5.2, the first step was the input of the preliminary data for the LCI: the overall building height (m), the floor area ($m^2$), the building type, building life expectancy, project location, project name and the choice of units (SI or Imperial). For the two design scenarios, The Binary Conventional and The Binary Precast were chosen as Project Names, for the conventional and precast methods, respectively. All other parameters remained the same. For the sake of simplicity, the Binary Conventional Building is hereon referred to as 'Binary A' while the Binary Precast Concrete, is tagged 'Binary B'.

The simulation of the whole building began with the input of any structural assembly. The foundations, walls, floors, columns and beams, and roof assembly were entered in based on the structural design of the building. Binary A was used as a basic model and then modified for Binary B. The latest version of IE had the advantage of user customization of building materials, thus modifications were easily made by a layer-by-layer build-up of the roof assembly for Binary B, which was not available in the database.



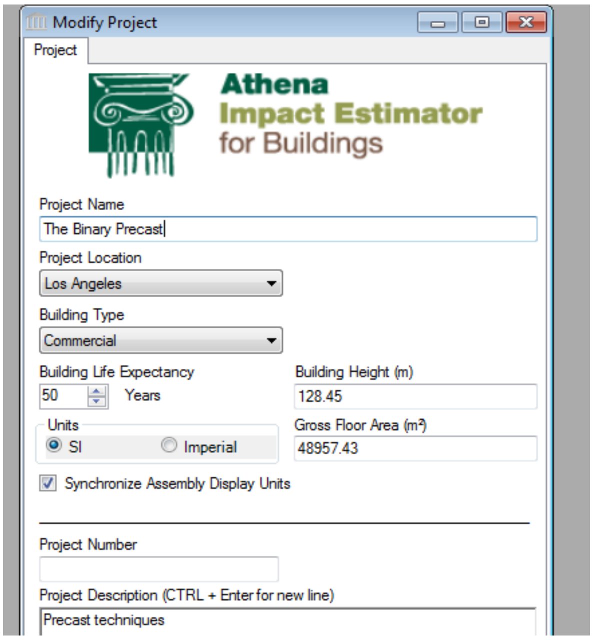




Figure 5.2: ATHENA Project Building Parameters Definition Dialog Box: Binary A (top); Binary B (bottom).

Table 5.1 lists the basic structural assemblies, which were used as-is, or modified to meet modelling requirements, for Binary A and Binary B.

Table 5.1: Types of Structural Assembly

| STRUCTURAL ASSEMBLY | TYPE |
|---|---|
| **FOUNDATIONS** | Concrete footings – perimeter and/or column |
| | Concrete slab on grade |
| **WALLS** | Concrete block |
| | Concrete cast-in-place |
| | Curtain wall |
| | Concrete tilt-up |
| | Insulated concrete form |
| | Structural Insulated Panels |
| **FLOORS** | Composite Metal |
| | Concrete suspended slab |
| | Concrete parking garage – drop panel system |
| | Concrete hollow core |
| | Concrete pre-cast double ”T” |

Figure 5.2 is an example of the input dialogue box for a wall assembly, the “Concrete Cast in Place” wall. The wall was assigned the name “Basement Wall”, and the height and length values were inputted provides an example of the input dialogue box for a wood stud wall.

The details of the wall assembly (concrete strength, wall thickness and size of reinforcement) were modified based on structural specifications provided (Figures 5.3 and 5.4).

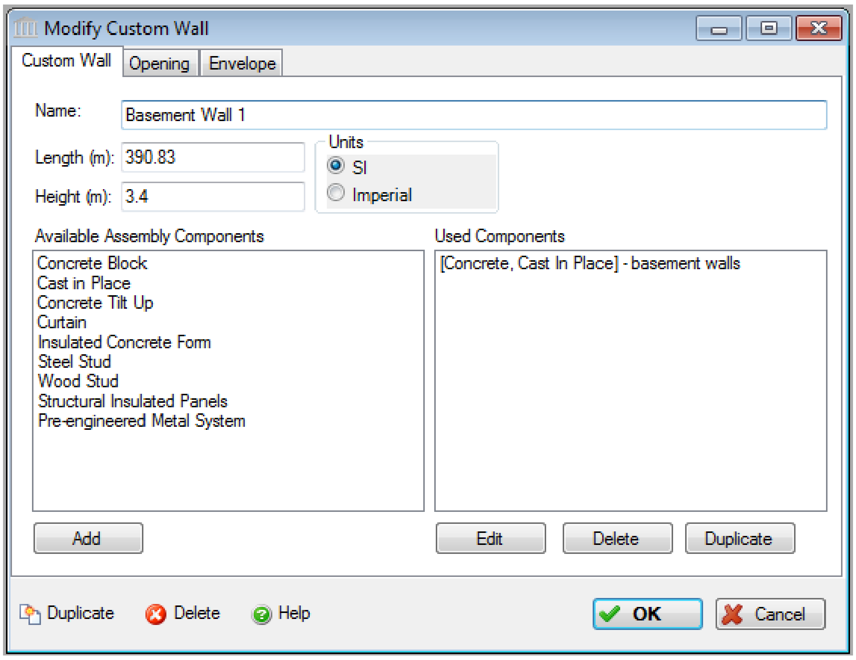



Figure 5.3: Input Dialogue Box for Wall Assembly Customization

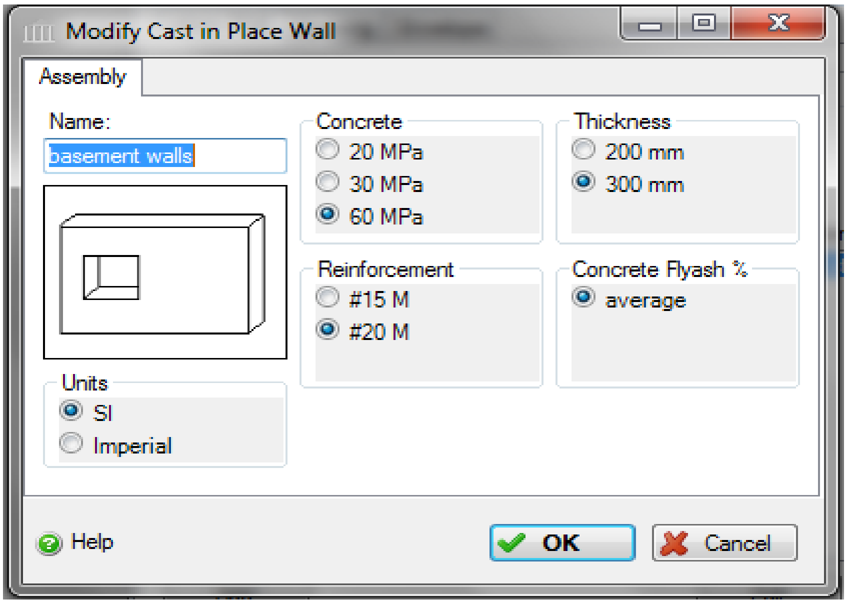



Figure 5.4: Wall Assembly Customization Parameters

Besides the basic assembly, ATHENA provided the option for the specification of the types of openings, inclusive of the number of openings, total area and materials as shown in Figure 5.5.

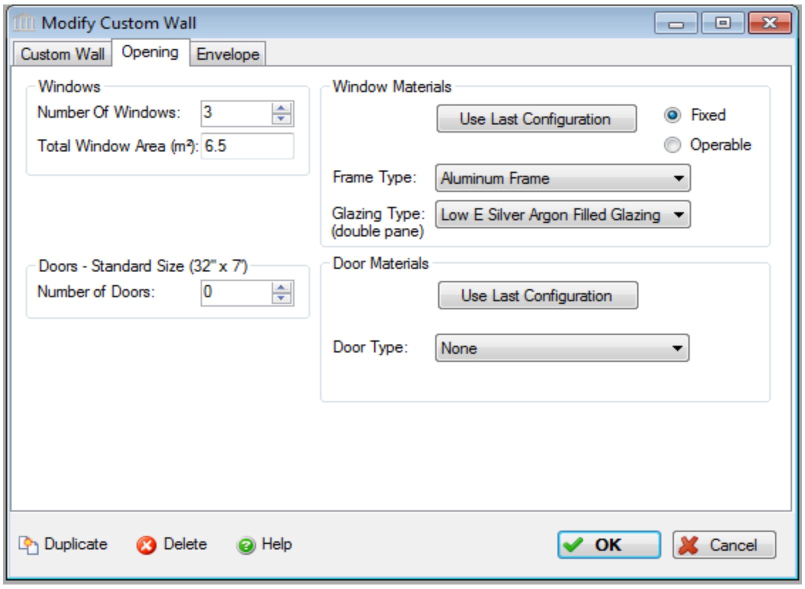



Figure 5.5: Wall Assembly Openings Parameters

Lastly, the envelope configurations (barriers, insulation, cladding and material layers) were defined as applicable to the assembly, as indicated in Figure 5.6. The specification of all the structural assemblies of Binary A and Binary B were used by ATHENA to estimate the total embodied energy of both buildings.

#### 5.2.3.4 CALCULATING THE TOTAL OPERATING ENERGY

The operational energy refers to the total of the energy generated and consumed by the building and its occupants throughout its lifespan. As mentioned previously, ATHENA can only calculate the total primary energy and the global warming potential (GWP) of a building, however, it cannot directly calculate the building's operating energy consumption. Thus, eQUEST was implemented for this task and the total estimated operating energy for both Binary A and Binary B were inputted in ATHENA's Operating energy calculator, shown in Figure 5.7.

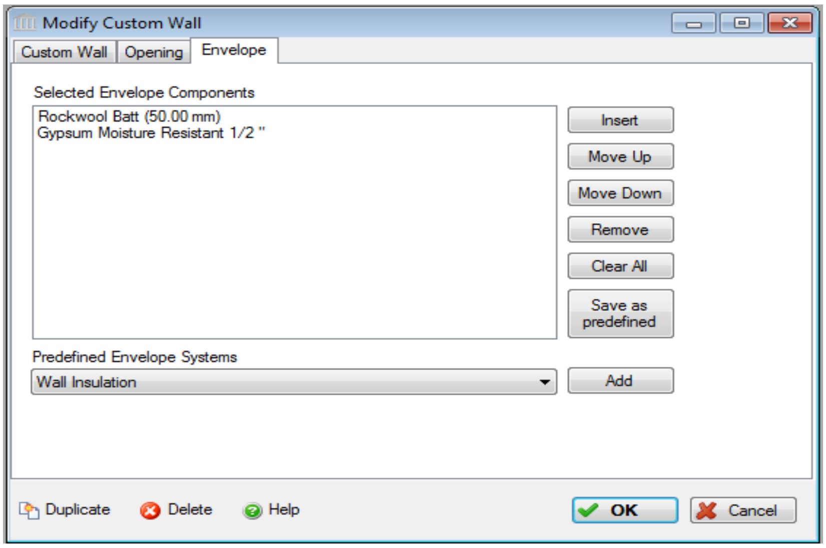



Figure 5.6: Wall Assembly Envelope Customization Dialogue Box

EQUEST has the capacity to calculate both the energy consumption of a building and HVAC system on the basis of recorded weather data.

Using The Binary's geometry, layout and structural data, a simplified model was developed with eQUEST's Building Simulation Wizard, as shown in Figure 5.8.

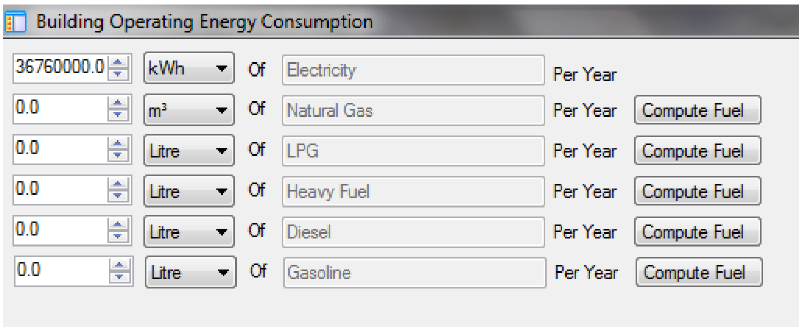



Figure 5.7: ATHENA Energy Converter

The building parameters are summarized in Table 5.2. For the comparative assessment of building operational energy of both cast-in-place construction and precasting, all input parameters, as previously mentioned, were kept identical,

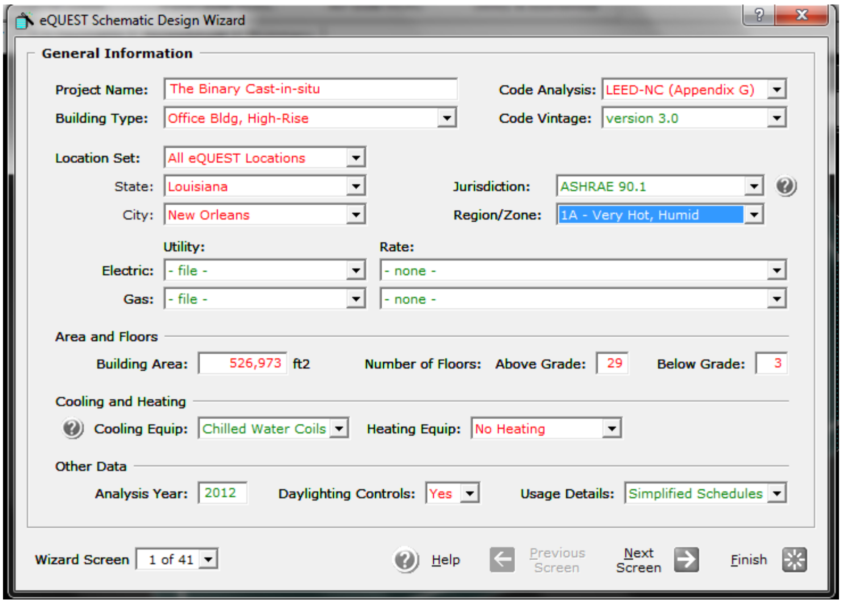



Figure 5.8: EQUEST Schematic Building Design Wizard Dialogue Box

Table 5.2: The Binary Operating Energy Design Parameters

| **BUILDING PARAMETERS** | **VALUES** |
|---|---|
| Location | New Orleans, Louisiana |
| Region/Zone | Very Hot, Humid |
| Number of Floors | 32 |
| Service Life | 50 years |
| Total Floor Area | 48957.43 $m^2$ |
| Floor-to-Floor Height | 4m |
| Daylighting Control | Yes |
| Cooling Equipment | Chilled Water Coils |
| Heating Equipment | None |

with the exception of building assemblies, wherein lies the difference between the construction techniques under comparison.

In addition to the building's orientation, size, layout, envelope and interior construction details, information for the HVAC system definitions, setpoint temperatures and schedule of operation, lighting intensity and requirements, as well as user occupancy patterns, were typical defining parameters for the simulation. Due to UAE's hot, humid climate, active heating systems were excluded in the calculation. The values for the lighting and cooling loads and systems were obtained from the mechanical and electrical drawings and specifications made available for the research. Two energy models were created for Binary A and Binary B. Upon simulation, eQUEST provided a comprehensive report of monthly and annual energy consumption by end use and total energy consumption. The achieved results were then used to project values for the operational energy demand. From this, the operational energy values for the 50-year life expectancy of the building were estimated. With the simulation carried out based on ASHRAE 90.1 standards, the results given by eQUEST could be considered valid and satisfactory, in order to proceed with the other stages of the LCA.

In order to avoid discrepancies, ASHRAE and British Standards were used as references for commercial high-rise building constructed with precast concrete, for the Binary B. From this point onwards, ATHENA was then able to calculate the total primary operating energy (TPOE) (a summation of the pre-combustion energy (energy from extraction, refinement and delivery) and energy-associated land, air and water emissions) for the whole building lifecycle. Subsequently, ATHENA was used to compare and contrast the embodied energy and TPOE, as well as the environmental effects of the building scenarios, namely Binary A and Binary B, with the aid of graphical and tabular representations.

#### 5.2.3.5 ALTERNATIVE SCENARIO

Due to lack of data for the LCA of precasting, the alternative construction system, these data were manually inputted into ATHENA in order to obtain the results based on studies of the precast construction system (Chapter 2 of this study). All the parameters were kept constant in the setting up of the alternative scenario (the precast Binary).

The structure of the components for Binary B was composed of precast columns and slabs. Since precast slabs have better structural strength than cast-in-situ slabs, the number of columns and spread footings required for Binary B was less than for Binary A (Van de Heede and de Belie, 2012). Hollow core slabs were used for the roof and floors. The slabs have a 120 – 125cm cross section are 16-40cm wide and span up to 9m. The building façade comprised 20cm non-load-bearing precast panels, sandwiched or solid and glazing with surface area measurements of 2.5 by 11m maximum, with smooth, painted surfaces. The slabs are covered with concrete toppings. The schematic of the assemblies for Binary B are illustrated in the Results section.

#### 5.2.3.6 ASSUMPTIONS

As part of the LCI, it is important to outline the assumptions made and limitations encountered in this study. The following assumptions were made:

a. One of the most significant assumptions in this study is the use of a non-UAE region as the project location for the LCA. This is solely attributed to the fact that there is as yet no available LCA tool suited to the region of the UAE. Thus, the results of the operational energy obtained from eQUEST as well as the International Energy Agency (IEA) database were weighed against other data sets in the North American continent (the United States and Canada), the regional base for ATHENA. Los Angeles, California, was observed to bear the closest similarity to the UAE in terms of operational and transportation energy values from 2007 onwards and was designated as the Project Location.

b. ATHENA assumed that the building was constructed on a site. However, the focus was restricted to building design issues as against site-specific issues: land disturbance, alternation of the ecosystem and damage to vegetation. The reason for this is that these issues are site-specific, and not the focus of the software.

c. ATHENA assumed that for repair and maintenance, materials and components would be similar in specification to the original. Although the probability of this is not high, it was projected that technological forecasting would create higher uncertainties than business-as-usual assumptions.

d. The construction considered environmental burdens from electricity generation for lighting, cooling and the operation of equipment on-site and at the factories. Every activity was accounted for, from the site excavation, installation of the structure and envelope of the building, installation of electrical, mechanical and plumbing facilities, as well as interior finishing. The software has in its database typical values for these data, and there was no provision for customization, except by selection of a region closest in nature to that obtainable in the study (Scheuer, Keoleian and Reppe, 2003).

e. For the operational energy, it was assumed that electricity supply was constant throughout the building's lifespan, and was from the same source as at the time of the building's construction. Incurred losses from the import and export of energy were not accounted for.

f. It was assumed that all construction and maintenance wastes were disposed to landfill. The environmental impact of the transportation of all materials to the landfill site and the landfill processes were included in the results. End-of-Life transportation was taken as the closest distance from the construction site to the waste disposal site. Recycling, downcycling, reuse and energy recovery processes were not included as there was no available data.

#### 5.2.3.7 LIMITATIONS

Perhaps the most significant limitation to this LCA study is the absence of a standardized method of LCA for the construction industry. This it was almost impossible to make comparisons between one study and another. The definitions of system boundaries as well as the wide variation in LCI databases for building materials and components is region specific, as there can be vast differences in sources of construction materials, techniques of construction and energy profiles from one country to another. Most available LCI and LCA data were for regions in US and Europe. The lack of data on the LCA of buildings in the UAE, with which to compare results, was a severe limitation to this study.

### 5.2.4 STEP THREE: LIFE CYCLE IMPACT ASSESSMENT (LCIA)

As mandated by ISO 14040, the LCIA is to be carried out in the following three stages: classification, and characterization and valuation. According to ISO 14042, LCIA does not measure safety margins, envisage actual impacts or estimate threshold boundaries.

#### 5.2.4.1 CLASSIFICATION

As mentioned earlier, classification involves the identification of relevant impact categories to the study, and then the assignment of related substances to these categories. These categories are in accordance with ISO21930 and ISO 21931 and are based on the EPA Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI Version 2.0, 2012). ATHENA's impact categories for the assessment of the lifecycle environmental impacts of Binary A and Binary B are as follows:

- Global Warming Potential - $CO_2$ equivalent mass (kgCO2-Eq)
- Acidification (Air) Potential - moles of H+ ions equivalent mass
- Human Health Criteria –$PM_{10}$ equivalent mass
- Eutrophication (air & water) Potential - N equivalent mass

- Smog (air) Potential – $O_3$ equivalent mass
- Ozone Depletion (air) Potential – CFC 11 equivalent
- Fossil Fuel Consumption – Total fossil fuel energy

For this study, GWP category was selected as the main environmental impact as a result of its global effect and also because it is currently the greatest environmental concern of the construction industry (Ortiz-Rodríguez, Castells and Sonnemann, 2010).

According to ATHENA, the GWP measure considers biogenic carbon as climate change neutral but excludes sequestered carbon in materials. The other impact categories are referenced according to related standard international documents for buildings and their evaluation.

#### 5.2.4.2 CHARACTERIZATION

The United States Environmental Protection Agency's (US EPA's) Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) version 2.0 is the basis for the actual impact assessment. TRACI characterizes impact categories using the method referred to as the midpoint approach or midpoint level. The following impact categories form TRACI's LCIA:

- Ozone depletion
- Global warming
- Acidification
- Eutrophication
- Photochemical smog formation
- Fossil fuel depletion
- Ecotoxicity (not implemented in ATHENA)
- Human health: criteria air pollutants
- Human health: carcinogenics and non-carcinogenics (not implemented in ATHENA)
- Land use (not implemented in ATHENA)
- Water use (not implemented in ATHENA)

A description and categorization of these indicators as implemented by ATHENA are given in Table 5.3.

Table 5.3: Description of ATHENA's Impact Categories

| IMPACT CATEGORY | UNIT | DESCRIPTION | MEDIA |
|---|---|---|---|
| **Global Warming Potential (GWP)** | $kgCO_2$-Eq. | Indicates the contribution of emissions associated with natural and human-induced activities to the global increasing temperature, leading to changes in global climatic patterns ($CO_2$ equivalent mass) | Air |
| **Acidification Potential (AP)** | Moles of H+ ions equivalent mass (kg $SO_2$-eq.) | Indicates the impact from sulphuric-acid-producing substances that when in contact with water, form acid rain (H+) within a local environment.<br>Moles of H+ ions equivalent mass | Air |
| **Human Health Criteria** | $PM_{10}$ equivalent mass ($kgPM_{10}$-eq.) | $PM_{10}$ equivalent mass | Air |

| | | | |
|---|---|---|---|
| **Eutrophication Potential** | N equivalent mass<br>(kg N-Eq.) | Refers to the "enrichment of an aquatic ecosystem with nutrients (nitrates, phosphates) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation | Air, Water, Soil |
| | | of algal biomass" (US Environmental Protection Agency 2008) | |
| **Ozone Depletion (OD) Potential** | CFC 11 equivalent | Indicates the contribution of Chlorofluorocarbons (CFCs), used as refrigerants, solvents and foam blowing agents, and halons, for extinguishers, to the decreasing stratospheric ozone level (US Environmental Protection Agency, 2008) | Air |
| **Smog Potential** | $O_3$ equivalent mass | Indicates the contribution of ground-level ozone created by various chemical reactions, usually occurring between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in sunlight. | Air |
| **Fossil Fuel Consumption (FFC)** | Gigajoules (GJ) | Total fossil fuel energy | ---- |

**eq – Equivalent*

#### 5.2.4.3 VALUATION

One important note is the lack of a scientific standard for the comparison of weighting categories; as such, weighting factors are subjective and determined by social and personal values. However, because the ISO 14040 does not allow weightings, due to the possibility of misrepresentation and misuse, they are not used by ATHENA. ATHENA uses the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) database. Following the directives of EPA, TRACI does not include normalization and valuation processes. Hence, this portion of the LCA is excluded. However, results are unaffected.

#### 5.2.4.4 ADDRESSING UNCERTAINTY AND VARIABILITY

According to Stephan, Crawford and de Myttenaere (2012), 'uncertainty' is defined as the want of knowledge for a particular parameter which would define its quality; whereas 'variability' relates to the inconsistencies of a particular parameter, or the deviations of results from average values. Such uncertainties include coefficients of hybrid embodied energy of construction materials, energy consumption levels of household appliances, travel patterns of building occupants, etc. ATHENA takes into account such parametric uncertainties and variability in the simulation application for the purpose of result validity. Thus, the region of Florida was used as the project location for the LCA. It is worthy of note that ATHENA develops its database based on personal research carried out by the institute and as such the data are said to be highly valid and reliable.

### 5.2.5 STEP FOUR: INTERPRETATION

This is the final stage of the LCA and concerns the processing of all the information obtained throughout the previous stages of the LCA – from identification through evaluation to presentation. The aim of interpretation is to analyse results (both from LCI AND LCIA) and to make unbiased conclusions and recommendations, based on the goal and scope of the study defined in stage one of the LCA. The final output should be the improvement models targeted at the reduction of environmental impacts of a system. ISO 14040 recommends a critical peer review, the results of which should be publicized.

Steps 3 (Validation) and 4 (Interpretation) constitute the “Results and Discussion” section of the methodology. Hence, they are discussed in more detail in the dedicated chapter.

# CHAPTER 6

# RESULTS AND DISCUSSION

## 6.0 INTRODUCTION

In the continuation of the LCA, the interpretation phase is the last of the stages, according to ISO 14040. In accordance with the defined goal and scope of the study, life cycle interpretation is carried out to identify and evaluate the most significant issues based on the results/findings of the LCI and LCIA, in order to effectively reach conclusions and recommendations.

This section is therefore a presentation of the results of the comprehensive LCA carried out for the comparison of the high-rise commercial building, The Binary, constructed in the UAE using two different construction techniques: conventional (cast-in-place concrete) and precast concrete construction. ATHENA allows for a side-by-side comparison of the results of the two construction scenarios, thus allowing for easier discussion and analysis of the results.

The given results are analysed categorically according to ATHENA's presentation report, as follows:

- The lifecycle stages - manufacturing, construction, operation, maintenance and end-of-life of the case study buildings;
- TRACI's impact categories - fossil fuel consumption, global warming potential, human health, and so on - given as summary measures;
- The air, water, land and resource use impacts in terms of their absolute values.

## 6.1 TOTAL EMBODIED ENERGY ANALYSIS AND GHG EMISSIONS

Within this section of the study, the results of the embodied energy of the case study building as given by ATHENA are presented. Embodied energy demand is the sum of all the processes of the pre-occupancy phase of the buildings. For emphasis, the embodied energy is defined as the energy from the processes of resource extraction, manufacturing and transportation of materials, on-site construction (for Binary A, or offsite production in the case of Binary B), on-site assembly (Binary B) and construction wastes. The evaluation includes a breakdown of all the energy emissions associated with all the assembly groups involved in the construction of the two buildings.

Of all the environmental impact categories, Fossil Fuel Consumption (FFC) and Global Warming Potential (GWP) are considered the most significant and are discussed in this section. The other impact categories are detailed in later sections of the study.

### 6.1.1 ASSEMBLY GROUPS

Four assembly groups were modelled for Binary A and Binary B: the foundation, walls, beam-and-column assembly, walls and roof. Details of the assemblies for both case study scenarios are discussed in the subsections below. The different assembly groups of Binary A and Binary B as modelled in ATHENA are discussed as follows.

#### a. The Foundation Assembly

According to The Binary's structural specifications, concrete pile foundation was the selected foundation type using the basement configuration. The piles were to be bored cast-in-place concrete piles constructed using grade 50/20/R with a minimum cement content of 390kg/cu.m and a maximum water content ratio of 0.42. The foundation was represented using ATHENA's slab-on-grade foundation assembly for both Binary A and Binary B. the same slab-on-grade was used as the base for Binary B. The difference between both foundations was in the wall support system, where Binary B's wall supports were made to be precast wall panels. The walls are discussed as part of the Wall assembly. P1 and P2 are sample piles as seen in the typical pile arrangement from the design drawings in Figure 6.1.

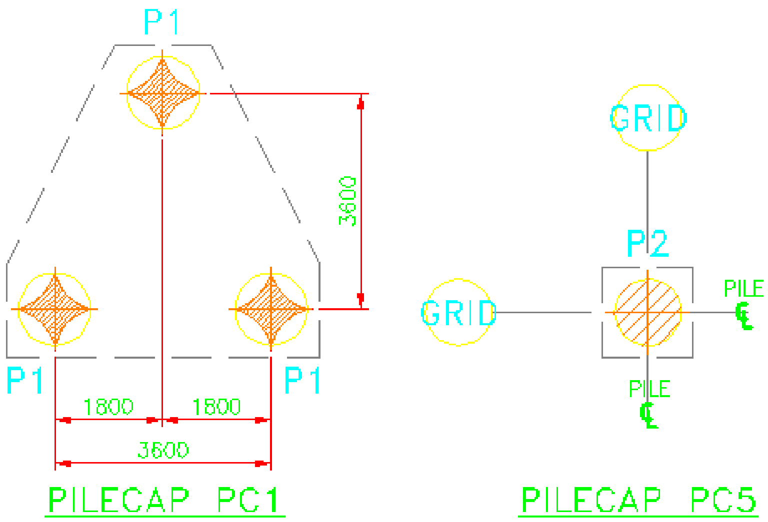
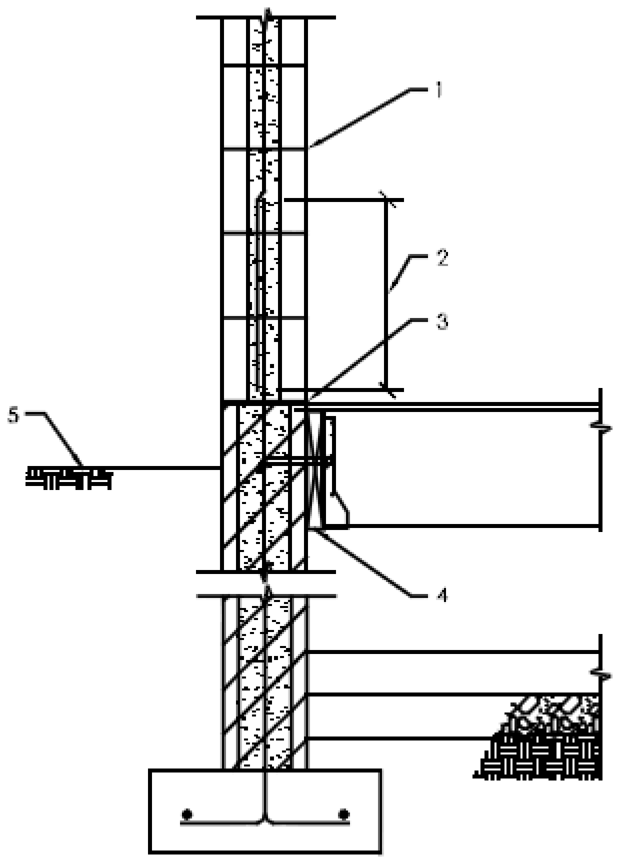



Figure 6.1: Samples of Typical Pile Foundation Schematic Arrangement (Dubarch, 2007).

**b. <u>Wall Assembly</u>**

The basement foundation walls which served as load-bearing exterior walls, constituted the wall assembly. The curtain walls were excluded primarily because they are a combination of double glazed vision glass and spandrel glass, and remain unchanged regardless of the construction scenario. Also, the interior columns and beams (CAB) were simulated in place of the interior walls due to their large numbers. The design specifications for The Binary's basement walls detailed the use of 200mm solid concrete blocks (as shown in Figure 6.2).

For Binary A, the foundation walls were simulated as concrete block walls. For Binary B, the basement walls were simulated as precast concrete foundation walls. Solid precast walls come either pre-insulated and are only in need of a wallboard, or with the insulation sandwiched in between the panels, thus eliminating the need for a wallboard and also increasing the R-value of the wall (Concrete Homes, 2012). Figure 6.3 shows the sectional detail of the precast insulated concrete basement wall and its connection to the foundation and floor slab using standard grout-filled reinforcement (Luttrell and Warnes, 2012).




1. AAC blocks with vertical walls reinforced in solid grouted cells.
2. Bar lap
3. 9.525mm type ‘M’ or ‘S’ mortar bed
4. Wood ledger and connection
5. Finished grade

Figure 6.2: Schematic Representation of Binary A’s Basement Foundation Wall Assembly (E-crete, 2012).

### c. <u>Column-and-Beam Assembly (CAB)</u>

Beams are horizontally spanned structural components that provide support for slabs and often, other beams Columns function as structural supports for beams and spandrels.

The conventional beam type used for the Binary was the reinforced cast-in-situ concrete beam (Figure 6.4). Precast beams are characteristically cast in similar orientation as would be used in the final building. The most common types are the inverted tee beams which are usually supported by columns or load-bearing walls. Typical precast beam depths range from 406-1016mm; widths range from 305-610mm; and span-depth ratios from 10-20. The dimensions, size, depth, width and

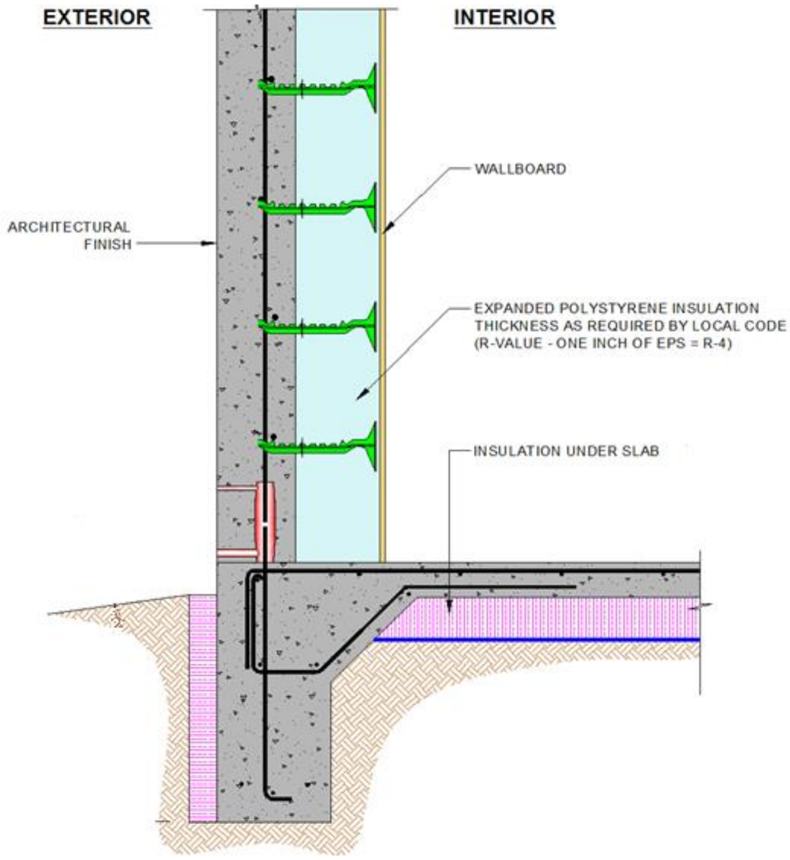



Figure 6.3: Schematic Representation of Binary B's Precast Basement Wall Panel (Tornado-Resisting Concrete Houses, 2012).

span-depth ratio are easily customizable. An example of precast beams is seen in Figure 6.5. Similar to conventional beams, conventional columns are poured-in-place reinforced structures. On the other hand, precast columns are cast horizontally and then rotated at the assembly site. Like precast concrete beams, the construction of precast involves mass pretensioning and reinforcing with prestressing stranding, or individual casting with prestressing strand or conventional reinforcement bars. Similar to precast beams, shape and size of the precast concrete column are at the designer's discretion. Typical shape is square or rectangular, with the size range of (305 by 305) mm to (610 by 1220) mm (PCI, 2012; WEI, 2012). The columns for Binary A were simulated under type: 'Concrete Column' while Binary B's columns were modelled as 'Precast Column'. Column sizes and reinforcement representations for the Binary are seen in Figure 6.6.

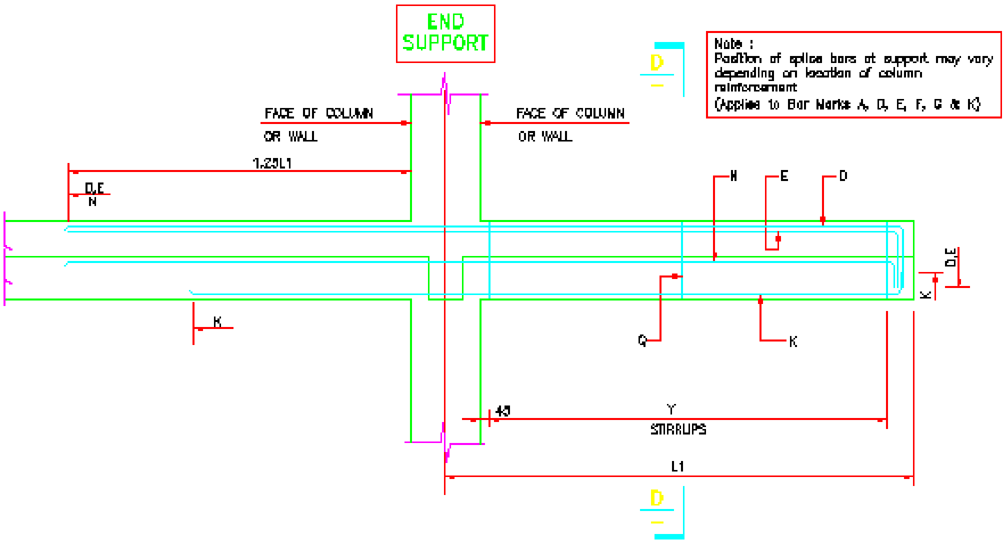



Figure 6.4: Schematic Showing Elevation of a Reinforced Concrete Beam for Binary A (Dubarch, 2007).

Figure 6.5: Manufactured Prestressed Precast Concrete Beam (Grace, 2012).

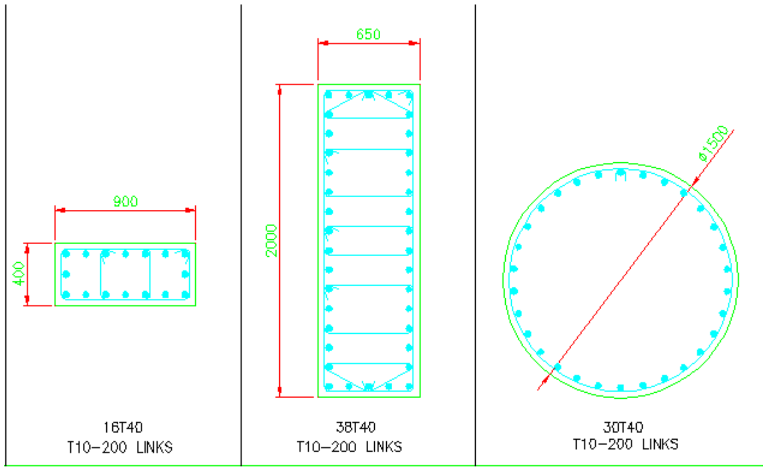



Figure 6.6: Sample of Column Schedule for the Binary (Dubarch, 2007).

The structural CAB system for Binary A was simulated as concrete beams and concrete columns. For Binary B, the CAB system was modelled as precast concrete columns and precast concrete beams. ATHENA modelled the number of columns and beams according to the span (the maximum distance between rows) and bay (main beam span) of the building. The spans and bays of the CAB for Binary B were chosen to be 12m each based on design averages (Bison, 2012; PCI, 2012; WEI, 2012). For Binary A, the typical bay was 8.45m while the span was 8.56m.

### d. **Floor Assembly**

For the Binary, the floor assembly is a 2-way spanning post-tensioned cast-in-place concrete slab floor, supported on the reinforced concrete columns. Post-tensioned slabs are used to create massive slabs that provide greater strength than typical slabs which are usually poured stage by stage. Due to concrete's poor performance in tension unlike its strong performance under compression, tendons or cables are stretched up to 25,000psi with the aid of hydraulic jacks and clamped tightly. This results in constant compression for the concrete, keeping the slab stronger and more durable. An on-going concrete slab production process is illustrated in Figure 6.7. The post-tensioned slab was represented in Binary A as a concrete suspended slab floor (Figure 6.8).

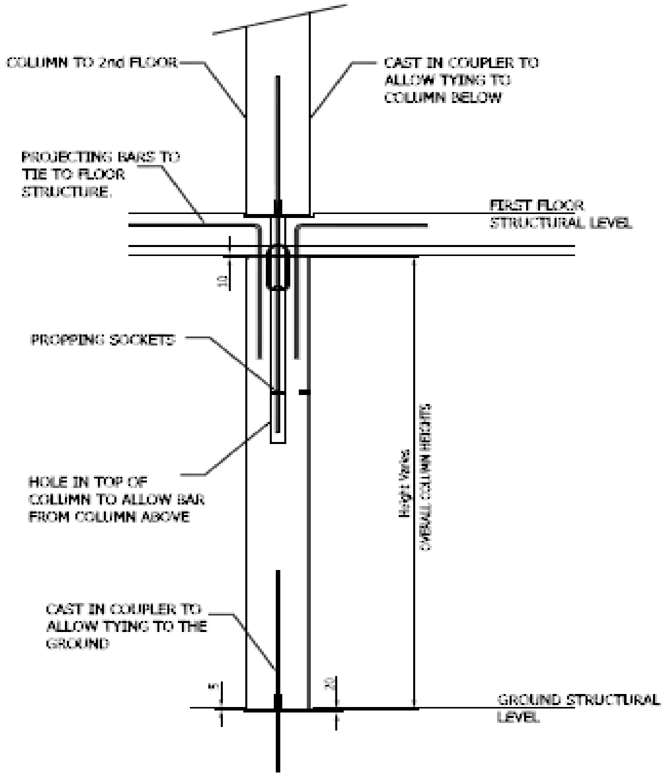



Figure 6.7: Schematic Illustration of a Precast Column Assembly (Bison, 2012).

Figure 6.8: On-site Constructed Post-tensioned Slab (Baker, 2009).

The casting method for these floor types is long-line manufacturing. The extrusion of the concrete is done using long casting beds which allow the slabs to be cut to any desired length, while the voids are created. Typical widths of hollow core slabs are 50mm, 101mm and 203mm; some precasters provide options of 254mm and 305mm. Depths start from 153mm and go as high as 406mm. The common span-depth ratio for the floor is 30 to 40. Thus, Binary B was assigned the hollow core floor slab as its floor assembly. Hollow core floor slabs are shown in Figure 6.9.

Figure 6.9: Hollow Core Floor Slabs (Concrete Technology, 2007).

**e. <u>Roof Assembly</u>**

Again, the Binary was constructed with cast-in-situ roof slab. The insulation of the roof was required to be one layer of 5cm thick rigid extruded closed cell polyurethane boards laid loosely over the waterproofing membrane. A conventional roof assembly is given in Figure 6.10.

For the precast scenario, the selected roof was the precast double tee roof for its ability to provide longer spans and support heavy loads. Double tees have progressed from the width of 1220mm to 2440mm and up to 3660mm, with a depth range of 300mm to 900mm and at least 33m spans. Several factors guide the dimensional choices of double tees: fire and transportation regulations, design efficiency and usage popularity (Osco Construction Group, 2007). Figure 6.11 shows the on-site assembly of a precast double tee roof.

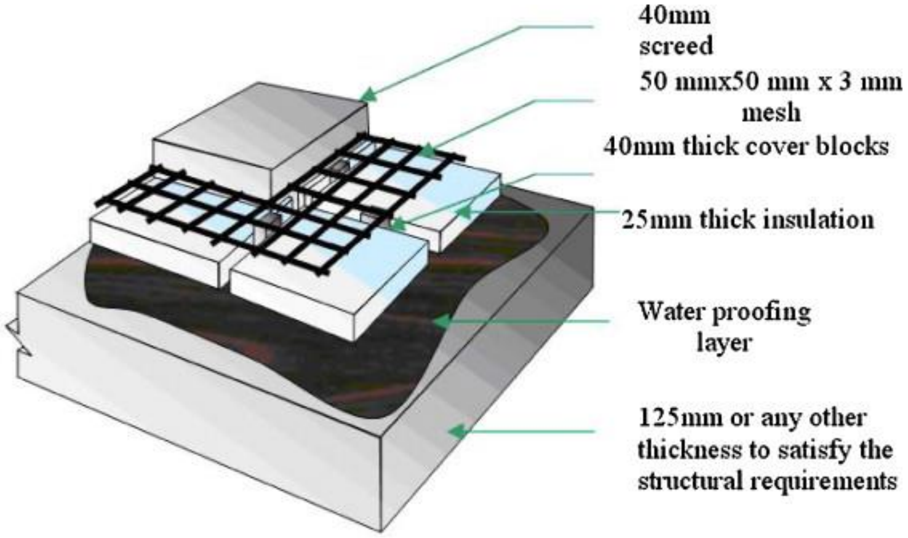



Figure 6.10: Schematic of a Reinforced Concrete Roof Slab and Insulation System (Halwatura and Jayasinghe, 2009).

Table 6.1 summarises all the assembly groups and their construction location, whether on-site or offsite. As indicated in the table, almost all of Binary A’s assembly components are produced at the site of construction, with the exception of doors and windows. On the other hand, Binary B has its assemblies produced offsite at a factory and then transport to the construction site already finished and ready to be assembled.

The total embodied primary energy (TEPE) is inclusive of all the energy, both direct and indirect, used for the transportation and transformation of raw resources


Figure 6.11: Double Tee Roof Panels in Position (Andrews Prestressed Concrete, 2003).

into products and subsequently, buildings. According to ATHENA, this also includes the inherent energy in the raw materials which serve as energy sources.

Table 6.1: Construction Location of the Assembly Groups of the Case Study Scenarios

| ASSEMBLY GROUP | BINARY A | | BINARY B | |
|---|---|---|---|---|
| | ON-SITE | OFFSITE | ON-SITE | OFFSITE |
| **FLOOR** | X | - | - | X |
| **COLUMN-AND-BEAM** | X | - | - | X |
| **ROOF** | X | - | - | X |
| **FOUNDATION** | X | - | X | |
| **WALL** | X | - | - | X |
| **DOORS AND WINDOWS** | - | X | - | X |

*X = Used Location

### 6.1.2 RESOURCE USE

A vast amount of resources was utilized for the construction of the case study building. These were broken down into solid mass materials and liquid and semi-solid resources. The list of the materials used for Binary A is summarised in Table 6.2, according to ATHENA's output.

Table 6.2: Resource Use for the Construction of Binary A's Assembly Groups

| Material ID | Foundations | Walls | Columns and Beams | Roofs | Floors | Total |
|---|---|---|---|---|---|---|
| **Limestone** | 8.51E+05 | 7.77E+05 | 2.15E+06 | 2.18E+05 | 1.49E+07 | **1.89E+07** |
| **Clay & Shale** | 2.36E+05 | 2.13E+05 | 5.61E+05 | 5.87E+04 | 4.09E+06 | **5.16E+06** |
| **Gypsum (Natural + Synthetic)** | 3.66E+04 | 5.98E+04 | 8.72E+04 | 2.78E+04 | 1.30E+06 | **1.51E+06** |
| **Semi-Cementitious Material** | 9.04E+04 | 8.11E+04 | 1.14E+06 | 4.04E+04 | 1.56E+06 | **2.91E+06** |
| **Aggregate (Coarse + Fine)** | 2.76E+06 | 8.81E+05 | 8.33E+06 | 1.51E+06 | 4.76E+07 | **6.11E+07** |
| **Scrap Steel (Obsolete + Prompt Scrap)** | 2.65E+05 | 9.22E+05 | 2.49E+06 | 2.23E+05 | 6.96E+06 | **1.09E+07** |
| **Coal** | 1.50E+05 | 1.50E+05 | 5.17E+05 | 4.68E+04 | 2.89E+06 | **3.75E+06** |
| **Water** | 2.53E+05 | 7.49E+06 | 1.77E+07 | 8.70E+05 | 2.63E+07 | **5.26E+07** |
| **Crude Oil** | 6.61E+04 | 1.04E+05 | 3.16E+05 | 9.03E+04 | 1.36E+06 | **1.94E+06** |

The mass of solid raw materials totalled 7.47E+07kg for Binary A. Of the solid materials, the most used materials included fine and coarse aggregates (58.8% of the total), limestone (18.2%), and scrap steel (obsolete and prompt scrap) (10.5%). Other resources were semi-cementitious material, gypsum (natural and synthetic), sand, ash, and clay and shale, among others. The floor assembly utilized the highest amount, approximately 76% by mass of resources. This was followed by the CAB with 15%, foundations 4%, walls 4.6% and roofs 2%. The breakdown of these resources has been charted in Figures 6.12 for the solid resources.

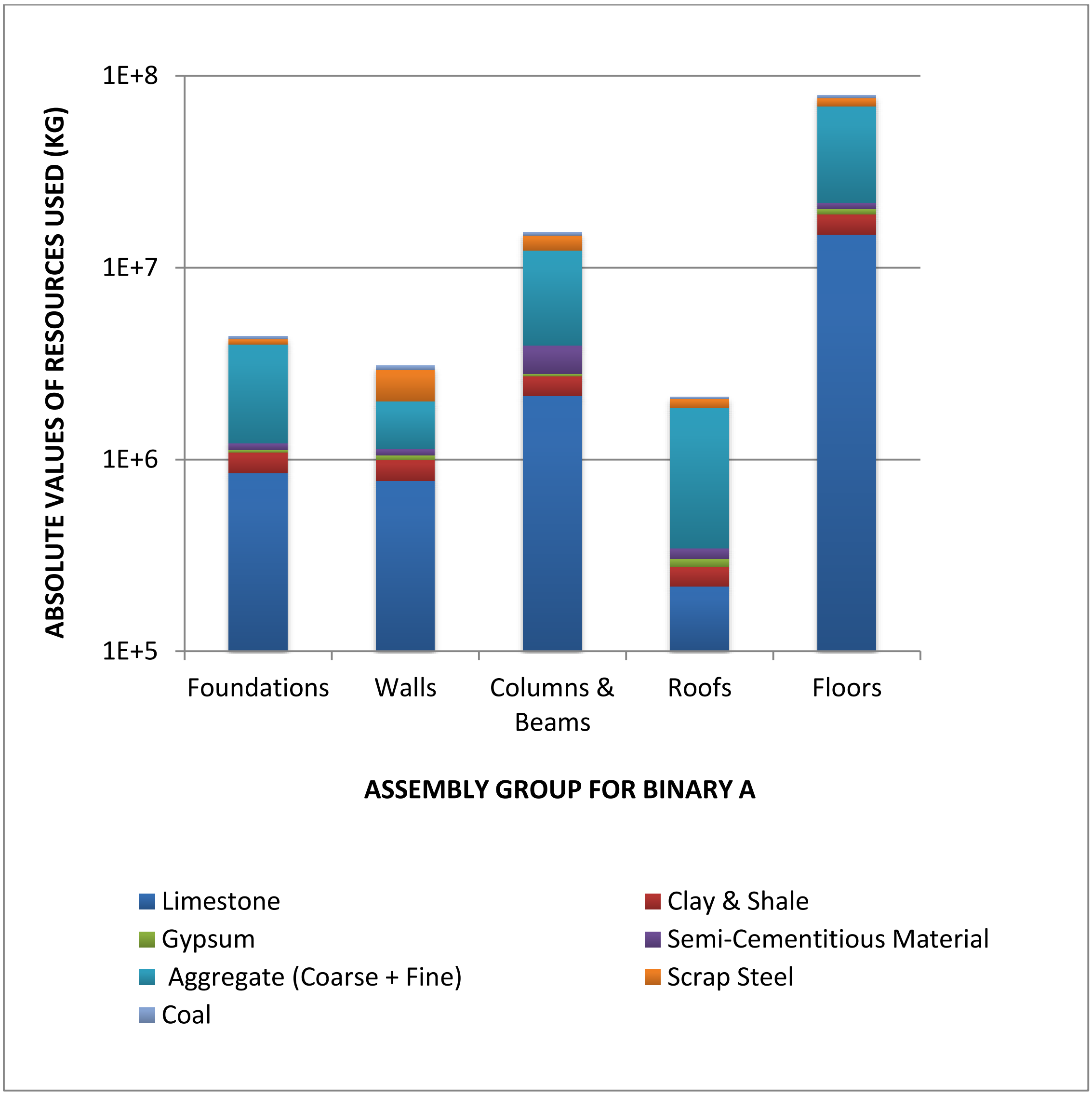



Figure 6.12: Solid Resource Use Absolute Value Chart by Assembly Groups for Binary A.

According to ATHENA's results, Crude oil was a total of 1.94E+06 litres, while water made up 5.26E+07 litres and was seen to be the most used resource for construction overall (1 litre of water = 1kg of water; therefore by mass, 5.26E+07kg of water was consumed in construction). The floor assembly consumed the most water 50%, and also the most crude oil, 70%. Figure 6.13 show the amount of water and crude oil resources used for the construction of Binary A's assemblies.

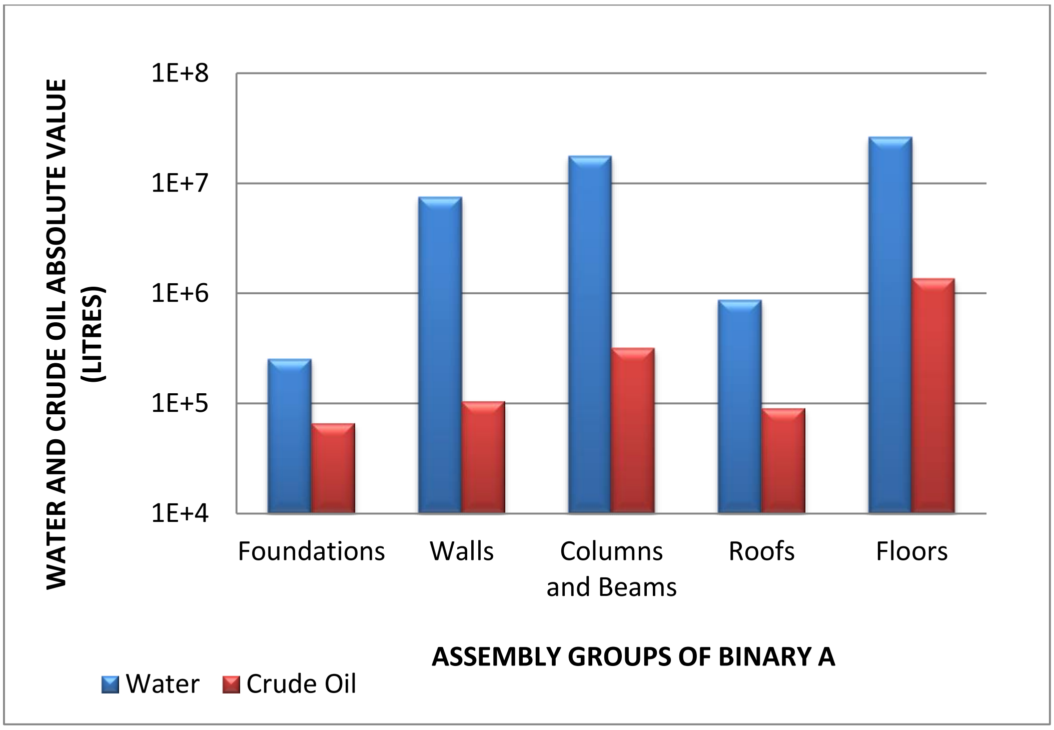



Figure 6.13: Absolute Value Chart Showing Water and Crude Oil Use for Binary A's Assembly Groups

Table 6.3 is a summary of the absolute values of the resources used for the construction of the precast assemblies for Binary B. The LCA result showed that for B, Binary the total solid material used was 2.89E+07kg. For Binary B, limestone was seen as the most consumed resource, a mass of 1.04E+07kg (38.4% of the total amount), followed by fine and coarse aggregates with a mass of

Table 6.3: Resource Use for the Construction of Binary B's Assembly Groups

| Material ID (kg) | Foundations | Walls | Columns and Beams | Roofs | Floors | Total |
|---|---|---|---|---|---|---|
| **Limestone** | 8.51E+05 | 6.01E+05 | 1.57E+06 | 1.86E+05 | 7.15E+06 | **1.04E+07** |
| **Clay & Shale** | 2.36E+05 | 1.63E+05 | 1.69E+05 | 3.08E+04 | 9.63E+05 | **1.56E+06** |
| **Gypsum** | 3.66E+04 | 5.97E-06 | 5.74E+04 | 2.56E+04 | 3.19E+05 | **4.39E+05** |
| **Semi-Cementitious Material** | 9.04E+04 | 1.91E+05 | 0.00E+00 | 8.83E+03 | 1.59E+05 | **4.49E+05** |
| **Aggregate (Coarse + Fine)** | 1.87E+06 | 0.00E+00 | 0.00E+00 | 3.05E+05 | 5.58E+06 | **7.76E+06** |
| **Scrap Steel** | 2.65E+05 | 2.22E+05 | 1.01E+06 | 1.66E+05 | 3.30E+06 | **4.96E+06** |
| **Coal** | 1.50E+05 | 1.22E+05 | 2.43E+05 | 3.25E+04 | 1.05E+06 | **1.60E+06** |
| **Water** | 2.53E+05 | 1.81E+05 | 1.36E+07 | 9.35E+05 | 3.55E+07 | **5.05E+07** |
| **Crude Oil** | 6.61E+04 | 3.56E+04 | 2.05E+05 | 7.52E+04 | 7.26E+05 | **1.11E+06** |

7.76E+06kg (28.6% of the total amount), and scrap steel with 4.96E+06kg (18.3%). Semi-cementitious material, clay and shale, gypsum (natural and synthetic), sand, and so on, made up the rest of the solid resources composition. Figure 6.14 represents this breakdown.

As with Binary A, the floor assembly of Binary B took the lead in the amount of consumed resources, with an estimated 1.85E+07 kg (or 68% of the total mass). This was followed by CAB with 3.40E+06kg (15%), foundations 3.50E+06kg (13%), walls with 1.30E+06kg (3%) and finally the roofs with the least mass of 7.55E+05kg (3%).

As was estimated for Binary A, the amounts of water and crude oil used for the construction of Binary B were 5.05E+07litres and 1.11E+06 litres, respectively, water being the more consumed of the two resources. The floor assembly was

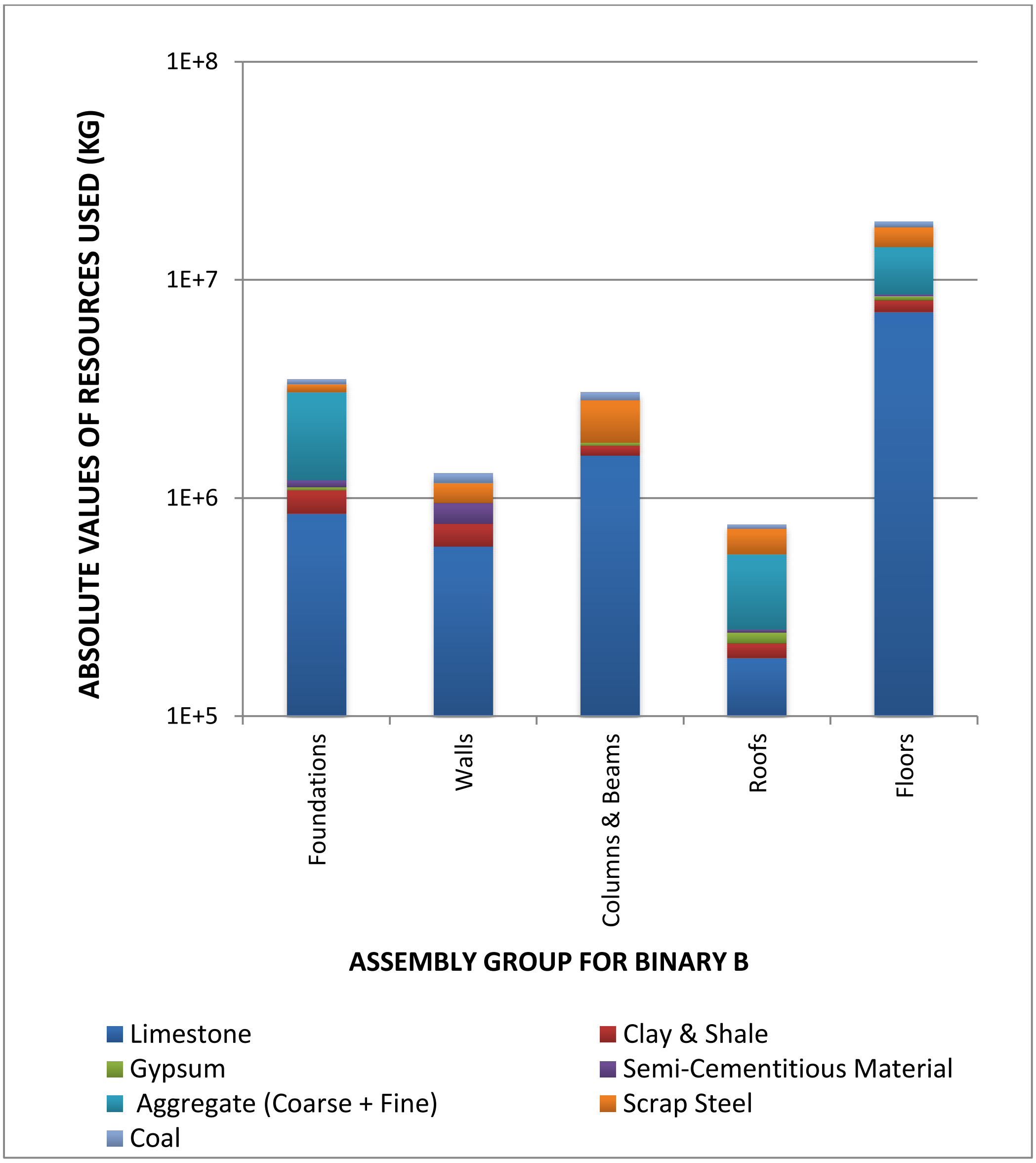



Figure 6.14: Solid Resource Use Absolute Value Chart by Assembly Groups for Binary B.

shown to be the highest consumer of both water and crude oil, using up about 70% and 65% of both resources, respectively. This was followed by 26.2% water consumption by the column-and-beam assembly. In comparison, the water and crude oil used for the roofs, foundation and walls are negligible. Figures 6.15 summarises these evaluations.

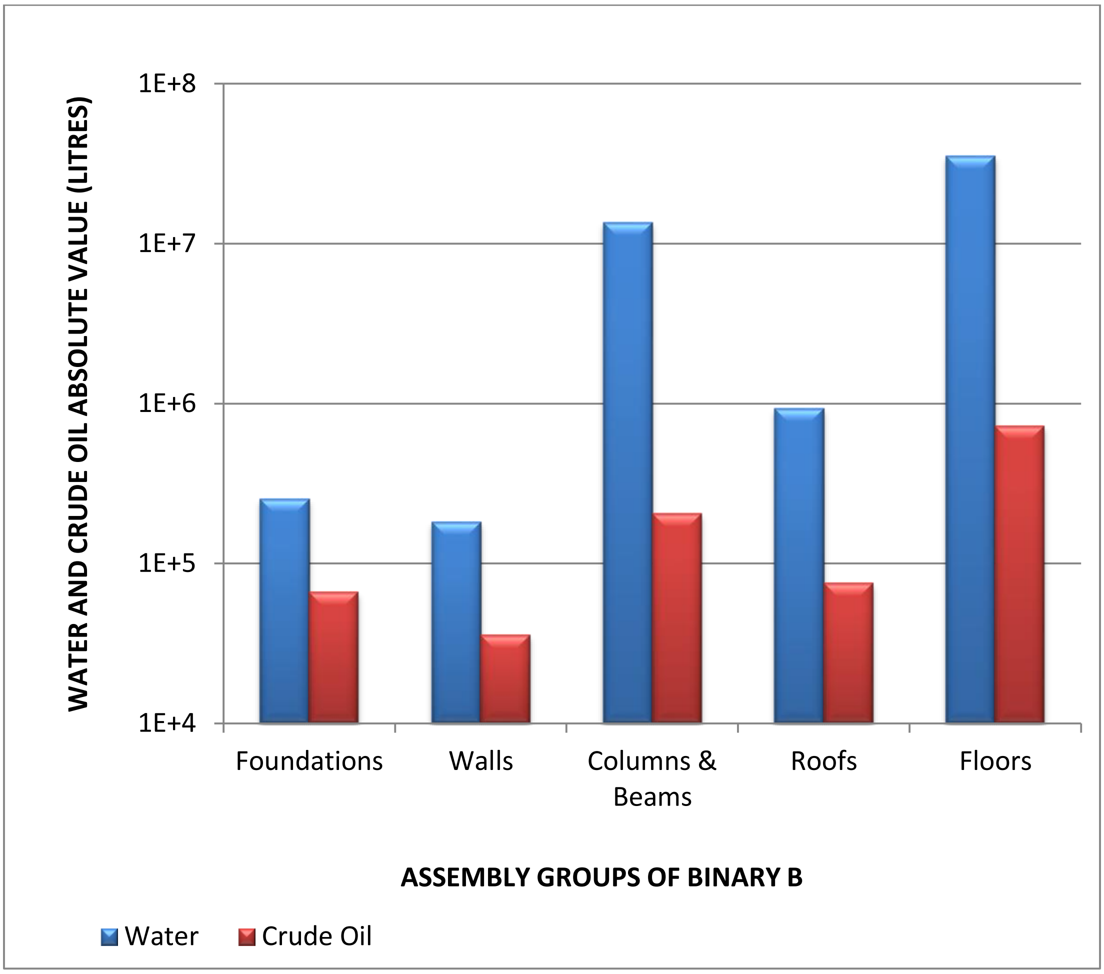



Figure 6.15: Water and Crude Oil Absolute Value Chart by Assembly Groups for Binary B

## RESOURCE USE RESULTS COMPARISON

In this section, all the absolute values of the resources used for both Binary A and Binary B. Table 6.4 gives a summary of the total values by mass of the solid materials used for construction of Binary A and Binary B,  as well as the total amount of water and crude oil consumed by both construction scenarios. It is important to note that in the simulation of Binary A and Binary B to represent the different construction techniques, the structural integrity of the case study building was maintained. All design specifications were used as obtained from the architectural and structural data provided (in the case of Binary A, the

Table 6.4: Comparison of Percentage Savings Achieved in Resource Use for Case Study Scenarios

| Resources Used | Binary A | Binary B | Percentage Savings Achieved By Binary B Compared To Binary A |
|---|---|---|---|
| **Solid Mass Materials (kg)** | 1.04E+08 | 2.71E+07 | 79.1% |
| **Water (litres)** | 5.26E+07 | 5.05E+07 | 40.0% |
| **Crude Oil (litres)** | 1.94E+06 | 1.13E+06 | 42.8% |

conventional concrete) and according to precast concrete manufacturers' specifications in line with building codes (in the case of Binary B, the precast concrete).

Firstly, the solid resource use consumption levels are compared. Table 6.4 shows that by consuming 2.71E+07kg of solid mass materials as against 1.04E+08kg consumed by Binary A, Binary B has shown savings in mass of 7.36E+07kg, which translates to a saving of 79.1%. Furthermore, in comparing the water usage quantity, Binary B saved 2.10E+06 litres of water in its construction, amounting to a 40% saving, in relation to the quantity of water used by Binary A. In the same vein, the amount of crude oil required for the production of the precast concrete assemblies for Binary B was almost 43% less than the required amount for Binary A's assemblies.

The reason for these achieved savings in resource consumption by Binary B over Binary A are explained as follows. Firstly, it was observed that the floor assemblies for both construction scenarios had the highest need for resource use. This is attributed to the structure of the building. As a high-rise building, the strength and durability of the structure are of utmost importance. This explains why the floors and CAB assemblies made up the largest portions of the structural components of the building. However, the difference in resource consumption savings is observed especially in the difference in material use levels between Binary A and Binary B (as results have shown) which in turn is a s a result of the composition and construction types of the assemblies in each scenario.

The use of post-tensioned cast-in-situ concrete floor slabs for Binary A are needed to create massive slabs in order to greatly improve upon the strength and durability of the floor system than would be provided for typical floor slabs. The construction of these massive slabs naturally implies the need for a large volume of concrete for construction, and consequently, a high amount of materials for the production of the desired concrete mix. Conversely, Binary B's floors comprised hollow core floor slabs. The same size of hollow core slabs weigh about half as much as traditional concrete cast-in-situ slabs as a result of their voids. This means that the amount of materials (solid mass materials, water and crude oil) consumed in the construction of Binary B's lighter structural frames would be up to half or even more (in this case 79% for solid mass materials, 40% for water and 42% for crude oil). In addition, the prestressing tendons installed in the hollow core slabs of Binary B would provide the capacity to meet the load-bearing requirements and accommodate longer span lengths with less use of resources than the massive cast-in-situ floor of Binary A (Bethlehem Construction, 2012), at the same time achieving significant savings in construction costs.

The same evaluation is applicable to the walls, CAB, foundation and roof assemblies of both construction scenarios. While Binary B's precast concrete sandwiched walls (5000 psi) are stronger than conventional concrete walls (2500 psi), they are by no means heavier. On the contrary, they are thinner and lighter in weight (HGTV Remodels, 2012). This means that the fabrication of precast walls required lower quantities of construction resources than the on-site construction of the conventional walls of Binary A. Also, the amount of concrete required for a cast-in-situ concrete foundation is at least three times more than the amount required for a precast concrete basement foundation, according to Kale Walker, a precast wall system manufacturer (McCrea, 2012).

Generally, in an offsite factory, the controlled conditions means there is better regulation of the concrete mixing and curing processes. This allows for reduced water to cement rations, which in turn result in a material whose density improves its water-resistant properties (Precast Solutions 2012). Conversely, cast-in-situ foundation wall systems require waterproofing in order to achieve water-resistance properties. Inadvertently, this means that more resources and materials are required, further explaining the increased consumption level of resources for Binary A than Binary B. In both cases, where it is seen that fine and coarse aggregates, clay and shale and limestone contribute the most to embodied energy, Scheuer, Keoleian and Reppe (2009) suggest that this is primarily due to the high masses of these materials, and not necessarily because of the energy required for their production.

In summary, the structural precast panels of Binary B were seen to consume less material than the conventionally constructed assemblies of Binary A. It also follows that the precast concrete system conserves resources more efficiently, and reduces on-site wastage and construction mess, as spillage is minimized because the precast panels and slabs are delivered installation-ready (McCrea, 2012).

### 6.1.3 LAND EMISSIONS

From the results of ATHENA, the total emissions to land for Binary A were 4.95E+06 kg for the entire lifespan of Binary A. Of this total, concrete solid waste is the highest contributor, about 63.3% of the total. This result is in line with Wilson (1993) who asserts that the fact that concrete is the biggest and most visible constituent of construction and demolition (C&D) waste cannot be ignored. The remaining 36.7% is distributed among bark/wood waste, blast furnace slag, blast furnace dust and other kinds of solid waste. Binary A's floors are seen to generate the most amount of waste, 78.3% in comparison to CAB 9.5%, foundations 4.1%, walls 4.8%, and the roofs which generate the least 3.3%. Figure 6.16 shows a summary of these results. The empty bars in the graph indicate a zero-level of steel waste. That is, the foundations, as well as the columns and beams, had no steel waste.

According to ATHENA's output, the total land emissions for Binary B, the precast scenario, was estimated at 1.96E+06 kg. Due to its structural composition, the precast floor assembly had the highest land emissions of all the assembly groups, as was the case with Binary A. In Figure 6.17, the absolute values of the different land emissions from the construction of Binary B are given.

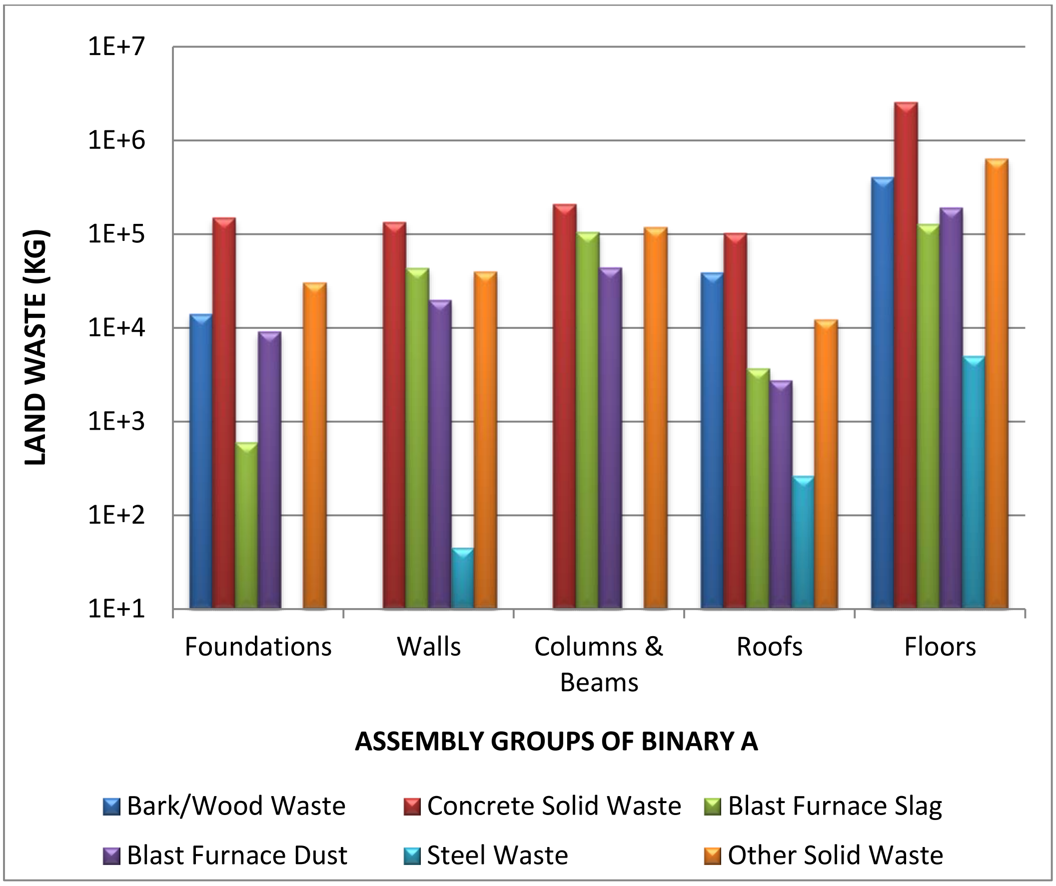



Figure 6.16: Land Emissions Absolute Value Chart by Assembly Groups for Binary A

Wilson (1993) quotes the estimates from AIA Environmental resource Guide which state that concrete waste accounts for almost 67% by weight and 53% by volume, of total C&D waste. One cause of concrete waste that has been a major source of concern is the concrete left over in return truckloads from ready-mix plants. Innovations to avoid the generation of such wastes such as the use of the concrete for the production of concrete highway dividers and retaining wall blocks, or the recovery of aggregate from the washing of unset concrete, have been the generated solutions. In addition, innovative technology has been developed in recent times which have significantly reduced these wastes. One such effective technology is the use of concrete admixtures which serve as concrete-setting retarders, so that return loads of concrete can be held at the ready-mix plants for as low as 24 hours to as long as three days and then reactivated for utilization in construction.

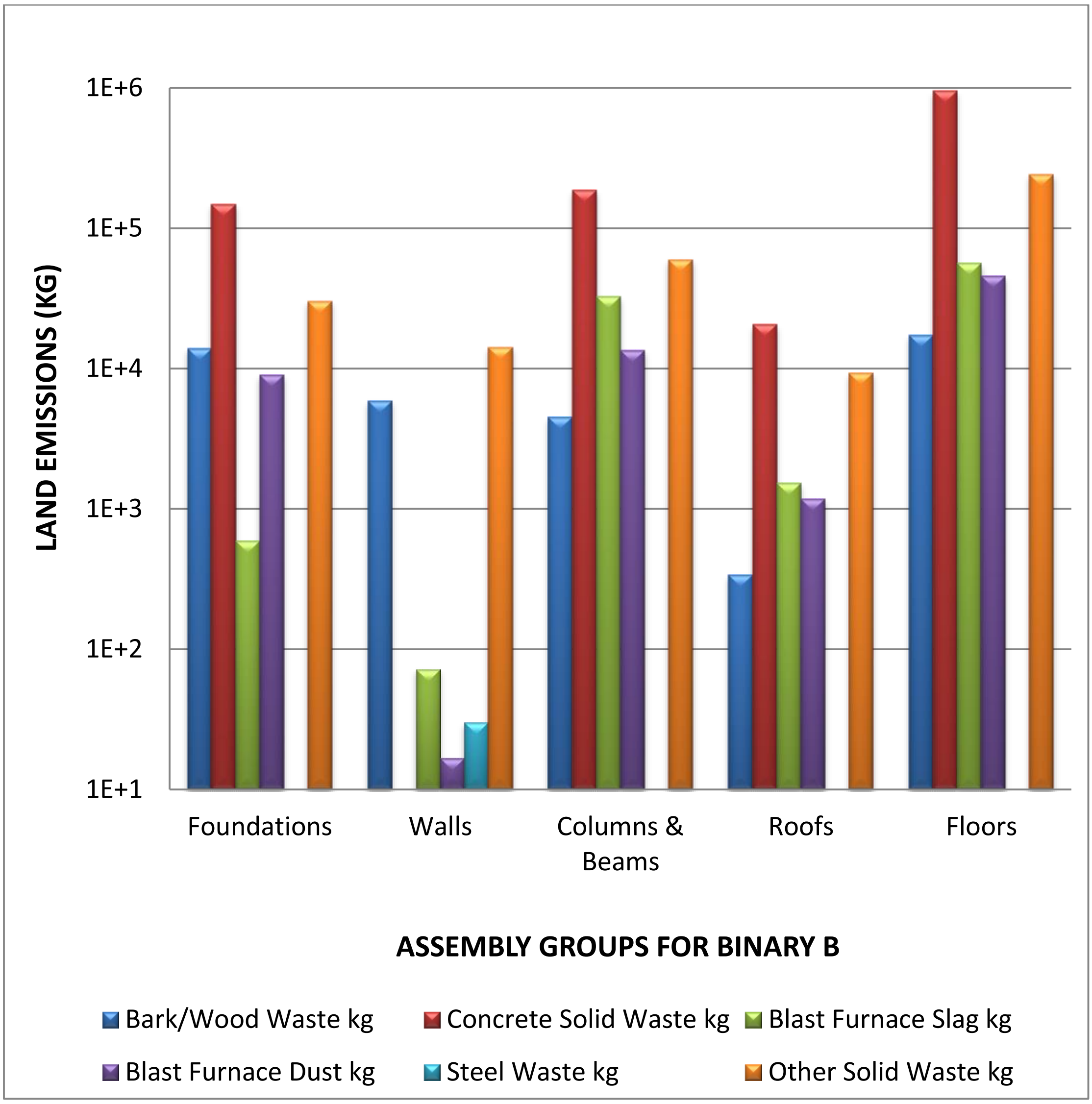



Figure 6.17: Land Emissions Absolute Value Chart by Assembly Groups for Binary B

In spite of this, the advantages offered by the use of precast assemblies are seen to provide even more benefits than all the technology for the mitigation of conventional concrete waste. The total waste from precast concrete is minimised due to offsite production. At the construction assembly site, only the required precast concrete components for the building are delivered. This means that there are no remnants from formwork and fasteners, thus less waste and dust are generated. Offsite fabrication also means less construction time and the need for fewer delivery trucks. This is a value-added advantage for Dubai, which is a very urban region where traffic congestion needs to be minimized (PCI, 2012).

In production, the estimation of material quantities is carried out with more precision and any excess material is easily utilized. In comparison of both construction scenarios however, Binary B provide as much as 60% reduction in land emissions than Binary A, the conventional. In addition, Binary B saved 58% more concrete than did Binary A, its total concrete solid waste being equal to 1.81E+06 kg less than that of Binary A.

The reduced amount of concrete waste is attributed to the use of precast components for Binary B. As seen in results, the hollow core floor slabs which weigh 50% less than cast-in-situ concrete floor slabs used in Binary A. Similarly, the structural precast wall panels and double tee roof, as earlier mentioned are constructed using lighter weight concrete, and therefore require less material for their construction. Wilson (1993) cites an instance of the 'Superior Wall Foundation System' which is known to require only a third of the amount of concrete required for the construction of cast-in-place foundation walls. Interestingly, the foundation walls of Binary B, as indicated from the result, show a very negligible amount in the concrete waste category.

Therefore, they generate much less waste than Binary A's cast-in-situ walls, roofs and massive floor slabs. Another factor for the reduced amount of land emissions as exhibited by Binary B's precast systems is the controlled factory environment for the mixing and curing of concrete. The carefully controlled fabrication environment for precast concrete provides the advantage of higher strengths of components with the use of lesser materials. As production is controlled and such paradigms as JIT and chain supply are implemented, waste generation is kept to the minimum. According to PCI (2012), the design of precast and prestressed concrete is optimised to reduce the amount of concrete. Precast concrete generates less waste than cast-in-place concrete with reduced levels with low levels of toxicity. The assumption is that concrete waste at the precast factory amounts to 2%, however 95% of that waste is asserted to be used beneficially, considering the factory production environment.

It should be noted that for the steel waste, the 99.9% difference between Binary A and Binary B might be attributed to the fact that steel use is limited to the walls of Binary B alone, while steel is factored into the production of the walls, roof and floor of Binary A.

The summary of the total land emission values for Binary A and Binary B as evaluated above are indicated in Table 6.5.

Table 6.5: Comparison of the Total Land Emission Values of Binary A and Binary B

| Land Emissions (kg) | Binary A | Binary B | Percentage Savings Achieved By Binary B Compared To Binary A |
|---|---|---|---|
| Bark/Wood Waste | 4.54E+05 | 4.20E+04 | 90% |
| Concrete Solid Waste | 3.12E+06 | 1.31E+06 | 58% |
| Blast Furnace Slag | 2.79E+05 | 9.08E+04 | 67.5% |
| Blast Furnace Dust | 2.64E+05 | 6.94E+04 | 73.7% |
| Steel Waste | 5.25E+03 | 3.00E+01 | 99.4% |
| Other Solid Waste | 8.31E+05 | 3.55E+05 | 57.3% |

### 6.1.4 AIR EMISSIONS

With 174 different contributors to air emissions (Appendices J and K), it is only of interest to this report to include the most significant. As such, the 10 highest air emitters were considered. They include: Carbon Dioxide ($CO_2$)(fossil), Carbon Monoxide (CO), Carbon Monoxide (fossil), Methane (fossil), Nitrogen Oxides (NOx), Particulates (<10µm and > 2.5µm), Particulates (<2.5µm), Sulphur Dioxide (), Sulphur Oxide (SOx) and Volatile Organic Compounds (VOC). Of these, NOx

(6.78E+07g), $SO_2$ (6.72E+07) and Particulates <2.5μm (4.34E+07g), had the highest air emissions for Binary A. For Binary B, while Nitrogen Oxides (5.21E+07g) and Sulphur Dioxide (3.84E+07g) produced the leading air emission values similar to Binary A, the third highest was different being Carbon Monoxide Fossil (1.99E+07g).

Particulate matter, one of the greatest contributors to air emissions is due to the manufacture of cement and the production of aggregates. The greatest contributor to the particulate matter emission is quarry operations (such as blasting and stockpiling), averaging 60% for cement manufacturing processes and accounting for almost 30% in aggregate production. Cement composition is primarily responsible for the amount of $CO_2$ and other forms of gases related to the production of concrete. According to PCI (2012), for every cement content, there is an equal unit increase in the emission of $CO_2$ gas. That is, for every 1kg of cement per volume of concrete, there will be a 1kg increase in the $CO_2$ emission. As a result of the $CO_2$ emissions from limestone calcination and fuel combustion during the manufacturing process of cement, about 90% of the $CO_2$ emitted is attributed to the contents of cement associated with the production of concrete. Furthermore, dust is generated not just from cement manufacturing but also from the production and transportation of concrete (if roads are unpaved). Dust sources are the mining activities of aggregate and sand, mixer loading and wind erosion.

In addition, per unit volume of concrete produced, 70% of the fuel used is as a result of the production of cement. This implies that emissions from combustion gases such as SO2 and NOx are related to the cement content in a concrete mixture (PCI, 2012). Besides this, fossil fuel is burnt during the transportation of concrete and other construction products. The SO2 and its associated oxides are also emitted as a result of the sulphur content of both the fossil fuel and the raw materials for the production of concrete. NOx is also a pollutant associated with fuel consumption as well as the combustion conditions of the cement kiln, depending on the temperature and type of kiln (Wilson, 1993).

It is therefore obvious why Binary B contributed less air emissions than Binary A. the offsite production process of precast concrete assemblies, as discussed earlier, requires much less concrete than is required for the construction of conventional assemblies. The lower the demand for concrete the lower the demand for cement production, therefore the lower the air emissivity associated with the concrete production.

### 6.1.5 WATER EMISSIONS

There are about 107 different sources of water emissions (Appendices L and M). The 5 most significant were selected and include the following: Dissolved Solids, Sodium Ion, Chloride, Suspended Solids Unspecified and Calcium Ion. Binary A had higher water emissions than Binary B in all categories of water emission pollutants, as indicated thus: Dissolved Solids (4.86E+11mg against 3.01E+11); Sodium Ion (1.04E+11MG against 6.89E+10mg); Chloride (3.80E+11mg against 2.47E+11mg); Suspended Solids Unspecified (5.14E+10mg against 2.32E+10mg) and finally Calcium Ion (3.30E+10mg against 2.17E+10mg).

Water pollution is a significant issue associated with the production of cement and concrete, more especially the concrete production stage. Richard Morris of the National Ready Mix Concrete Association reports that the number one issue is run-off water with high pH. Although the use of water varies from site to site, run-off water can have alkalinity of up to pH12. Water with high alkaline content is toxic to aquatic life. Sources of run-off include the discharged waste water from the washing and cleaning of equipment at the batch plant which is discharged into nearby ponds. Often during concrete production, washed-off concrete flows back to the site and is sent back into the ponds in order to reclaim the aggregate. Once this waste water becomes ground water or infiltrates rivers and ponds, the natural aquatic environment becomes vulnerable to pollution. The toxicity levels of the water due to the soluble compounds from this washed-off concrete are harmful to the aquatic life and humans in general (Bremner, 2001; Murray-White, 2012).

The precast concrete production process is less harmful in this way to water bodies and aquatic life firstly as a result of the reduced amount of concrete production for its components and assemblies. As earlier mentioned, the fabrication of precast concrete assemblies requires a lower water-cement ration than that required for cast-in-place concrete mixes, hence less water pollution risks. In addition, production is carried out in a controlled factory environment in which wastes are more carefully disposed of, as well as minimised. In such a case, water will tend to be reused at the factory instead of being discharged as run-off.

The difference in the concrete production processes of Binary A and Binary B clearly influence the emission levels generated. In comparison according to the absolute water emission values given by ATHENA, Binary B emphasizes better environmental performance than Binary A.

### 6.1.6 MANUFACTURING AND CONSTRUCTION

To aid the comparative evaluation, ATHENA provided separate estimates of the fossil fuel consumption (FFC) and global warming potential (GWP) of the manufacturing and construction of Binary A and Binary B. The FFC and GWP values are obtained as the summation of the materials and transportation FFC and GWP values for both the manufacturing and construction processes. For Binary A, 2.01E+08MJ of primary energy were produced in manufacturing and 2.72E+07MJ in construction. The manufacturing and construction processes for Binary B, the precast, consumed 1.17E+08MJ and 1.23E+07MJ, respectively.

According to the results, the manufacturing of concrete and associated materials and components for Binary A had higher energy consumption than the actual construction of the cast-in-situ assemblies. The reverse is the case for Binary B. Due to the fact that the precast components are manufactured offsite, there are less transportation needs and therefore less FFC was required for transportation (3.42E+06MJ for Binary B compared to 8.06E+06 MJ for Binary A). Similarly, the material energy demands for Binary B are lower than for Binary A, in both the manufacturing and construction processes. This indicates that the activities leading up to the construction of a precast concrete building (Binary B) are less in demand of materials than in the case of a conventionally constructed building (Binary A).

Manufacturing includes the extraction, transportation and conversion of raw materials to construction materials. Construction comprises the stage by stage production of the finished building. According to the results, in both scenarios, the manufacturing of construction materials is more demanding in energy and generates higher GWP than construction. The most significant reason for this is the high fossil fuel demand from cement production, which as earlier mentioned is the most energy intensive stage (from processes such as quarrying and the calcification of limestone) in a building's pre-occupancy phase. When all is said and done, construction itself is merely the assembly of all the construction materials and components whose energy demands have already been accounted for, thus the lower demand for fossil fuel energy and lower GWP. In comparing Binary A and Binary B, results indicate a significant difference of 46.5% and 43.8% FFC in manufacturing; and 57.2% and 56.4% GWP in construction. Similar results have been indicated in earlier sections of this report. In summary, the manufacturing and construction of the precast concrete assemblies of Binary B had lower FFC and GWP values than did Binary A's cast-in-situ assemblies. This summary is given in Table 6.6. Detailed outputs are given in Appendices H and I.

### 6.1.7 TOTAL PRIMARY ENERGY CONSUMPTION (TPEC) OF THE PRE-OCCUPANCY PHASE

The total primary energy consumption (TPEC) value is given in mega joules (MJ) for all the activities and processes leading up to the production of all the assembly groups. It is the value of the different components of the electrical energy generated (kWh) from all sources, converted to the energy unit Megajoules (MJ). In the case of the UAE, the primary source of electricity is fossil fuels. For Binary A, the TPEC was estimated to be 2.53E+08MJ. The massive post-tensioned floor slab assembly consumed the highest energy, 1.71E+08MJ amounting to 67.7% of the total primary energy, more than half of the total TPEC of the entire Binary A building. The reason for this is the high energy demand associated with the high volume of concrete required to achieve the desired floor slab thickness in order to meet load-bearing design criteria. The CAB assembly had 4.92E+07MJ, equivalent to 19.4%. The walls' TPEC was 7.5%, the foundation gave a value of approximately 3% and the roof had the least TPEC, 2.4%.

Binary B's estimated TPEC was 1.42E+08MJ. Once again, the hollow core floor assembly exhibits the highest energy consumption value, 9.08E+07MJ (63%) of the TPEC as it seen to make up the highest proportion of the structural components, followed by 2.62E+07MJ (18.5%) for the CAB with the least produced by the roof, 5.62E+06MJ (4%), being the least in proportion of the structural components.

Table 6.6: Percentage Savings Comparison for the Manufacturing and Construction of Binary A and Binary B

| Summary measures | Manufacturing | | | Construction | | |
|---|---|---|---|---|---|---|
| | Binary A | Binary B | Binary B Savings Compared to Binary A | Binary A | Binary B | Binary B Savings Compared to Binary A |
| **Fossil Fuel Consumption (MJ)** | 2.00E+08 | 1.07E+08 | 46.50% | 2.85E+07 | 1.22E+07 | 57.20% |
| **Global Warming Potential (kg CO2 eq.)** | 2.01E+07 | 1.13E+07 | 43.80% | 2.03E+06 | 8.86E+05 | 56.40% |

Figure 6.18 gives a comparative representation of the TPEC for both construction scenarios. From earlier mentions, the similarity in design specifications for the foundation assemblies means that there was no difference in the TPEC values for Binary A and Binary B. Other assemblies had marked differences. Binary B had lower TPEC values than Binary A, incurring in savings for the 46.9%, 46.7% 35.6% and 16.7% for the floors, CAB, walls and roofs, respectively. Overall, the TPEC of Binary B was seen to be 1.11E+08 MJ less than that of Binary B. Hence, precast concrete construction incurred a saving of 43.9% in relation to conventional cast-in-place construction.

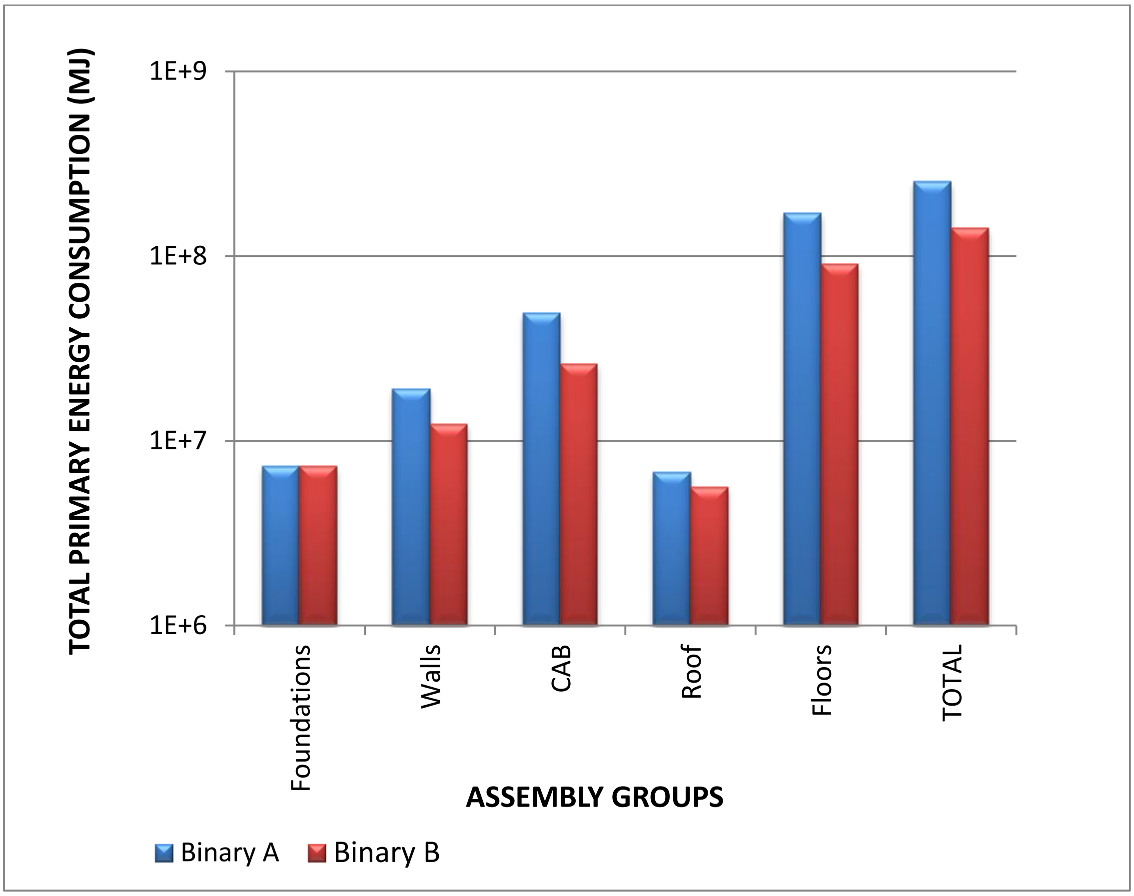



Figure 6.18: Comparison of the Total Primary Energy Consumption of Binary A and Binary B

### 6.1.8 PRE-OCCUPANCY PHASE: FOSSIL FUEL CONSUMPTION (FFC) AND GLOBAL WARMING POTENTIAL (GWP)

The contribution of manufacturing and construction activities for both Binary A and Binary B are discussed in relation to the two primarily significant impact categories in this section, Fossil Fuel Consumption (FFC) and Global Warming Potential (GWP) (also referred to as the GHG emissions) which are usually considered as the most important environmental impacts by LCA researchers. FFC is calculated in Megajoules (MJ) indicating the amount of energy consumed, while GWP is given as the equivalent amount of carbon contained in a mass of material (kg CO2 eq.).

Tables 6.7 and 6.8 show the total values of the FFC and GWP respectively for both Binary A and Binary B, inclusive of the percentage change between these, as obtained from ATHENA. For Binary A, the FFC total was given as 2.42E+08MJ while its GWP was 2.31E+07kgCO2 eq. On the other hand, Binary B had an estimated total of 1.26E+08MJ of FFC and 1.23E+07 kgCO2 eq. GWP. Therefore, Binary B had 48% less FFC than Binary A, and contributed a 46.8% lower GWP than Binary A.

Table 6.7: Fossil Fuel Consumption (FWC) Comparison in the Pre-Occupancy Phase

| Assembly | Fossil Fuel Consumption (FWC) (MJ) | | Binary B Savings Compared to Binary A |
|---|---|---|---|
| | Binary A | Binary B | |
| **Foundations** | 7.04E+06 | 7.04E+06 | 0.0% |
| **Walls** | 1.68E+07 | 2.50E+06 | 85.0% |
| **Columns & Beams** | 4.71E+07 | 2.48E+07 | 47.3% |
| **Roofs** | 6.58E+06 | 5.46E+06 | 17.0% |
| **Floors** | 1.65E+08 | 8.59E+07 | 48.0% |
| **TOTAL** | **2.42E+08** | **1.26E+08** | **48.0%** |

As indicated earlier, FFC is associated with the fuel combustion during cement production, concrete manufacturing and the transportation of concrete and other construction materials. According to USEPA (2008), the sources of GHG have increased over the years, with the greatest contributor being the combustion of fossil fuels. 70% of the FFC comes from the production of cement. This therefore means the more cement and concrete manufactured, the greater the amount of fuel combusted. As results have shown, the production of the assemblies for the precast concrete scenario, Binary B, have required less concrete and other construction products, than the conventional concrete scenario of Binary A. What this translates to is the fact that Binary B's precast construction burns less fossil fuel than Binary A does. The direct implication of this is seen in the tabulated results (Table 6.8).

Table 6.8: Global Warming Potential (GWP) Comparison in the Pre-Occupancy Phase

| **Assembly** | **Fossil Fuel Consumption (FWC) (MJ)** | | **Binary B Savings Compared to Binary A** |
|---|---|---|---|
| | **Binary A** | **Binary B** | |
| **Foundations** | 8.55E+05 | 8.55E+05 | 0.0% |
| **Walls** | 1.17E+06 | 1.54E+05 | 86.0% |
| **Columns & Beams** | 3.51E+06 | 2.26E+06 | 35.6% |
| **Roofs** | 3.98E+05 | 3.13E+05 | 20.9% |
| **Floors** | 1.72E+07 | 8.75E+06 | 49.1% |
| **TOTAL** | **2.31E+07** | **1.23E+07** | **46.8%** |

The foundations of Binary A and Binary B had similar design specifications; hence there was no difference in FFC values for their comparison. The difference is seen in the basement foundation wall assembly used. The precast insulated wall panel used for Binary B saved 85% in FFC and 86% GWP than Binary A's conventionally constructed concrete block wall. The wall assembly is where the highest difference in FFC was observed, in other words, the highest saving in FFC was achieved in the wall assembly. This shows that much less fossil fuel energy is required for the manufacture of precast concrete walls than needed for concrete block walls, thus resulting in reduced GWP. This observation is not limited to the precast concrete walls. All the other precast concrete assemblies showed similar behaviour. The hollow core slabs of Binary B had 48% less FFC need than Binary B and a GWP which was lower by 49.1%. The CAB system of Binary B generated over 47% less FFC than its counterpart CAB system in Binary A along with over 35% savings in GWP. More so, the precast double tee roof of Binary B achieved a saving of 48% in FFC and 20% in GWP.

As usual, the optimised precast concrete production method in addition to the lighter weight of Binary B's assemblies is the factors responsible for the FFC savings and the reduced environmental GWP contribution. The offsite factory environment reduces transportation needs as the materials are transported directly to one location and the finished products delivered directly to another; whereas for cast-on-place concrete, materials need to be gathered from factory to site in several trips as well as the repeated transportation of on-site labour. The use of fewer materials means the use of fewer natural resources which in turn means the need for less manufacturing processes and less transportation energy demand, in addition to the reduced emissions from the manufacturing, construction and transportation of both unprocessed and finished materials.

Finally, comparisons have been made of the assembly groups of Binary A and Binary B to the total values across the FFC and GWP impact categories. As seen in Figure 6.19, the greatest difference in FFC is in the wall assembly. The offsite construction and assembly of the basement walls for Binary B using precast insulated panels had a significantly lower need for fossil fuel energy than the conventional construction of the concrete block walls of Binary A. The precast wall panels are as earlier mentioned considerably lighter in weight yet structurally better performers than the latter. On the other hand, a slight difference is observed between the roof assemblies of Binary A and Binary B. This indicates that there is slightly lower fossil fuel energy combustion for the precast double tee roofs used in Binary B than the traditional reinforced roof system implemented in Binary A. The CAB and floor FFC rations of Binary B are also of lower values than those of Binary A. Overall, the total FFC across tall the assembly groups indicates an approximated 65% (Binary A) to 35% (Binary B). This indicates that the amount of fossil fuel energy required for the pre-occupancy phase of a conventionally constructed high-rise building in UAE is estimated to be twice as much as the fossil fuel demand for a precast concrete high-rise building.

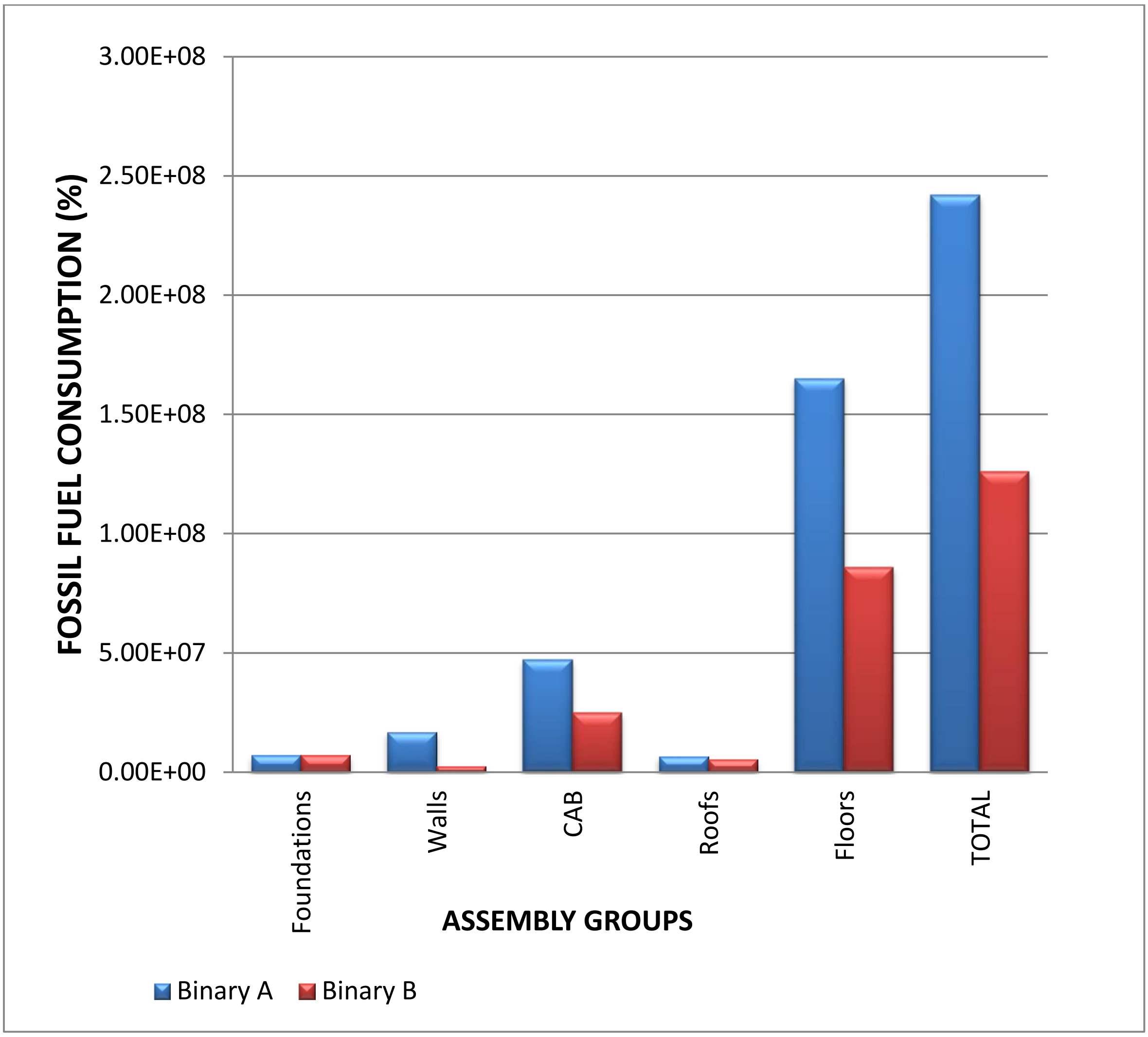



Figure 6.19: Comparison of the Fossil Fuel Consumption (FFC) of Binary A and Binary B

Figure 6.20 summarizes the comparative evaluation of the assembly groups of Binary A and Binary B in terms of the GWP. In the GWP impact category, the results of the FFC impact category are replicated. To expatiate, the walls have the highest difference in GWP, where there is an approximate 90:10 ratio for Binary A to Binary B. the roofs have the closest GWP value of all the assembly groups, while for the floors and CAB assemblies, Binary B indicates less GWP than Binary A. On the whole, the precast concrete building (Binary B) has almost half the GWP of the traditionally constructed concrete building (Binary A). The results of the GWP impact category are markedly similar to the results of the FFC impact category. This indicates the relationship between FFC and GWP. The higher the demand for fossil fuel energy (or the greater the amount of fossil fuel energy burned) for the pre-occupancy phase of a building, the higher its GWP (or $CO_2$ emission), and vice versa.

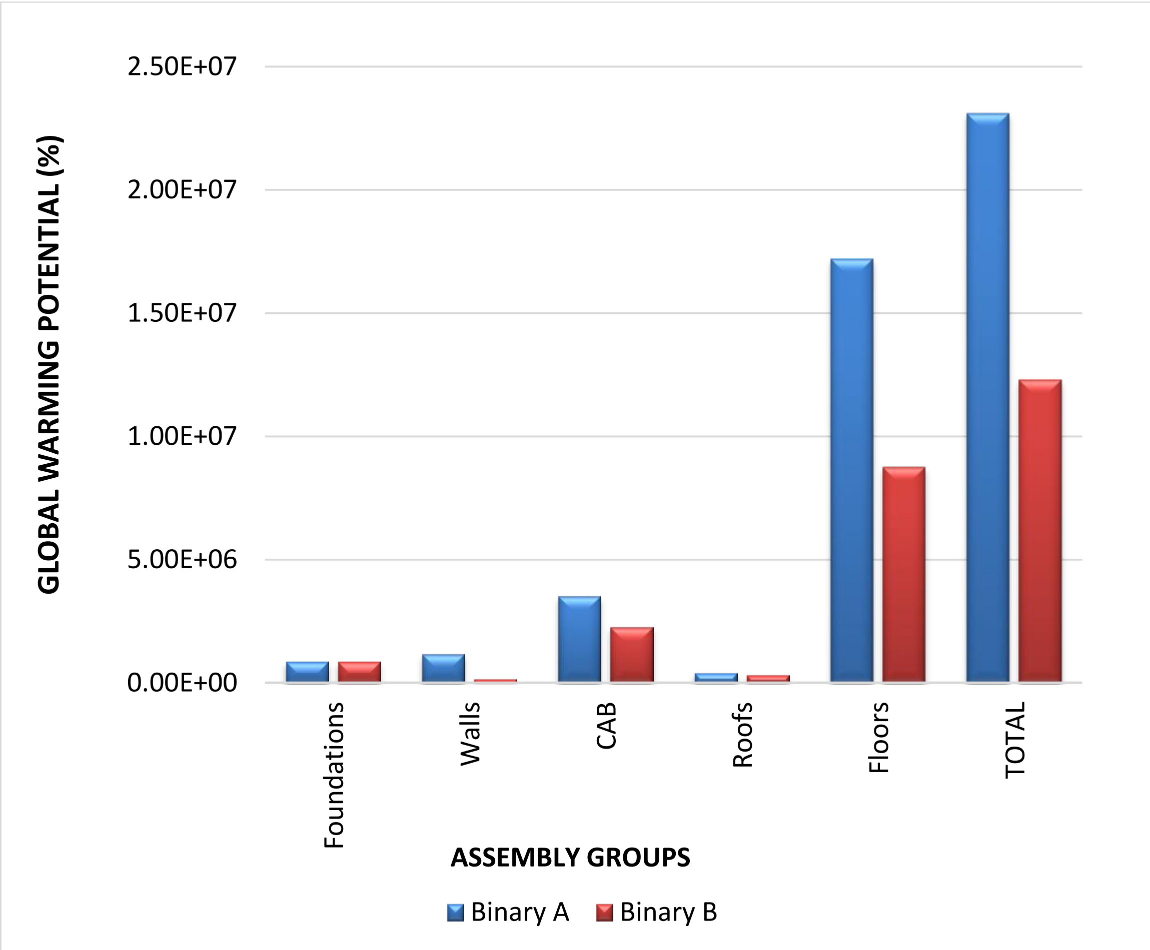



Figure 6.20: Comparison of the Global Warming Potential (GWP) of Binary A and Binary B

According to Bremner (2001), for every tonne of cement produced, almost a tonne of $CO_2$ is emitted. Half of that tonne is generated from limestone decomposition, while the other half is a result of the electricity generation plant for the turning of the kiln and the grinding of the cement, along with the fuel combusted for firing up the kiln. The other operations such as the operation of the ready-mix truck contributes only a minor portion to the total amount of $CO_2$ generated. The production of precast concrete requires lower amount of cement than conventional concrete. The supplementation of conventionally produced assemblies with substantially reduces the GWP, as the results above have indicated.

The maintenance of the building does generate land emissions as indicated in Figure 6.21. Binary A produces very high quantities of bark/wood waste and concrete waste, while Binary B generates none of these wastes. Clearly, these wastes are wastes generated over the building's lifecycle as a result of the initial construction choice of cast-in-situ slabs and walls, as explained earlier on. Conversely, Binary B generates more blast furnace slag and blag furnace dust. This too is the generated waste associated with the post-construction activities of the precast concrete building. Precast concrete is manufactured using fly ash, slag and dust as the cementitious materials, hence the reason for the larger emissions from these than from concrete wastes, and vice versa. In other words, for each construction scenario, the majority of the land emissions are borne from the associated construction concrete content of each scenario.

## 6.2 TOTAL OPERATING ENERGY ANALYSIS AND GHG EMISSIONS

The maintenance and refurbishment needs of both Binary A and Binary B potentially involve the repair of old components or their replacement with new ones. The production of new conventional concrete and precast concrete assemblies, such as walls, floors and roofs, involves the use of concrete and other materials in either case. Therefore, similar to the initial construction phase, construction waste is generated. The difference is that the waste emitted during the occupancy phase is much lower than the waste from the pre-occupancy phase, as there are much less requirements for materials and construction for building renovation and maintenance than there are for the initial, first-time construction of the building. Furthermore, it is observed that the highest generation of land emissions is from other solid waste. This refers to other waste generated apart from the construction wastes. They include emissions from the operation of the building as well as from the replacement of components such as doors, windows, and so on. Figure 6.21 is a comparative illustration of the land emission differences between Binary A and Binary B.

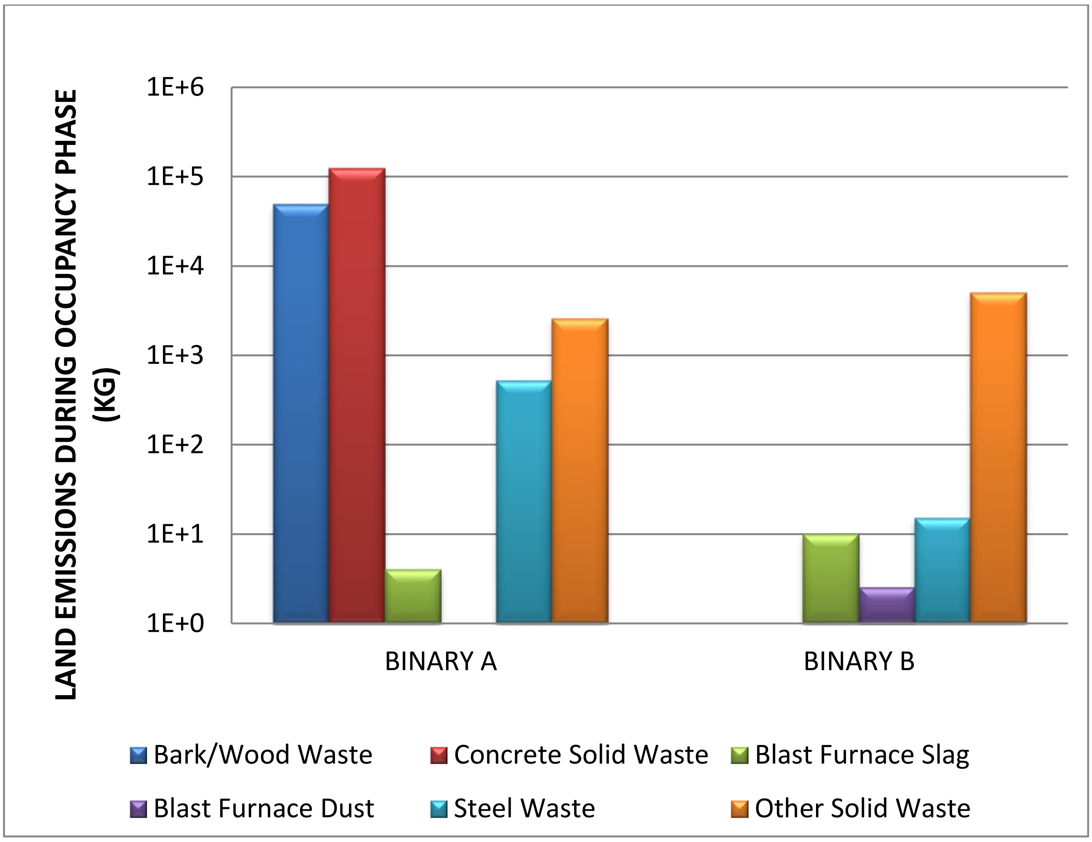



Figure 6.21: Total Land Emissions by Mass Generated from Occupancy Phase

The figure shows that no blast furnace waste was generated from both Binary A and B. Also, there was no concrete solid waste from Binary B. In spite of the varying, significantly large differences in land emissions between Binary A and Binary B, the total land emissions from Binary B are 7.7% lower than the land emissions from Binary A. This shows that the occupancy phase of a precast concrete building is more environmentally friendly than that of a conventionally constructed building in the UAE. Detailed results are seen in Appendices F and G.

### 6.2.1 OCCUPANCY PHASE: FOSSIL FUEL CONSUMPTION (FFC) AND GLOBAL WARMING POTENTIAL (GWP)

The building's occupancy phase consists of all the operational and management activities carried out in the building throughout its 50-year lifespan. The energy required to run the building is measured in terms of the amount of fossil fuel energy the building consumes for lighting, HVAC and occupant-related activities during its life. As mentioned earlier, for every tonne of fuel burnt, there is almost a half-tonne of $CO_2$ generated. These associated emissions of the operational and maintenance activities constitute the GWP of the building's occupancy phase. The FFC and GWP values of both Binary A and Binary B are summarised in Table 6.9.

As depicted in Figure 6.22, the maintenance of Binary A is more energy intensive than that of Binary B, by about 4.5%, while generating 5% more GHG emissions (GWP). Similarly, Binary A requires higher operating energy than Binary B. Binary B is seen to save 7.2% in FFC than Binary B, with 7.3% less associated GHG emissions. This implies that more than just in the pre-occupancy phase, a precast concrete building is more environmentally friendly even in the occupancy phase of the building, than a conventionally constructed concrete building.

### 6.2.2 TOTAL PRIMARY ENERGY CONSUMPTION (TPEC) OF THE OCCUPANCY PHASE

Similar to the pre-occupancy phase, the TPEC value is given in mega joules (MJ) as a converted value of the electrical energy generated (kWh) from all sources for all building's operation. These operations include area and task lighting, power supply for HVAC systems, and so on. The TPEC values of Binary A and Binary B during the occupancy phase are presented in Figure 6.23.

The TPEC from maintenance activities, 3.00E+06MJ and 3.81E+06MJ, are negligible (about 0.04% in each case) in comparison to the operating energy requirements by the both case study buildings. As discussed, more energy is required for the building systems and operation than its maintenance in either case study scenario. According to the chart, Binary A consumes 9.40E+09MJ while Binary B generates 8.72E+09MJ. From this, it can be seen that Binary B actually saves more energy than Binary B, as much as 7.2%. This is an indicator of the energy saving potential of precast concrete construction in comparison to the conventional cast-in-situ concrete method.

Table 6.9: Percentage Savings Comparison for the Occupancy Phase of Binary A and Binary B.

| Summary measures | Maintenance | | | Operating Energy | | |
|---|---|---|---|---|---|---|
| | Binary A | Binary B | Binary B Savings Compared to Binary A | Binary A | Binary B | Binary B Savings Compared to Binary A |
| **Fossil Fuel Consumption (MJ)** | 1.90E+06 | 1.05E+06 | 4.50% | 7.60E+09 | 7.05E+09 | 7.20% |
| **Global Warming Potential (kg CO2 eq.)** | 8.10E+04 | 3.94E+04 | 5.00% | 4.68E+08 | 4.34E+08 | 7.30% |

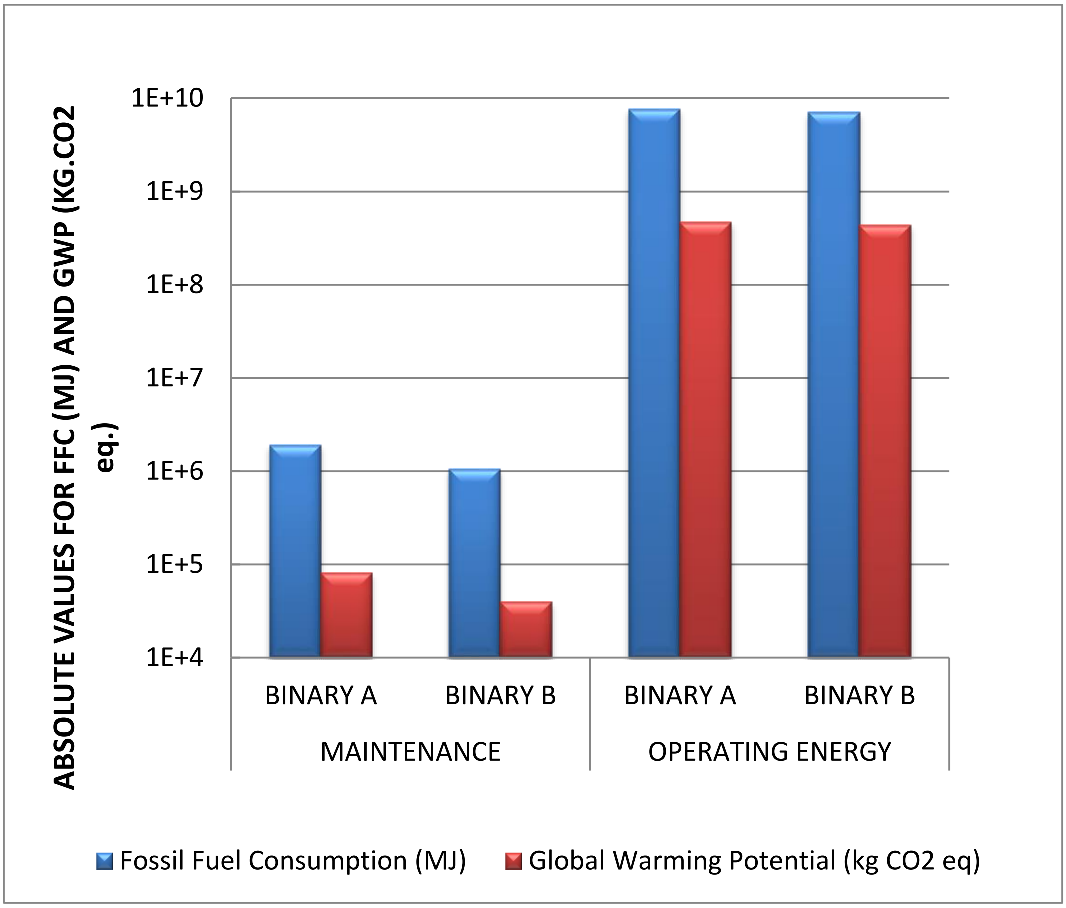



Figure 6.22: Absolute Values of FFC and GWP in the Occupancy Phases of Binary A and Binary B.

## 6.3 DECOMMISSIONING

In this section, an account of the total energy demand for the post-occupancy/end-of-life, also referred to as decommissioning energy, of the case study building is given. For both construction scenarios, the total decommissioning energy and GHG emissions are the totality of the energies generated during demolition, along with the demolition machinery implemented in the process. It also includes the energy required for the removal and transportation of the generated demolition wastes to the landfill site, the assumed final destination.

At the EOL of a building, waste is generated and deposited to land, thereby causing the release of emissions to land. As seen in Appendices F and G, the only land emission reported by ATHENA was from ‘other solid waste’ (OSW), waste from other sources exclusive of the construction wastes (concrete waste, steel waste, wood waste, blast furnace slag and blast furnace dust). This result is expected as there are no manufacturing or construction activities during the decommissioning of a building. The results indicate that 8.41E+03 kg of OSW were produced from the decommissioning of Binary A. Binary B was estimated to have produced 6.35E+03kg of OSW, that is 24.5% less land emissions than Binary A. This once again indicates the significantly higher advantage of a precast concrete building in the UAE to land than a conventional building would provide.

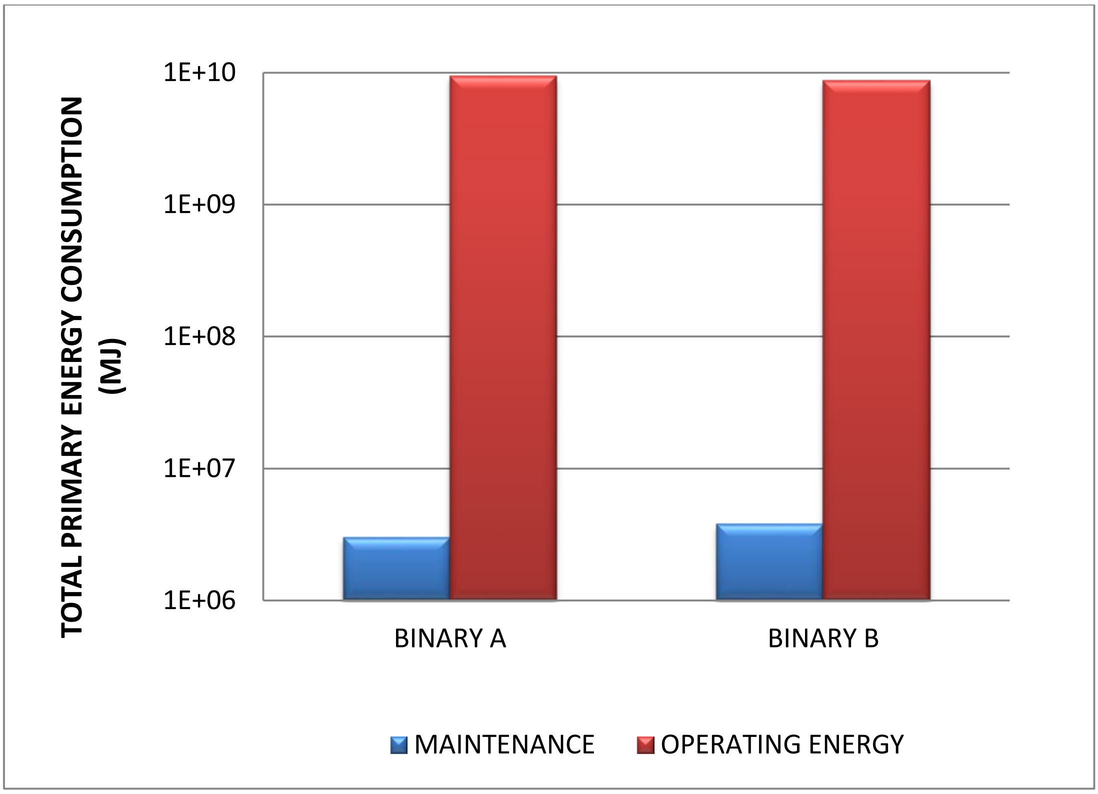



Figure 6.23: Total Primary Energy Consumption (TPEC) During the Occupancy Phases of Binary A and Binary B.

From the appendices, it is observed that Binary B generated less water emissions than Binary A, although the emissions to water are negligible. There were no recorded air emissions, that is no air pollutants or emissions were produced at the end of the 50-year span, for either Binary A or Binary B. This means that construction technique, whether conventional cast-in-place concrete or precast concrete technique, does not have any impact on the post-occupancy phase of a building. As with the other phases, the FFC and GWP are considered the most significant impact categories of the post-occupancy phase of the case study building based on ATHENA's results. The FFC for Binary A and Binary B were estimated at 1.22E+07MJ and 9.2E+06MJ. From this, Binary A is calculated to have 25.8% more fossil fuel energy demand than Binary B. In terms of GWP, Binary A had a value of 8.48E+05 kgCO2eq., whereas Binary B has a value of 6.40E+05 kgCO2eq. This means that Binary B had a 26% lower GWP value than Binary A, once again asserting the viability of precast concrete construction as an alternative to conventional cast-in-situ construction, in terms of saving on the need for the use of fossil fuel for energy production, as well as mitigating the generation of GHG.

Electricity is required for this phase of the building in order to power the demolition equipment for the building's demolition. This energy demand is converted to the TPEC. For Binary A, the TPEC is given as 1.25E+07MJ while Binary B has a TPEC value of 9.22E+06MJ. With a 26.2% less TPEC value required for the building's decommissioning, and as with all the other phases of the case study building, the TPEC of Binary B is seen to be lower than that of Binary A.

As stated in the methodology chapter of this study, no account is made for the potential energy savings from either the recycling of materials or the use of recycled materials recovered from the demolition waste, as ATHENA does not include these data in its LCA. However, as also mentioned earlier, previous studies assert that the recovered energy only accounts for not more than 1% of the overall building energy and is therefore not significant to the results of the study. Nevertheless, the renewal, reuse and recycling (3Rs) potentials of the waste materials from the post-occupancy phase of the building in the conventional and precast concrete scenarios, and a comparison of both is made.

## REDUCE, REUSE, RECYCLE (3Rs)

The 3Rs of waste reduction are applicable in building construction.

One unique feature of precast concrete components is that they each product is individually engineered to facilitate disassembly. This is a noteworthy benefit of precast concrete technology compared to conventional construction. Building design is simplified as decisions on the future applications of these dismantled components can be made easily. Once disassembled, these components can provide other uses. This reduces the amount of material required for construction as well as toxicity of waste materials. Reuse of precast concrete components is only possible by virtue of their durability. Precast modular and sandwich panels such as was used for the foundation walls, lend durability to the building's interior and exterior. This characteristic as well as the low-maintenance needs of precast concrete surfaces, lengthens the service life of the components. As durability enhances reusability, precast concrete proves to be sustainable in construction. Firstly, the depletion of natural resources is greatly minimized; solid waste contribution to landfills is significantly reduced; and finally, the generation of air and water pollutants is mitigated. In comparison, conventional concrete components do not have the option for piece-by-piece disassembly. Once a conventional concrete building is demolished, it is only useful as debris for reuse or recycling.

Precast concrete is downcycling-friendly, much more so than conventional concrete. This means that when broken down, the dismantling of precast concrete construction materials requires a very low amount of energy, (less than would be demanded by conventional concrete) and the inherent qualities of precast concrete are better retained. The down-cycled precast concrete is reusable in such applications as shoreline protection; precast concrete could be crushed and used as aggregate for new concrete production, or as base materials for concrete slabs, roads or sidewalks. This alternative use eliminates the need for costly recycling procedures. Furthermore, by incorporating industrial wastes (fly ash, slag, and silica fume), which would otherwise go to landfills, as supplementary materials for cement, the amount of cement required for concrete will be reduced significantly. This would also improve upon the performance of the newly produced precast concrete (PCI, 2012).

The general assumption is that at a precast concrete factory, 2% of the produced concrete is waste, and of this 95% is beneficially applied for the fabrication of new components. Furthermore, the amount of concrete used for manufacturing a particular component is reduced, which subsequently reduces its weight, transportation cost and the energy required for its erection; at the same time environmental degradation is minimized (Mid-Atlantic Precast Association, 2012).

The results of the post-occupancy phase indicate that at the end of the 50-year lifespan, Binary B, the precast concrete building, offers better potential for application of the 3Rs than Binary A, the conventional concrete building.

## 6.4 OVERALL ENERGY

The overall energy of the building is a sum of the embodied energy and the operational energy of the building throughout its lifespan. The given values comprise all the energy associated with the pre-occupancy, occupancy and post-occupancy phases of the building.

The embodied and operating energy demands of Binary A and Binary B were calculated and combined in order to determine the total energy needs of both case study scenarios over a 50-year lifespan. ATHENA estimates the overall energy values for both the FFC and its associated GWP as separate values. These results are discussed in the next section.

In calculating the overall energy of the building, ATHENA considers the total (embodied and operating) FFC and total (embodied and operating) GWP. The overall energy values are given in Table 6.10.

### 6.4.1 TOTAL GLOBAL WARMING POTENTIAL (TGWP)

The Total GWP (TGWP) is given as the sum of the embodied GWP and operating GWP. For Binary A, the total FFC is as summed up from the values in Table 6.10.

Therefore, Binary A has a total GWP of 4.90E+08 kg$CO_2$ eq. The embodied GWP (EGWP) accounts for only 5% of the total, meaning that the required operating GWP (OGWP) is 95% of the total GWP.

Similarly for Binary B, TGWP = EGWP + OGWP. From this, the TGWP for Binary B is given as 4.50E+08 kg$CO_2$ eq. The EGWP makes up 3% of the TGWP, leaving 97% for the OGWP.

Table 6.10: Overall Building Energy

| **Summary measures** | **Embodied Energy** | | | **Operating Energy** | | |
|---|---|---|---|---|---|---|
| | **Binary A** | **Binary B** | **Binary B Savings Compared to Binary A** | **Binary A** | **Binary B** | **Binary B Savings Compared to Binary A** |
| **Fossil Fuel Consumption (MJ)** | 2.42E+08 | 1.30E+08 | 46.3% | 7.60E+09 | 7.05E+09 | 7.20% |
| **Global Warming Potential (kg CO2 eq.)** | 2.31E+07 | 1.29E+07 | 44.2% | 4.68E+08 | 4.34E+08 | 7.30% |

As seen from the results in Figure 6.24, the EGWP of the manufacturing, transportation and construction of the case study building represent a minute portion of its TGWP in comparison to the 50-year lifespan OGWP from the building's operation and maintenance. In comparing the above values, Binary B produces less TGWP, an approximate 9%, than Binary A. Thus, Binary B shows better performance in terms of both embodied and operating environmental impacts than Binary A.

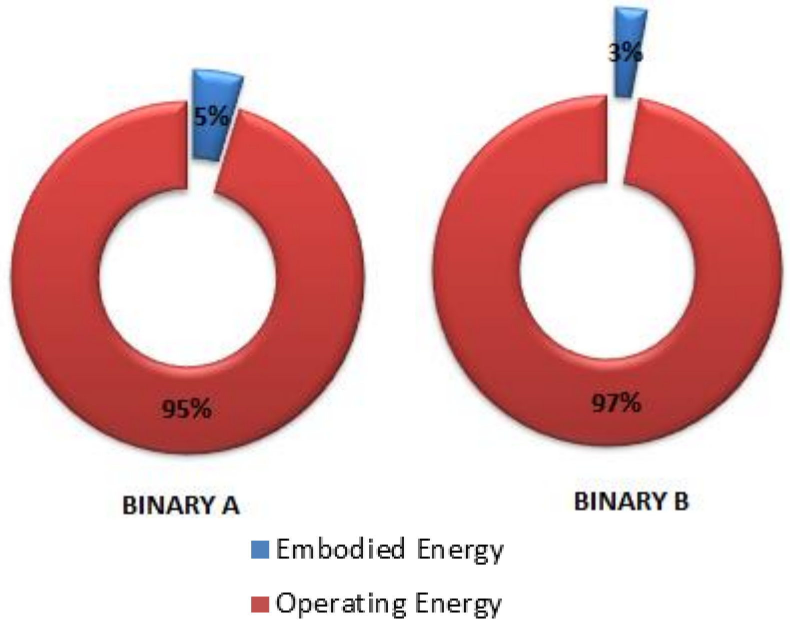



Figure 6.24: EGWP versus OGWP of Binary A and Binary B

### 6.4.2 TOTAL FOSSIL FUEL CONSUMPTION (TFFC)

As was calculated earlier, the total FFC (TFFC) is the sum of the embodied FFC and the operating FFC (OFFC).

For Binary A, the TFFC is summed up to be 7.83E+09 MJ. The EFFC makes up 3% of this total; in other words, Binary A requires 97% of its TFFC to meet its operating demands over the 50-year lifespan. Similarly, the TFFC for Binary B is 7.17E+09 MJ. The EFFC is 2% of the total, thus the OFFC represents 98% of the total energy 50 years after its construction. Figure 6.25 gives an illustration of the ratio of EFFC to OFFC for both Binary A and Binary B.

A comparison of the total embodied FFC and GWP for both Binary A and Binary B are given in Figure 6.26. As seen, Binary B exhibits a lower embodied FFC and GWP overall than Binary A. Similarly, the total operating FFC and GWP are illustrated in Figure 6.27, where it is seen that Binary B had lower operating energy needs in its 50-year lifespan than Binary A.

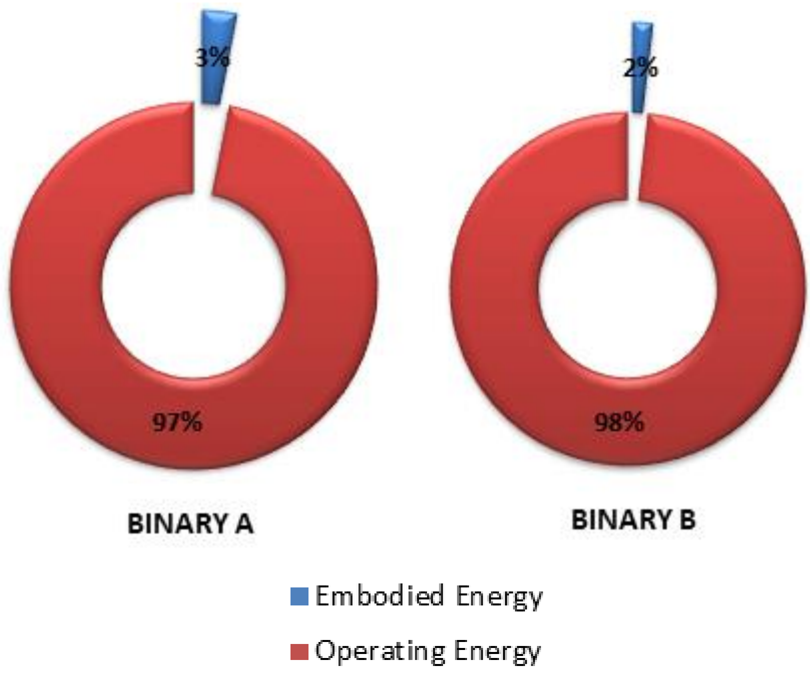



Figure 6.25: EFFC versus OFFC of Binary A and Binary B

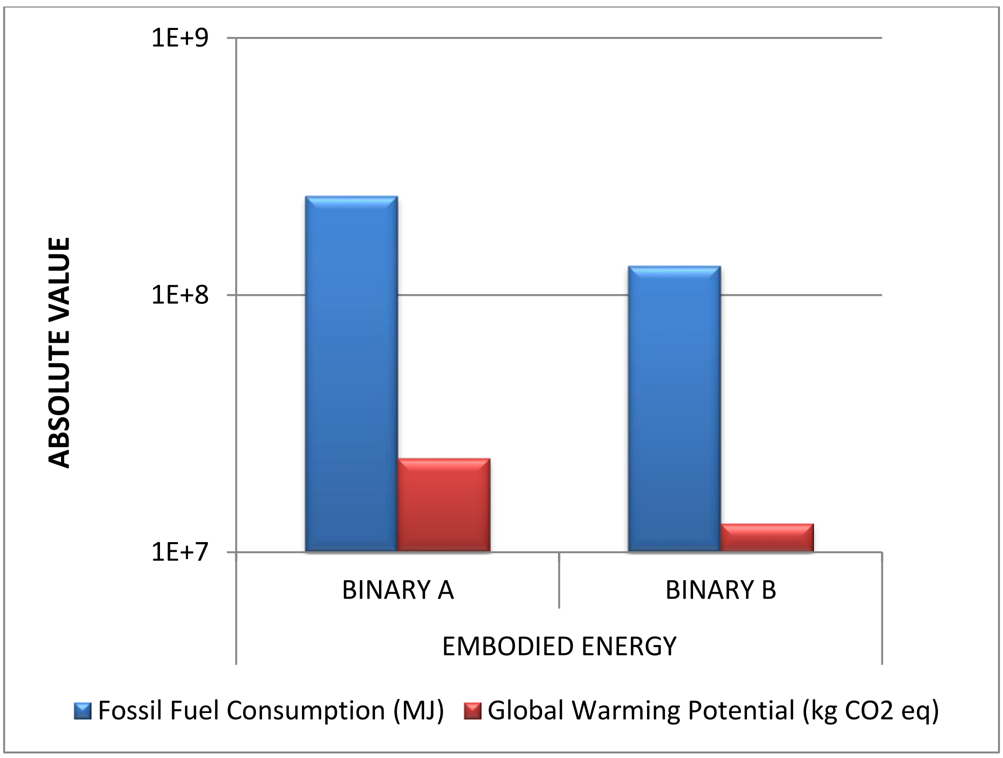



Figure 6.26: Total Embodied FFC and GWP

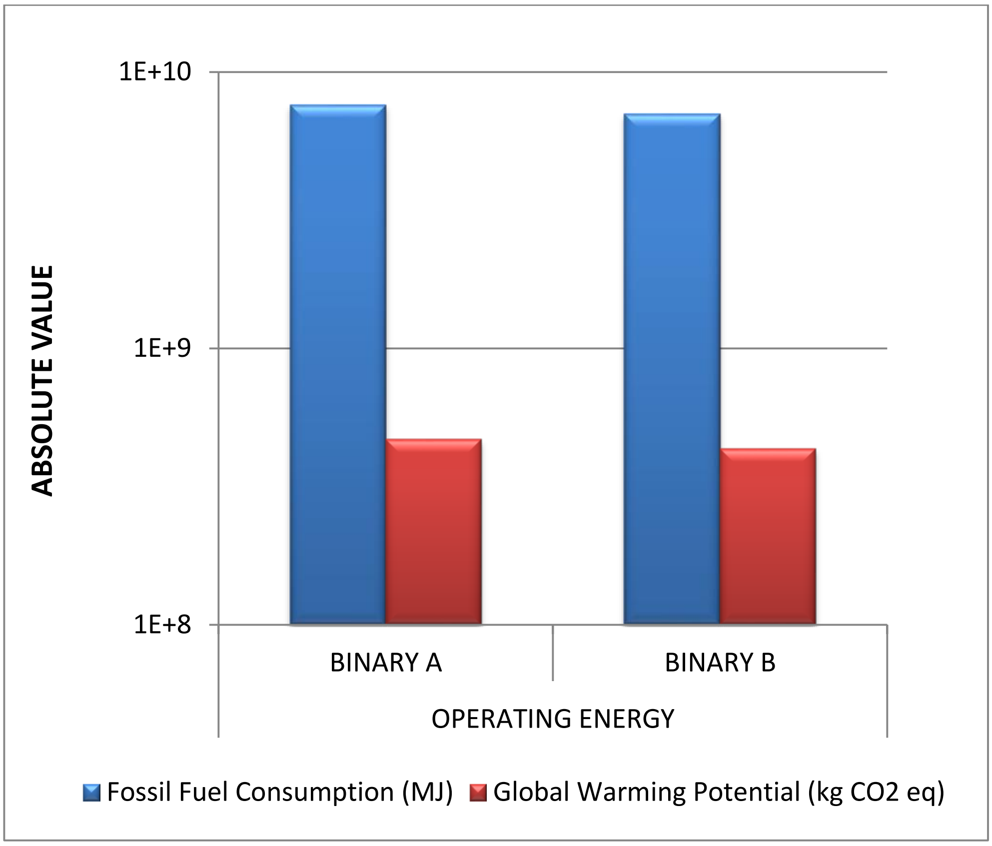



Figure 6.27: Total Operating FFC and GWP

By comparison, Binary A has a higher FFC value than Binary B. Binary B expends 46.2% less energy in its construction, as seen from the values of embodied energy, than Binary A. This shows the significant influence of the type of construction for a high-rise building on its embodied effects on the environment. In addition, during its 50-year life span, the operating energy demands of Binary B are 7.2% less than the demands for Binary A in the same lifespan. Overall, Binary A consumes approximately 10% more energy, measured in TFFC, than Binary A. also, Binary B has a 9% less output of GHG emissions, measured in TGWP. The reduced energy consumption advantages of Binary B over Binary A can be attributed to the savings achieved as a result of the optimization in material and construction which precast concrete construction provides. An optimized precast concrete system results in structural members with longer spans, higher strengths and less on-site material requirements. The need for fewer materials has been shown to have a major influence on the result of the overall embodied energy advantage shown by Binary

B over Binary A, as fewer materials needs directly translate into less need for natural resources and less energy demand in manufacturing and transportation, the consequences of which are economic and environmental impact savings. This indicates that Binary B shows better promise as a building construction system than Binary A.

The results above clearly indicate that the proportion of embodied energy to operating energy demands is negligible in terms of the overall energy requirements of the building during its lifespan. This is whether the energy is determined in terms of FFC or GWP. This therefore supports the results of studies that have shown that the operating environmental effects of a building outweigh by far its embodied effects after its lifespan. That being said, the results indicate that Binary B represents less operating energy needs in its occupancy phase than does Binary A. Therefore, employing precast concrete technology to the construction of a high-rise commercial building in UAE using has less environmental (embodied and operating) effects than one constructed using the conventional cast-in-situ concrete.

## 6.5 LIFE CYCLE ENVIRONMENTAL IMPACTS

The impact categories used by ATHENA to determine the environmental impacts are FFC, GWP, acidification potential, human health (HH) criteria, eutrophication potential, ozone depletion potential and smog potential. The results of the environmental impacts are summarised in Table 6.11 and then discussed in detail. In Appendices H and I, the values of the impact categories are demonstrated explicitly for all the life cycle stages of the building under study for Binary A and Binary B, respectively.

As indicated from the results, FFC, GWP and acidification potential had the highest environmental impacts for both case study scenarios. The results are illustrated in Figure 6.28 and discussed thereafter.

Table 6.11: Summary Values of Environmental Impacts of Binary A and Binary B for the 50-year lifespan

| Impact Categories | Binary A | Binary B | Binary B Savings Compared To Binary A |
|---|---|---|---|
| **Fossil Fuel Consumption (MJ)** | 7.84E+09 | 7.17E+09 | 10.0% |
| **Global Warming Potential ($kgCO_2$ eq.)** | 4.91E+08 | 4.47E+08 | 9.0% |
| **Acidification Potential (moles of H+ eq.)** | 1.92E+08 | 1.76E+08 | 8.3% |
| **Human Health (HH) Criteria (kg PM10 eq.)** | 8.18E+05 | 7.05E+05 | 13.8% |
| **Eutrophication Potential (kg N eq.)** | 3.71E+04 | 3.16E+04 | 14.8% |
| **Ozone Depletion Potential (kg CFC-11 eq.)** | 1.85E-01 | 7.48E-02 | 59.6% |
| **Smog Potential (kg $O_3$ eq.)** | 9.04E+06 | 8.13E+06 | 10.1% |

**a.** **FFC:** The highest environmental impact, FFC, was the largest contributor to the overall environmental impacts in both scenarios. The high emissions could be attributed to the amount of fossil fuel combustion during the operations of the building, as a result of the occupancy phase of the building's lifespan, particularly the generation of electricity. Although each impact category symbolizes the various emissions for the impact categories used for this LCA study, there are generally not more than three major pollutants responsible for the total impact. Binary B was proven to have 10% less FFC than Binary A, reasons for which have been discussed in earlier sections.

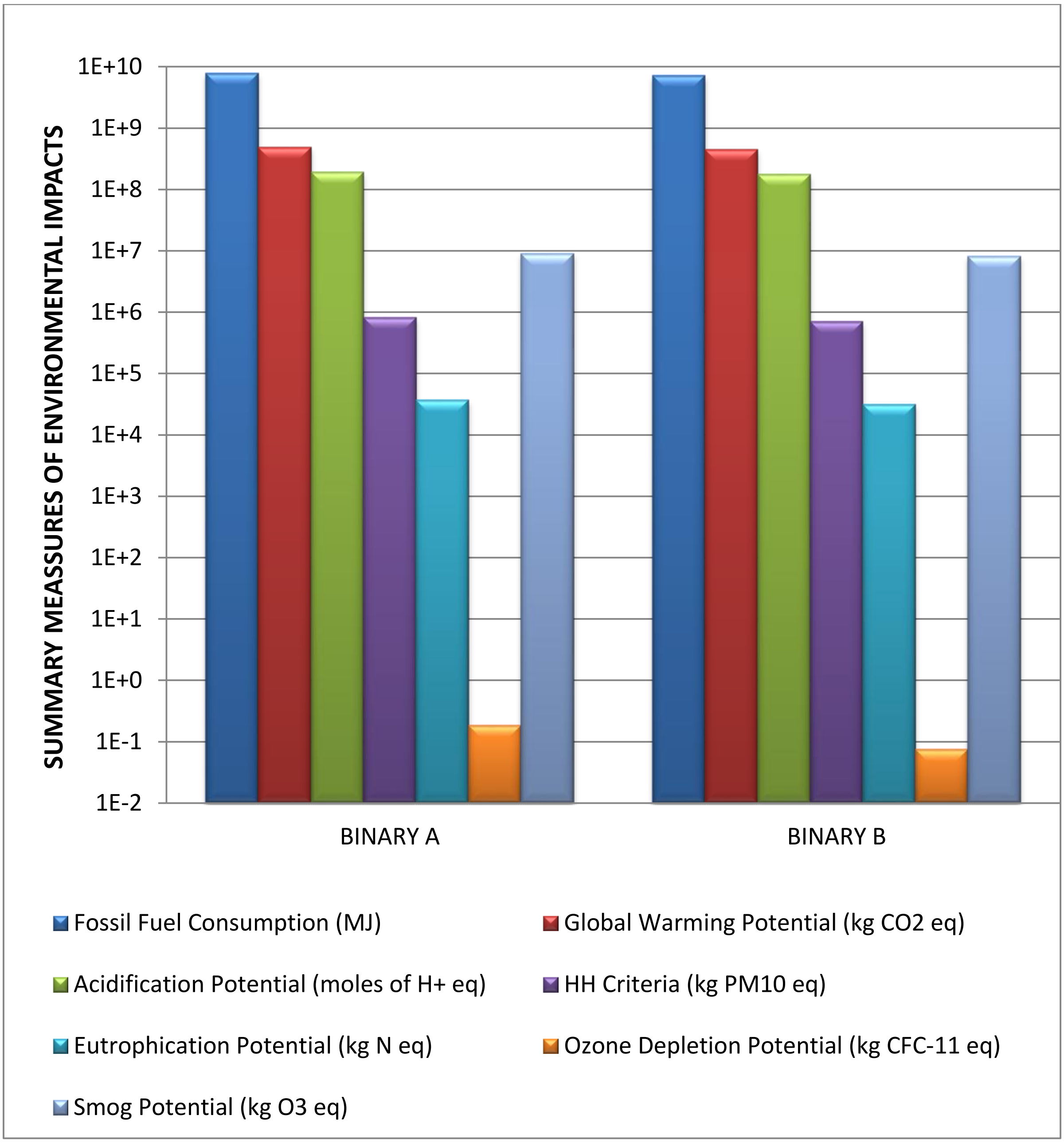



Figure 6.28: Distribution of Lifecycle Environmental Impacts for Binary A and Binary B

**b.** **GWP:** GWP is defined as a measure of the contribution of a building to global warming in relation to the contribution of the same mass of $CO_2$ (Union Investment, 2012). The total lifecycle GWP, similar to FFC, is mostly the result of the occupancy phases of the case study buildings, as was indicated by the study's results. This high impact category is a close match of the life cycle energy dissemination due to the carbon release associated with the energy generation from the combustion of fossil fuels. Due to the FFC associations, the GWP shows similar distribution to the FFC results - GHG emissions of Binary B were seen to be lower than those of Binary A by a value equal to 9%.

**c.** **ACIDIFICATION POTENTIAL:** Acidification is defined as the conversion of air-borne pollutants to acid (Union Investment, 2012). This occurrence is a result of the direct outlets of acids or gases that upon contact with humid air, form acids. The deposits of these acids to water bodies and soil are the cause of the negative environmental impact. Acidification potential ranks third highest, on the heels of FFC and GWP, in the list of impact categories. The major elements associated with this are Sulphur Oxides (SOx), Ammonia ($NH_3$) and Nitrogen Oxides (NOx) emissions to the air European Commission (2012), primarily from the FFC for cement manufacturing, materials and components transportation during the pre-occupancy phase, as well as electricity generation for space cooling, area lighting and direct water heating, during the building's occupancy phase. In addition, the production of cement and steel during construction contributes to the acidification potential but only to a small degree. This is also the case with the transportation and decommissioning activities at the end of the building's lifecycle. It can be observed that the acidification potential of Binary B is lower than that of Binary A by a measure of 8.3%.

**d.** **HUMAN HEALTH CRITERIA:** Human Health criteria impact category is sub-divided into cancer, non-cancer, and criteria pollutants, according to Environmental Protection Agency (EPA) regulations. Criteria pollutants include various sizes and types of particulate matter. It was seen earlier that the air emissions from particulates (particularly $PM_{2.5}$ and $PM_{10}$) had one of the highest values of all air emissions. These emissions relate particularly to human respiratory impacts and are associated with such diseases as asthma, bronchitis and emphysema (Bare, 2011).

Adverse health effects begin as early as the manufacture of cement for concrete production. According to Bremnrer (2001), the health of labourers is at risk due to the increased content of chromium in cement which is mostly derived from the incineration of construction waste products. The only viable solution would be the prevention of fresh concrete with human flesh. Another health hazard of cement production is the extraction of sand and gravel at quarries which is responsible for the occurrence of visual pollution. These health hazards are mitigated when the amount of cement required for construction is reduced. Precast concrete production offers this solution as a reduced quantity of concrete - and therefore cement – is required for building construction.

Additionally, noise pollution is another health risk, although it is not a major public concern. The cause of this is the noise from ready-mix batch plants and the heavy construction machinery. Although the location of batch plants (for conventional concrete production) as well as offsite factories (for precast concrete manufacture) at a far-off location from habitation mitigates this health hazard. The use of superplasticizers for the production of high slump concrete that requires vibration is another way this risk has been mitigated (Bremner, 2001). During the occupancy phase of the building, the use of precast concrete assemblies such as precast insulated wall panels acts as a buffer between outdoor noise and the interior spaces of the building. Although conventional concrete walls with thick masses reduces sound (more so, the thicker the walls), precast concrete walls are known to provide better sound barriers, especially in situations where buildings are constructed close to each other in order to save land space; and they are produced using lightweight concrete thus reducing the volume of concrete required for construction, thereby mitigating health risk (PCI, 2012).

The LCA result shows that as much as 13.8% is saved on the risk to human health when precast concrete technique is applied for building construction in comparison to the application of conventional concrete construction technique.

**e.** **<u>SMOG POTENTIAL:</u>** Smog potential was previously considered part of the HH criteria because of the health effects associated with smog emissions. For this case study, the smog potential was seen to have a higher impact than the HH Criteria. This impact category is related to the air emissions which were seen to be very high during the manufacturing and construction activities in the pre-occupancy phase of the case study building under both scenarios. Again, the majority of smog potential is associated with cement production. Particulate air emissions are generated from the kiln dust released and re-used during cement manufacture, and also from asphalt production. More so, smog and particulate emissions occur due to FFC during transportation. This has led the EPA to mandate the use of cleaner vehicle fuels and the use of precast concrete for building construction is encouraged as there is less demand for cement in the precast construction technique than there is for conventional cast-in-place concrete. The results provided by ATHENA revealed that the precast concrete building (Binary B) mitigated the negative impact of smog potential and air pollution by 10% in comparison to conventional concrete building, Binary A. Another suggestion is the installation of high-albedo walls and roofs in buildings as a cost-effective means to the reduction of the negative impact of smog (PCI, 2012).

**f.** **<u>OZONE DEPLETION:</u>** Ozone is formed from the mixture of VOC and NOx in sunlight. Ozone depletion contributes the least of all the environmental impact categories. According to Scheuer, Keoleian and Reppe (2003), this could be due to the fact that materials and processes associated with ozone depletion, which were formerly used for buildings, are being phased out gradually. Ozone depletion is attributed mainly to ozone-depleting substances (ODS0, the most common of which are: chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl bromide, methyl chloride, and Halon 1301, among others. These ODS are responsible for the degradation of construction materials. Their breakdown under sunlight releases chlorine and bromine atoms. Ozone released close to the ground poses harmful health effects such as coughing, asthma, sore throat and other respiratory problems (Bremner, 2001). Ozone depletion showed the highest percentage change between Binary A and Binary B, in which the latter was seen to have 60% savings in this impact category than the former. The apparent reason for this is the controlled fabrication environment obtained in the precast concrete construction factory, as well as the reduced need for construction materials, thus the negative impact of ODS is significantly reduced.

**g. <u>EUTROPHICATION POTENTIAL (EP):</u>** Eutrophication is the "transition of water or soils from a nutrient-poor to a nutrient-rich state" (Open House, 2012). It is a result of the emergence of nutrient supply (particularly phosphor and nitrogen compounds) as a result of the manufacture of building products. However, the main cause is the emissions which are washed out into the environment. The PO4 is the main pollutant associated with EP. The lower the PO4 value, the lower the EP, and therefore the lower the environmental and health impacts. EP (otherwise referred to as nitrification potential) is based on water, air and soil emissions. Once again, the occupancy phase of the building's lifecycle bears major responsibility for this impact, although in relation to FFC and GWP, its overall contribution is somewhat insignificant. The release of Nitrogen Oxide (NOx) is seen to come from the energy consumption due to the FFC used during the activities carried out in the building's occupancy phase, and is also associated with the cement production (PCI, 2012). Based on results, Binary B was deduced to have a lower EP, having about 15% less than Binary A. Generally, the results of the impact categories, while significant in cases such as FFC, GWP and acidification potential, are less in impact in Binary B than in Binary A. The given results indicate that on the whole, a precast concrete building results in less environmental impact than a conventionally constructed building. This study did not include a simulation and LCA of different precast concrete technologies that could be applied to Binary B. However, with the ever-increasing precast systems becoming more available in the construction industry, perhaps there is the potential for even better optimization of the precast concrete technology to further reduce its embodied effects on the environment. More so, efforts should be aimed at the reduction of energy demand in the building's occupancy phase.

On the whole, Binary B showed better environmental performance than Binary A in terms of the eight different impact categories used for the LCIA. It can therefore be concluded that precast concrete construction technique has proven to be a more viable construction method than conventional cast-in-place construction technique for constructing high-rise buildings in the UAE.

## 6.6 PRECAST SCENARIO COMPARISONS

One important aspect this study aimed to consider was an analysis to show the proportion of savings in a case of semi-prefabrication. That is, where the some components are precast and others are conventional, in order to determine the potential savings which could be achieved. However, due to the constraints of ATHENA, this analysis could not be carried out. Alternatively, an analysis was made to determine the most optimized precast concrete scenario. The floor assembly was selected for this comparison, as it was the greatest portion of the entire structural assembly. As such, an alternative floor assembly, the precast double tee floor was simulated and tagged as Binary B1. All other parameters were kept constant, and the structural integrity of the building was not compromised in this analysis.

Double tee floors are constructed of two prestressed ribs together with a connecting top slab. Both the ribs and the slab have variations of thicknesses, depending on user configurations. Similar to hollow core slabs, double tee floors have the advantage of being lightweight and versatile, providing excellent structural strength and maximum durability, first-rate acoustic and fireproofing properties, and providing accelerated construction with less costs (Banagher Precast Concrete, 2011; Stresscrete, 2012). Therefore, the purpose of this comparison was to determine which of the two floor assemblies would provide better environmental performance for The Binary.

As seen in Table 6.12, the following categories were compared: resources used (solid materials, water and crude oil), land emissions, FFC and GWP impact categories. The results indicated that Binary B achieved savings in all compared parameters in comparison to Binary B1. The hollow core floor slabs of Binary B were seen to consume less resources in their production than the precast double tee floors. As seen, 8.4% savings were achieved in the solidi resources (which include limestone, clay and shale, aggregate and coal), while water and crude oil were 12.1% and 8% less in requirement. These savings are a result of the manufacturing process involved in these compared floors. Although both assemblies are manufactured from lightweight concrete, hollow core floors require less concrete than double tee floors. Therefore, the cement to water ratio will equally be less as indicated in the savings in water.

The manufacturing and transportation of double tee floors was seen to contribute more to land emissions than the processing of hollow core floors. As seen in Table 6.13, as much as 28.7% is emitted as concrete waste, a pointer to the earlier mentioned fact that the more the concrete requirement, the greater the potential for its waste at the end of production. The highest savings however were seen in the blast furnace slag, a component of limestone, which is the principal material for cement production. The high content is as a result of the high content which is necessary to improve the compressive strength of the double tee floor (National Slag, 2009). However, while the structural property of the double tee floor is increased, its environmental impact is equally increased. Similar results are observed in the other types of land pollutants, each saving is attributed to the fact that Binary B's hollow core floor slabs require less material for construction and as such have less environmental impacts.

Since the floor assembly of Binary B1 consumed more resources in its manufacture, it follows that the double tee floors consumed more fossil fuel for manufacturing and transportation and therefore generated a higher GWP than Binary B's hollow core floor slabs. A saving of approximately 8% was achieved in FFC and 7.4% in GWP by Binary B relative to Binary B1.

The results indicate that more than just the choice of precast concrete construction is the need to select the precast assembly system that will optimize the advantages of precast concrete technology, such as energy and resource savings, as well as minimize waste and environmental emissions. However, the values for Binary B1 in the compared parameters were still lower than those of Binary A. This indicates that precast technology is still advantageous over conventional concrete construction.

Table 6.12: Comparison of the Floor Assemblies of Binary B and Binary B1.

| Parameter | Binary B | Binary B1 | Binary B Savings Compared to Binary B1 |
|---|---|---|---|
| **Solid Materials (kg)** | 1.85E+07 | 2.02E+07 | 8.4% |
| **Water (litres)** | 3.55E+07 | 4.04E+07 | 12.1% |
| **Crude Oil (litres)** | 7.26E+05 | 7.89E+05 | 8.0% |
| **Land Emissions (kg)** | 9.93E+05 | 1.31E+06 | 24.2% |
| **FFC (MJ)** | 8.59E+07 | 9.33E+07 | 7.9% |
| **GWP (kg $CO_2$ eq.)** | 8.75E+06 | 9.45E+06 | 7.4% |

## 6.7 ECONOMIC ANALYSIS

Besides the environmental impact assessment, the integration of economic analysis into the LCA of this study is important in order to determine the most cost-effective or economically-efficient construction alternative between conventional construction and precast concrete construction. Economics analysis is defined as the "monetary evaluation of alternatives for meeting a given objective" (Whole Building Design Guide, 2012, p. 1). The basis of the evaluation is a comparison of benefit-cost ratio over a fixed duration. The limitation of economic analysis however is the identification of the costs and benefits that cannot be quantified, such as safety, environmental impacts and aesthetics (Whole Building Design Guide, 2012). Another limitation encountered in undertaking the

Table 6.13: Comparison of Land Emission Values of Binary B and Binary B1

| Land Emissions (kg) | Binary B | Binary B1 | Binary B Savings Compared to Binary B1 |
|---|---|---|---|
| **Bark/Wood Waste** | 1.07E+04 | 1.73E+04 | **38.2%** |
| **Concrete Solid Waste** | 6.78E+05 | 9.51E+05 | **28.7%** |
| **Blast Furnace Slag** | 2.57E+04 | 5.61E+04 | **54.2%** |
| **Blast Furnace Dust** | 3.58E+04 | 4.57E+04 | **21.7%** |
| **Other Solid Waste** | 2.43E+05 | 2.42E+05 | **0.4%** |
| **TOTAL** | **9.93E+05** | **1.31E+06** | **24.2%** |

economic analysis was the lack of data on the prices of precast concrete components. As such, the comparison could not be made. However, the steps necessary for an economic analysis are outlined as follows.

In making the economic analysis, Binary A, the conventional concrete building is used as the baseline scenario. The assemblies of Binary A and Binary B are compared as seen in Table 6.14.

The foundation, doors and windows are excluded from the comparisons as they are the same for both Binary A and Binary B.

Equal cost weights are to be assumed. The cost of each assembly is specified per unit of the assembly in order to accurately represent the incurred cost over the 50-year life span of the case study building. Costs to be analysed include: the cost of construction, transportation and labour, as well as the operational cost of the building during its life cycle, and in addition, the cost of decommissioning the building at its EOL. Differences in economic outputs between Binary A and Binary B are estimated to determine the economic costs of each construction scenario. The cumulative costs over the 50-year service life of each construction scenario (Econtech Pty, 2008) are then compared on a discount rate.

Table 6.14: List of Assemblies to be compared in the Economic Analysis

| Assembly | Binary A | Binary B |
|---|---|---|
| **Floor** | Post-tensioned concrete floor slab | Hollow core floor slab |
| **Wall** | Precast foundation basement wall panels | Concrete block foundation basement walls |
| **Column and Beam** | Precast concrete CAB | reinforced cast-in-place concrete CAB |
| **Roof** | Double tee precast concrete roof | Reinforced concrete roof |

## 6.8 SUMMARY

In summary, the results of this study have shown that the energy demands and global warming potential of the life cycle phases of a building constructed using two different construction techniques show the significance of the method of construction. The results indicated that about 44% savings in embodied energy could be incurred from the use of precast concrete technology for building construction in relation to conventional construction of the same building. In addition, the precast concrete building has over 7% better performance during its occupancy phase than the conventional concrete building.

The most significant impact categories were FFC and GWP, as they had the highest environmental results of all eight categories, hence their selection as the representative impact categories for all the evaluated life cycle phases of the case study construction scenarios. The final results of the GWP were in contrast to Chau et al.'s study results which indicated that the GWP was 5% more from the use of offsite prefabricated materials than from on-site construction. However, this study showed reverse to be the case as the use of offsite constructed materials (in this case the precast hollow core floor and roof slabs, precast wall panels and precast CAB) produced 9% less GWP overall than from the use of on-site construction.

Waste management was not given major consideration as it has been suggested by several LCA studies that its contribution is no more than 1% of the overall environmental impacts of either the conventional construction or the precast constructions method. However, the study revealed that concrete was the most used construction material, and concrete waste was the most prominent of all construction wastes, which supported the findings from a civil engineering firm in a study to show that the construction material most likely to be wasted was concrete (Building Metabolism, 2009). This result is a pointer to the significance of the method of fabrication of the concrete used for the construction of a high-rise building. As there was less embodied energy and GWP from Binary B than Binary A, precast concrete components were better assemblies than conventionally constructed assemblies.

According to the results, the choice of construction technique is significant to the impact on the embodied energy demands of construction. Therefore, more emphasis should be placed on the choice of construction technique in order to gain from the savings on embodied energy of a building. Nevertheless, the savings in operational energy, although seemingly minor, are still significant to the reduction of environmental degradation and conservation of natural resources.

The results of previous researches assert that waste management has less than 1% by proportion of the overall energy demand and GWP of a building. Yet, there are indications that recycling and other waste management methods reduce environmental impacts because they contribute to the energy savings in construction resources and production/manufacturing of construction assemblies. For instance, Chau et al. (2012) suggest that in addition to maintaining the building's shell, recycling and reuse are the significant to the reduction of emissions. Their study showed that maintaining the existing structural and non-structural components of the building provided a reduction of 17% of the overall

GWP. The other alternative, recycling of construction wastes, could effectively lend almost 6% in carbon emissions savings. Reuse, not as effective as the first two options, could reduce 3.2% in GWP and save on landfill. Therefore these alternatives could be given serious consideration for the post-occupancy phase of the building, as an alternative to outright demolishment in order to save on the FFC and GWP.

# CHAPTER 7

# CONCLUSIONS AND RECOMMENDATIONS

# 7.0 CONCLUSIONS

Evidence from several studies showed that precast concrete construction, besides the improvement of a building's sustainable performance, include shortened construction time; overall reduced costs; enhanced quality and durability; improved health and safety, conservation of materials and energy; waste reduction; and finally reduced environmental emissions.

Therefore, this research undertook a comparative life cycle assessment (LCA) of the performance of the conventional construction method in relation to the use of a selected prefabrication method – precast concrete construction. Using a case study high-rise commercial building in Dubai, UAE, the aim of the study was to evaluate the differences in energy consumption and environmental impact profiles for both construction technologies throughout the 50-year lifespan of the building, in order to determine which of the two had lower environmental impacts and energy consumption demands, and would be a better-performing alternative for the UAE's construction industry.

The selected LCA software tool was the ATHENA Impact Estimator. The operational energy of the building, which could not be determined directly by ATHENA was estimated using eQUEST Energy Analysis tool. The Binary was simulated in ATHENA as 'Binary A' (the conventional concrete scenario) and 'Binary B' (the precast concrete scenario). The compared building assembly groups were floor, wall, column-and-beam and roof assemblies. The same foundation assembly specification (concrete slab-on-grade) was kept the same.

The following were the results of the LCA of Binary A and Binary B, the comparative analysis of conventional concrete and precast concrete construction technologies. The results showed that Binary B, the precast concrete scenario, represented a more friendly environmental impact overall, in all evaluations, than Binary A, the conventional concrete scenario.

- Binary B had 44.2% less FFC and 43.4% less GWP in terms of the total embodied energy than Binary A.
- Binary A consumed an estimated 9.40E+09MJ in operational energy, 7.2% more than Binary B which generated 8.72E+09MJ.
- In comparing the solid resource use of Binary A and Binary B, it was seen that Binary B consumes an estimated 79.1% less than Binary A. In addition, Binary B was seen to consume 40.0% less water and required 42.8% less crude oil than Binary A.
- Binary B had 60% less land emissions, with 58% lower mass of concrete solid waste than Binary A. Similarly, Binary B had less water and air pollution values than Binary A.
- For Binary A, the total FFC (TFFC) was summed up to be 7.83+09MJ. The EFFC made up 3% of this total; in other words, Binary A required 97% of its TFFC to meet its operating demands over the 50-year lifespan. Similarly, the TFFC for Binary B was 7.17E+9 MJ. The EFFC was calculated as 2% of the total, thus the OFFC represented 98% of the total energy 50 years after its construction.
- Binary A showed a TGWP of 4.90E+08 kg$CO_2$ eq., while Binary B had 4.50E+08 kg$CO_2$ eq., depicting 9% less potential for GHG emissions.
- Overall, Binary B consumed 10% less energy, measured in TFFC, and had 9% less GWP values than Binary A after the 50-year building lifespan. Binary B expended 44% less energy in its construction, as seen from the values of embodied energy, than Binary A. In addition, during its 50-year life span, the operating energy demands of Binary B were 7.2% less than the demands for Binary A in the same lifespan.

The results showed that the highest environmental impact during the 50-year lifespan was its occupancy phase, at least 95% of the total building energy in both construction scenarios. The 7% savings achieved by the precast concrete building should not be dismissed as insignificant, considering that no effort is too little to contribute to the conservation of our environment. The 44% difference in embodied energy values between both scenarios indicated that the replacement of conventional components with precast concrete components generated lower embodied energy and GWP. Therefore, considerations in the choice of construction technique are significant to the optimization of embodied energy demands for a building. This is important, especially as concerted efforts are already being made to reduce the operational energy demands of buildings through passive strategies such as passive lighting and cooling.

The 50-year lifespan perspective of a typical commercial high-rise building in the UAE has shown that precast concrete construction has the potential to improve the environmental performance of a high-rise building by optimizing its embodied energy demand and reducing its operational energy requirements, in a more advantageous way than conventional concrete construction. Precast concrete construction also has the potential to contribute to UAE's Kyoto self-imposed target for GWP reduction.

The results of this study bear significance in dealing with the lack of data on the LCA of commercial high-rise buildings in UAE. An awareness and understanding of the environmental impacts as presented by the LCA results could have a key influence on the selection of building construction techniques in future.

## 7.1 CHALLENGES AND RECOMMENDATIONS

- Due to the lack of LCA data in UAE and the constraints of climate, geography and energy sources, any extrapolation of existing LCA data might indicate uncertainties in results. In addition, current LCA building data are limited to generic building types as against detailed building systems and construction assemblies. There is therefore the need for more detailed LCA data design phase LCAs will be better customized to enhance building performance evaluations and material trade-offs across building lifecycle phases, without the stress of extensive inventory compilation, such as was required for this study.

- Although previous studies indicate less than 1% value of waste management, there are indications that recycling and other waste management methods reduce environmental impacts because they contribute to the energy savings in construction resources and production/manufacturing of construction assemblies. Therefore these alternatives could be given serious consideration for the post-occupancy phase of the building, as an alternative to outright demolishment in order to save on the FFC and GWP.

- There is as yet no possibility to simulate future building scenarios such as renovations, energy generation systems and dynamic characteristics of the phases of a building. Changes in system performance, environmental regulations, and government policies and so on, may increase the impact of a material in one region while decreasing it for another region. The inclusion of these dynamic building parameters would significantly enhance the building's model and therefore the LCA results, as these simulations would provide better views of the possibilities of material and assembly trade-offs in a building throughout its expected lifespan.

## 7.2 FUTURE RESEARCH

These challenges and recommendations show that there are several considerable areas for future research. Possible areas of study are listed as follows:

- Future research could be carried out in the area of documentation of inventories for a build-up of LCI for different building types and functions in order to establish a database in the UAE with sufficient data to assist in the implementation of an LCA for the design phase of a building. Software such as BEES and ATHENA could serve as a research database for this purpose.
- This study was limited to commercial high-rise buildings in the UAE. Opportunities abound for studies on other designs and functions of buildings, which would increase the LCA database in the UAE.

- Research in the area of material replacement and waste management scenarios could provide a basis for the exploration of design decisions.
- Detailed economic analysis could be conducted using the available data, for an all-round LCA study. Also, detailed sensitivity analyses for LCA of commercial high-rise buildings in UAE are recommended as a research area in order to improve upon the validity of results of future LCA studies.

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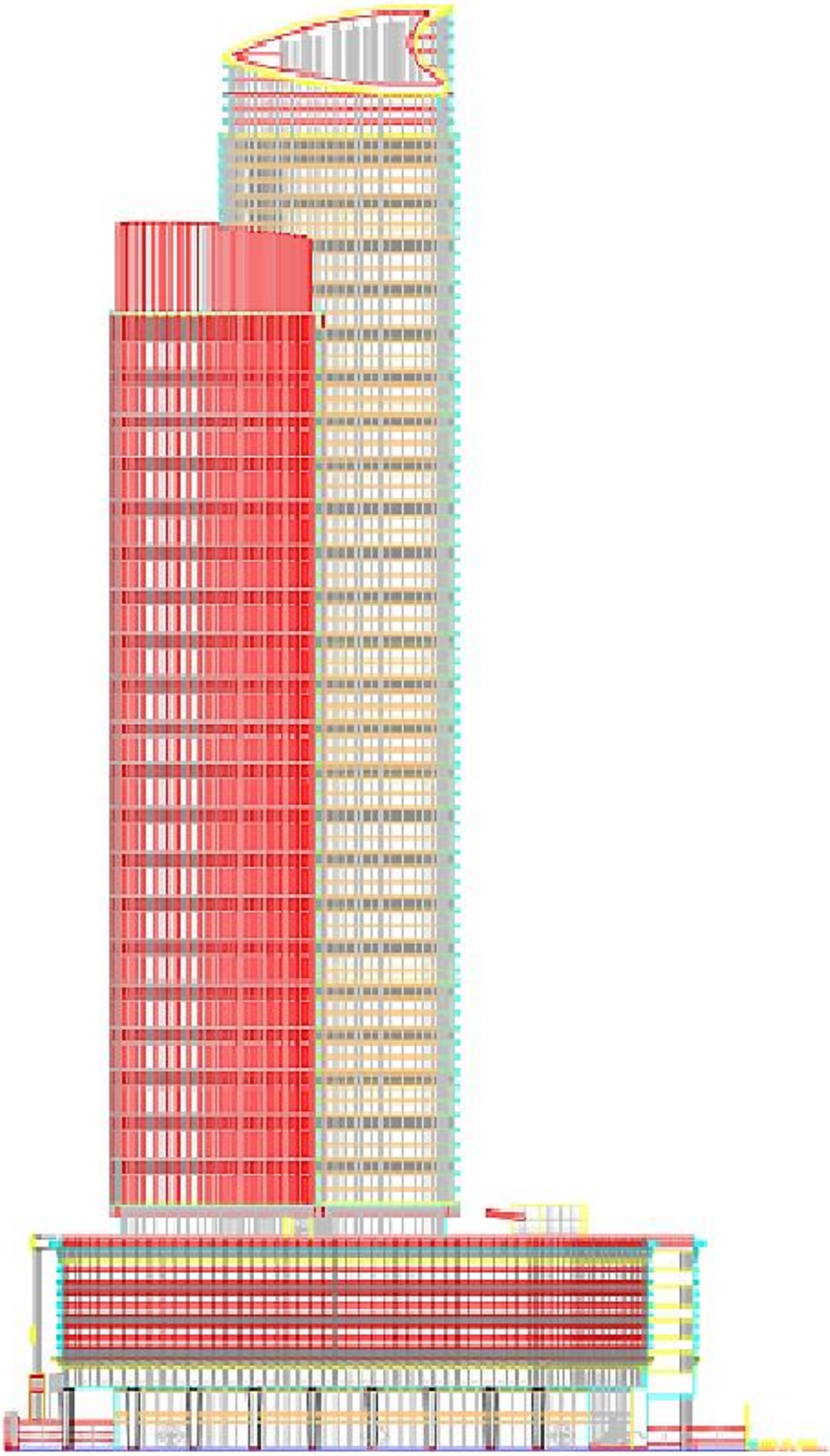
# LIST OF APPENDICES

# APPENDIX A

# AN EXTERNAL PERSPECTIVE OF THE BINARY

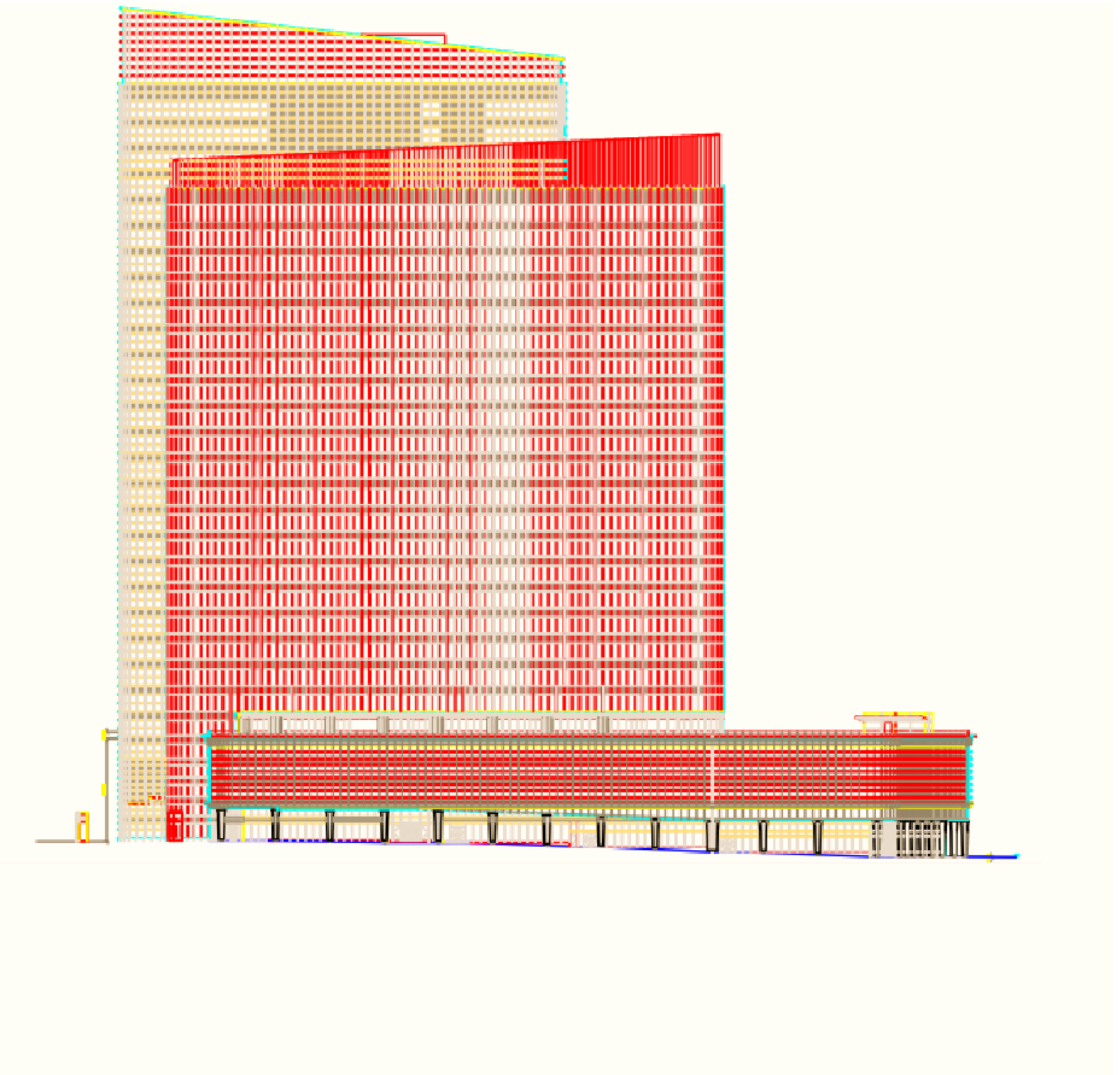
# APPENDIX B

## THE BINARY: SOUTH EAST ELEVATION



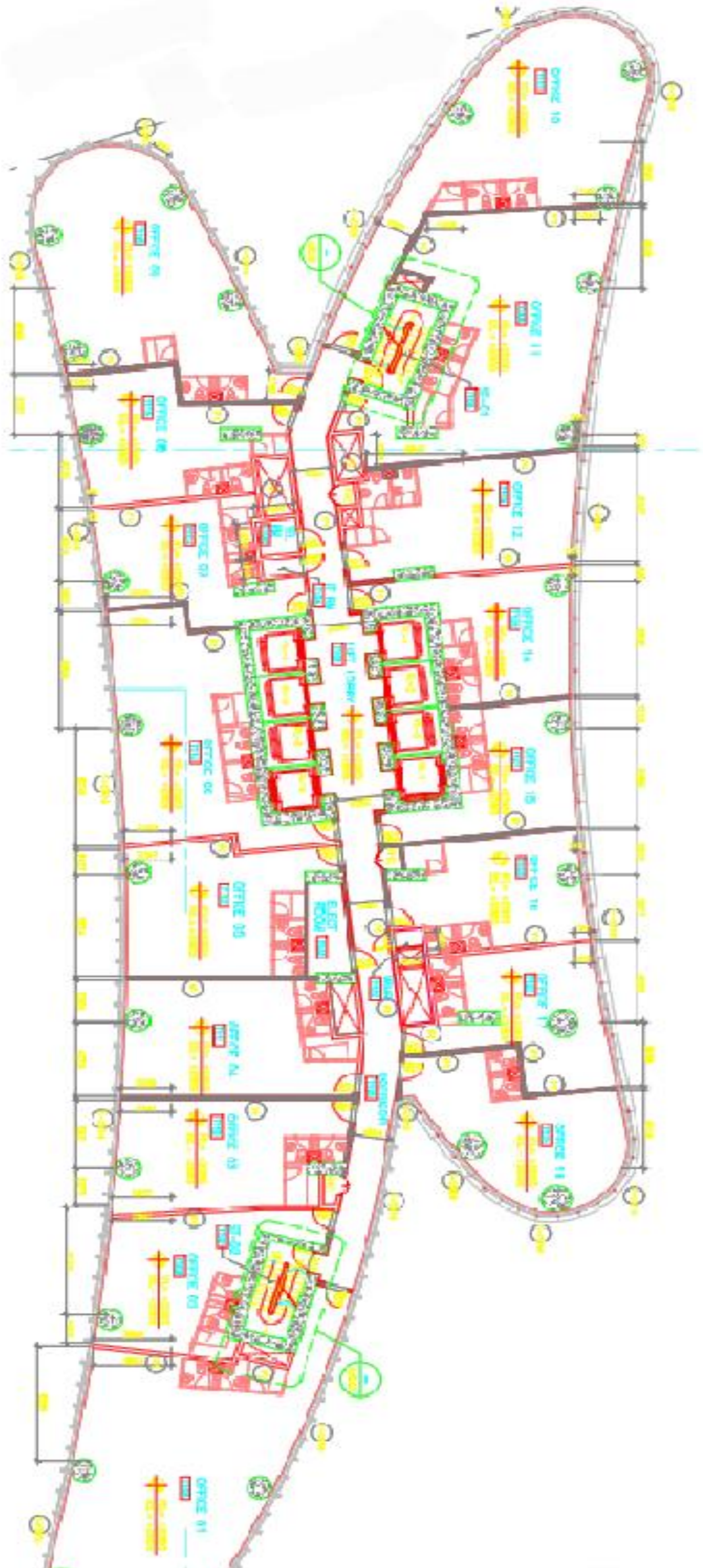
# APPENDIX C

## THE BINARY: SOUTH WEST ELEVATION



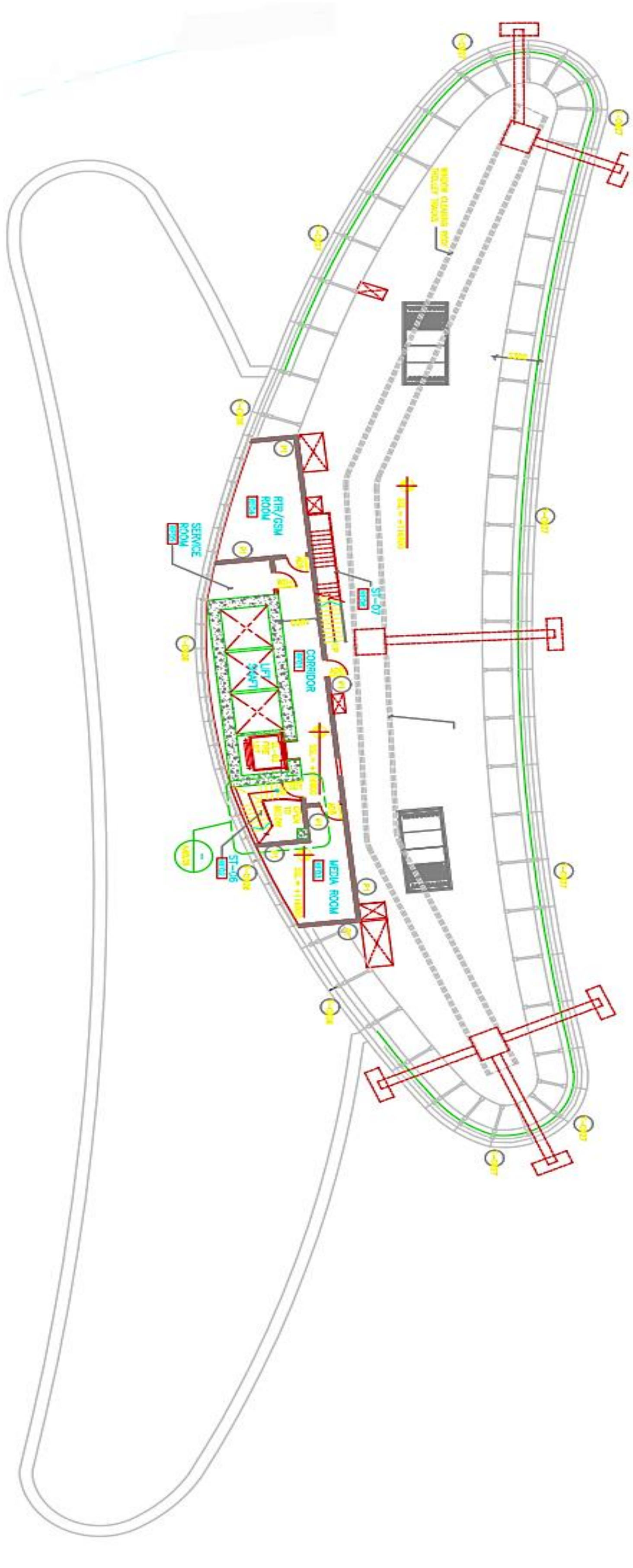
# APPENDIX D

## THE BINARY: TYPICAL FLOOR PLAN



# APPENDIX E

# THE BINARY: ROOF FLOOR PLAN


RTR/GSM ROOM
SERVICE ROOM
CORRIDOR
LIFT
MEDIA ROOM
ST-07
ST-06

# APPENDIX F

# LAND EMISSIONS BY LIFE CYCLE STAGES OF BINARY A

# APPENDIX G

# LAND EMISSIONS BY LIFE CYCLE STAGES OF BINARY B

# APPENDIX H

## SUMMARY MEASURES OF IMPACT CATEGORIES OF BINARY A

# APPENDIX I

# SUMMARY MEASURES OF IMPACT CATEGORIES OF BINARY B

# APPENDIX J

# EMISSIONS TO AIR BY ASSEMBLY GROUPS OF BINARY A

# APPENDIX K

# EMISSIONS TO AIR BY ASSEMBLY GROUPS OF BINARY B

# APPENDIX L

# EMISSIONS TO WATER BY ASSEMBLY GROUPS OF BINARY A

# APPENDIX M

## EMISSIONS TO WATER BY ASSEMBLY GROUPS OF BINARY B