EMBODIED TRANSPORT ENERGY OF PREFABRICATED TIMBER WALL PANELLING UNITS

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ABSTRACT

Increased demand for more affordable homes in recent years has led to recent resurgences in the use of prefabricated construction method. Although there have been various environmental advantages associated with prefabricated construction techniques, the judgement against it is believed to be based on limited understanding and without the necessary detailed research on its environmental performance. The main environmental issues associated with prefabricated houses lies in its transportation pattern and the effect it has to the overall embodied transport energy. The complexity and dynamics of transportation processes, e.g. from forest to site in the case of building prefabricated timber houses, reveals the importance in having a better understanding of the significance of embodied transport energy consumption associated with prefabricated construction.

Due to high dependency on imported timber, concern has been raised over transport energy consumption when using prefabricated timber elements on UK construction sites in contrast to masonry materials that are readily available locally. This research therefore analyses the embodied transport energy consumption when using prefabricated timber elements for building affordable homes in the UK with particular reference to the use of prefabricated timber wall panelling unit.

The evaluation of embodied transport energy has been carried out through the use of process flow analysis. This research has developed a generic process flow model for using prefabricated timber wall system in the UK. Primary data has been gathered through questionnaires to identify the most commonly used prefabricated timber panelling system, its components, the origins of raw material along with the transportation and material processes involved for each component. The questionnaires revealed that open wall panelling system is the most marketed prefabricated timber wall type in the UK. Based on the findings of the questionnaires and the developed process flow model, a number of mathematical formulae have been developed in order to systematically quantify the intricate embodied transport energy consumption associated with using prefabricated timber wall panelling unit on construction sites.

Scenario analysis has been employed in order to test the functionality of the system methodology and to demonstrate the way embodied transport energy may vary within a set of variables. The results suggest that the unit difference between the embodied transport energy of a scenario when delivering a single wall panelling unit to site compared to having vehicles fully loaded with panelling units is as much as 16.83GJ/panel. The process flow analysis concludes that it is environmentally friendly to employ prefabricated timber frame construction for large housing development projects such that delivery to site is always with a full load. Another important finding is that waste factor of building materials has a significant effect on the overall embodied transport energy consumption especially the waste factor of converting the logs onto plywood and studs used to produce the prefabricated timber wall panelling unit .

The research has provided a better understanding of the effect of transport load, choice of transport, and the transportation distances on the overall embodied transport energy for prefabricated building elements and their associated materials. It can be concluded that the developed process flow analysis model has potential to be used as a base model to analyse other type of materials used within prefabricated house construction to aid decision making.

DECLARATION

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author.

The thesis has not been previously submitted to this or any other University for a degree, and does not incorporate any material already submitted for a degree.

Signed: Jennifer Hardi

Dated

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Westframe

Creative Estates

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Not everything that can be counted, counts, and not everything that counts can be counted.

Albert Einstein (1879 – 1955)

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This work is dedicated to:

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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

LIST OF EQUATIONS

Chapter Five

ABBREVIATIONS

BRE	Building Research Establishment
CAD	Computer Aided Design
CRISP	Construction, Research and Innovation Strategy Panel
CCC	Committee on Climate Change
CLG	Communities and Local Government
CoC	Chain of Custody
DEFRA	Department for Environment, Food, and Rural Affairs
DETR	Department of the Environment, Transport and Regions
DTI	The Department of Trade and Industry
DfT	Department for Transport
EPSRC	The Engineering and Physical Sciences Research Council
FEU	Forty foot Equivalent Unit (refer to 40ft container)
FSC	Forest Stewardship Council
FU	Functional Unit
GER	Gross Energy Requirement
IMMPREST	Interactive Method for Measuring Pre-assembly and Standardisation benefit in construction
LPS	Large panel system
MMC	Modern Methods of Construction
MCDA	Multi Criteria Decision Analysis
OSM	Off Site Manufacturing
PALC	Precast Autoclaved Lightweight Concrete
PER	Process Energy Requirement
POST	Parliamentary Office of Science and Technology
S24	2400mm studs
S36	3600mm studs
S60	6000mm studs
TEU	Twenty foot Equivalent Unit (refer to 20ft container)
TRADA	Timber Research and Development Association
WWF	World Wide Fund for Nature

Chapter 1

Introduction

CHAPTER 1: INTRODUCTION

1.1 Background

Climate change caused by human factors is a major topic of contention both locally and globally. The biggest contribution to this include greenhouse gases emitted from activities such as increased human dependents on fossil fuels, cement manufacturing, deforestation, ozone depletion and animal agriculture.

The construction industry alone is cited as a major contributor to greenhouse gases, generating 40-50% of the global output of greenhouse gases and the agents of acid rain (Asif et al, 2005). In addition to that, 27% of carbon emissions have been attributed simply to the housing industry (WWF, 2003), with the materials used in housing construction being accounted for around 10% of mineral extraction and 1% of climate change (Anderson and Howard, 2000).

The need to increase housing supply to meet the increase in global human population will lead to further environmental impact and thus may cause a higher proportion being contributed to climate change. In the UK alone, access to affordable housing remains the single most important housing issue in the South East. In an attempt to combat the growing backlog of current and future housing demand, the UK Government is targeting two million new homes by 2016 plus an additional one million new homes by 2020 (CLG, 2007). Because the construction of new homes will impact the environment, the need for affordable homes that are also sustainable has never been more crucial and important.

Due to concerns of climate change, the UK government has acknowledged the increasing need to reduce CO_2 emissions. The Climate Change Bill was drafted to position carbon emissions reduction targets into law of which stated a commitment for the UK to reduce carbon dioxide emissions by 60% before 2050 against the baseline year 1990 (DEFRA, 2008). The improvements in household energy efficiency are believed to be central to meeting this CO_2 emission reduction target (DEFRA 2004). The most recent call by the Committee on Climate Change, as an independent body to provide expert analysis, has been to consider an increase of this reduction to 80% (CCC, 2008).

The current increase in housing demand and the pressure on the British government to provide a fast, "greener", but affordable housing solution, has led to prefabricated construction methods being re-examined and eventually re-introduced as a viable construction platform. In fact, the intention of using the modern prefabricated construction techniques has been reflected in the English Partnership's requirement for developers. It was stipulated that at least 25% of the homes delivered should be built using this prefabricated construction methods. This was aimed at reducing the construction time, reducing waste through improved waste management during production stages, improving the quality of the finish product and to overcome skilled labour shortages.

Despite the benefits stated, the use of modern prefabricated construction techniques in the UK are still considered new and its overall environmental knowledge are less than complete. Further exploration within this subject is thus necessary.

1.2 Aim and objectives

The use of renewable energy, increased investments in insulations and other energy efficiency initiatives over the last 30 years meant that the operational energy consumption of a typical house has since been considerably reduced. On the contrary, the development of initiatives to reduce the impacts arising from other stages throughout the life cycle of a particular house has been comparatively slow. It is therefore important to examine this particular area in greater detail.

The wall element within prefabricated timber frame house construction is specifically chosen for this research study. Timber was chosen as it is known to have a lower embodied energy consumption compared to other materials such as steel and concrete. Several studies shows that CO2 emission related to material use in construction sector can be reduced by 30-85% (Buchanan, 1996; Suzuki, 1995 and Koch, 1992). Nevertheless, its uses in the form of prefabricated wall panelling unit meant that they are built off site and transported to site as modules or panels. This requires more volume and may not be feasible to be transported in a maximum weight load per journey. This raises concerns regarding potential increase of environmental impact due to the diversity in transportation pattern compared to the traditional house construction. All in all, there is a need to establish a better understanding of the significance of embodied transport energy consumption associated with prefabricated timber house.

The aim of the research therefore is *to analyse the embodied transport energy consumption within prefabricated timber wall panelling unit by means of process flow analysis.*

The following objectives are adopted:

1. To investigate the level of technological advancement within prefabricated house construction
2. To identify the vital environmental impact factors associated with prefabricated timber wall panelling unit
3. To develop a process flow model that depicts embodied transport energy system of a typical prefabricated timber wall panelling unit
4. To develop a methodology that can be used to assess the embodied transport energy of prefabricated timber wall panelling.
5. To evaluate the significance of embodied transport energy of prefabricated timber wall panelling system using a typical functional unit

1.3 Research methodologies

1.3.1. Level of technological advancement within prefabricated house construction

The purpose of this first objective is to identify and provide understanding of the various available prefabrication construction techniques, its history and current trend in the UK housing market. These were identified by consulting relevant studies, technical information and research papers.

Literature review indicates that modern prefabricated construction techniques in the UK are at the early stage and research that focuses on its environmental implication is still considered to be very limited.

Prefabricated timber wall element is adopted as a reference feature in this research as this type of wall construction is considered to be an alternative to traditional masonry wall construction.

1.3.2. Environmental impact factors associated with prefabricated timber frame house construction

The key environmental impact of prefabricated timber wall within this research was addressed and assessed on the natural environment basis rather than the social and economic view. This was identified using similar environmental criteria employed to assess building and its material components.

Energy, transport and material resources were recognised as the major environmental impact factors associated with prefabricated timber wall. Further qualitative review in this objective indicates that there has been a drive to use timber material that are being acquired from certified forest which reduce the concern of over-exploited material resources, as part of the implementation of responsible sourcing for timber material. The improvement in build quality of prefabrication construction techniques also ensures consistent standards of building and services insulation thus ensuring that operational energy can then be reduced. The use of prefabricated construction techniques also suggests a better waste management and an increase in recycling opportunity. The reduction in these areas however meant that the environmental impact caused by energy consumption that still dependent on fossil fuel, such as embodied energy; is at the increase and therefore is a significant area to be assessed in greater detail.

Embodied transport energy has been considered to be the main environmental issue in need for further assessment as imported timber is used to construct prefabricated wall panelling and may contribute to the overall embodied energy. Traditionally, construction site is the point where materials are measured, cut and assembled into the finished building. Within prefabricated construction, the site is simply a location for final assembly of major components. This differing transportation patterns tightened the need to assess embodied transport energy of building constructed using prefabricated construction techniques in order to enhance greater understanding of its environmental performance.

1.3.3. Process flow model

The complexity in evaluating the significance of embodied transport energy within prefabricated timber wall element necessitates the need to generate a generic process flow model. The components associated within this generic forest to site process flow model were identified with the aid of primary and secondary data collection. The generic process flow model has been developed based on both material and transport process flow.

A questionnaire survey has been designed and addressed to a list of Timber Research and Development Association (TRADA) accredited prefabricated timber wall manufacturer as a mode of collecting primary data. This was done to determine the most marketed prefabricated timber wall system within UK housing construction industry. Questionnaires were also designed to gather information on the origins of timbers being used, transport processes associated with the timber hauling and the amount of timber being transported on each stage from the forest to site. Due to companies' confidentiality, data gathered through these questionnaires were limited and therefore additional secondary data were collected in order to support the identification of components within its embodied transport energy.

The development of transport flow model was aimed to illustrate the transport movement and pattern of the associated material from the forest to the site as the finished product and the type of transport used throughout. The material flow model, on the other hand, aims to aid in illustrating how the various size and types of timber materials were transported from the forest to the site as the finish product. Together, the transport and material flow model were combined to create a generic flow model that can be used to determine the embodied transport energy of a particular prefabricated wall type.

1.3.4. Embodied transport energy

To achieve this objective, a Functional Unit (FU) was established and employed within the generic process flow model established earlier in Objective 3. There have been various types of prefabricated timber wall construction techniques available in the UK housing construction. For the purpose of this research, it was decided that the FU is based on the mostly marketed technique available at the time of questionnaire being carried out.

Embodied transport energy per FU depends considerably on various factors. Due to the complexity in quantifying the embodied transport energy within the developed process flow model, a series of mathematical formulae were developed and employed to aid analyse the significance of the embodied transport energy associated within the FU.

1.3.5. The significance of embodied transport energy

The significance of embodied transport energy within prefabricated timber wall panelling was assessed based on three different scenarios. These scenarios takes into account the differing loading amount associated throughout the hauling process from the forest to site stage.

Through these scenarios, the model was then used to evaluate and measure the significance of embodied transport energy per FU.

1.4 Structure of thesis

This thesis is composed of seven chapters. It begins with an introduction and ends with a conclusion as well as further work recommendations. This thesis is organised with the following layout:

Chapter two presents an understanding of technological advancement within the current modern prefabricated construction methods, the history and current public perception towards prefabrication techniques. Through literature review, it was revealed there is currently a lack of research data that focuses specifically on the environmental performance of prefabricated house of which drives the necessity to conduct this research area in greater detail.

Chapter Three provides an overview of the major environmental issues associated with prefabricated timber frame house throughout its life cycle. Within this chapter, embodied transport energy was emphasised as the major environmental issues that needed to be assessed further. To assess the embodied transport energy quantitatively, the third chapter highlights the importance of identifying the components associated with the embodied transport energy of the particular prefabricated wall panelling unit.

With various types of prefabricated timber frame construction available, this research has placed its emphasis on the mostly used prefabricated timber wall panelling system within UK prefabricated housing construction. The components within the embodied transport energy of a typical prefabricated wall panelling unit were identified using primary and secondary data collection. The methodology and the outcome of the data collections are explained explicitly in Chapter Four. The components within the embodied transport energy were developed in the form of a process flow model, used to illustrate and provide greater understanding of the embodied transport energy and material flow of a typical prefabricated wall panelling unit.

A series of mathematical formulae were generated in order to analyse the process flow model. The methodologies in generating these mathematical formulae to support the embodied transport energy and material process flow model were explained further in Chapter Five.

Chapter Six presents the validation and analysis of the embodied transport energy per given FU based on mathematical and process flow models developed in Chapter Four and Five respectively. The quantification and analysis of these process flow models were based on three different scenarios. The first scenario represents the situation in which the means of transports were fully loaded throughout the forest to site phase. The second scenarios, on the other hand, is based on a two bedroom case study of which represent the difference of embodied transport energy if the 40 tonne lorries transporting the finish product from assembly factory to site only carries loads that were equivalent to the number of required house per site. In addition to that, the third scenario is based on a worst case scenario, where the supplies of structural timbers to produce the particular prefabricated wall panelling were low. It is assumed that the amount of wall panelling and its associated timber materials transported from forest to site were equivalent to the number of houses required per site.

The final chapter presents the overall research conclusion and further recommendations as a suggestion for improvements prior to the findings and limitation established within this research study.

1.5 Summary

Table 1.1 demonstrates the frameworks and structure of thesis in matrix. Research methodology used in coloration with each stated objectives. As illustrated, this signifies the chapter corresponding to each of the objective.

Table 1.1 Research framework and thesis layout

		Chapters						
Objectives	**Methodology**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Objective 1 **To investigate the level of technological advancement within prefabricated house construction**	1. Review of current technological advancement within prefabricated house construction techniques 2. Review of current research available 3. Identify the area in need of further research 4. Identify the suitable type of prefabricated house construction for assessment within this research		√					
Objective 2 **To identify the vital environmental impact factors associated with prefabricated timber wall panelling**	1. Review specific technological advancement within prefabricated timber frame house construction techniques 2. Preliminary evaluation of environmental issues associated with prefabricated timber frame house 3. Identify the specific environmental factors associated with prefabricated timber frame house			√				
Objective 3 **To develop a process flow model that depicts embodied transport energy system of a typical prefabricated timber wall panelling unit**	1. Identify the Goal and Scope of research 2. Identify the components associated with embodied transport energy flow of a typical prefabricated timber frame house by means of questionnaire 3. Identify the research Functional Unit based on the most commercialised type of prefabricated timber frame within the UK construction industry 4. Identify system boundaries				√			
Objective 4 **To develop a methodology that can be used to assess the embodied transport energy of prefabricated timber wall panelling**	1. Review the existing studies and methodologies developed to assess embodied energy and embodied transport energy 2. Identify assumptions used within research 3. Develop a methodology to quantify the transport energy model 4. Develop a methodology to quantify the material flow model 5. Develop a methodology to quantify the set FU based on the transport and material flow model					√		
Objective 5 **To evaluate the significance of embodied transport energy of prefabricated timber wall panelling system using a typical functional unit**	1. Quantification and analysis of embodied transport energy of a set FU based on three different scenarios						√	
Objectives 1 – 5 with emphasis on findings established in Objective 5	Critical review of the findings, drawing of conclusions and recommendation of application in practice	√	√	√	√	√	√	√

Chapter 2

The Technological Advancement of Prefabricated Construction Techniques

CHAPTER 2: THE TECHNOLOGICAL ADVANCEMENT OF PREFABRICATED CONSTRUCTION TECHNIQUES

2.1 Introduction

This chapter presents an overview of prefabricated construction techniques and underlines the need for further environmental studies associated with prefabricated house construction.

The chapter begins by highlighting the rationale of UK government's initiatives to use prefabricated construction techniques for newly built houses, the general overview of the technological advancement of prefabricated construction techniques, the history as well as the current UK public perception of it.

The relevant research literature associated with prefabricated housing construction is then reviewed to identify the current research trend of prefabricated construction techniques within the construction industry. This allows for a better understanding of the current major research trend and development as well as to identify other important areas of which to be assessed in greater detail.

2.2 Prefabricated construction

2.2.1 Background

The recent interest in prefabricated house within the UK is driven by the growth in the number of households to meet the exceeding demand of housing supply in the UK. The Government is keen to address the shortfall by encouraging more affordable and sustainable house buildings. It is anticipated that good application of prefabricated construction methods is a way to help construction industry to meet the current need for housing supply (Egan, 1998). The UK Government is committed to promoting the use of prefabricated construction techniques in home buildings. Housing Corporation, for example, has a target that 25% of new build in the Registered Social Landlords' sector should use prefabricated construction techniques. In addition to that, there is also an agreement being made between the Housing Corporation and English Partnerships to build 1,300 key workers homes in South East England by 2005, half of which to be built by means of prefabricated construction techniques (POST, 2003).

The aim of this construction is to lessen the construction time with the ability to reduce waste through better waste management in the factory, to overcome skilled labour shortages, and to provide a better health and safety towards a safer working environment in a controlled factory environment. The use of prefabricated construction techniques also aimed to reduce noise and dust pollution on site as well as to generate a better quality product.

2.2.2 The construction types

There are a variety of definitions used to describe prefabricated construction system. Key terms which also represents prefabricated construction techniques includes *Modern Methods of Construction* or *MMC* (Egan, 1998), *Off Site Manufacturing* or *OSM* (DTI, 2004), *industrialisation* (Richard, 2005), *off-site assembly* (Gibb, 1998), and *pre-assembly* (CIRIA, 1999). For the purpose of clarity and consistency, the term "prefabricated" is used in this thesis.

Prefabricated houses elements are manufactured in parts and off-site. They are constructed in a specially designed factory aimed at reducing noise and dust pollutions, as well as speeding up construction time through standardisation. This allows manufacturers to provide an improved quality and more affordable finished product through the use of mass production techniques. Standardisation can be done with either the help of mechanisation (where motorised tooling are present to ease the work of manual labour), automation (where tooling takes over all tasks usually performed by manual labour, whereas the foreman is still needed), or robotisation (where tools takes control of the entire production line).

In contrast to traditional houses, of which are masonry made, prefabricated house is constructed with its elements built in factory before being assembled on site. There is a wide variety of construction materials that can be used for prefabricated housing construction such as bricks, concrete, timber, and steel.

MMC can be categorised into three groups, as shown on Figure 2.1 below

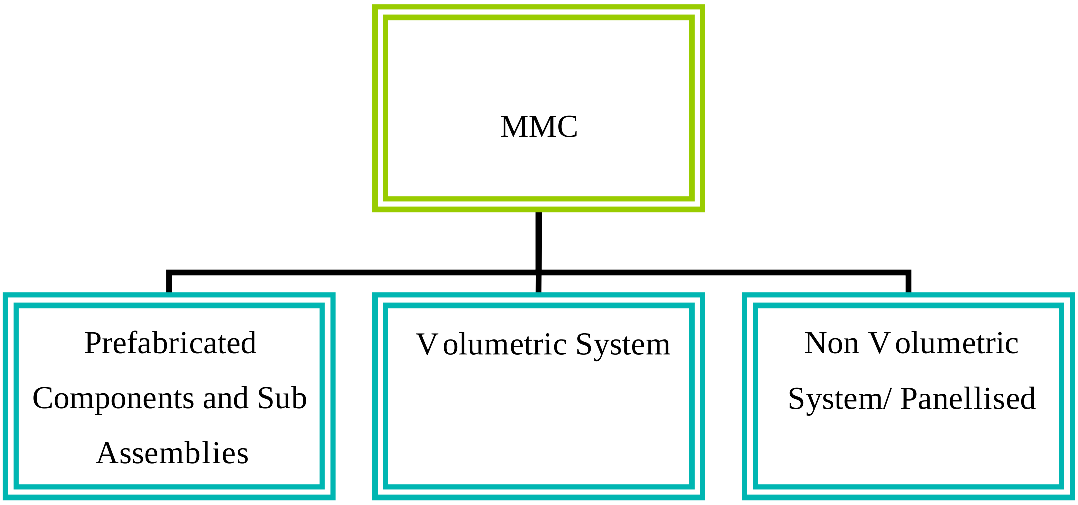


Figure 2.1 Types of MMC

Prefabricated components and sub-assemblies are considered as common pre-assembly techniques and are usually in the shape of component manufacture such as bricks, tiles, door furniture and window frames. Whereas volumetric prefabrication, known as **hybrid** [Richard (2003 a and b)] or **modularisation** (CIRIA, 1999) is recognised as a pre-assembled unit that creates usable space, fully factory finished internally, installed within, or onto an independent structural frame. Plant rooms, toilet pods, and shower rooms are also included in this category.

Non-volumetric prefabrication, also known additionally as Panellised, Meccano or Site Intensive Kit of Parts, consists of pre-assembled units which do not create usable space. This type of unit can be in the form of skeletal (structural frames), planar (cladding and wall panels) or complex units (bridge units and services). One well known example is the lightweight concrete as used by the Japanese construction industry. The pre-cast autoclave lightweight concrete (also known as PALC) has been developed by Misawa ceramics and made from an aerated lightweight concrete acting as structure air barrier, thermal insulation, vapour barrier, sound insulation as well as both interior and exterior finish when covered with an appropriate coating.

2.2.3 History and current perception of prefabricated construction

Due to the perception of post war “prefab houses”, there is a negative impression of prefabricated housing construction from UK house buyers. This instead led to low demand for housing constructed using prefabrication methods even when housing supplies remain low; lower demand in prefabricated houses has also caused higher cost in providing prefabricated housing in the UK.

Prefabricated systems for housing construction in the UK can be traced back to the early part of the 20th century (Philipson, 2001). The motivation for developing mass prefabrication techniques occurred after the First World War when the necessity for the provision of new housing could not be handled through the use of traditional building methods. But due to the gap between expectations and actual provision, which contributed to the perception of poor programme, prefabricated system virtually ceased not long after the Second World War (White, 1965).

A condition survey undertaken by BRE in the 1980s and early 1990s revealed that while most prefabricated dwellings have performed structurally very well, a number of other minor structural and non-structural problems had been reported. These include corrosion of steel reinforcement rods in concrete columns, caused either by carbonation or the presence of cast-in chlorides in the concrete. The large panel system (LPS - one of the three types of concrete structures system), additionally, had also being reported to have weaknesses that could contribute to progressive collapse, as in the case of the Ronan Point Collapse. Many LPS have also suffered from problems relating to weather tightness.

On the other hand, timber frame structure had problems which includes rot occurring in the roof trusses and roof sheets resulting in wet rot in the timber purlin, floor and ceiling joists that our of plumb, condensation and mould growth, rotten discovered in the timber framed cladding units. Due to the problems stated above and as a result of high profile failures that came from the building boom of the 50s and 60s, public opinions of the system declined.

The current need to increase housing supply in a faster construction time of which are also affordable and lower waste output has led to prefabricated construction methods being re-introduced. The recent public perception has since improved due to innovation introduced through modern prefab. Prefabrication supported with standardisation also provide an improvement in predictability and a better working environment in factories by minimising site activity of which lead to a risk reduction in health and safety. Other benefits include better quality in its finish product and reduction of on-site pollution.

2.2.4 Review of current research trends on prefabricated construction techniques

The previous review of historical development suggests that the concept of prefabricated construction techniques is not new to the UK construction industry. The re-introduction to prefabricated construction techniques occurred along with the need to meet the current housing demand of which is also affordable.

Over the recent years, there have been numerous researches and interest in the area of prefabricated construction techniques. Most of these were centred on innovation, cost and automation areas. The literature reviews within this study concentrated specifically at a selection of key research projects and publications as it is outside the scope of this research to appraise the full international review of prefabricated construction techniques.

Between 1997 and 2001, almost £5 million has been invested in the UK by the DETR and EPSRC in a research project that include pre-assembly in construction, of which £1.1 million covers the general innovation (including prefab construction) and the remainder looking at technological advancement on prefabricated system itself (Gibb, 2001a).

Other example of research projects within the UK includes those being carried out by Construction Industry Research and Information Association (CIRIA) [(CIRIA, (1997);

CIRIA (1999) and Gibb (2001)]. Prior to further detailed research and in collaboration with Department of Trade and Industry (DTI), a project toolkit for standardisation and pre-assembly was developed in order to provide understanding and ways to optimise the use of standardisation pre-assembly and modularisation. This toolkit is presented particularly to construction industry clients and their advisers to aid in the pre-contract decision making process.

Pre-assembly research in the UK construction sector also includes those from EEC (Engineering Education Centre) at Loughborough University of whom had developed an interactive modelling tool known as IMMPREST (Information Management for Projects and Estates) an interactive model for measuring pre-assembly and standardisation benefit across the supply chain (Pasquire and Gibb, 2003) and COMPREST (Cost Model for Pre-assembly and Standardization) of which is a cost and value comparison tool for offsite construction (Pasquire and Gibb, 1999). This toolkit was designed as a tool to enable detailed costing evaluation and analysis. In terms of health and safety, a project called HASPREST (funded by EPSRC and DTI under Loughborough University) was developed to deliver improved understanding and greater awareness of the way prefabricated construction system affects occupational health and safety as well as facilitating effective management of the off-site process so as to improve the health and safety of all those involved.

Prefabrication construction methods are still considered new in the UK with the majority of research and studies centred at improving the quality and benchmarking status of the UK industry against development in overseas countries such as Japan, Sweden and Germany. This technological advancement research concentrated on the possible new areas of progress, potentially disruptive technologies and operational efficiency.

PREPARE (Preventive Environmental Protection Approaches in Europe), for example, is one of the many European research bodies who had created a series of programmes aimed at improving the efficiency in prefabrication methods. They are also working to develop prefabrication construction with optimal flexibility and functionality in order to increase the quality of product and reducing production cost as well as reducing material input.

Japan is known to have been the most quoted non-UK example of manufacturing techniques for construction. Much of the interest was generated following a project called OSTEMS, funded by CIRIA and DTI, which highlighted the scale of the new housing market in Japan. It is well known that the Japanese housing market is eight times larger compared to the UK built using prefabricated method [Bottom (1996) and Palmer et al (1998)]. Japanese prefabricated building has also been the stimulus for a European research project called Future Home, focussing instead on high-rise apartments. The output of the project has confirmed a 70% reduction in labour costs, 20% reduction in material costs and an overall saving of 50% (Takada, 2000) rather than an increase of costs as experienced in UK construction industry (POST, 2003).

CIRIA in its 1999 report stated that the Japanese prefabricated system, also known as mass customisation (Noguchi, 2003), has been delivered to a higher degree of choice and flexibility. This is caused by its construction industry of which is based on a consumer driven market and demand where competitive advantage is seen as providing an increased level of quality on consumer choice. However in the UK, where the industry is based on public sector (which is seen as more of a political gesture) than market demand led, this is untrue.

Germany is another example where prefabrication techniques is well known and well accepted. This view is supported in one of the publication prepared by Venables et al in year 2004 on behalf of CIRIA. Similar to Japan, Germans housing has been delivered to a higher degree of choice, flexibility and quality with the public view in regards of prefabrication techniques being positive in contrast to the UK. The only different between Japanese and German's prefabricated housing is on the techniques being employed. Rather than constructing prefabricated housing in the form of high rise buildings, the Germans uses prefabrication techniques to built chalet-detached residential housing types.

At the time when this research is carried out, research on modern prefabrication techniques tends to concentrate more on the health and safety, innovation, quality and cost aspects. Research that examined the environmental point of view, especially those within the UK, is still limited and many of which are still under development.

It is believed that there have been various important environmental benefit associated with prefabrication techniques, one of which is on the reduction in production and construction waste. Pre-assembly components are produced using pre-programmed automated machinery, resulting in waste minimisation at the production stage. As pre-assembly components are transported as finished product from the factory to site ready for site assembly, this resulted in further waste reduction at the construction stage. In addition to that, on-site noise and dust pollution also believed to be reduced due to controlled factory environment.

EC Funds Eurohouse Research, a European oriented research scheme being developed with EC funding, is one example of research project of which specifically look at the environmental point of view in the use of prefabricated construction. It has been concluded that the use of prefabrication methods has achieved 50% reduction in the amount of water used for construction of a typical house, the use of quarried materials used in the construction and reduction in energy consumption (Building Design, 1999).

Other more relevant environmental literatures are those published by Aldaberth (1996a and b), Mats (1997) and Sarja (1997). Aldaberth (1996a and b) provides a significant study of which concentrated towards the total energy use in the whole building life cycle instead of the operational stage only. The research has presented a method of calculating the total energy use throughout the life cycle of a particular dwelling. Her second publication was presented to put the method into practice by implementing case study using three timber prefabricated single unit dwellings located in Sweden. The study has concluded that "in order to save energy, it is essential to produce dwellings that require small amounts of energy during their management phases". The findings shows that the energy used for manufacturing all the construction materials (including erection and renovation) has counted of approximately 15% of the total energy use. Moreover, Aldaberth's research concluded that energy required for manufacturing heatinsulating materials for the dwellings (in this case mineral wool and polystyrene) corresponds to less than 2 years of energy use during actual occupation (for space heating, hot water and electricity). The study has also discovered that the transportation and process energy used during the erection and demolition of the dwellings comprises approximately 1% of the total energy requirement, which means that very little energy is used for such purposes and that even though the dwellings were prefabricated, the extra transportation requirements do not result in any significantly increased use of energy compared to the total energy requirement. Nonetheless, the publications made by Aldaberth have been about ten years old and therefore an up to date figures will need to be established.

The literature review carried out in this chapter suggests that research concentrated at prefabrication methods, especially those within the UK, is very limited. It is of importance to carry out further research to justify any associated environmental factors contributor to better understand how UK prefabricated house perform environmentally.

2.3 Summary

This chapter is written as a background review of prefabricated construction techniques. It is compiled to provide a better understanding towards the current existing knowledge of the various technological advancement, the history and current perception of prefabricated construction techniques and the current research trends.

The need to build more housing has led to the re-introduction of prefabricated construction techniques as a way to deliver better quality, improved efficiency, lower costs and faster construction. Nevertheless, this judgment is believed to be based on limited environmental understanding and without the necessary deeper understanding of its environmental performance.

With the support of various literature reviews, it can be concluded that various researches has been performed in terms of general prefabricated construction. Nevertheless, most of these are centred on construction innovation and cost effectiveness and only very limited studies of which focuses on the environmental aspects of prefabricated buildings especially those within UK.

With the construction policy becoming increasingly focused towards prefabricated construction technologies, it has become a necessity to develop a programme of research to contextualise and analyse the environmental issues associated with modern prefabricated house.

It is acknowledged that the large variety of materials used within prefabricated house construction meant that it is beyond the scope of this research to possibly analyse all of them. It is therefore essential that a particular type of prefabricated house construction is to be selected for this particular research study and that its associated environmental impact factors then being identified and assessed in greater detail. Prefabricated timber wall element is adopted as a reference feature in this research as this type of wall construction is considered to be an alternative to traditional masonry wall construction.

Chapter 3

The Environmental Impact Factors Associated with Prefabricated Timber Frame House

CHAPTER 3: THE ENVIRONMENTAL IMPACT FACTORS ASSOCIATED WITH PREFABRICATED TIMBER FRAME HOUSE

3.1 Introduction

The previous chapter introduced the technological advancement of prefabricated construction techniques and underlined the lack of environmental studies associated with prefabricated construction techniques.

Among many various choices of materials available to build a prefabricated house, this research focuses exclusively at timber built-it houses. It is known that timber is a renewable material and is believed to retain lower embodied energy compared to other type of materials used. Nevertheless, as construction techniques of prefabricated houses differs to traditional on-site construction, its environmental attribution within prefabricated housing construction remains unclear.

This chapter begins by providing the definition and technological advancement of current modern prefabricated timber house construction techniques. This follows with the identification of possible major environmental impact factors that may be associated within prefabricated timber frame. The most significant factor is then identified and to be assessed in greater detail.

3.2 Prefabricated timber frame construction

3.2.1 Definition

Timber frame construction techniques is a method of building construction which relies on timber frame as a basic means of structural support (UKTFA, 2006). It is fabricated with the use of timber studs, rails and a wood-based sheathing to form a structural frame for the purpose of distributing all vertical and horizontal loads uniformly to the foundations.

Modern prefabricated timber frame housing may be broadly defined as a type of house of which has generally been constructed using factory manufactured wall panelling and comes in various types of construction. It is then transported to site ready for an on-site assembly.

3.2.2 Types of Prefabricated Timber Frame Housing

Prefabricated timber frame housing consists of various different structures. This takes a number of forms that are generally classified in as either a volumetric or non volumetric method.

Non volumetric methods are divided into further categories: a light frame wall panelling system and a post and beam system. The breakdown of the system and the way it is being assembled are shown in Figure 3.1 below.

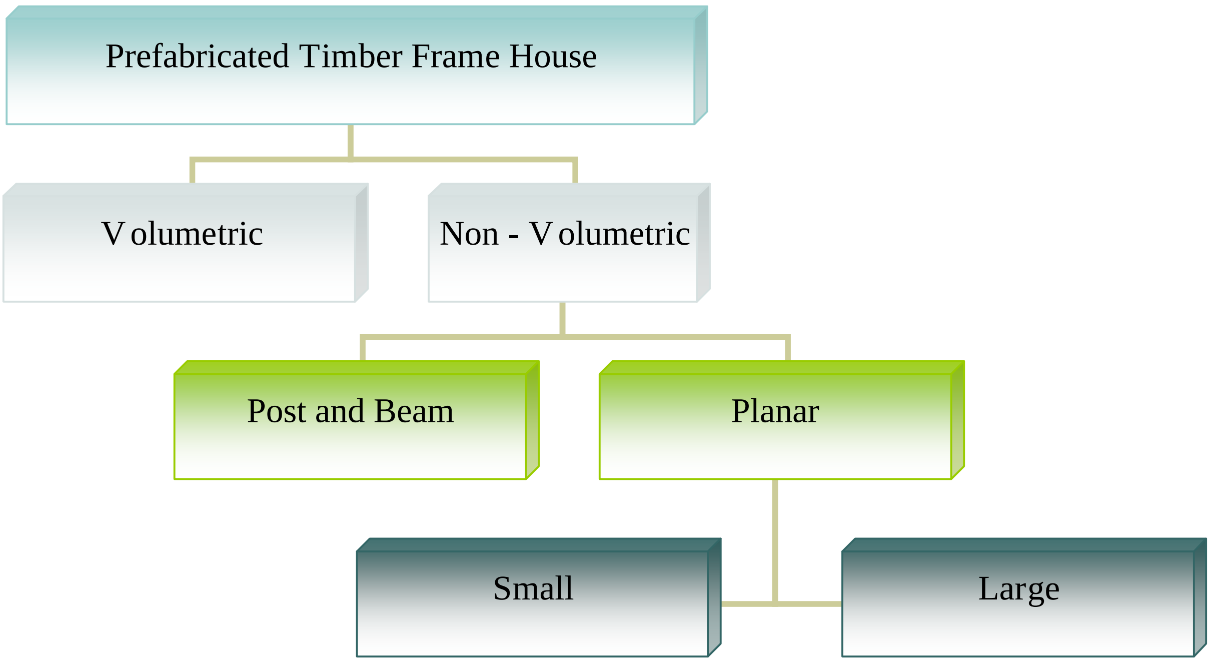


Figure 3.1 Type of Prefabricated timber frame housing construction.

3.2.2.1 Volumetric

Volumetric method is generally known as a construction method where a particular building is constructed using a factory fabricated box units (also known as pod or module). These modules are then formed into individual rooms or larger spaces, complete with finishes and services as shown in Figure 3.2 below.

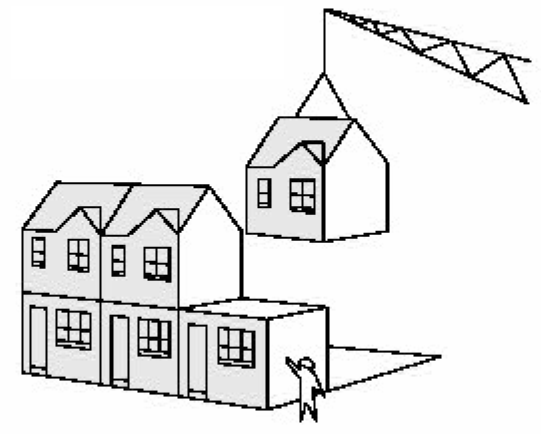


Figure 3.2 Modular construction method (picture courtesy of TRADA)

Building assembly will require at least one crane. This type of building assembly method is most commonly suited to repetitive units such as hotels, hostels, medium rise flats or nursing homes.

3.2.2.2 Non Volumetric

Non volumetric timber construction is divided into two categories, which are Post and Beam (also known as skeletal or structural frames) and Planar (also known as cladding or wall panels and can be in the small or large form)

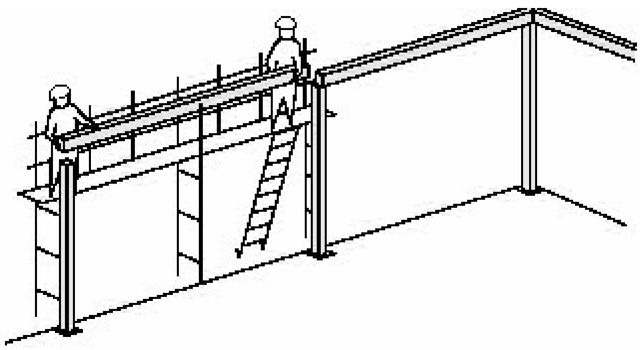


Figure 3.3 Post and Beam Construction Method (Picture courtesy of TRADA)

Post and beam, the simplest use of non volumetric pre-assembly (seen in Figure 3.3), is described as a skeleton which is open to horizontal and vertical infill, designed to provide more adaptable solution and having most of its jointing and finishing on site.

Post and beam method can be in the form of continuous column, continuous beam or segmented components.

The drawback of this however lies in its limitation to be used for a low-cost housing as they needed an additional vertical support beside the cross wall to provide a better acoustic insulation. This type of construction therefore tends to be more expensive compared to the usual load bearing construction.

Huf Haus is one of the examples that fit into this category and constructed using laminated timber.

Figure 3.4 Huf Haus Project in Surrey, UK

Similar to other prefabricated housing company in Germany, it offers a “chalet” type design and based on the medieval German design. Huf Haus, like most other high-end German prefabricated houses, is characterised by an open plan living areas, large areas of glazing and mostly built with basements.

Post and beam systems are usually aimed at the upper end of the market and its application in the UK is likely to be limited as the demand was on the fast but good quality affordable housing.

There have been other more advanced approaches to the simple columns and beams which uses a three dimensional system included within a single element. Nevertheless, it is relatively inefficient for shipping where dimensional variation is very limited.

Planar (also known as Cladding and Wall Panels), on the other hand is the type of panelling which is well known as a continues load bearing flat components distributing the loads on one axis. This slows for more room for connections and contributing to soundproofing, but also limiting the planning on one axis.

It is believed that factory made panel has greater flexibility compared to the simple prefabricated columns and beams. This is because prefab wall panel can be constructed to serve as structure and closure between one apartment and next. This type of timber construction known to have many advantages which include faster construction time and relatively low foundation loads. Factory environment also means that the construction and assembly is not weather sensitive and reduced the dependency on skilled labour/worker.

Timber wall panelling can be constructed in either close or open panels (shown in Figure 3.5). Close Panel systems are constructed with the insulation material installed into the panel in the factory and retained with some other layer of material to “close” the panel. This type of system allows for more value to be added in the factory but often requires its building services to be pre-planned. As they are also heavier, they tend to require crane for the on-site assembly stages.

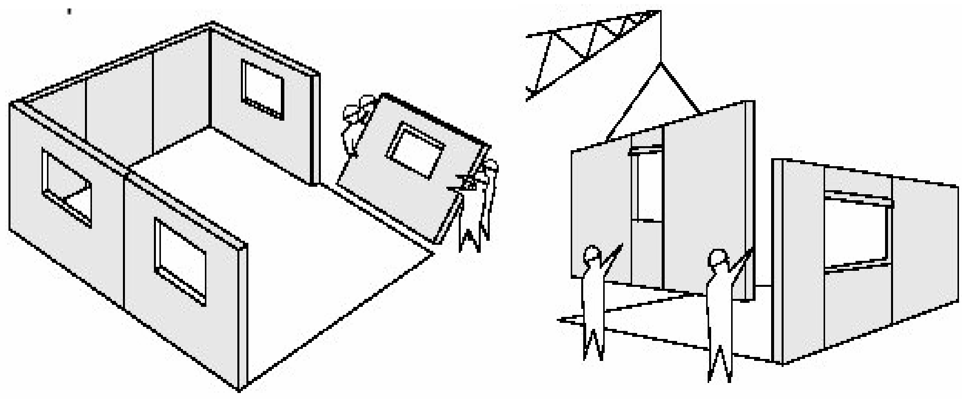


Figure 3.5 Small and Large Panel Construction Methods (Pictures courtesy of TRADA)

Open Panel system on the other hand, has a 35 year track record in the UK market. Research has shown that this system performs well against all types of measure and NHBC statistics even suggested an extremely low claims ratio in respect of defects (Palmer, 2000). It has the same components as close panel but with the insulation, external joinery and services installed on site.

Open wall panelling unit is designed so that it can be incorporated as both external and internal walls within a typical prefabricated timber frame house. For the external walls, cladding, vapour control and insulation were added for aesthetic and protection from the weather. Further details relating to the typical prefabricated wall panelling system can be found on Appendix A, which shows in more detail, a typical external wall panelling construction taken from Space 4 prefabricated timber frame manufacturer website.

In the UK, SIP (Structural Insulated Panels) is the latest system to appear on the market made from timber and consists of two sheet materials sandwiching a rigid foam core. This latest panelling system may have doors and windows as well as services conduits fitted into them in the factory.

3.3 Major environmental impact factors associated with prefabricated timber frame housing

3.3.1 Background

The need for environmental assessment is largely driven by the intention of building design professionals and other project stakeholders to provide its client with an environmentally friendly and energy efficient buildings (Foliente et al, 2004).

Environmental assessments are performed to examine any potential environmental risks and benefit associated with a certain type of materials, products or buildings. They are identified so that a suitable measure can be incorporated. These measures can be in the form of energy consumption and greenhouse gases reduction, conservation of natural resources through waste minimisation, recycling and reuse of materials, preventing and/or minimising environmental pollution as well as improvement in health and safety environment for people to work and live in.

There are several environmental criteria or performance indicators that are used to assess the sustainability of certain construction projects, buildings or materials. One known example, that of the research body The Movement for Innovations (M4i) who set up a performance indicator to measure the sustainability of construction projects. This performance indicator is divided into several criteria and looking specifically at operational energy use, embodied energy, transport energy, waste, water and species index per Hectare. Phillipson (2003) qualitatively identified the environmental factors associated with prefabrication construction techniques against the M4i indicator as presented in table 3.1 below. This qualitative assessment suggests that transport energy is considered as the only negative environmental factor related to prefabricated house construction in general.

Table 3.1 Qualitative performance of prefabrication against the M4i Environmental Performance Indicators (Phillipson, 2003 p. 16, table 1)

M4i Sustainability Indicator	Effect of using prefabrication
Operational energy	Positive – Improvements in build quality ensure consistent standards of insulation and service insulation
Embodied energy	Positive – Reduced waste and increased recycling in off-site manufacture should reduce the embodied energy associated with the manufacture of a given part.
Transport energy	Negative – movement of prefabricated components will necessitate the transport of some additional volumes of air (particularly for volumetric solutions)
Waste	Positive – Manufacture of components in a factory environment should reduce much of the waste associated with site activity
Water	Positive – Manufacture of components that require water in their manufacture in factory environment allow more control, and potential for water recycling than would be found on site.
Species per hectare	Positive – Reduction of pollution onsite by undertaking manufacture in a controlled environment should limit the impact on existing species on site, whether or not prefabrication methods are used.

According to Phillipson (2003), the use of prefabricated construction will have a negative impact on the transport energy but will achieve a positive impact on the embodied energy. The assessment suggests that reduced waste and increased recycling in prefabricated construction techniques (of which is refer to as off-site manufacture by Phillipson, 2003) corresponds to the reduction of embodied energy associated with the manufacture of a given part.

One major drawbacks associated with the M4i environmental indicators is that it does not take into account material resources believed to be an important environmental factor related to prefabricated timber frame house. This view is supported by Foliente et al (2004) who divided its environmental criteria assessment of which includes material resources as its environmental indicators.

The approach taken by Phillipson however, was only intended as an initial qualitative assessment to underline the basic environmental factors associated with prefabricated construction in general, rather than a thorough detailed research. It is believed that due to the differing prefabricated construction techniques, it is necessary to assess the various prefabricated construction techniques on an individual basis in a greater detail to provide better understanding on the different environmental impact associated with different type of prefabricated construction techniques.

From prefabricated timber house perspective, material resources and transport energy within the embodied energy are deemed to be the major associated environmental factors. Sections 3.3.2, 3.3.3 and 3.3.4 below describes the relevance of these environmental factors to prefabricated timber frame house in much greater detail.

3.3.2 An overview of material resources

There are various environmental advantages and disadvantages in the use of timber material itself. It is known however for its advantages as a renewable material with the lowest embodied energy consumption and CO_2 emissions of any commercially available building material (Forintek et al., 2001). One of the low CO_2 emission contributors was associated with the “carbon sink” ability that forest has, of which occurs when photosynthesis take place. Another contributor to the rather low amount of CO2 emission is through the use of wood residues and recovered wood in the production of wood products.

The environmental impact caused by the use of timber materials in housing construction in particular might be less than other materials such as steel or concrete. However, that does not mean that timber is 100 percent sustainable. During its life span, for example, poor environmental management and awareness may contribute to various environmental impacts such as pollutant run-off into land and water of which were originated from fertilizers and pesticides. In addition to that, the conversion of forest lands for other purpose and over-harvesting will lead to deforestation. This will cause among many things, the loss of biodiversity as well as a net increase in atmospheric CO_2, often associated with the global climate change.

In general, logging stages and lumber production may also cause environmental impact such as soil erosion, altering the flow of water and solubility of nutrients and a further pollutant run-off into land and water caused by cutter chain oils.

The fear of pollutant run off, however, can be reduced by the use of environmental friendly pesticides and fertilizer. In addition to that, the fear of deforestation can also be eliminated by making sure that only sustainably certified timber are being utilised for UK prefabricated house construction.

A number of initiatives have been taken to allow for better forest management in light of deforestation. The Forest Stewardship Council (also known as FSC) has developed certification systems to allow forest management operations to be evaluated against performance based standards. This certification enables forest product manufacturers and traders to source materials from certified sources and to be passed on through the supply chain as certified timbers. This trail of information is also known as Chain of Custody (CoC) of which provide the path taken by products from the forest (or in the case of recycled materials, from the reclamation site) to the customer. This certification also includes each successive stage of processing, transformation, manufacturing and distribution where progress to the next stage of the supply chain involves a change of ownership.

The awareness to use timber from legal and sustainably managed forestry has been acknowledged by the UK Government within their timber procurement policy. According to the executive summary of UK Government timber products advice note published on 1st August 2008, the new revision of the UK Government timber procurement policy that will take into effect from 1st April 2009 will tighten its current 2005 timber policy so that it requires:

".. Only timber and timber products originating either from independently variable legal and sustainable sources or from a licensed Forest Law Enforcement, Governance and Trade (FLEGT) partner will be demanded for use on the Government estate".

(Proforest, 2008)

This step forward taken by the UK Government is regarded as a positive example for private sector construction industry in the UK to follow suit.

3.3.3 An overview of embodied energy

The building industry is a main consumer of energy resources from the extraction of raw material for building components to the energy required to operate the particular building through to its end of life stage. It is believed that buildings themselves are responsible for over 43% of the European's energy consumption and 46% of the UK's CO2 emission (DTI, 2002).

Energy consumption itself does not necessarily cause a burden on the environment. It is considered more in terms of its contribution to fossil fuel depletion or in terms of its contribution to embodied CO2 emissions that lead to greenhouse gases and global warming.

The increase in sustainable designs such as improved insulations, the use of energy efficient appliances and the increased use of renewable energy means that operational energy consumption can thus be reduced. It is understood that this will increase the proportion of environmental concern in other part of building or material's life cycle.

With the fact that embodied energy could account for up to 40% of the total energy consumption throughout the life cycle of residential buildings [Cole (1996), Adalberth (1996) and Chen et al (2001)], it is increasingly of importance to analyse this further.

In the perspective of UK prefabricated timber frame house, transport energy within the embodied energy is considered as one of the environmental factors where prefabricated construction techniques could perform worse than traditional construction. In the case of volumetric construction, in particular, the transport of components to site necessitates the movement of some volumes of air which is not as efficient as the delivery of building materials for traditional masonry construction. Due to the scarcity of prefabricated manufacturers within the UK (of which is less than traditional masonry supplier), it is believed that their transport efficiency will also be dictated based on the location of the factory. This has drawn the need for this research to focus particularly in assessing and analysing the embodied transport energy attributed within prefabricated timber frame house in greater detail.

3.3.3.1 Definition of embodied energy

The use of embodied energy term itself is open to different interpretations. Different methodologies produce different understandings of the scale and scope of application and the type of energy embodied. It is still the case that embodied energy figures are often quoted and published without explicitly stating the scale and scope in generating the particular total embodied energy figure.

In general, embodied energy is defined as:

"the quantity of energy sequestered or embodied in the product or service resulting from the many stages of its production, from mining through enrichment, transporting, processing and production to the usable product" [Alcorn, 1998]

Within this research study, embodied energy is regarded as the "upstream" or "front-end" component of the full life cycle analysis of a home. It will not include the operation and disposal of the building materials as this would be considered in a full life cycle approach instead.

3.3.3.2 Methodologies to measure embodied energy

According to an in-depth study carried out by Lawson (1996), embodied energy can be measured based on either GER (Gross Energy Requirement) or PER (Process Energy Requirement).

GER is a way of measuring all the net energy inputs. These includes not only the main stages of the life cycle but also the support service and transport to the building site, including the transport of the workers, equipment and materials as well as the embodied energy of the urban infrastructure (such as road, drains, water and energy supply). GER also includes the calculation of construction of the plant used in the extraction and processing of the raw materials and the repair action needed for damage caused by the component manufacturing process. Due to the various factors that are needed to be taken into consideration, GER is generally impractical to employ and its boundaries require to be stated clearly to prevent uncertainty.

PER on the other hand, is known as a readily assessable method which provides a firmer basis for material comparison. It is known as a measure of the energy directly related to the manufacture of the material and hence allowing it to be quantified in a more straightforward manner. PER would include the energy used in transporting the raw materials to the factory but not energy used to transport the final product to the building site. The components within PER relates directly to GER and may account for between 50-80% of the GER (Baird, 1994).

3.3.3.3 Embodied energy in the context of prefabricated timber frame house

There have been various published embodied energy figures for common building materials and timber material in particular. Most of them were based on PER measurement. Nevertheless, there is an inconsistency towards these various figures as those that has been included within the analysis and the way of which the result is being generated is not always clearly identified. In addition to that, Miller (2001) indicates that transportation component within the embodied energy are often being omitted or considered only using gross simplification.

It is recognised that transportation energy embodied within a material is often small compared to the total embodied energy of a material as a whole. Nevertheless, the reduction of waste and increased recycling through the use of prefabricated construction techniques indicates that embodied energy associated with the manufacture of a given part can be reduced, thus increasing the proportion of transport energy embodied instead. In addition to that, with the differing transportation pattern of prefabricated house construction techniques to the traditional on-site masonry house construction, the need to specifically analyse the embodied transport energy consumed within prefabricated timber frame house in greater detail has become increasingly important.

3.3.4 An overview of embodied transport energy

In the context of sustainable development, transport is considered to be one of the major factors affecting the energy consumption of a particular development both direct and indirectly. In the UK alone, the Department for Transport (DfT) suggests that freight transport through road accounts for 86% of total movement (DfT, 2006). Building materials are recognised as the main commodity of freight transport.

Transport statistics gathered from DfT in 2006 also reported that freight moved by road has reached 150 billion tonne kilometres in 1995. This figure has increased to 163 billion tonne kilometres by 2005 (DfT, 2006). The increase in this particular activity has cause further concern over the environmental impacts associated with air quality and fossil fuel depletion. The major contributor to air pollution was by the production of hazardous substances such as PM10, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Ground Level Ozone, Volatile Organic Compounds, Toxic Organic Micro pollutants, Particulate Lead and Acid Rain), visual intrusion, congestion, noise, energy use and accident damage.

Researchers at the Argonne National laboratory from The University of Chicago in the United States has also stated that some of the additional environmental impact contributed by heavy duty lorries and trains comes from them spending a great deal of time running their engines when stopped. The practice, known as idling causes, lose energy to wind resistance (aerodynamic losses) and operation of components such as pumps and compressors (parasitic losses) (Argonne National Laboratory, 2005). Although HGVs are a relatively small percentage of overall traffic, their effect is seen to be disproportionately high. The impact it caused is therefore worrying.

James and Hopkinson (2001) and Bos (1998) stated that the environment and social impacts of transport stages has been shown to be influenced by several aspects:

- The size and characteristics of the vehicles and thus the composition of the vehicle fleet
- Whether the traffic under concern is traffic inside or outside the built up areas, traffic on the main routes or traffic on secondary and tertiary roads, etc
- Whether values include refinery energy requirements and emissions or not
- The average load factors
- The amount (weight) of goods transported
- The distance that they are transported
- The mode (e.g. rail, air, road or water) and sub-mode (e.g. articulated lorry) used to transport them.

- The power source of the transport unit and their performance
- The nature of infrastructure
- The number of handling operations required.

This means that the length of transportation chains, the type of transportation and its loading limitation may significantly affect how a building and its material performed environmentally.

3.3.4.1 Embodied transport energy in the context of prefabricated timber frame house

In contrast to masonry houses, prefabricated houses require its components to be transported from the prefabrication manufacturing factory to site more as a finished product. The factory assembled structures therefore convey a load limit per transport journey hence there is the possibility that it may need more frequent transportation to site compared to traditional masonry house.

In addition to that, the numbers of pre-assembly factories within the UK are still considered to be limited compared to factories supplying building materials for masonry houses which can usually be obtained from a local supplier.

Another major concern lies in the dependency of UK construction industry towards imported structural timber. A statistic figure generated by the Timber Trade Federation (TTF, 2007) in 2007 suggests that 67% of total timber and panel consumption by volume has been imported from other countries.

All these factors believed to have an impact associated with embodied transport energy within a particular prefabricated timber frame house.

3.4 Summary

Prefabricated timber house perspective, material resources, embodied energy and transport energy within the embodied energy are deemed to be major environmental factors. The relevance of these environmental factors to prefabricated timber frame house was explained and reviewed in greater detail within this chapter.

The reduction of waste and increased recycling in off-site manufacturing plants indicates that embodied energy associated with the manufacturing of a given part can be reduced. With the implementation of legal and sustainably managed timber on the increase, the concerns associated with material resources therefore decreases. Nevertheless, these resulted in the proportion of environmental impact associated with transport energy within the context of prefabricated timber frame house to be on the increase.

The reduction in transport energy in general is considered of high importance due to its high dependency on the utilisation of finite fossil fuels, which subsequently resulted in them displaying a direct correlation to environmental impact.

The need to assess the embodied transport energy within prefabricated timber frame housing was due to the significant difference between the transport patterns of a traditional construction site and one using the latter type of construction techniques. Traditionally the construction site is the point where materials are measured, cut and assembled into the finished building. With prefabricated construction techniques, the site is simply a location for final assembly of major components.

This means that, in the case of volumetric construction, in particular, the transport of components to site necessitates the movement of some volumes of air which is not as efficient as the delivery of building materials for traditional masonry construction, of which usually are transported on full load mode.

In addition to that, due to the scarcity of prefabricated manufacturers within the UK (of which is less than traditional masonry supplier) and the high dependency of UK construction industry towards imported timber, it is believed that their transport efficiency will be dictated based on the location of the factory and source of timber.

The qualitative review accomplished within this chapter has successfully revealed that embodied transport energy plays an important role within prefabricated timber frame house, and that the embodied transport energy analysis warrants a more detailed focus within this research study.

Chapter 4

Development of the embodied transport energy process model

CHAPTER 4: DEVELOPMENT OF THE EMBODIED TRANSPORT ENERGY PROCESS MODEL

4.1 Introduction

Chapter three establishes that embodied transport energy is a major environmental impact factor contributor within prefabricated timber frame housing construction. The importance of environmental impacts is believed to be clearer when the materials or buildings intended were examined from a life cycle approach, usually known as Life Cycle Assessment (LCA).

In order to assess the transport energy embodied within a generic prefabricated timber frame house, this research study employed a partial life cycle assessment approach. It covered stages from the forest as the raw material acquisition stage to development site.

The assessment of embodied transport energy of a particular prefabricated timber frame housing alone is recognised to be of a complex things to do. Hence, a generic model is developed for the purpose of this assessment. The methodology and framework for the development of this model is specified and defined within this chapter in greater detail.

4.2 Life Cycle Assessment approach

Life Cycle Assessment (LCA) has evolved from energy analysis work of the 1960s and 1970s [Slesser (1974) and Boustead (1979)], and was originally designed to improve efficiency of industrial processes (CIRIA, 1995). Energy Analysis, also known as Process Energy Analysis (PEA) [Bos, 1998] or Cumulative Energy Demand [Verein Deutscher Ingenieure, 1997] was established to perform an analysis of the energy use of certain human action.

Life Cycle Assessment (LCA), also referred to as ‘cradle to grave’ or ‘cradle to cradle’ analysis, is a systematic concept to consider the environmental effects of building products before and after they become part of a building. The process associated with the manufacturing of materials, their installation and use in buildings, and their eventual reuse, recycling or disposal at the time buildings are renovated or demolished are all evaluated.

LCA is applied to a whole product (a house or a unit) or to an individual element or process included in the particular product and commonly employed to consider a range of environmental impacts such as resource depletion, energy and water use, greenhouse emissions, and waste generation.

The comprehensive definition of Life Cycle Assessment is:

"A compilation and evaluation of inputs, outputs and associated potential environmental impacts of a product throughout its life cycle (i.e. cradle to grave)" [ISO14040, 1997, p.2]

There has been various work carried out in the arena of LCA, of which attempting to achieve a refinement and standardization of LCA, specifically in the area of methodology. Organisations such as The Society of Environmental Toxicology and Chemistry (SETAC), Environmental Protection Agency (EPA) and Eco Balance provide unique differences in its individual approach to LCA. Nevertheless, it appears that the major components within the methodologies do not differ much. For instance, most LCA methods generally begins with a scoping and goal definition component that defines the purpose of the study. Other common methodology stage is an inventory analysis, an evaluation of the inputs and outputs of the product, and process or activity that is the subject of study. Most methodologies encourage an improvement component based on the inventory discharges and impacts on the environment.

LCA methodology has progressed enormously and the International Organization for Standardization (ISO) has published a series of Standards on LCA in the form of ISO14000 series. ISO 14040 in particular provides information on LCA principles, requirements and the general framework. The Life-Cycle Assessment framework as laid down in this standard is shown in Figure 4.1 below:

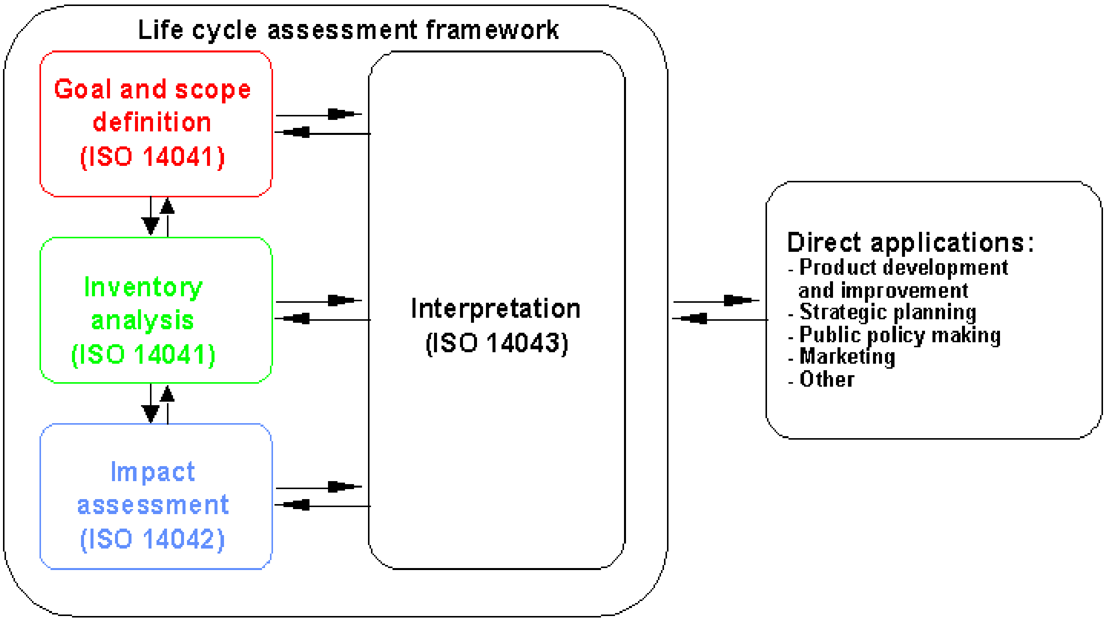


Figure 4.1 LCA phases framework as laid down in ISO 14040:1997 (taken from www.boustead-consulting.co.uk/iso14040.htm)

4.3 Partial LCA approach for embodied energy assessment

LCA has been considered as the most holistic and objective approach. It is because of this that this particular research chooses the partial life cycle assessment approach as a way to assess the embodied transport energy associated within prefabricated timber frame house.

Figure 4.2 illustrates the energy consumption and possible transportation energy flow throughout the life cycle of prefabricated timber frame housing.

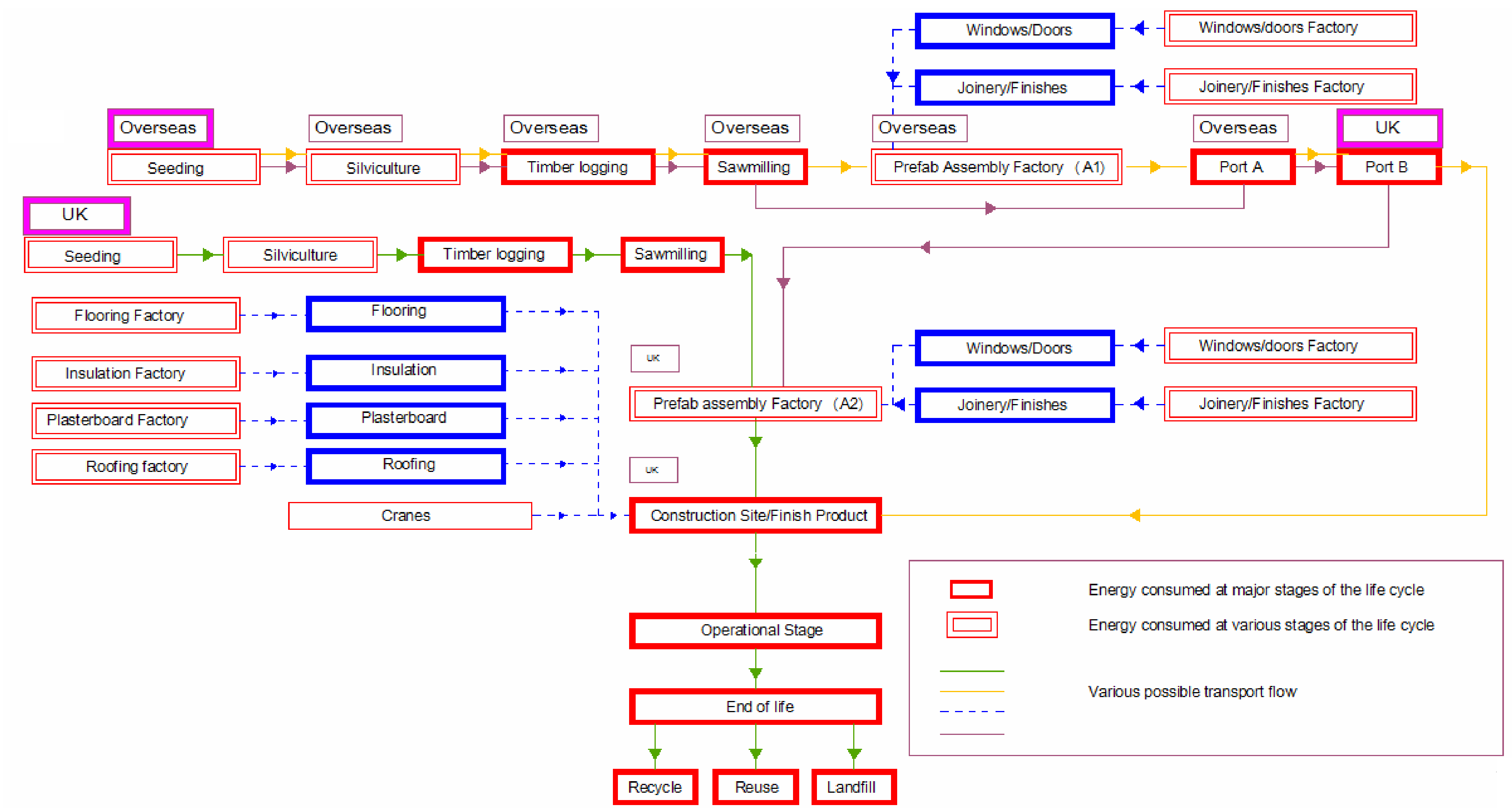


Figure 4.2 Possible energy consumption and transportation flow throughout the life cycle of a typical prefabricated timber frame house

The flow diagram above illustrates the possible energy consumed at each stage throughout the life cycle of prefabricated timber frame house and the possible transportation flow associated within it. It starts from the forestry and continues to timber sawmills, all the way to the factory and finally onto site. Transport also occurs at the end of the building life where the material waste is either transported to various recycling facilities, landfills or further development sites for reuse.

The possible transport flow illustrated in Figure 4.2 suggests that the location of factory, forests and site can be considered as an influencing factor in the overall embodied transport energy consumption of a particular building or product. The number of pre-assembly factories associated with the production and manufacturing of elements within prefabricated timber frame house also plays an important role. Transporting prefabricated components and its associated material from one factory to the other for further assembly process is believed to contribute further onto the total embodied transport energy of a particular prefabricated building or houses.

The limited research publication that focuses on the life cycle of prefabricated timber frame house in the UK and its embodied transport energy in particular has drawn the need to generate process flow model that is unique to the research. All the components and stages within the process flow model were identified using primary and secondary data collection.

It is understood that building is divided into several elements and it is beyond the scope of this research to analyse the embodied transport energy associated in every elements within prefabricated timber frame house construction.

4.4 Data collection

4.4.1 The use of questionnaire as a form of primary data collection

Questionnaires were chosen as a way to gather primary data collection. It is produced to determine the most commercialised type of prefabricated timber frame house. The first aim in the development of the questionnaires was to undertake an exploratory investigation to gain further understanding into the transportation and material flow associated with various prefabricated timber house techniques.

The questionnaires were carried out on the 6th of November 2006 and were distributed to a number of TRADA (Timber Research and Development Association) accredited prefabricated timber frame housing manufacturers through post, with the enclosed covering letter explaining the purpose of the questionnaire. Further details regarding the questions asked can be found on Appendix B.

The structured questionnaires in this research were produced and aimed at all the addressee in the same order with the same wording. The questionnaires were divided into three sections.

The first section of the questionnaire was developed to identify the most common prefabricated construction type used in the UK at the time of research, the second section of which is designed to identify the transport processes throughout the cradle to site stage of the particular prefabricated construction type. The aim of this second section is to reveal the origin and type of timber used, to identify whether there is more than one factory involved in the production of the finish product and to establish the most common transport processes undergone, the means of transport and the related distances on each stage. Finally, the third section was designed to reveal the amount of associated timber materials being transported from the forest to site.

4.4.2 The outcome of the questionnaire

Questionnaires were distributed to fifteen TRADA accredited timber frame manufacturer with a 50% response rate. Table 4.1 below demonstrates the summary of the data collected.

4.4.2.1 Trends in prefabricated timber frame construction for housing development

Data gathered from the questionnaires at the time of research indicates that non volumetric open wall panelling unit was the most common construction system used by TRADA prefabricated timber frame housing manufacturers.

The data collated highlights a very small percentage of manufacturers producing Structural Insulated Panels (SIPS), post and beam as well as modular timber frame construction type. The responses gathered suggested that open wall panelling unit was the most commercialised prefabricated construction techniques within the UK. It also indicates that 37.5% of the manufacturers who responded back were also supplying Structural Insulated Panels (SIPS) and only 25% of them were supplying post and beam construction. Based on the responses gather, it was concluded that open wall panelling system was the most commercialised construction at the time questionnaires were answered.

The use of open wall panelling construction meant that the wall panelling units will be transported to site without its fittings, windows or doors, insulation, vapour barrier and plasterboard which in turn will be supplied and transported separately by the main contractor. It is also clear from the responses received that the foundations were supplied or arranged by other companies or client themselves.

Table 4.1 Outcome of primary data collection

No.	Name of Companies	Timber Construction Type Used			Source of Timber	Type of transport	Transport Loads	Foundations supplied by others	Transportation Processes	Distance limitation for client
		Panelling	Post&Beam	Pod				Y/N		(miles)
1	Guildford Timber Frame Ltd (West Sussex, Billinghurst)	Open/SIPS	√		Sweden	Rigid HGVs Arctic HGVs	Full load	Y	Sweden sawmill – Goteborg harbour – Kent harbour – Billinghurst factory – on site	50-100miles
2	Thomas Mitchell Homes Ltd (Thornton, Fife)	Open			Norway	HGVs	Full load	Y	Europe sawmill – Europe harbour – UK harbour – factory - site	No limits
3	Timber Developments Ltd (Wales, Spain, Manchester)	Open			Europe	HGVs	Full load	Y	Europe sawmill – Europe harbour – UK harbour -	<150miles
4	Space 4 Ltd (Birmingham)	Open/SIPS			Sweden	HGVs	Full load	Y	Sweden-Goteborg harbour-Tilbury docks-factory (Birmingham)-site	100 miles
5	Acacia Timber Ltd (Huddersfield)	Open/SIPS			Sweden, Finland, Canada	HGVs	Full load	Y	Europe harbour – Hull (Huddersfield) harbour – factory - site	Average 40 miles
6	Westframe (Leicester)	Open	√		Sweden	HGVs	Full load	Y	Sweden sawmill – Goteborg port– Sileby port – factory - site	Average 50 miles
7	Creative Estates (Swindon)	Open			Scanbaltic states	HGVs	Full load	Yes	Scanbaltic line – Newport harbour – Swindon factory - site	200 miles
8	Custom Homes	Open/SIPS			Scotland	HGVs	Full load	Yes	Various but within UK	No limits

4.4.2.2 Material Resources

From the reply of the questionnaires, the majority of the structural timber used for prefabricated timber frame house construction is softwood timber of which is being imported from various European countries and manufactured based on Canadian Lumber Standards (CLS).

4.4.2.3. Production and transport processes

Data collected suggests that structural timber studs used for prefabricated timber frame house were felled and rough sawn before transported directly from the timber supplier to an assembly factory in the UK to be vacuum treated against fungal and insects (also known as vac-vac protim treated). This structural timber is then cut to length before being assembled, ready to be transported as the finished product to the site for the final assembly. Nevertheless, as most of the prefabricated timber manufacturer obtained their timber studs and plywood from third party merchants with third party transport arrangement, information surrounding the transport processes and distances from the European sawmills to the European port proof to be limited and often difficult to obtain due to company's confidential policy.

The outcome of the primary data collected from the questionnaire indicates that the transportation process from the acquisition of timber from the forest to the site as the finished product was carried out mainly by road transport rather than train. Articulated 40 foot lorries with gross weights of 40 tonne per lorry is generally used as the means of transport and are believed to carry full load whenever possible. Rigid lorries are only used when access to site is limited. It was also noted that containerised shipping were used to transport the timber materials from the designated European port to the nearest UK port.

Another similarity in the answers received from the respondents suggests that most of them own at least one pre-assembly factory of which is located within the UK to serve local clients with transport distance from the factory to development site ranges between 50-150miles.

4.5 The development of the process flow model

Based on the data collated from the questionnaires, this research aims to concentrate on the production of transport flow analysis of an open wall panelling system.

Based on the outcome of the questionnaires, the basic embodied transportation energy flow was developed and broken down into six stages as illustrated in Figure 4.3 below. Data gathered from the timber prefabricated manufacturer suggests that its structural timber was originated from European countries. It is assumed that plywood and studs associated with prefabricated timber open wall transportation flow is transported onto two different sawmills and therefore this has been divided and counted as two separate transport energy. From the plywood and studs sawmills, this associated timber materials are then transported onto the nearest European port and imported onto the UK before being hauled onto the pre-assembly factory ready to be processed and assembled as prefabricated timber open wall panelling units. The finished products were then transported to site ready for on-site assembly.

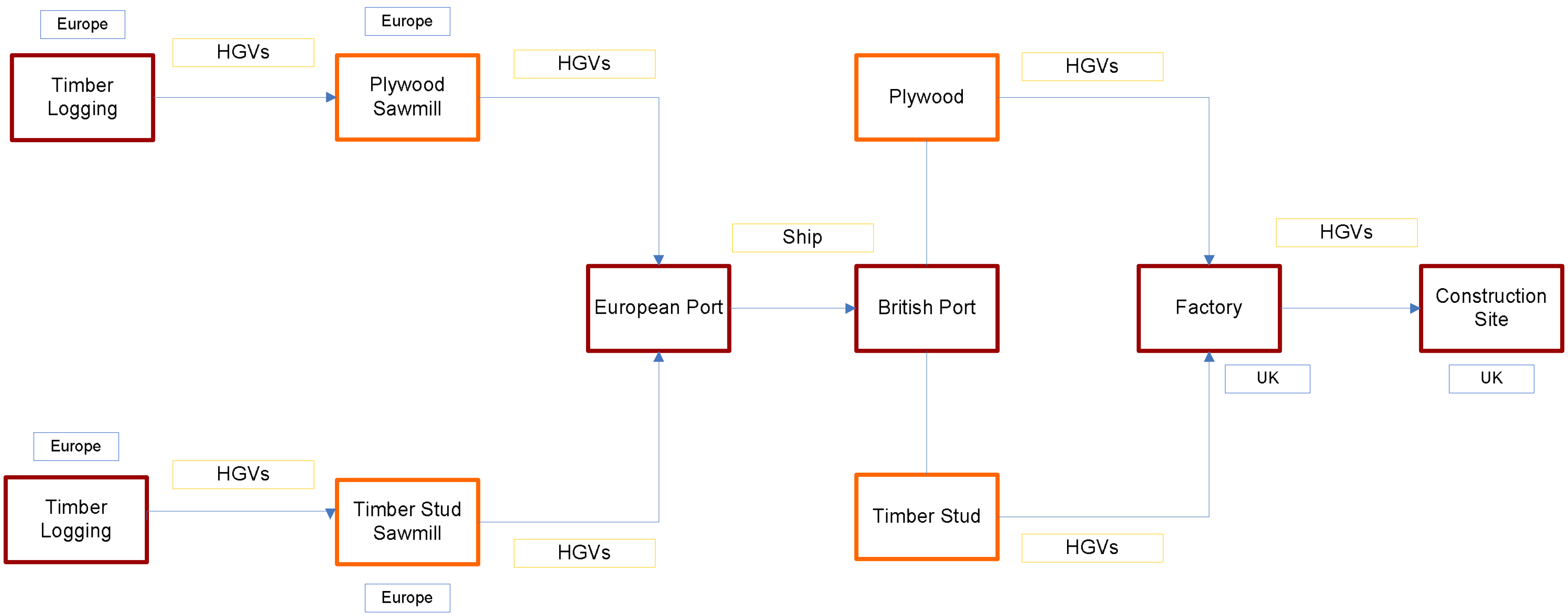


Figure 4.3 Transport process flow model being employed within this research study

Despite the availability of data showing the process from the forest to site, it is acknowledged that as manufacturer out sourced their studs and plywood supplier, tracing the exact information from the forest to the nearest UK port is a complex task to perform.

Some of the data required from between the manufacturers to develop the suitable mode for the embodied transport energy flow of the particular systems was also proven to be limited and inconsistent between one another. One of the differences lie in delivery arrangement in regards of its vehicle loading amount on the return journey. Space 4, for example, which uses Wincanton logistic company to distribute their wall panelling to site has stated that they tends to carry full load on their return journey to minimise the transportation impact. Nevertheless, this does not necessarily mean that similar arrangements were taken by other manufacturers and its logistic companies.

4.5.1 System boundaries

The embodied transport energy and associated transportation flow for projects may vary widely depending on the varying system environmental envelope and hence it is important that a system boundary correctly determines which process stages are to be included in this particular research study.

4.5.1.1 Location of sawmills

Swedish timbers derives from a variety of out-sourced sawmill companies and forests locations. This in turn results in a high number of possible transport combinations. The employment or out-sourcing of sawmill depends on the best suited scale of production and other factors of which are not easily measured (MacGregor; 1956). Transportation energy consumption are also highly dependent on the amount of timber productivity per sawmill. The lower productivity of timber also means that the requirement of mills with larger procurement areas for some volume requirement thus increasing the energy consumption during the transportation stages.

Due to this limitation, establishing the transport routes and distance in order to quantify the transportation energy embodied from forestry to the nearest Swedish port is believed to be one of the most complex routing problems since there are no straight answers towards the choice of routes taken in the timber transportation. It is understood that different companies may plan their logistic transportation needs through different means. Some companies allow their drivers to decide their own schedules, while others schedule at a higher level in the company.

This research boundaries were set on the Swedish timber located in the South side of the country where better developed road network and higher timber growing rate are considered as a benefit and more environmentally friendly approach to be imported to other countries. The average distance as referred to in Swedish Statistical Yearbook of Forestry (Swedish Forestry Agency, 2004) and personal communication gathered from Mikael Frisk (Frisk, 2007) were used in this research study. Based on both references, transportation from Swedish forest to the saw mills is estimated to be 93km, as sawmills are typically located close to the forest and transportation from sawmills to the port of Goteborg to be 189km (Frisk, 2007).

4.5.2.2 Types of lorries used from the forest to site

In terms of lorries weight and size restrictions, Sweden has a larger gross lorry weight allowance, up to a maximum gross weight vehicle of 60 tonne (40tonne net load) compared to UK or other European countries which only allowed a maximum weight of 44 tonne (24tonne net load).

Two means of transport, 60 and 40 tonne gross vehicle lorries were used as an assumption in this research study. The 60 tonne gross vehicle lorry as shown on Figure 4.4 was used as an assumption during the transportation stages between forestry to the plywood and studs sawmills and as described Palmgren (2005), consists of three blocks and two axles with self loading function.

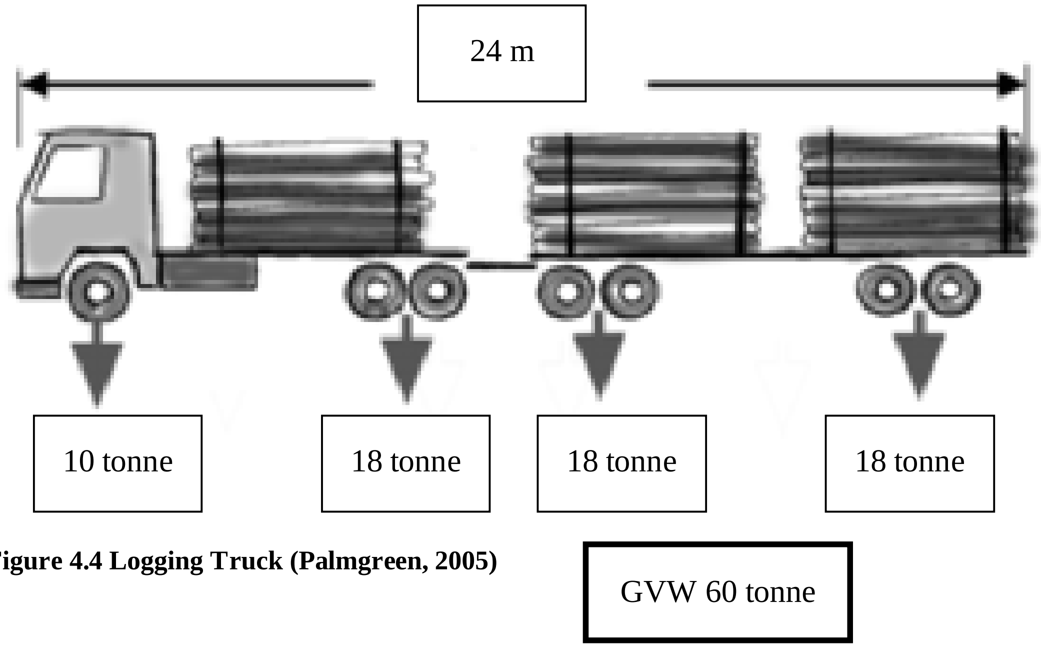


Figure 4.4 Logging Truck (Palmgreen, 2005)

The timber material in the form of plywood and studs that were being packaged in the standardised 40 feet ISO container (also known as FEU) are then transported from the sawmills to the nearest Swedish port using 40 tonne gross weight lorry where it is assumed to return to the garage empty loaded. This assumption is based on data gathered from the returned questionnaires which has indicated that the plywood and studs transported from the nearest UK port were transported to the manufacturing factory in a 40 feet and 40 tonne gross weight lorry.

The research takes into account that the vehicles used for the manufacturing processes are fully loaded. However, the use of independent haulage manufacturers has resulted in rather limited information that can be gathered in regards of its return journey. This has resulted in the research assumption requirement of a worst case scenario, where delivery vehicle returning empty to their starting point. This means that the delivery distance to be doubled to represents the total distance travelled per delivery.

It is understood that in certain towns and cities, permits are required to travel in restricted areas and load restrictions may vary too. In this research these varieties has been neglected and best scenarios applied where the heavy goods vehicles will travel on the best and nearest possible routes.

In general, energy consumptions during road freight transport might also be greatly dependent on traffic jam during transportation processes as well as the time the driver spent during resting time on the road. Despite it being acknowledged, this point will not be included in the system boundaries.

Secondary energies such as the consumption by the drivers and the environmental impacts caused by the infrastructures or their fabrication were also neglected since they are considered to be insignificant compared to the impact generated by the product that uses these infrastructures.

In terms of material flow analysis from forestry to the plywood and studs sawmills, this research assumes that there will be at least two different fully loaded 60 tonne lorries carrying logs heading to plywood and sawn wood sawmill.

4.5.2.3 Type of ship used to transport the associated timber materials

Calculations to determine the amount of studs and plywood in FEUs transported per ship can be very complicated as these varies widely depending on various factors such as vessel types and its energy intensity, as well as the amount of load it can carry.

The wide varieties of published energy intensity data that could be applied to generate the shipping transport energy within this research were noted. West et al (1994), for example, stated that the energy efficiency of a ship is 0.25 MJ/tonne km, where as Kanyama and Carlsson (2001) differ slightly at 0.18 MJ/tonne km. International Chambers of Shipping (ICS, 2005), on the other hand, reported a value of 0.12MJ/tonne km for a 1,226 TEU containerised vessels travelling at 18.5knots.

With various range of published data available but with limited primary data obtainable, there was a restraint in determining the exact published data to be used for this particular research quantification. Further assumption had to be drawn for this research which assumes that 1,226 TEU containerised vessels with net tonnage of 6720 tonne travelling at 18.5knots were used to transport the associated timber materials to produce the particular functional unit (please see Appendix C2.3 for further details of typical 1,226 TEU containerised vessels used within this research). It is also assumed that 25% of its full load has been allocated to transport 12mm thickness plywood and the other 25% of its full load has been allocated to transport the S60 studs.

4.5.2.4 Return factors

The development of the research model to quantify the embodied transportation energy relies on an assumption that ship used to transport the associated timber materials was fully loaded. Nevertheless, while the containerised ships are assumed to return back fully loaded as well, lorries were assumed to return empty loaded.

4.5.2 The establishment of transport energy flow model

Based on the system boundaries set above, transport energy flow of which is unique to this research is generated. Figure 4.5 illustrates the possible transport process flow in greater detail. This transport energy flow has used an assumption that timber being analysed within this research is originated from Swedish forests. With the aid of 60 tonne lorry type, the logs as the raw timber material were conveyed from the forests to the Swedish plywood and studs sawmill to produce the desired number of plywood sheets and studs. 40 tonne lorry were used to haul the studs and the sheets of plywood from both sawmills to the nearest European port, assumed to be Goteborg, before being imported to the UK using a containerised ship. The journey from the nearest UK port continues to the prefabricated open wall panel factory where the studs and sheets of plywood were assembled onto prefabricated timber open wall panelling unit before then finally conveyed to the site ready for on-site assembly. The transport routes within this transport process flow were based on the factory locations of TRADA manufacturers' who responded back.

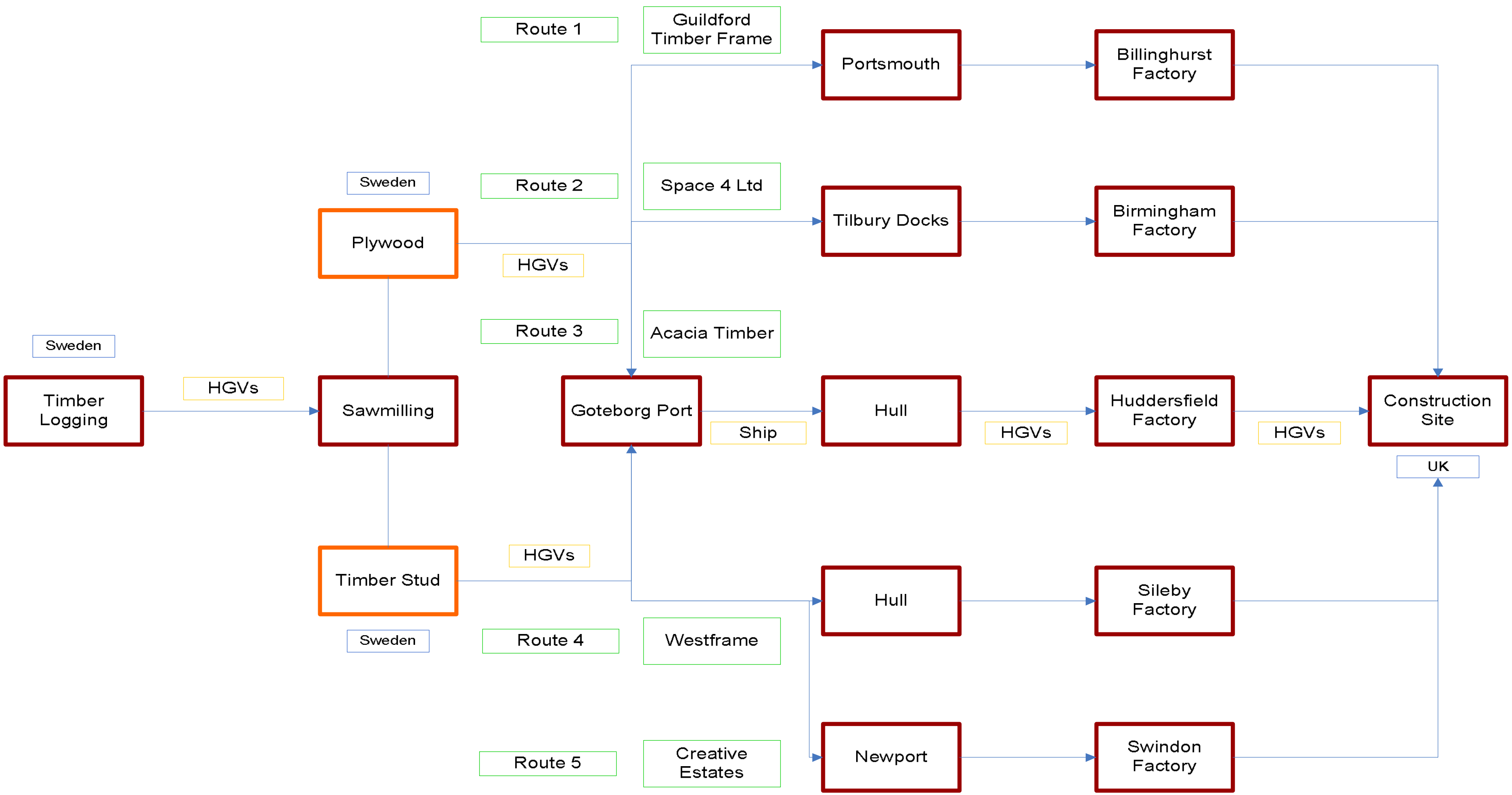


Figure 4.5 Possible transport routes for the prefabricated timber wall element and its associated timber materials from forest to site

4.5.3 The establishment of raw material flow

In order to estimate the transport energy required by a particular prefabricated timber wall unit, it is essential to also reveal the process flow of the associated timber material used to produce the particular prefabricated timber wall element.

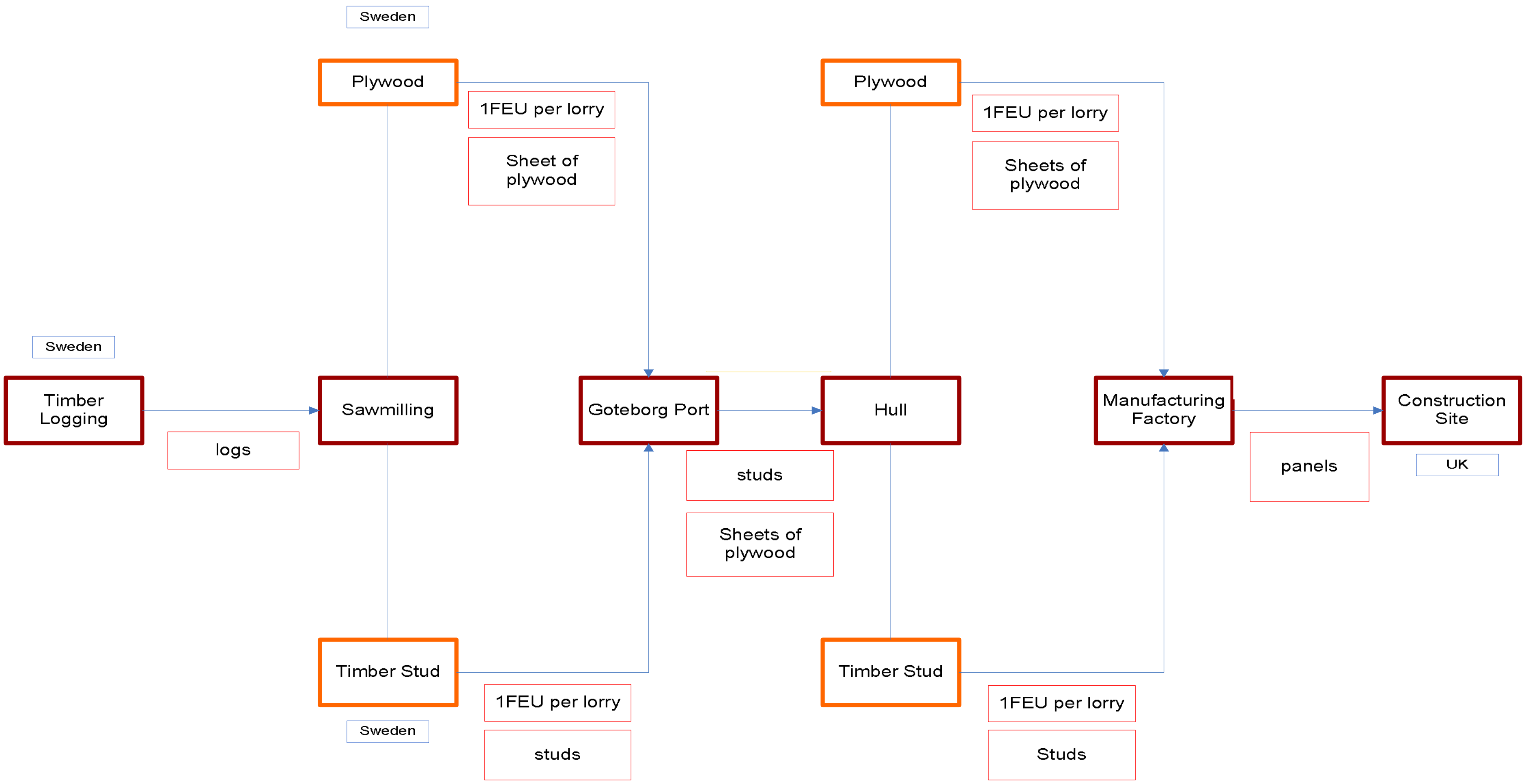
The characteristics of the timber material products transported in terms of its shapes, density and the composition or packaging of the goods, may vary in each stage. It depends on the supply and demand as well as the location of its factory and the timber origin. This research study therefore underlines the importance to establish a model to illustrate the raw material flow throughout the cradle to site gate undergone in the given functional unit before quantifying the amount of raw materials required per panel.

Due to the limitations of data gathered during the questionnaires, further assumption taken from available published literature to help in the generation of mathematical formulae has been used to aid the quantification of the transport energy flow, the material flow and the equivalent transport energy per panel.

Figure 4.6 shows how raw material were transformed and transported as wall panelling ready to be assembled on site.

At the cradle gate, the raw timber material was in the form of logs. The logging process involved trees being cut and transported to the roadside with the top and limbs intact. The trees are then de-limbed, topped, and cutting it into the optimal length, also known as bucked, at the landing. This method requires the branches and other woody material (also known as slash) to be treated at the landing. In areas with access to cogeneration facilities, the slash can be chipped and used for the production of clean electricity or heat. Logs that were piled and sorted for plywood and studs sawmill and of which were located on the roadside were then picked up by 60 tonne lorry type to be transported to the plywood and studs sawmill.

Figure 4.6 Material flow analysis for the given route



At the sawmill gate, there were two processes being differentiated in this part. One of which is process for studs and the other is processes undergone for plywood. In terms of stud, logs were being examined and cut to various lengths in what is called a log merchandising operation. Machinery, as shown in Figure 4.7 below, was used to remove the bark of the log (also known as de-barker), and to include a saw which was used to break-down the round logs (known as head saw). The machinery also to have a system for handling logs during the sawing process in the form of carriage or conveyor to then pass it on to the trimming boards to produce a smooth parallel edges. Finally this will be cut and trimmed on a cutting board to square and precise lengths.

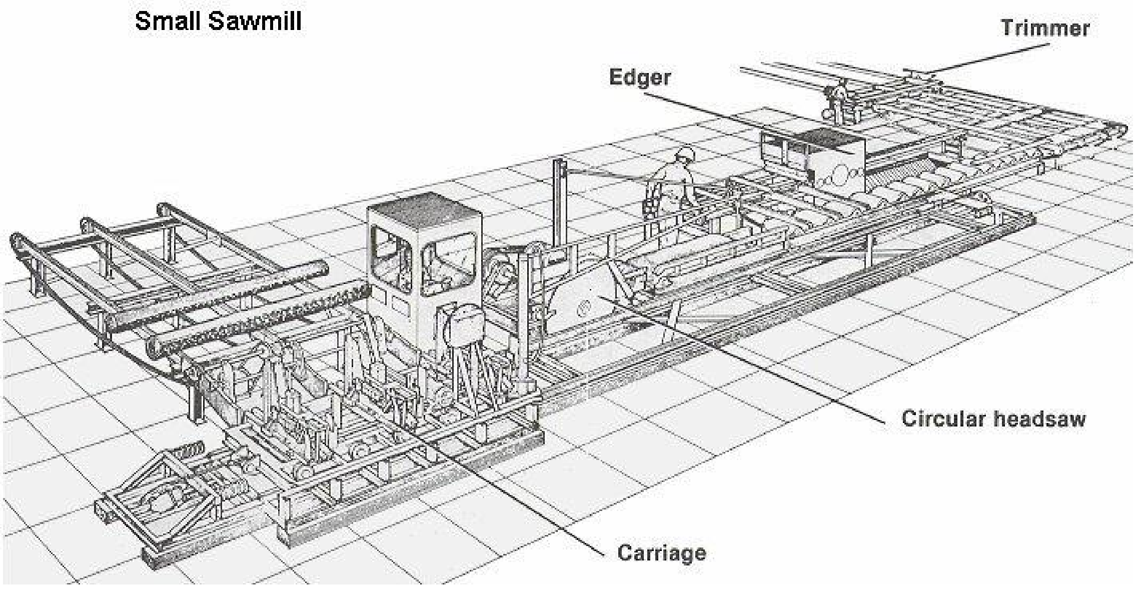


Figure 4.7 Small sawmills process. (Haygreen and Bowyer, 1996)

There are several possible sawing patterns that can be used as shown further in Figure 4.8, taken from Berge (2002) publication. It can be in the form of sawing through and through, boxing the heart, true quarter cutting and/or quarter cutting. Boxing the heart works well with the circular saw and is almost the only method used today. A number of panelling that may be produced from different type of sawing pattern is also shown at the bottom of Figure 4.8.

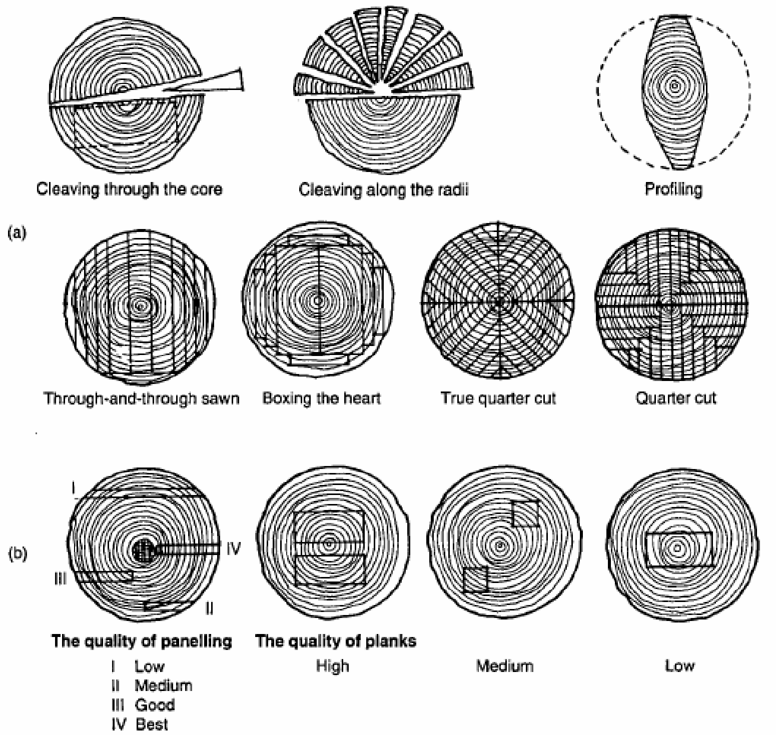


Figure 4.8 (a) Different methods of dividing up timber; (b) qualities of panelling and planks (Berge, 2002)

The production stage of plywood is more complicated than stud production. The quality of a particular log will also play a major role since the more flaws a log has, the more wastage it will produce and the less plies it will generate. The quality of plies can also be affected by peeler log temperature.

As the amount of plywood production dependent highly on various factors during its production stages, it is important to recognise its production stages. A range of coniferous species is used in plywood manufacturing and each has special characteristics that may affect the performance level of the final product. It is common that veneer of different species can be combined but with the facing to come from the same species.

Based on the method of production, it can be classified as rotary-cut (cut on a lathe by rotating a log against a knife blade in a peeling operation), sliced (cut with a knife blade sheet by sheet from a log section, or flitch), or sawn (produced with a special tapered saw). Figure 4.9 shows a rotary method and several flitch methods.

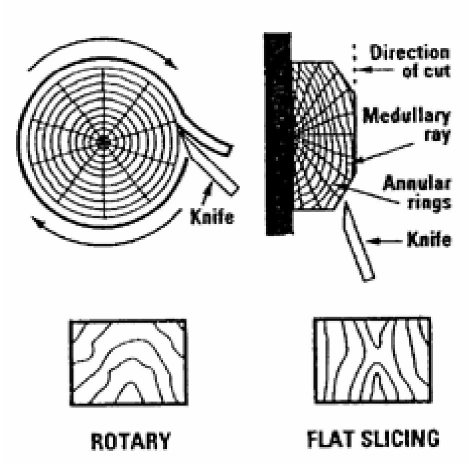


Figure 4.9 Methods used to produce plywood (Metrohardwoods, 2007)

In the rotary cut method, the log is mounted centrally in the lathe and turned against a razor sharp blade, like unwinding a roll of paper. Rotary cut veneer is exceptionally wide. Flitch method, on the other hand is where the half log is mounted with the heart side flat against the flitch table of the slicer and the slicing is done parallel to a line through the center of the log. This produces a variegated figure.

More than 90 percent of all veneer is rotary-cut, but figured woods producing veneer for furniture and other decorative purposes are sliced. Sawn veneer is seldom produced, because it is a wasteful operation.

Softwood plywood has raw material graded as “peelers”. The first stage of plywood production is involving the peeler logs to be delivered to the veneer mill and sorted by grade and species. It then is debarked and carried into the mill on a chain conveyor where a huge circular saw cuts them into sections about 2.5m to 2.6m long, suitable for making standard 2.4 m long sheets with the log sections known as peeler blocks.

Before the veneer can be cut, often the peeler blocks are heated and conditioned by steaming or soaked in hot water to soften the wood prior to peeling. This process takes

12-40 hours depending on the type of wood, the diameter of the block, and other factors. This is done to reduce the possible veneer breakage and results in smoother and higher quality veneer.

The heated peeler blocks are then transported to the peeler lathe. To maximise veneer yield, each peeler block is gripped on the ends at the block's geometric centre. While rotating at high speed, the block is fed against a stationary knife parallel to its length and peeled into plies with desired thicknesses. When the diameter of the block is reduced to about 127 to 51mm, the remaining piece of wood, known as the peeler core, is ejected from the lathe and a new peeler log is fed into place. Peeler core may then be sawn into standard 38 x 89 mm lumber, used for fence posts and landscape timbers or chipped for use as pulp chips or fuel. The ribbon of the veneer will then be cut into pieces under the clipper knife at 1.25m or 0.64m intervals, except when a narrower, a blemish free piece of veneer can be produced.

The plies were dried, graded and glued together. These plies were then trimmed, patched and assembled by taping or edge gluing into sheets large enough to make plywood panels. Following the final grading, plywood is piled in the standard quantity units called lifts, about 75cm high. The lifts are securely bound with steel strapping for protection and ease of handling. They are labelled for type, grade and size of panel. The lifts are delivered to the warehouse for storage or shipment. In most cases, only about 50-75% of the usable volume of wood in a tree is converted into plywood.

The processes undergone during the logging and manufacturing processes has concluded that during the transformation from logs to plywood sheet and studs, where logs were firstly un-barked and then transformed to the required size and dimension of plywood sheet and studs, there were material losses during the process hence it is important to make sure that its waste factor were taken into account when the mathematical formulae were established to quantify the flow material analysis later on.

4.6 Summary

The assessment of embodied transport energy of a particular prefabricated timber wall panelling unit could be carried out with the aid of process flow model. The model illustrates the way in which prefabricated wall panelling unit were produced and transported from the forest to site.

Questionnaires have been used to collect primary data and was used to define the boundaries and guiderails that govern the development of the embodied transport energy process flow model e.g. the type of prefabricated housing construction mostly used in the UK, the origin of the raw timber materials and the means of transport employed to haul the associated timber materials from forest to the construction site.

The questionnaires were developed as the primary data collection and were sent to a number of TRADA accredited prefabricated timber frame manufacturers. Eight replies out of fifteen TRADA accredited prefabricated timber frame manufacturers were recorded. The 50% response back was proven to be useful and the outcome suggests that, at the point of questionnaire being received, most UK prefabricated timber frame house was constructed using open wall panelling system. Response also verified the fact that the majority of raw timber used to produce prefabricated timber wall unit were imported from other countries and that all road haulage was carried out using lorries. The majority of response also suggests that most of them tend to have only one assembly factory with the distance between the assembly factories to site within the 50-100 miles radius.

Nevertheless, there are some limitations in gathering primary data collection using this technique:

- Questionnaires which were being post mailed did not allow the opportunity for further investigation and the answers were to be accepted as final. There were no opportunities to clarify ambiguities.
- The quality of feedback received varied between the companies as their timber materials were being subcontracted from third parties timber merchants and freight logistics. Possibly confidential policies may also be a factor

Because not all data required to generate the embodied transport energy were obtainable through the primary data collection alone, a further desk study was called for and assumptions were made based on the available literature.

The following system boundaries and assumptions were considered when generating the transport and material flow analysis:

1. The focus in this research is on timber materials used to construct the internal and external open wall panelling unit and not other materials that were also present in the wall panelling unit such as cladding, vapour control layer, plasterboard lining and insulation which were also part of the external wall construction.
2. Although it is also of importance to investigate the environmental impact and transportation energy embodied in the glue and nails used during the production of plywood and the construction of wall panelling, they are outside the scope of this study and has not been included within this research study.
3. The two year research study concentrates particularly at the direct embodied transport energy and does not include the transport energy consumption when cranes and labours are being transported to site.

4. It is understood that transport energy also occurs during the end of life and of which could include potential waste recovery and recycling stages. This has been excluded from this research as the recent prefabricated timber frame housing construction are still considered new to the market and therefore its exact life span is still unknown and very much dependent on assumption.
5. Infrastructure and transport systems vary from one region to another. This research aims to analyse timber materials of which being originated from Sweden as the outcome of the primary data collection established in section 4.4.2 earlier concluded that the majority of timber materials for UK prefabricated timber wall panelling unit are being originated from Sweden.

Figure 4.10 shows the transport and material flow model for the production and delivery of panels to site. It is understood that analysing the embodied transport energy of prefabricated timber frame wall panelling unit is a complex thing to do. It is therefore of importance that appropriate mathematical equations are developed beforehand to aid in the quantification and analysis process.

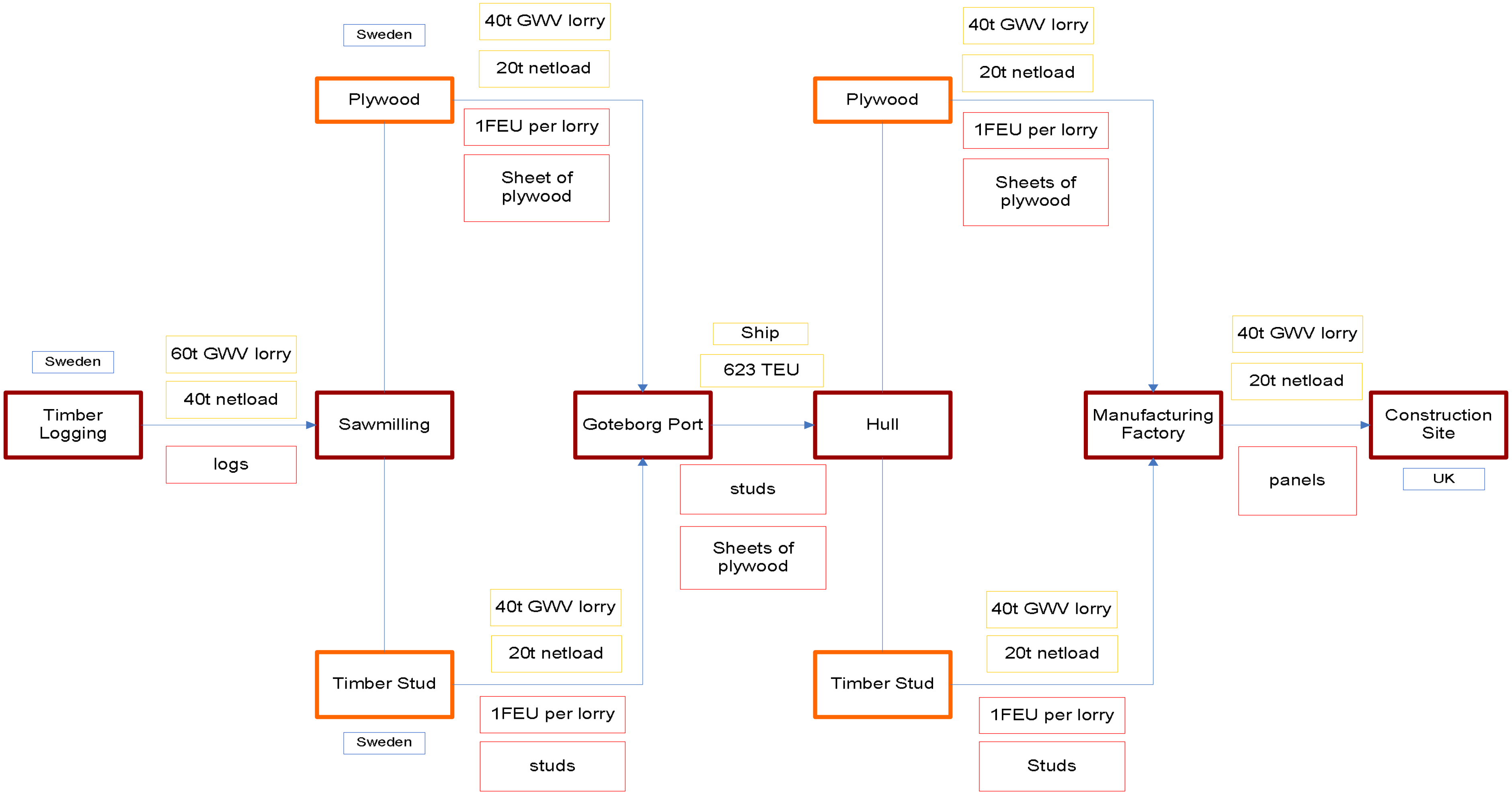


Figure 4.10 Detailed transport and material flow

Chapter 5

Embodied Transport Energy Analysis Methodology

CHAPTER 5: EMBODIED TRANSPORT ENERGY ANALYSIS METHODOLOGY

5.1 Introduction

Chapter five is written and set to explore the quantification technique undertaken to assess the process flow created earlier in Chapter 4. A set of mathematical equations were developed for each and every stages illustrated within the process flow. These mathematical equations are developed to present further understanding on the correlation between the loading quantities, the choice of transport used, the transport distances and the origin of timber to the total embodied transport energy of a particular prefabricated timber wall panelling. An overview of the available techniques is firstly explained, and the most suitable techniques were adopted and developed further.

In order to generate an embodied transport energy flow analysis, a Functional Unit (FU) is established and defined within this research as an open wall panelling unit measuring 3600mm x 2400mm.

The mathematical equations developed were divided into three sections. They were set to aid in the quantification of transport energy, the associated timber materials per means of transport per stage and the total embodied transport energy per FU. They are developed based on a combination of road and maritime transport. These theoretical transport and material analysis were then applied to the illustrated processes flow to evaluate the significance of embodied transport energy per FU further.

5.2 Functional Unit

Data collected from the questionnaire concludes that prefabricated timber open wall panelling system is the most commercialised type of prefabricated timber house construction type at the time of questionnaire being distributed.

The functional unit used in this research, as shown in Figure 5.1 below, consists of:

- 3 number of 1200 x 2400mm plywood sheathing with thickness of 12mm,
- 7 number of vertical 38 x 89 x 2400mm studs, 600mm c/c
- 2 number of horizontal 38 x 89 x 3600mm studs

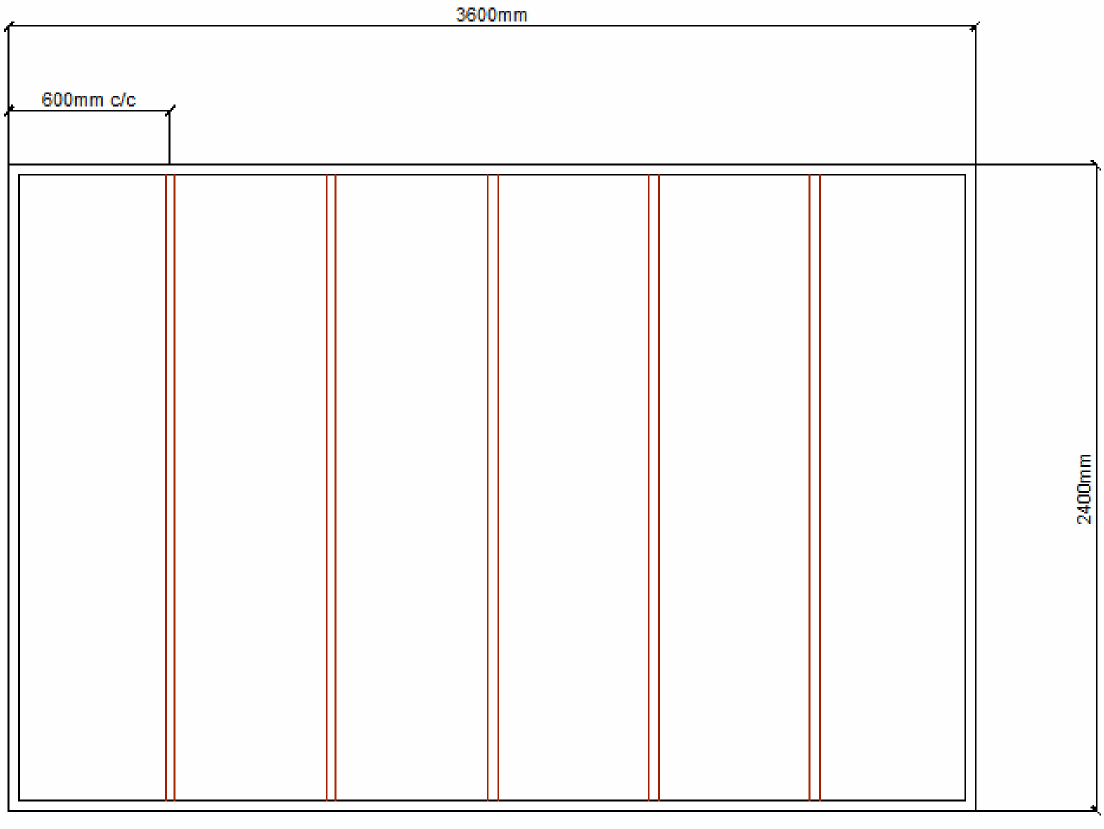


Figure 5.1 Details of a typical 3600 x 2400mm prefabricated timber open wall panelling unit

5.3 Methods to quantify the transport energy flow

Transport energy consumed depends greatly on how the goods were moved, the variation in transportation weight and the haulage length.

5.3.1 An overview of available techniques employed to quantify embodied transport energy

There have been various mathematical models developed to assess embodied transport energy within a particular building or material life cycle and of which has been made available for a number of years [(Bos, 1998), (Lensink, 2005), (Adalberth, 1996), (Chen et al, 2001), (Howard et al, 1999), (Miller, 1996), (Flanagan, 2000), (Anderson and Edwards, 2000)].These calculations are commonly developed in order to generate the overall embodied energy of a particular building or material life cycle.

This section reviewed the methodologies developed by Adalberth (1996), Chen et al (2001), Flanagan (2000) and Anderson and Edward (2000) in greater detail. The mathematical models within this research were produced based on these three particular publications. The expressions within all the equations reviewed here were adapted for the purpose of this research.

Adalberth (1996) transport energy calculations (as shown in Equation 5.1 below) has taken into account the estimated transport distance between manufacturers and building sites during construction and renovation. Transport from the building site to a waste disposal site during renovation and demolition has also been taken into account. Nevertheless, transport of the raw and semi-manufactured material is included within the manufacturing energy category rather than within this transport energy.

The transport energy correlation for Adalberth (1996) is presented as follow:

$$E_{transport} = \sum_{i=1}^{n} m_i \cdot (1 + \frac{w_i}{100}) d_i \cdot T_c$$ **Equation 5.1**

Where

$E_{transport}$, the transport energy (measured in kWh), n = the number of materials, m_i = the amount of building materials (tonne), W_i = factor of waste of the material i produced during erection of buildings (%), d_i = distance from manufacturer to site (or factory) (km), and T_c = energy required for the conveyance concerned (Kwh/tonne km)

Based on Tillman et al (1991), Adalberth has taken into account the difference in transport energy use between lorries for long and short distance transportation. Tillman (1991) mentioned that lorries used for long distances tend to carry larger loads, whereas lorries on short distance trips normally carries smaller loads and often take place on streets and roads in cities as oppose to country roads, hence requiring more fuel.

Transport energy consumption can be measured either in kWh or Joules. Adalberth (1996) uses kWh as the unit to measure the transportation energy whereas Flanagan (2000), Anderson and Edward (2000) as well as Chen et al (2001), on the other hand, used Joules to represent the transportation energy embodied.

To estimate the transportation energy embodied in the life cycle of a particular building, paper presented by Chen et al (2001) has developed the following equations:

$$E_{transport} = \sum_{j=1} (1 + w_j) m_j \, m_j (T_c + T_d)$$ **Equation 5.2**

Where $E_{transport}$ is the energy required for transportation of the building materials and elements (MJ/kg.km), w_j is a factor of waste of the materials j produced, m_j is a replacement factor for building elements j during the lifespan of a building, m_j is the amount of building material j (kg), T_d is the energy used in demolishing buildings and transporting the demolished building components from building site to landfill, subscript t refers to transportation, and T_c refer to the average energy use for transportation of material to the building site (MJ/kg).

T_c may be obtained by:

$$T_c = \sum_{j=1}^{k} \frac{M_{ij}}{m_j} \left[\sum_{l} T_{c,l} d_l \right] \qquad \textbf{Equation 5.3}$$

Where M_{ij} is the amount of building material or component j imported from country i, $T_{c,l}$ is the energy use for transportation of building materials by means of conveyance l (MJ/kg.km) and d_l is the transportation distance by the conveyance l (km).

Chen et al (2001) has emphasised the importance of quantifying the transportation energy embodied in it as most of the raw building materials used in Hong Kong are often imported which may results in a significant impact on the embodied energy consumed by buildings in Hong Kong. Because of this a mathematical model was produced to quantify the energy attributed during the transportation of building materials and its components to and from the building site.

Both Chen et al (2001) and Adalberth (1996) acknowledged the need to take into account the waste factor of materials, and the average energy used for transportation of materials to building sites.

While Adalberth (1996) took into account the renovation factor during the transportation stages and the effect life span of buildings and its materials are on the whole life cycle performance, Chen et al (2001) does not taken this into consideration. Chen et al (2001), on the other hand, considered the transportation energy consumed during demolition in transporting demolished building components from building sites to landfills, whereas Adalberth only accounts this as a different type of energy consumption.

The transport energy per kg of material established by BRE (Anderson and Edwards, 2000) and Flanagan (2000), however, only focused specifically at the transport energy use, the loading, distances and return factors. The particular transport energy does not include within its calculation the replacement factor nor the waste factor of the particular materials being transported. The equation based on Anderson and Edwards (2000) as well as Flanagan (2000) were as follow:

$$E_{transport} = (T_c \times \frac{d}{1000} \times r) \quad \textbf{Equation 5.4}$$

Where $E_{transport}$ is the transport energy (MJ/kg), T_c is the specific transport energy (MJ/tonne.km), d is the transportation distance by (km) and r is the return factor.

It was decided that the best method to be adopted in this research is the methodology set by both Flanagan (2000) and Anderson and Edwards (2000). These equations have therefore been applied directly to the embodied transport energy mathematical model within this research. This mathematical model is then adopted further to represent the transport energy per panel.

5.3.3 Road transport

Road transport energy is highly dependent on variables such as return factor, types of fuel used, fuel consumption per lorry and its calorific value.

The total transport energy for a lorry can be expressed as follow:

$$E_{Lt} = d \times F_c \times r_{fuel} \times c \times r \qquad \textbf{Equation 5.5}$$

Where E_{Lt} refers to the total transportation energy per lorry (GJ), d is the distance from a to b (km), F_c is the fuel consumption (litre/100 km), ρ_{fuel} with value of 0.831 kg/litre, c which is the net calorific value of 0.0434GJ/kg and r is the return factor.

The distances of the road travelled were established based on the best route journeys as evaluated by the use of Microsoft AutoRoute computer software. Calculating the road distances using this method, however, had an implication owing to the fact that it does not take into account the restricted routes for heavy traffic and heavy goods vehicles, which could result in detours to prevent noise and other pollution on certain roads. Despite this being noted, data gathered during questionnaire are limited which prevents the more detailed version of distance calculation being used.

Net calorific value, rather than gross calorific value, was employed in this research to aid the generation of transport energy calculation. Net calorific value is known to corresponds to the case where water remains as a vapour and hence it is considered as a better indication of the "useful heat" available from the fuel. The very same reason was also given by Hinchcliffe (2004).

The fuel consumption value within this research is expressed in litre/100km. DfT (1997) suggested that fuel consumption values varies considerably depending on the type of lorries, traffic, roads, driving behaviours and many more. For further details on the various available data on fuel consumption, please refer to Appendix F.

The assumption established earlier in section 4.5.2.2 states that for the road transport energy model, lorries with a gross weight of either 60 and 40 tonne were used as the means of transport. Fully loaded 60 tonne lorries are assumed to be used as the main transportation vehicle for shipping logs from forestry to the plywood and studs sawmill, whereas the 40 tonne lorries are used for the remaining road-level transport stages beginning from the plywood stages and sawn wood sawmills to the nearest Swedish port and also from the designated UK port to the site.

For this particular research, fuel consumption data and the return factors employed were based on the most recent data taken from Volvo (2006) and detailed in Table 5.1 below.

Table 5.1 Fuel consumption and return factors based on data provided by Volvo (2006)

Type of lorry	Fuel consumption on full load (litre/100km)*		Fuel consumption on empty load (litre/100km)*		Average Fuel consumption (litre/100km)		Return Factor
	Min	Max	Min	Max	Full load (a)	Empty load (b)	$=\frac{(a+b)}{a}$
60 tonne	45	53	29	35	48	32	1.66
40 tonne	29	35	21	26	32	23.5	1.73

5.3.4 Maritime transport

Shipping remains by far the most efficient means of transportation, in both energy efficiency as well as cost. It has been reported by International Maritime Organization and International Chamber of Shipping (IMO, 2007 and ICS, 2005) that energy consumption of road transport by lorries lies in the range of 0.0007 to 0.0012 MJ/kg.km and by comparison whereas the consumption of a 3,000 dead weight tonnage (dwt) coastal tanker at 14 knots is about 0.0003MJ/kg km and a medium size 18.4 knots container ship, which was used in this research, is about 0.00012 MJ/kg km. Shipping is also known to have a relatively small contributor to the total volume of atmospheric emissions compared to road vehicles.

Shipping transport energy within this research is quantified using equation established below:

$$E_{st} = d \cdot E_{fs} \cdot r \cdot m$$ **Equation 5.6**

Where E_{st} = Shipping transport energy, d = distance from one port to another (km), E_{fs} = Energy intensity of a particular containerised ship (MJ/tonne.km), m = loading amount of S60s and/or plywood per ship (tonne), r = return factor (value of 1.0 as it returned fully loaded)

In terms of maritime shipping distances, predefined routes must be followed and are calculated based on nautical miles using Maritime route software of which has taken into account the sea distances on a certain cargo shipping maritime line. To apply this shipping distance into the transport energy calculation, the nautical miles were then converted into kilometres.

The energy intensity data of 0.12MJ/tonne km is used to generate the shipping transport energy within this research. It is noted that this particular value was in accordance to the recent published data by ICS (2005).

5.4 Methods to quantify the material flow

In terms of material flow analysis, it has been identified that the prefabricated timber wall panel used as the functional unit contained two different structural timber materials, consists of studs and plywood.

5.4.1 Assumptions made for the material quantification

5.4.1.1 Waste Factor

The characteristics of the timber material products transported (for example their shape, density and the composition or packaging of the goods) varies in each stage. It is therefore of importance to firstly quantify the equivalent amount of raw materials required per panel, its waste factor and the quantity of associated timber materials being conveyed on each of the transport stage.

Wood waste occurred during the conversion from logs to a particular structural building part in particular during storage, transport and installation of the final product. It represents the amount of wastage that the material undergoes and the amount of resources lost. It is normally expressed as a percentage (%) of the required amount and varies depending on the quality and size of logs, the machinery used to produce the particular studs and plywood, sawing pattern chosen and many other aspects.

Figure 5.2 illustrates a typical material flow and waste factor that may occur during the cradle to site stages based on Hakkinen (1998). While Hakkinen (1998) employed the use of percentage to illustrate the basic material and energy flows in the production of timber constructions in general and its waste factors attributed per stages in particular, Swedish Forestry Agency has produced a conversion figure of 0.88 to convert the logs, presented in the unit of m^3 f pb (cubic metre solid volume including bark) to the equivalent log after de-bark in the sawmill, presented in the unit of m^3 f ub (cubic metre solid volume excluding bark).

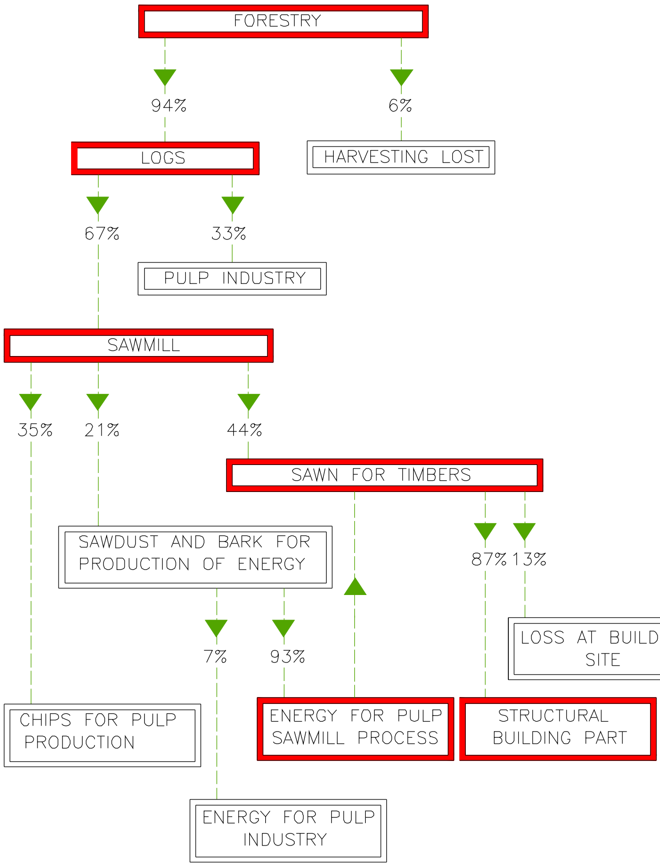


Figure 5.2 Basic material and energy flows in the production of timber constructions adapted for Hakkinnen, 1998

The waste factor in this research has taken into account the conversion of logs to studs and sheets of plywood. Because prefabricated construction uses automated system, wastage was considered as minimum during the production and assembly of the finish product and therefore its waste factor was considered as negligible at the manufacturing stage. It has also been assumed that there is no waste occurs during transportation stage.

5.4.1.2 Studs production per log

The sizes and lengths of timbers used to produce a 38 x 89mm CLS stud varies widely and is very complicated to determine. They depend considerably on the quality of the tree, the type of timber logs used and its growing rate. These can range between 102-800mm diameter. MacGregor (1956), for example, stated that standard log can reach an average of around 4.5metre high with 203mm diameter, whereas Green (2005) stated that Douglas Fir, one of the European softwood species that can also be used to produce CLS stud has its diameter ranges between 102-184mm diameter.

Keyworth (1987) on the other hand, stated that spruce-pine-fir, another type of European softwood species that were used to produce CLS stud, is available in diameter widths of up to 300mm and lengths up to 9m. In addition to that, a European research project carried out by Biomatnet (1997) for FAIR, an Agriculture and Fisheries programme for European scale, has revealed that a typical Norwegian Spruce used to produce CLS stud, has a stem diameter of about 250mm, and total height of 23m. It has been noted, however that most Canadian Lumber Standard timber imported into the UK is kiln dried at source to approximately 19% moisture content (Keyworth, 1987).

There is difficulty and limitation in estimating studs produced per log. There is a high possibility that not all logs transported in a fully loaded lorry from the forestry to the studs sawmill were able to be transformed into S60 studs. It was recognised that several lengths and dimensions may be produced from a log. In a real scenario, a log may be converted to various sizes of studs which are highly dependent on various factors such as the supply and demand for a particular dimension of timber materials needed.

For the purpose of this research study, it was assumed that the softwood trees being harvested from the particular Swedish forestry were cut into average 6m length logs and then fully loaded onto a 60 tonne lorry to be sent onto a designated sawmill and that all the logs transported on a fully loaded lorry to the stud were used to produce S60 studs.

5.4.1.3 Plywood production per log

Plywood can be made from either softwood or hardwood. It is defined as a structural material in the form of a flat panel made of layers of sheets of which are known as plies or veneer that are glued together and united under pressure to create a panel with an adhesive bond between plies. It usually is bonded with the grain of adjoining layers at right angles to each other.

Plywood export markets are usually manufactured in several sizes such as 1220 x 2400mm, 1820 x 2800mm, 1250 x 2500mm, 310 x 1820mm and 1220 x 2775mm.

Further details of its construction and other technical details are available in Appendix C1.1. The dimension of plywood used in the functional unit within this research was assumed to be 2440 x 1220mm. This assumption was based on the dimension of plywood sheet generally used in the construction of the open wall panelling unit according to TRADA (2006).

5.4.1.4 Production and transportation of studs

To clarify the quantification of studs during the material flow analysis the 38 x 89mm studs with length of 6m, 2.4m and 3.6m are referred to as S60, S24 and S36 respectively. Since a S60 stud can be divided into S24 and S36 studs as shown in Figure 5.3 below, this research notes that the amount of S24 and S36 per fully loaded vehicle will be equivalent to the amount of S60 per fully loaded vehicle.

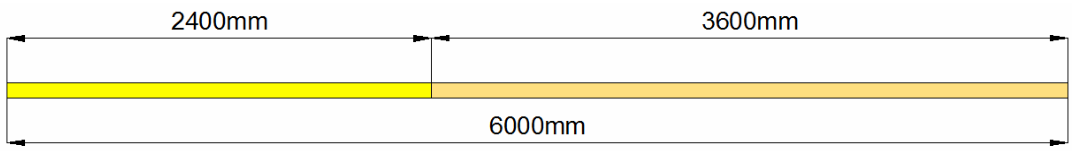


Figure 5.3 Dividing S60 into S24 and S36

The results from the questionnaires concludes that studs and plywood were transported using an ISO standardised 40ft container (also called FEU), hauled on the road from the sawmill to the nearest Swedish port by 40tonne lorry and then transported using containerised ship from the particular Swedish port to the nearest possible UK port before being picked up in the UK using another 40tonne lorry to be distributed to the manufacturing factory (ies).

It is to be acknowledged that in practical scenario, there might be more than one type of studs being transported on each FEU and that it might not be entirely fully loaded to allow some space for movement etc. This however is not within the scope of this study and therefore the allocation percentage attributable to the particular studs and sheets of plywood has not been taken into account during the quantification process. This research has made an assumption that 100% of the studs and sheets of plywood transported in each means of transport is uniform in size, type and weight.

5.4.2 Estimating the amount of logs per lorry

Waste occurs in two different stages. The first appears at the logging stage, and second, at the conversion of logs into studs or sheets of plywood. During these two stages, wood wastages are generated when timber logs were de-barked and converted into studs and sheets of plywood.

Because the de-barking process occurs at the sawmill level, the total volume of logs transported from forest to the sawmill tends to be bigger compared to its useful volume associated in the production of the S60 studs and the sheets of plywood. In order to incorporate these waste factors into the material flow analysis, data published by Swedish Forestry Agency (2006) was used. To convert the un-barked logs into the equivalent barked volume, Swedish Forestry Agency (2006) has stated that 1m^3 of solid volume including bark (m^3 f pb) is equivalent to 0.88 m^3 solid volume of log excluding bark (m^3 f ub).

However, because logs retained different diameter and length from one another, the number of studs per log may vary widely. It is therefore not possible to establish the equivalent number of studs per log based on the total number of logs in a fully loaded lorry. The total volume, rather than the number of logs, of un-barked logs on the fully loaded lorry were to be firstly established instead.

Assuming the lorry is fully loaded with logs, the total volume of un-barked logs on a fully loaded lorry can be determined using the following equation:

$$V_{pb} = \frac{W_L}{r}$$ **Equation 5.7**

Where

V_{pb} is total equivalent of un-barked logs per fully loaded lorry (m^3 f pb)

W_L is total net load weight when lorry is fully loaded (kg)

r is density of the chosen tree type (kg/m^3)

Once the total volume of un-barked logs per fully loaded lorry has been established, the total equivalent of barked volume of log per fully loaded lorry can be determined using the following equation:

$$V_{ub} = V_{pb} \times f$$ **Equation 5.8**

Where

V_{ub} is total equivalent volume of barked log per fully loaded lorry (m^3 f ub)

V_{pb} is total equivalent volume of un-barked log per fully loaded lorry (m^3 f pb)

f is conversion factor

Determining the equivalent amount of un-barked logs required to produce certain dimensions of plywood sheet and S60 studs means that the equivalent number of plywood sheet and S60 studs produced per fully loaded lorry were established using the conversation factor given also by the Swedish Forestry Agency (2006). To convert the barked logs onto the equivalent volume of sawn wood or plywood produced, Swedish Forestry Agency (2006) also stated that sawn wood softwood has a raw material that is equivalent to $2.1m^3$ f ub/m^3

Therefore, the total equivalent volume of barked logs needed per stud and plywood, also known as v_{ubs} and v_{ubp}, were calculated with the following equation:

$$V_{ubp} = V_p \times f_p$$ **Equation 5.9**

Where

V_{ubp} is the equivalent of logs barked volume required to produce a 1.2 x 2.4m sheet of plywood (m^3 f ub)

V_p is the volume of 1.2 x 2.4m sheet of plywood (m^3)

f_p is the conversion factor of 2.5m^3 f ub

$$V_{ubs} = V_s \times f_s$$ **Equation 5.10**

Where

V_{ubs} is the equivalent of logs barked volume required to produce S60 stud (m^3 f ub)

V_s is the volume of S60 stud (m^3)

f_s is the conversion factor of 2.1m^3 f ub

Once the total equivalent volumes of barked log per fully loaded lorry were obtained, the corresponded number of studs and plywood produced from it were established with the following equations:

$$N_s = \frac{V_{ub}}{v_{ubs}}$$ **Equation 5.11**

$$N_p = \frac{V_{ub}}{v_{ubp}}$$ **Equation 5.12**

Where

N_s is the total equivalent number of studs produce per fully loaded lorry

v_{ubs} is the total equivalent volume of barked logs needed per stud

N_p is the total equivalent number of plywood produce per fully loaded lorry

v_{ubp} is the total equivalent volume of barked logs needed per plywood

V_{ub} is the total volume of barked logs per fully loaded lorry

5.4.3 Estimating the amount of studs per FEU container

The amount of studs on each FEU container was based on an assumption that each container is fully loaded.

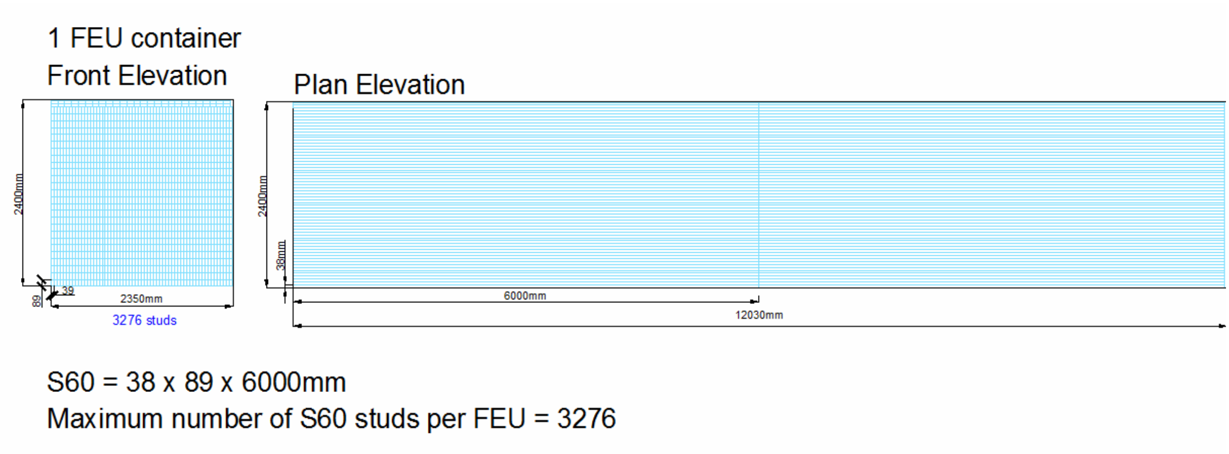


Figure 5.4 Estimating the quantity of S60 studs per FEU container

Figure 5.4 above shows an estimation on how 38x89mm studs with standardised length of 6000mm can be loaded into an FEU with an overall dimension of 2350 x 12030mm and 2400mm height. Rough calculation has suggested that if fully loaded, each FEU container can hold maximum of 3276 studs.

The weight of studs is also influenced by two main factors – the size of studs and the wood species. Weight of studs per FEU container can be established when density of wood species used and the size of the particular studs are known.

For a stud with a density of 450kg/m^3 and a stud dimension of 38 x 89 x 6000mm length, its weight is equal 9kg. If a fully loaded FEU container consists of 3276 studs of 38 x 89 x 6000mm, the weight per FEU is 29, 812kg (an equivalent of 30 tonne). Further detailed calculation can be found on Appendix C2.2.

5.4.4 Estimating the amount of plywood per FEU container

It is recognised that the amount of plywood in an FEU container will be highly dependent on various factors such as the size of plywood in a particular FEU container, its required thicknesses, and the amount of plies required per plywood and the amount of plywood per packaging.

The weight of plywood panel is influenced by two main factors – the panel compression during the manufacturing process and the wood species. Due to variations between brands, the weight of plywood is not constantly proportional to thickness. Further details can be found on Appendix C2.2

Assuming the dimensions of the plywood sheet used in this research is 2440 x 1220mm, a possible number of plywood sheets that can be loaded per FEU container can be assumed as shown in Figure 5.5 below:

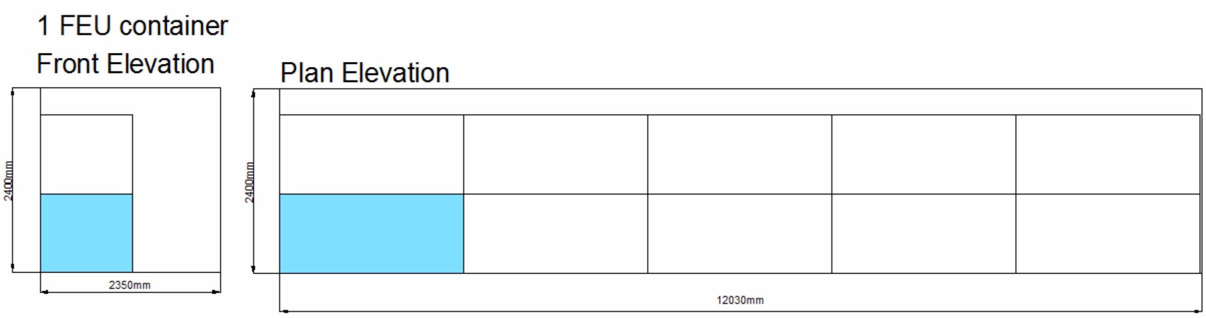


Figure 5.5 Estimating the quantity of plywood sheet per FEU container

Assuming that plywood will be fully loaded on each FEU container, with one plywood packaging equals to 85 plywood and each FEU able to contain 10 plywood packaging, the total number of 2440x1220mm sheet of plywood with thickness of 12mm per FEU container to be equivalent to **850 number of plywood sheet** and weighted a total of 13,600kg (an equivalent of 14tonne). Further detailed calculations can be found on Appendix C2.2.

5.4.5 Estimating the amount of plywood and studs FEU containers per ship

During shipping, the abbreviation "TEU" is occasionally used for "Twenty foot Equivalent Unit" and refers to a 20ft container. A 40ft container (FEU) used to transport the associated timber materials on the road is an equivalent to two TEUs.

To estimate the amount of studs and plywood carried in FEUs transported per ship, it is necessary to first comprehend the amount of plywood and studs per FEU container, the amount of FEUs allowed per ship and the percentage of FEUs in the ship of which consists of plywood and studs.

Since each type of containerised FEU have different weights, depending on the type of loading it carries, the amount and percentage of FEUs consisting of plywood and studs per ship are assessed based on the weight of each FEU containing studs and each FEU containing plywood. This is then added to see how many FEUs containing plywood and studs can be carried for maximum loading.

As discussed earlier in section 5.3.4, the type of ship used to transport the S60 studs and plywood sheets from one port to another was a fully loaded 1,226 TEU containerised vessel with gross weight of 6,720 tonne. This is under the assumption that 25% of its full load has been allocated to transport 12mm thickness plywood and the other 25% of its full load has been allocated to transport the S60 studs.

The number of FEUs containing sheets of plywood and the S60 studs along with its allocated weight per fully loaded ship are determined on the possible amount of plywood sheets and studs per FEU containers, which has been established earlier in section 5.4.3.2 and 5.4.3.3. Based on the weight of a plywood and S60 FEU container and based on the weight allocation per fully loaded ship, it has been determined that the fully loaded ship will be able to transport an equivalent of 120 FEU containers that consists of plywood sheets and a further 56 FEU containers consists of S60 studs. Further detailed calculation can be found on Appendix C2.2

5.5 Application of Components to the FU

The purpose of mathematical equations being developed in this chapter is to enable the prediction of total embodied transport energy consumed per FU based on a generic process flow model. In order to do this, a series of mathematical equations were developed to aid estimate the transport energy and material quantity per means of transport and applicable for each transport stage from forest to site.

The mathematical equations developed to quantify the embodied transport energy per FU are based on the assumption and boundaries set in Section 5.4.1. The transport flow analysis and its associated material flow analysis has been derived from an assumption that timber material used to construct the particular open wall panelling unit comes from Sweden and transported using fully loaded 60 tonne lorry at the forest to sawmill stage and 40 tonne lorry for the rest of the journey to site with an additional aid of 1226 TEU containerised ship to import the timber materials from Goteborg port in Sweden to the nearest UK port.

Studs and plywood that came from a Swedish forestry as logs are transported and fully loaded on a 60 tonne lorry and then distributed to two separate sawmills to process this logs onto the suitable size plywood and S60 studs. The finished products that arrive as 1.2 x 2.4m plywood and S60 studs from two different sawmills are then transported to Goteborg port using 40 foot 40 tonne lorries.

Using containerised ships with net load of 1226 TEU per ship and net weight equivalent to 6720 tonne, the plywood and S60 studs are then hauled in a number of 40 foot long ISO standardised container (also known as FEU) from Goteborg to a UK port. The amount of materials transported per shipping vessel are based on the assumption that ship are fully loaded and of which 50% of its load were to carry S60 studs and the other 50% of its load were to carry plywood.

From the nearest UK port, the FEU containing S60 studs and plywood were picked up by 40 tonne lorries and transported to the manufacturing factory where the S60 studs will be cut to 2.4m and 3.6m length, along with the plywood, to construct the required number of panel for the particular house. From the assembly factory, the finished products were then transported using 40 tonne lorries again to the site ready for on-site assembly.

The predicted total embodied transport energy per FU was carried out as follow:

1. Total embodied transport energy per panel

Total E_{TE} (GJ/panel)

= $TE_{\text{per stage}}$

= $TE_{\text{forest to sawmill stage}} + TE_{\text{sawmill to Goteborg port}} + TE_{\text{Goteborg port to UK port}} + TE_{\text{UK port to assembly factory}} + TE_{\text{Assembly factory to site}}$

Equation 5.13

2. Transport energy per panel per stage

$TE_{\text{per stage}}$ (MJ/panel)

= **7**(*Te S24*) + **2**(*Te S36*) + **3**(*Te plywood sheet*) **Equation 5.14**

Where

Te S24	transport energy to transport S24 studs per stage
Te S36	transport energy to transport S36 studs per stage
Te plywood sheet	transport energy to transport the plywood sheets per stage

3. Allocation of Te S24 and Te S36

Despite the number of S24 and S36 studs transported on each means of transport will be identical to S60 studs, their weight and size are actually different. This will indirectly lead to a difference in its transportation energy. In other words, transport energy per S60 stud is not equivalent to transportation energy per S24 and S36 studs. To establish the transportation energy per S24 and S36 stud, the transportation energy per S60 stud is broken down where 40% of transportation energy per S60 stud represents the transportation energy per S24 stud and the other 60% of transportation energy per S60 stud contributed to the transportation energy per S36, which can be explain in the following equations:

Te24 = 40% (Te S60)

Te36 = 60% (Te S60)

Equation 5.15

Where Te S60 = total embodied transport energy per S60 calculated from forest to site stage.

4. Embodied transport energy per S60 and per sheet of plywood per stage

For road transport

$$E_{Lt} = \frac{(d \cdot F_c \cdot \rho_{fuel} \cdot c)}{N_s} \times r$$ **Equation 5.16**

$$E_{Lt} = \frac{(d \cdot F_c \cdot \rho_{fuel} \cdot c)}{N_p} \times r$$ **Equation 5.17**

Where E_{Lt} = transport energy per S60 or per plywood sheet, N_s or N_p = equivalent number of S60 and 12mm sheet of plywood per fully loaded 60 or 40 tonne lorry, d = distance from a to b (km), F_c = fuel consumption (litre/100km), r = return factor, ρ_{fuel} = 0.831 kg/litre, c = calorific value (GJ/kg).

The number of plywood sheets and S60 studs per fully loaded lorry from forest to sawmill stage was taken into account as waste factor associated with converting the un-barked logs onto barked logs. The waste factor was also incorporated within the present conversion of barked logs onto the associated plywood sheets as well as the S60 studs at the sawmill stage. Road transport between S60 and plywood sawmills to Goteborg port and from UK port to site is considered to be negligible and therefore not included.

For maritime transport

$$E_{st} = \frac{d \cdot E_{fs} \cdot r \cdot m}{Np}$$ **Equation 5.18**

$$E_{st} = \frac{d \cdot E_{fs} \cdot r \cdot m}{Ns}$$ **Equation 5.19**

Where

E_{st}	Shipping transport energy,
d	distance from one port to another (km),
E_{fs}	Energy intensity of a particular containerised ship (MJ/tonne.km),
m	net weight of load per fully loaded ship (tonne),
r	return factor (value of 1.0 as it returned fully loaded)
N_s or N_p	equivalent number of S60 and 12mm sheet of plywood per fully loaded 60 or 40 tonne lorry

Within the research, waste factor is incorporated on the embodied transport energy per functional unit calculation at the forest to sawmill stage. Any waste that occurs at assembly factory level is considered to be negligible and therefore omitted from the calculation.

5.6 Conclusion

This chapter describes how a series of mathematical equations has been developed based on both transport energy as well as material flow diagram established earlier in Chapter 4. The mathematical equations to represent the quantification methodology for the embodied transport energy and its associated timber materials per given FU were developed based on the existing methodologies that has been established through the adaption of equations that has been developed by Flanagan (2000) and Anderson and Edward (2000) and revised to represent the prefabricated panelling structure. The application methodology of these components based on the set FU has been laid out in detail within section 5.5.

As the quantification and analysis of transport energy embodied within the set FU and its associated timber material is known to be a complex thing to do, a step by step detailed systematic procedure and assumption used within the quantification of the process flow has been developed in this chapter and summarised as follow:

- review and incorporate the most appropriate methods to quantify the transport energy per stage
- develop a set of mathematical equations to aid in quantifying the transport energy flow per stages
- develop a set of mathematical equations to aid in quantifying the material flow process for a given FU
- develop a set of mathematical equations to aid in quantifying the transport energy flow for a given FU
- The total embodied transport energy per FU was then identified as the sum of the equivalent transport energy per FU per stage.

The methodology to quantify and analyse the material flow has taken into account components such as waste factor that occurs especially at the stage where logs were converted into studs and sheets of plywood prior to the pre-assembly of the prefabricated timber wall panelling unit. The reliability and applicability of it is then tested and evaluated further in Chapter Six.

Chapter Six

Results and Discussions

CHAPTER 6: RESULTS AND DISCUSSION

6.1 Introduction

Chapter 6 is established with the purpose to present, interpret and analyse the embodied transport energy per given FU. These results were generated based on the flow model and quantification methods established earlier in Chapter 4 and 5 respectively.

In order to demonstrate the way embodied transport energy may vary within the set variables, the embodied transport energy per FU were established based on three sets of scenarios.

This chapter is laid out to firstly explained the quantification and analysis of the material process flow and followed by the embodied transport energy analysis based on the varying scenarios.

6.2 Material flow analysis

The evaluation of embodied transport energy for prefabricated timber open wall panelling were prepared, first by quantifying the transport energy consumed to haul the raw material of the wall panel from forest to sawmill per fully loaded 60 tonne lorry. This form of raw material was in the form of logs.

The second stage of the quantification involves the evaluation of transport energy consumed per plywood and S60 studs during the haulage stage from both the plywood and studs sawmill to the designated Swedish port. During this stage, 40 tonne fully loaded lorries were used as opposed to the 60 tonne lorries.

The third stage of quantification comprised of the number of FEU containers containing plywood and S60 studs being hauled onto a containerised ship. During this stage, it is assumed that the containerised ship has 50% of its load filled with FEU containing plywood and the other 50% with FEU containing S60 studs.

For the fourth stage, 40 tonne fully loaded lorries were used again to pick up the FEU containers of plywood and S60s from the designated UK port and haul this to the manufacturing factory to be assembled into certain amount of desired open wall panel.

The final stage has the finished product in the form of prefabricated open wall panels transported using 40 tonne lorries to site based on full load. The transportation energy per various timber forms evaluated on each stages were then converted further to achieve the transportation energy per given FU.

The stages and figures used to quantify the equivalent amount of studs and plywood sheet transported per fully loaded 60 tonne lorry were summaries below:

1. Determine the total volume of logs transported per fully loaded lorry using **equation 5.7** and with an assumption that:

   W_L is total net load weight when lorry is fully loaded (= 4,000kg)

   r is density of the spruce (= 450kg/m^3)

2. Determine the equivalent of barked logs in a fully loaded 60 tonne lorry (m3 f ub) using **equation 5.8** and with an assumption that:

   f is conversion factor of 1.14m^3

3. Determine the equivalent amount of barked logs required to produce the 1.2 x 2.4m sheet of plywood and S60 studs using **equation 5.9** and **5.10**, with an assumption that:

f_p is the conversion factor of 2.5m^3 f ub

and

f_s is the conversion factor of 2.1m^3 f ub

4. Finally, to establish the equivalent number of plywood sheet that can be produced per fully loaded 60 tonne lorry, **equation 5.11** and **5.12** was used,

6.2.1 Forest to sawmill stage

At the forest to sawmill stage, logs were transported using timber lorries from the forest to the plywood and studs sawmill. These logs were de-barked at the plywood and studs sawmills before being converted to either studs or sheets of plywood.

To establish the total volume of logs transported on a fully loaded timber lorry, **equation 5.7** was used. A figure of 88.9m^3 solid volume of timber (which includes barks) was generated based on this equation. Because not 100% of logs transported on this timber lorry will be used to produce stud and plywood due to the de-barking activity in sawmill, it is necessary to determine the equivalent of barked logs volume per fully loaded timber lorry.

Using **equation 5.8**, the total volume of barked logs per fully loaded timber lorry was generated to be an equivalent to 78.2m^3.

Based on **equation 5.9** and **5.10**, the equivalent amount of barked logs required to produce the plywood and S60 studs were established.

Finally, the equivalent number of plywood sheets and S60 studs that can be produced per fully loaded 60 tonne lorry was generated based on **equation 5.11** and **5.12** which is an equivalent to 1861 number of S60 and 108 sheets of 12mm thick plywood. For further details of calculation, please refer to Appendix C2.1

6.2.2 Sawmill to Goteborg Port stage and UK port to assembly factory stage

During the sawmill to Goteborg port and from UK port to the particular UK assembling factory stages, plywood and S60 studs were transported using FEU containers on 40 tonne lorries and picked up at the chosen UK port using another 40 tonne lorries that will carry it to the manufacturing factory.

The loading amount of plywood transported per 40 tonne lorry and the amount of S60s transported per 40 tonne lorry from the particular UK port to manufacturing factory will be the same as transporting the plywood and S60 per fully loaded 40 tonne lorry from the plywood and studs sawmill to Swedish port. Based on the assumption that each 40 tonne lorry transporting a fully loaded FEU container and using the calculation methods established in sections 5.5.2 and 5.5.3 to determine the estimated number of plywood and S60 studs respectively, results indicate that there is an equivalent of 850 sheet of plywood per and 3276 number of S60 studs for every 40 tonne fully loaded lorry used to transport both the studs and plywood product separately. Please refer to Appendix C2.2 for a more detailed calculation.

6.2.3 Goteborg Port to UK port stage

During the transportation stage between Goteborg Port and the nearest UK port, the studs (in the form of S60) and sheets of plywood were loaded and transported using containerised ship in a certain number of FEU containers.

Within each FEU container carrying sheets of plywood, it has been assumed that they come per package and that each sheets of plywood package contains 85 sheets of plywood. Based on this assumption, the maximum number of plywood per FEU has therefore been quantified as equal to 850.

The total amount of plywood and S60 containers on each of the containerised ship will vary widely depending on the cargo companies used, the particular demand of studs and plywood, particular size and weight allowance of containerised ship used and many other things.

This research is based on an assumption that 1226 TEU containerised ship was used to transport the sheets of plywood and studs FEU containers. The 1226 TEU assumed to have a net load of 6720 tonne and that 50% of the load was appointed for FEU containing plywood whereas the other 50% load carried were FEU for S60s. Presuming that the 1226 TEU containerised ship is fully loaded, the amount of plywood and S60 that can be transported per journey is 204,000 and 366,912 correspondingly. Please refer to Appendix C2.2 for details of calculation.

6.2.4 Assembly factory to site stage

In the factory, S60 will be cut into S24 and S36 and combined with the plywood to make a suitable panels needed to be then transported to site. The amount of panels transported to site will be depending highly on the number of panels needed to construct a house and a number of house required per development.

Figure 6.1 below summarises and illustrates the material flow with the equivalent number of wall panelling and its associated timber materials on each of the transport stage process.

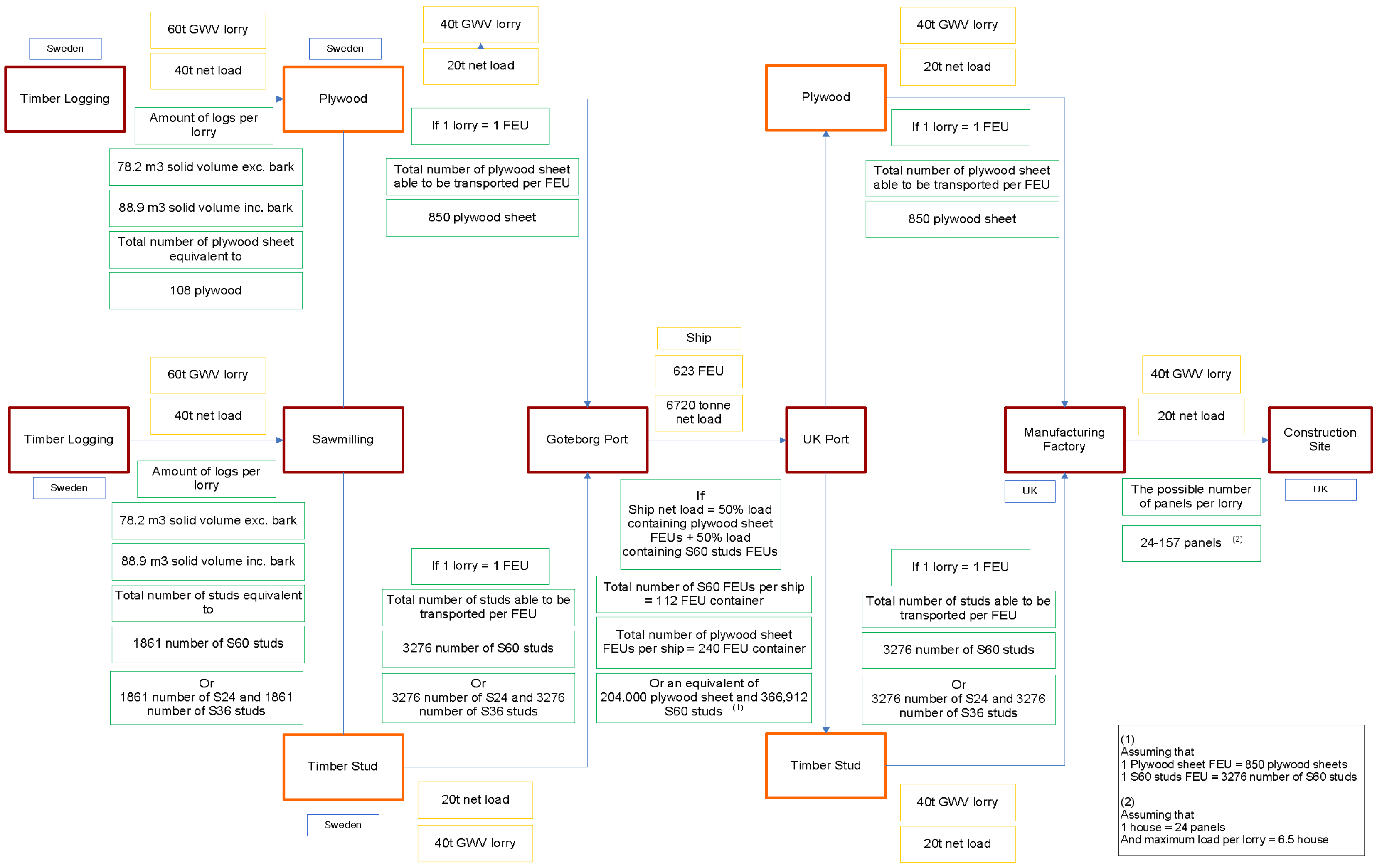


Figure 6.1 **Material flow analysis based on full load means of transport**

6.3 Embodied transport energy flow analysis

The embodied transport energy flow analysis within this research was quantified with its distance range based on the outcome of the questionnaire in section 4.4.2 earlier. Due to companies' confidential policy and limited access of information from the third party logistic, the distance range from the Goteborg Port to the assembly factories was set based on the location of the particular assembly factory and the nearest UK port to this particular assembly whilst the distance from the forest to Goteborg port was based on secondary published data.

Transport energy flow model specific for detailed quantification was then established based on these distances. Further details on the range of distances per stage can be found on Appendix B3.

Embodied transport energy per FU was then determined against the quantification methodology established in section 5.3.3 and 5.3.4 and in accordance to the type of means of transport incorporated on the particular stage. The detailed calculation for the material flow analysis and total embodied transport energy for full load transport can be found on Appendix C and D2 respectively.

Based on these range of distances, the possible embodied transport energy consumed per stage was generated in Table 6.1.

Table 6.1 Average embodied transport energy based on the average distance per stage

Means of transport	based on minimum distance (km)	Minimum TE(GJ)	based on maximum distance (km)	Maximum TE (GJ)	based on average distance (km)	Average TE (GJ)
60tonne GWV lorries	93	2.718	93	2.718	93	2.718
40 tonne GWV lorries	189	3.837	189	3.837	189	3.837
1226 TEU vessel	926	373.363	1860	749.952	1393	561.658
40 tonne GWV lorries	64	1.299	234	4.751	149	3.025
40 tonne GWV lorries	80	1.624	160	3.248	120	2.436
Total TE (GJ)		328.842		764.506		573.674

6.3.1 Scenarios associated with transport energy process flow analysis

The significance of embodied transport energy within prefabricated timber wall panelling unit depends on a number of variables. One of the most important variables is the transport loading capacity associated within the forest to site stage.

The loading capacity dependent highly to the form in which prefabricated timber wall panelling unit was being transported throughout the forest to site stage. In order to assess the significance of the embodied transport energy per FU, the generic forest to site process flow model was firstly divided into three sections, as shown on Figure 6.2. These sections were divided based on the material form in which prefabricated timber wall panelling unit is constructed.

The splits were then incorporated onto the different scenarios as shown in table 6.2 below and illustrated further in Figure 6.2 and 6.3.

Table 6.2 Loading scenarios and sections within the process flow analysis

Section	Timber form	Stage	Loading Scenarios		
			1	2	3
I	Logs	Forest to sawmill	Full	Full	Partial
II	Sheets of plywood and studs	Sawmill to assembly factory	Full	Full	Partial
III	Prefabricated wall panelling unit	Assembly factory to site	Full	Partial	Partial

The first scenario demonstrates the embodied transport energy consumed per FU where means of transport has been set to carry full load all the way from the forest to the site. It is understood that full load capacity will provides the opportunity to maximise efficiency. Nevertheless, invariable of goods transportation is influenced not only by the potential maximum carrying capacity of a vehicle but also by volume. These were demonstrated further in the second and third scenarios.

The second scenario endeavours to reveal the embodied transport energy consumed per FU based on the set two bedroom house model and where its vehicle was set to carry full load from forest to assembly factory but with the loading capacity from factory to site being dictated by the number of house being built on the particular site.

The third scenario represents the worst case scenario when demand is low and where loading from forest to site depends fully on the number of house being built on the particular site.

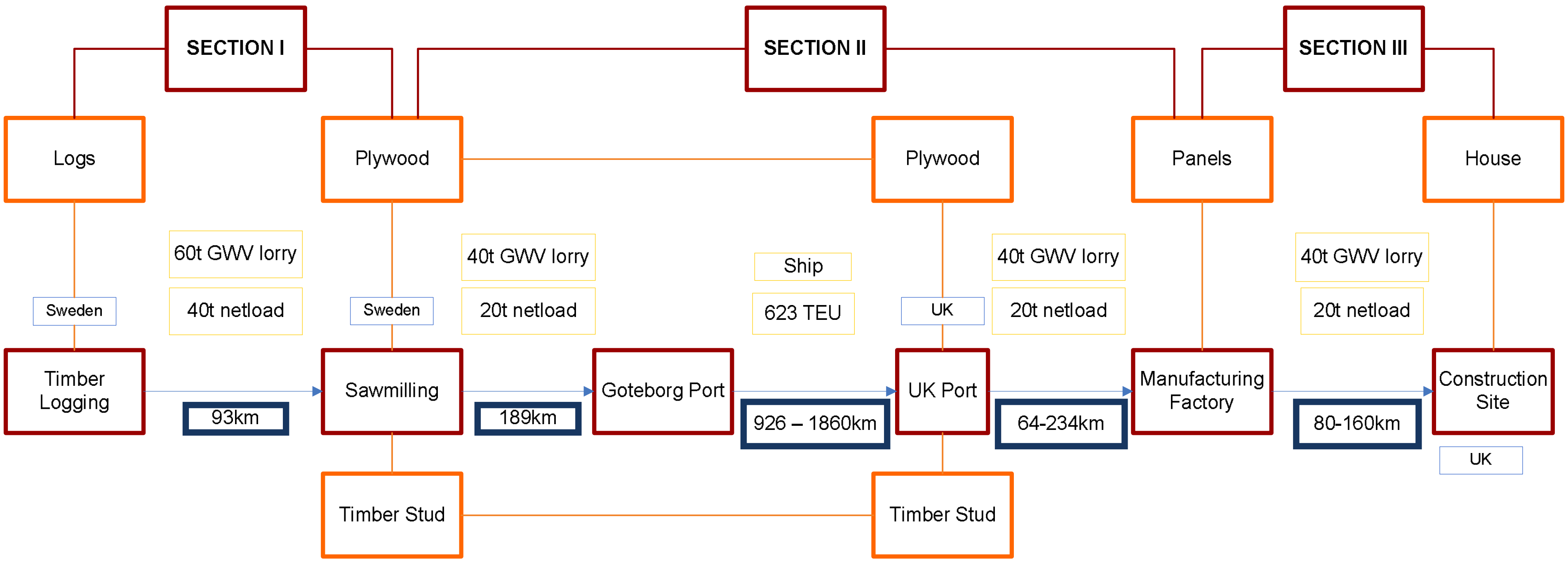


Figure 6.2 **Range of distances used for further quantification**

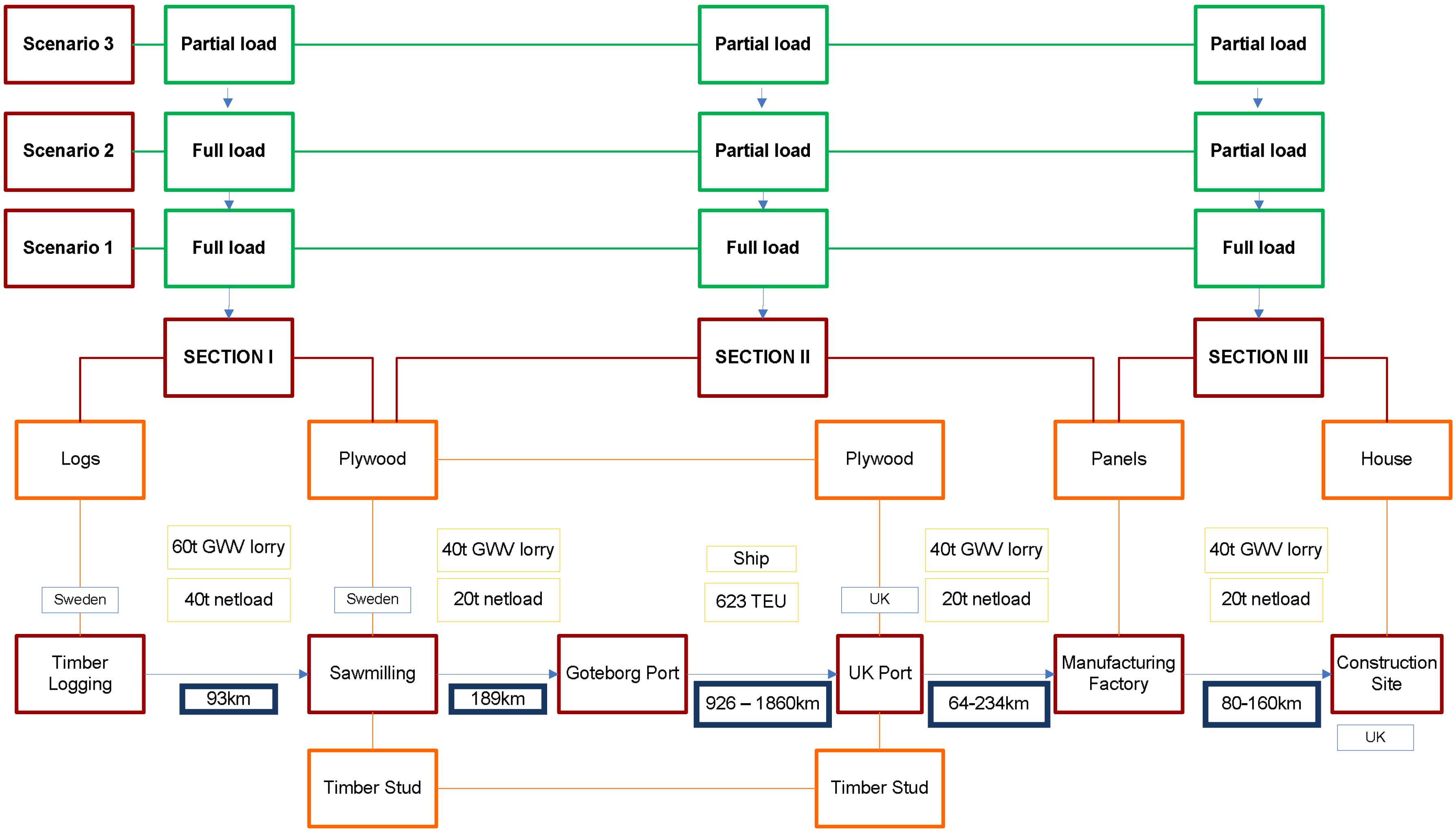


Figure 6.3 **Diagram illustrating the difference of loading capacity between Scenario 1,2 and 3**

6.3.1.1 Transport energy flow analysis per FU based on the first scenario

In this first scenario, means of transport per journey from forest to site stage has been assumed to be fully loaded. The total embodied transport energy per FU were established and broken down further in Table 6.3. For further details of the calculation, please refer to Appendix D2.

Table 6.3 Quantification of embodied transport energy (TE) (MJ/per panel) based on full load transport

Stages	TE per S60	TE per S24	TE per S36	TE per plywood	TE per panel
	(MJ/S60)	(MJ/S24)	(MJ/S36)	(MJ/plywood)	(MJ/panel)
Forest to Sawmill	1.46	0.58	0.88	25.2	81.3
Sawmill to Port A	1.17	0.47	0.70	4.51	18.2
Port A to Port B	1.02 – 2.04	0.41 – 0.82	0.61 – 1.23	1.83 – 3.68	9.56 – 19.21
Port B to Factory	0.31 – 1.14	0.13 – 0.46	0.19 – 0.68	1.20 – 4.39	4.85-17.74
Factory to Site					8.13-16.27

The breakdown of these transport energy from the forest to site were illustrated in Figure 6.4 and 6.5. Figure 6.4 shows transport energy consumption per stage based on the associated timber materials whereas the second figure (Figure 6.5) were based on transport energy consumption per panel. Figure 6.5 has been broken down further into two parts with the top part indicates the embodied transport energy per panel per stage based on the shortest and longest distances and the bottom part based on the averaging distance.

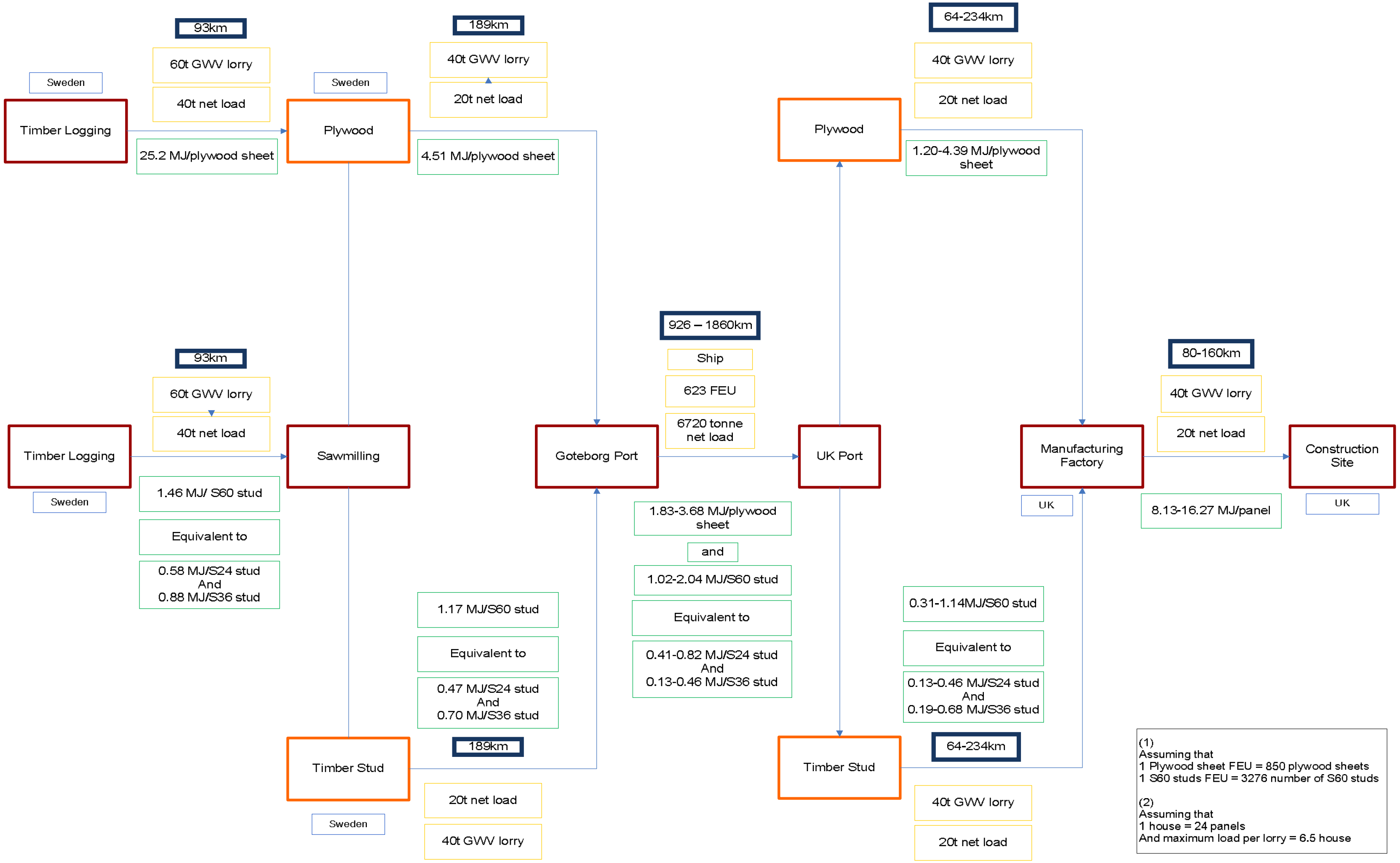


Figure 6.4 Embodied transport flow analysis based on prefabricated wall panelling unit and its associated timber materials

Figure 6.5 Embodied transport flow analysis

The bar chart below (Figure 6.6) was produced based on the data established and illustrated in Table 6.1 and Figure 6.5 respectively. It demonstrates the range of embodied transport energy consumption per panel based on the set distances data and based on the assumption that vehicles were carrying full load throughout the journey but return empty for the road transport.

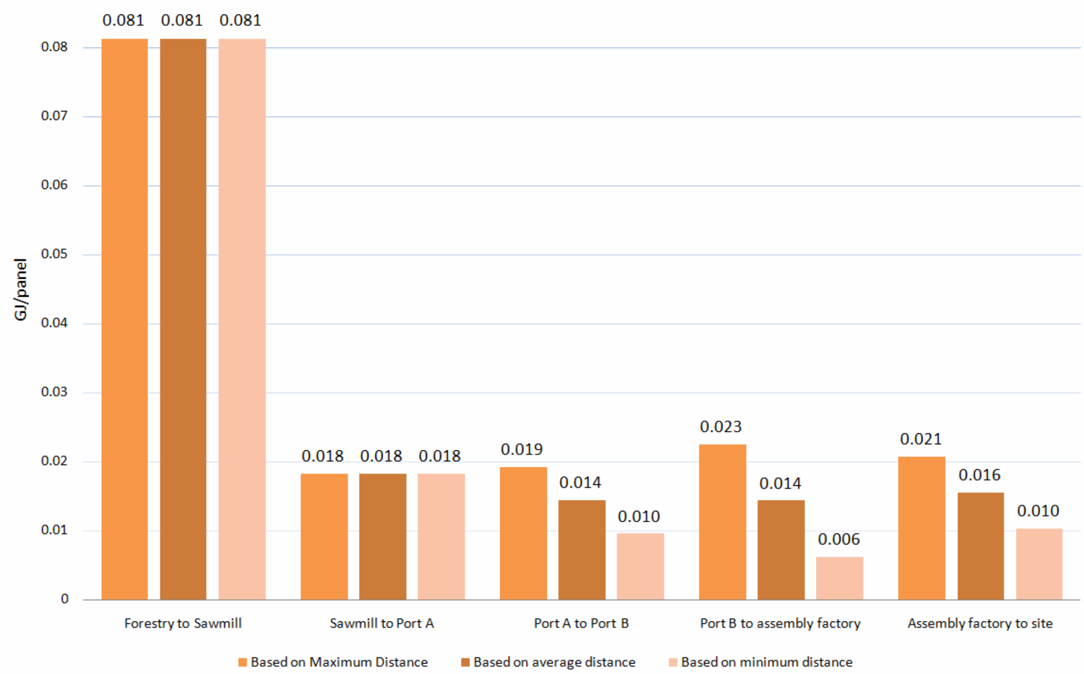


Figure 6.6 **Transport energy per panel based on full load (GJ/panel)**

From the bar chart illustrated above, it is apparent that the forest-to-sawmill stage consumed the highest transportation energy per equivalent panel. This is the stage during which logs were hauled from forestry to sawmill and where the conversion to the desired studs and plywood take place. The highest transportation energy figure at the forest stage, despite the use of 60 tonne fully loaded lorries, believed to be due to waste factor of converting logs onto plywood and studs as well as to negligible waste factor at the later stages.

Figure 6.7 below represents the percentage breakdown of embodied transport energy consumed per equivalent panel per stage.

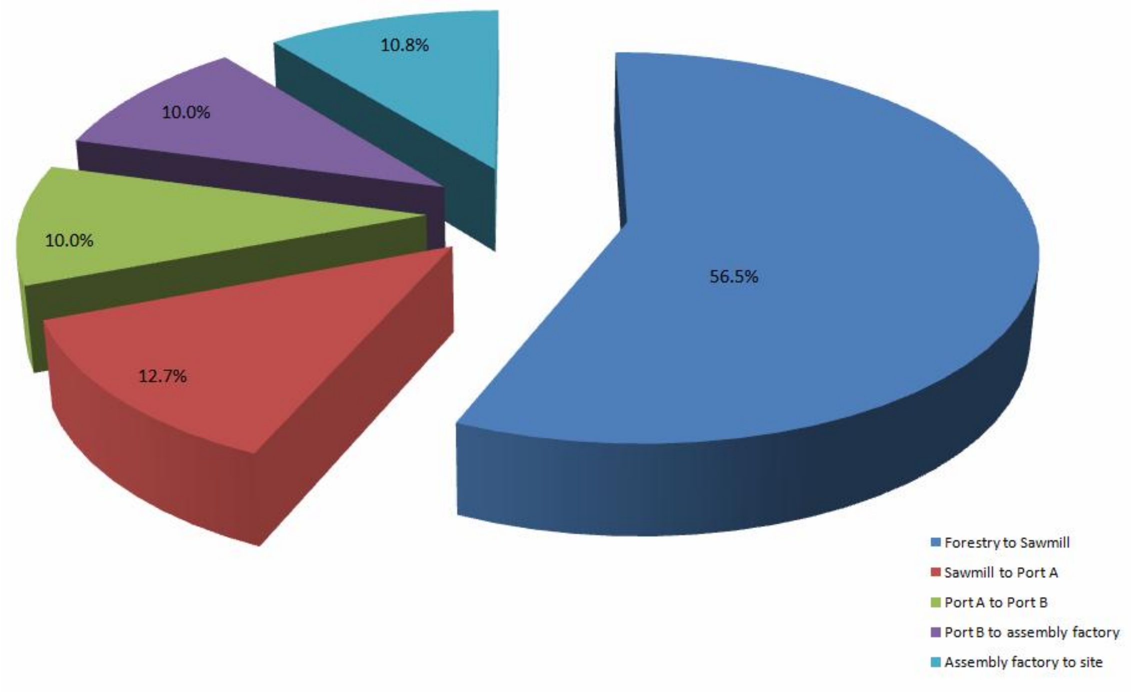


Figure 6.7 Percentage of transport energy consumed from cradle to site stage for the given functional unit

The pie chart above has indicated that almost 60% of the total transport energy embodied at the forest to site stage was consumed on the forest to sawmill stage whereas the rest of the 40% transport energy consumption were consumed almost equally on other stages.

6.3.1.2 Transport energy flow analysis per FU based on second and third scenarios

Up to this point, the quantification of transport energy flow analysis in this research was based on the fully loaded transport mode throughout the forest to site stage. This method of quantification provides the best possible transportation energy value for the given FU. In the real life scenario however, fully loaded means of transport might not always be the case especially at the factory to site stage.

Two additional scenarios were therefore established in order to identify the significance of loading capacity throughout the forest to site stage to the overall transport energy consumption per FU. The second scenario derived from a situation where transport carries full load from forest to factory but part load from factory to site, depending on the number of houses constructed on a particular site whilst the third scenario demonstrate the worst case scenario where transport carries partial load throughout the forest to site stage. The illustration and summary of these scenarios can be found on Figure 6.7.

The model house in the form of a two bedroom house was produced in order to demonstrate a more practical scenario in quantifying the transportation energy embodied from the manufacturing factory to the site.

The model house was set to give comparison in the significance of embodied transport energy per FU if transport load dependent fully on the number of house to be developed on site and to justify the difference in embodied transport energy based on the worst case scenario when made to order were necessary and where means of transport carrying load throughout forest to site stage are equal to the number of house needed in a particular development..

In order to quantify the transport energy of an open wall panelling unit in greater detail, a two bedroom terrace house has been set within this research as a typical model house. The decision to choose two bedroom terraced house for this research comes from the consideration of the highest demand and need to supply certain size and type of affordable housing properties to tackle the increase in population especially in the South East England area, where the intense housing pressure lies. It was also based on the most preferred type of house currently desired and required for the new development [(Craine and Mason (2006) and Housing Strategy Team (2005)].

In addition to that, terrace house type is chosen as the model house due to the growing preference compared to other type of housings as it has the ability to be built in a dense area, where easy access to amenities would lead to a more sustainable way in reducing the need to use private transportation (Blamey, 2006), hence ensuring the reduction of carbon footprint.

Figure 6.8 shows the layout of the model home used in this research as a two bedroom end of terrace house designed for single family with four person occupancy. For further details of the house plan, please refer to Appendix E.

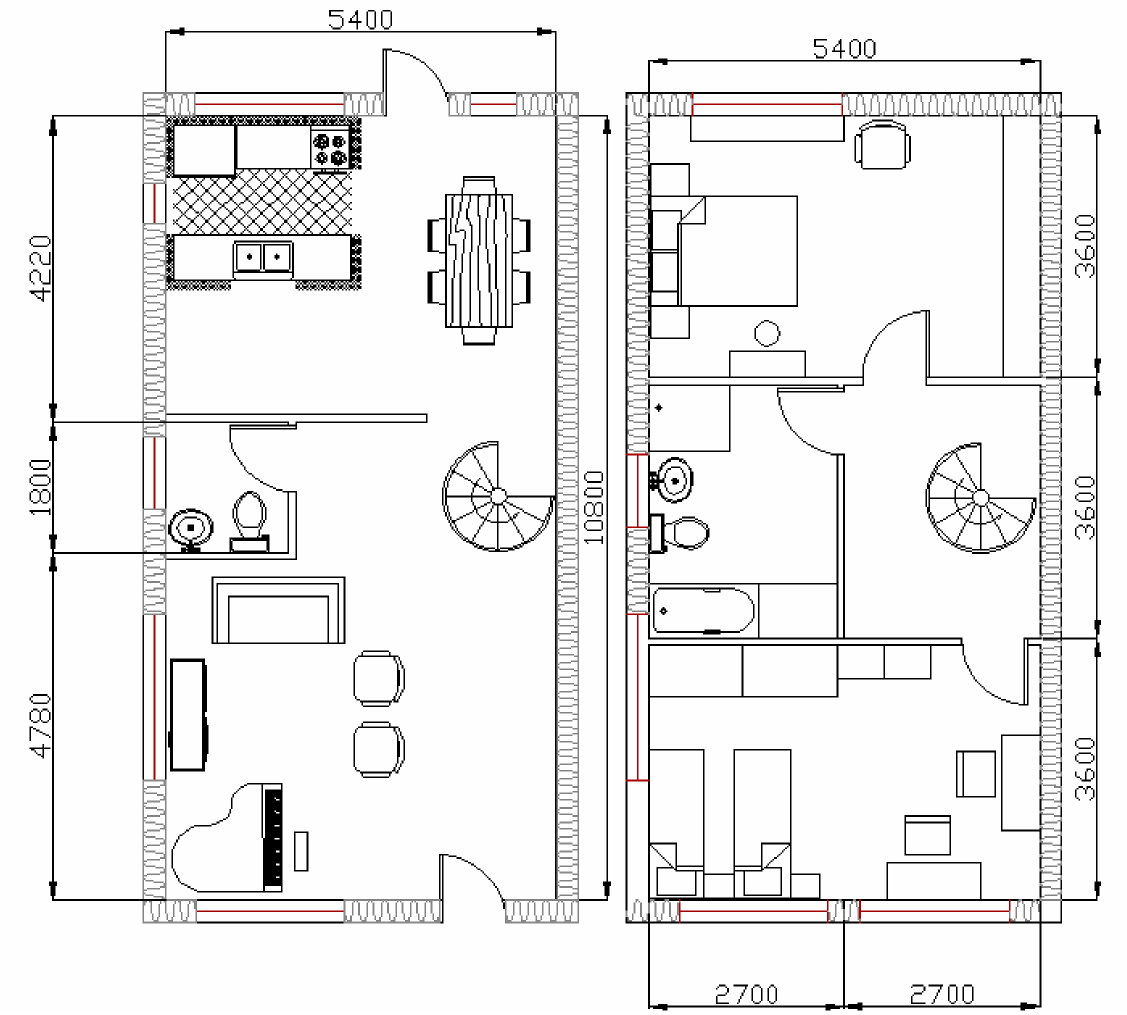


Figure 6.8 Floor plan of the studied home (in mm). This drawing is for illustrative purposes only and not to be scaled.

Described earlier, the FU employed in this model house is in the form of a prefabricated timber open wall panel system, each with a given dimension of 3.6m width x 2.4m height. Figure 6.9 and 6.10 shown and underlined number of internal and external wall panels needed for the studied home. The blue colour represents one panel with the dimension of 3.6m width x 2.4m height, and the yellow colour represents ½ panel, with the dimension of 1.2m x 2.4m height.

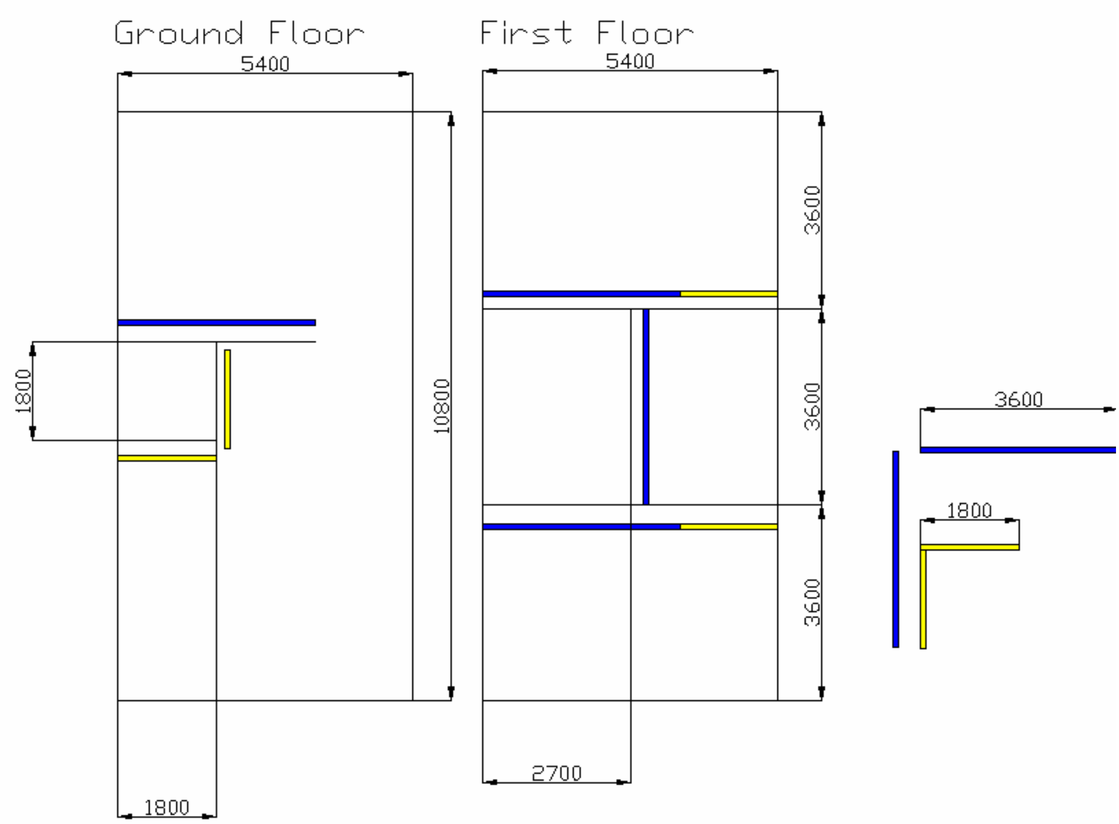


Figure 6.9 Estimated number of internal wall panels needed for the two bedroom studied house

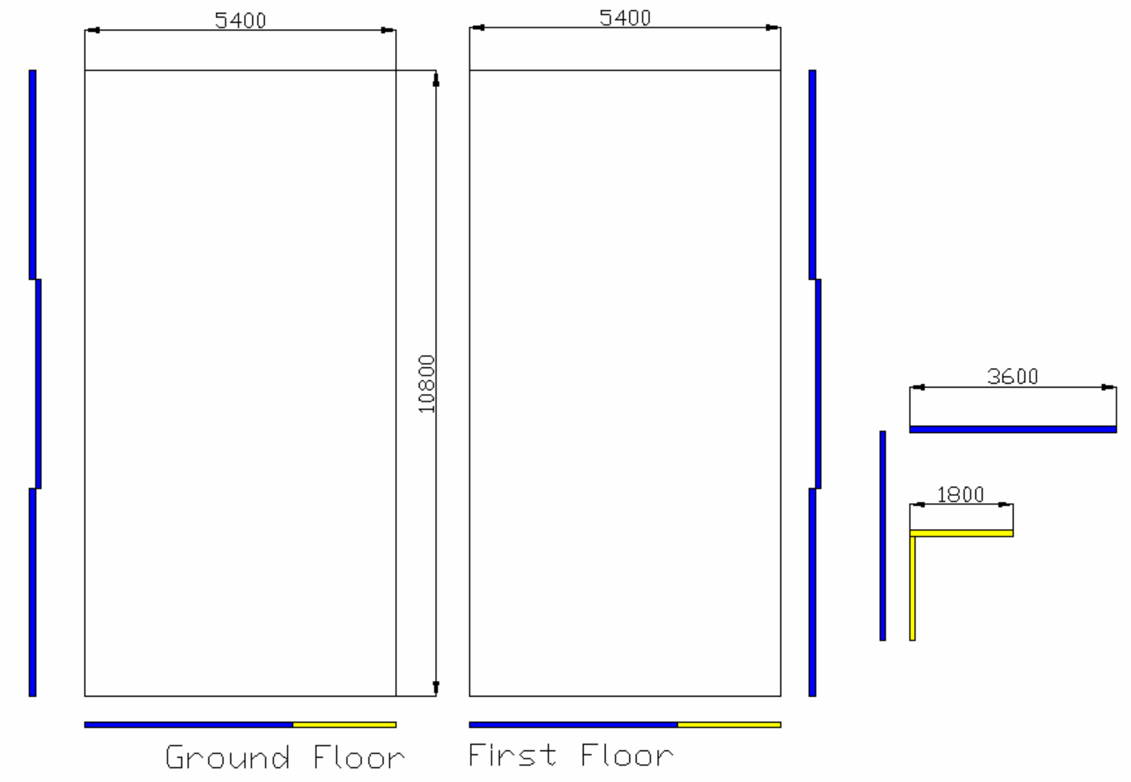


Figure 6.10 Estimated number of external walls panels needed for the two bedroom studied home

From the estimation on Figure 6.9 and 6.10 above, the amount of external walls for the two storey two bedroom end of terrace house used as the studied house were 18 panels with additional amount of 6 panels needed for internal walls, bringing a total of 24 panels needed for 1 house. Further details of the calculation can be found on Appendix F.

As referred to earlier, this research concentrates on prefabricated open wall panel which consists of 7 number of vertical studs measuring 38 x 89 x 2400mm (S24), 2 number of horizontal studs measuring 38 x 89 x 3600mm (S36) and 3 conifer plywood with thickness of 12mm measuring 1200 x 2400mm in width and height. With the studied home needing 24 panels, the amount of studs and plywood required for the wall panel systems used to construct the whole house are as follows:

- 168 number of S24
- 48 number of S36
- 72 number of 12mm thickness plywood.

Assuming that the transport load from cradle to assembly factory was based on full load and the transport load from assembly factory to site was based on a development which only require one house (an equivalent of 24 panels), the breakdown of transport energy on each stage from the forest to site were as described in Table 6.4 below:

Table 6.4 The quantification of embodied transport energy (MJ/panel) based on one house development.

Stages	TE per S60	TE per S24	TE per S36	TE per plywood	TE per panel
	(MJ/S60)	(MJ/S24)	(MJ/S36)	(MJ/plywood)	(MJ/panel)
Forest to Sawmill	1.32	0.53	0.79	22.7	73.5
Sawmill to Port A	0.92	0.37	0.55	3.55	14.33
Port A to Port B	1.02 – 2.04	0.41 – 0.82	0.61 – 1.23	1.83 – 3.68	9.56 – 19.21
Port B to Factory	0.31 – 1.14	0.13 – 0.46	0.19 – 0.68	1.20 – 4.39	4.85-17.74
Factory to Site					67.7 – 135.3

From Table 6.3 above, a bar chart as seen on Fig 6.11 below was produced to compare the data per transport stages. As illustrated the shipping transportation to haul several number of FEU containing the timber materials in the form of S60 and plywood has the lowest transport energy embodied both per S60 and plywood as well as its equivalent transport energy per panel.

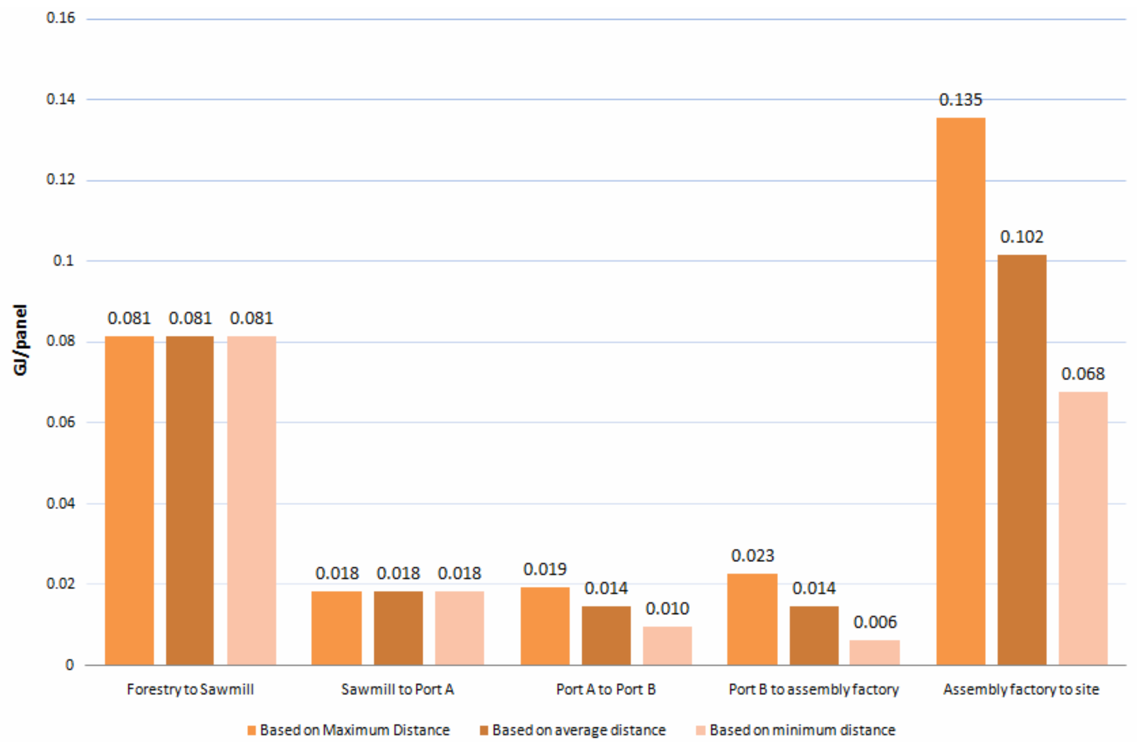


Figure 6.11 Transport energy per stage based on one house development

It is apparent that the highest transport energy equivalent to one panel occurs at the beginning and the end of the cradle to site stages. The site stage, which signified the part when panels for one house development were transported as the finished product from the factory to site using 40 tonne articulated lorry, has been illustrated as contributing to the highest transport energy consumption throughout the cradle to site phase.

This result might be explained by the fact that a one house development needed only 24 wall panels, which is only 15% of the amount of panels that can be transported on a 40tonne lorry from the factory to site which triggered 6.5 times more transport energy consumption compared to a 40tonne lorry transporting open wall panels on a full load from the factory to the development site. Similar to quantification done earlier in this chapter, the high energy consumption that taken place during the cradle site were caused by the less equivalent amount of plywood sheet and S60 studs that were able to be produced from the logs that was fully loaded onto the 60 tonne lorry.

Compared to the amount of equivalent plywood and S60 studs that were transported during the sawmill to factory gate, only an equivalent of 1861 number of S60 studs and 108 sheets of plywood were transported at the cradle to sawmill stage. This is around 56% and a sheer 13% of the amount of S60 and plywood sheet transported on the fully loaded 40 tonne lorry from both of the sawmills to the Goteborg Port in Sweden.

Figure 6.12 below shows the analysis of the total transport energy embodied in a one house development.

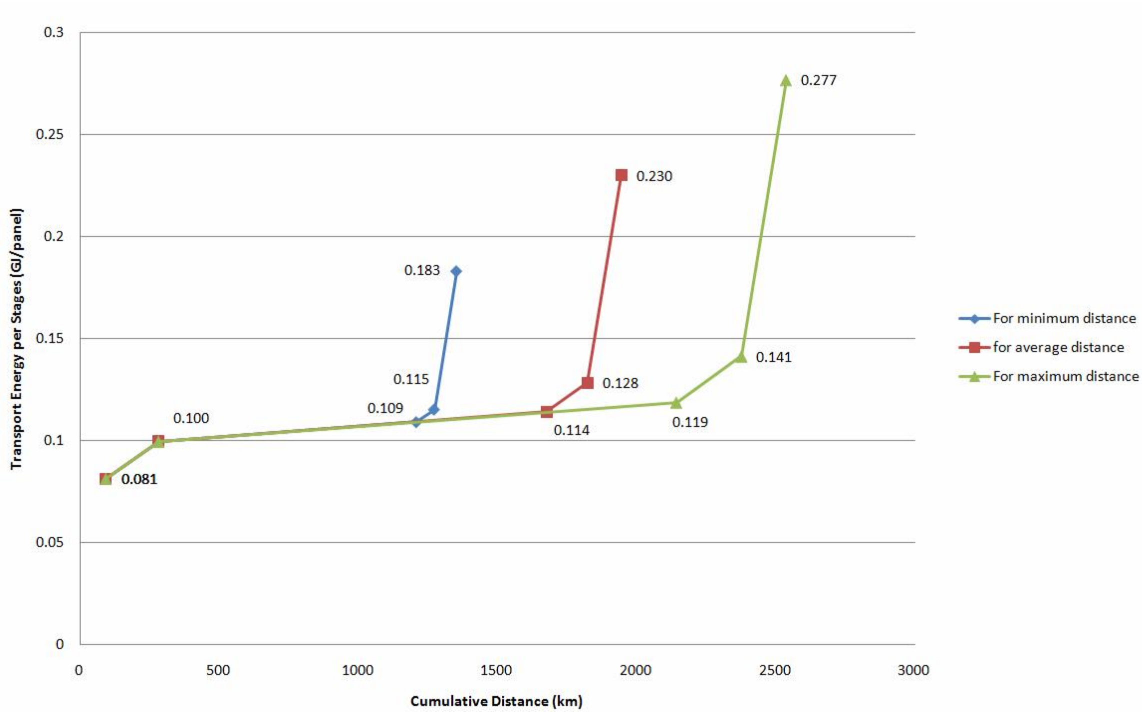


Figure 6.12 Cumulative Transport Energy per panel for 1 house

Illustrated in Figure 6.12 is the cumulative transport energy based on shortest, average and longest possible distance. Based on the graph, the total transport energy per panel for 1 house is 0.230 GJ/panel on the average distance, ± 0.047GJ/panel. Further details can be found in Appendix G.

In terms of transport energy per panel from factory to site stage, to achieve the lowest transport energy per panel, it is necessary to transport the maximum possible load allowed per 40 tonne lorry. As presented in Figure 6.13 below, to achieve the best minimum transport energy per panel, a 40 tonne lorry has to transport a maximum of 6 ½ house (an equivalent of 157 panels).

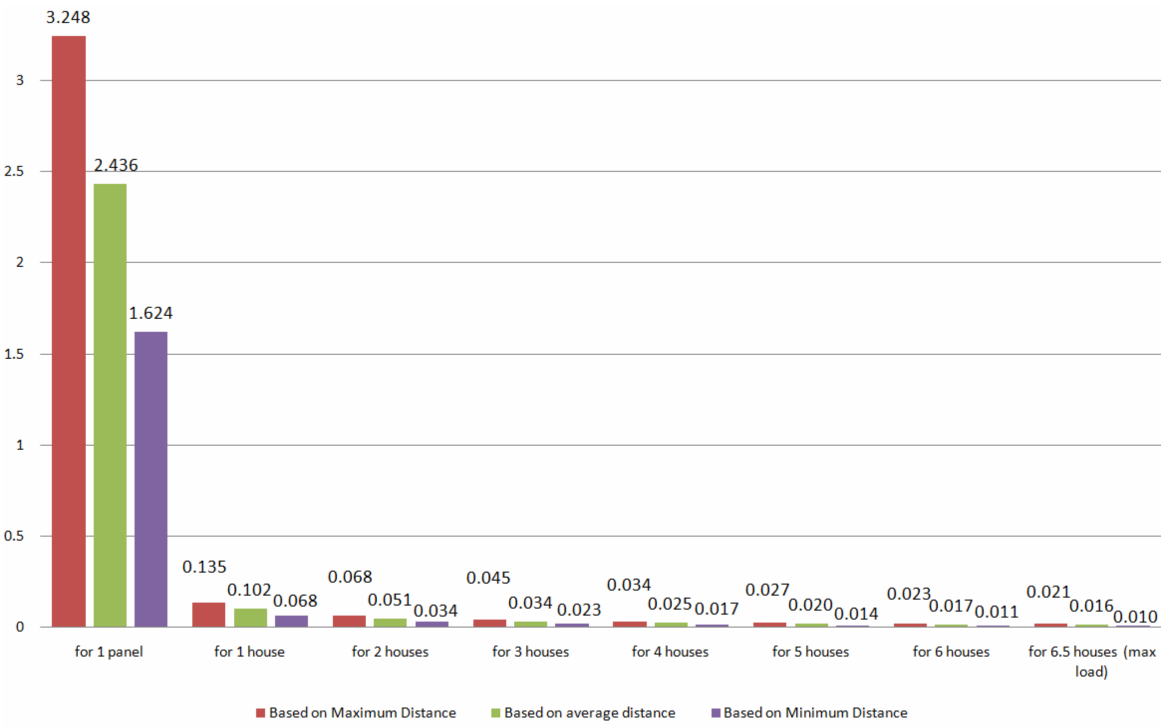


Figure 6.13 Range of total embodied transport energy value per lorry from factory to site based on the maximum, average and shortest possible distance.

Transporting just one panel to site is illustrated as the worst case scenario when a replacement panel needed to be sent to site. Even though it is highly improbable, the bar chart on Figure 6.15 demonstrates that transporting just one panel to site will result in almost 160 times more transport energy consumption compared to a full load transport.

The quantification done in this research so far was based on the assumption that all the transport mode used throughout the cradle to factory stage were carrying full load. It was assumed that the excess transport load was kept in the factory for future use. Figure 6.14 below, on the other hand, shows the variations initiated based on average distances if the transport mode only hauling the amount of timber materials equivalent to the one needed per development from the cradle to site gate.

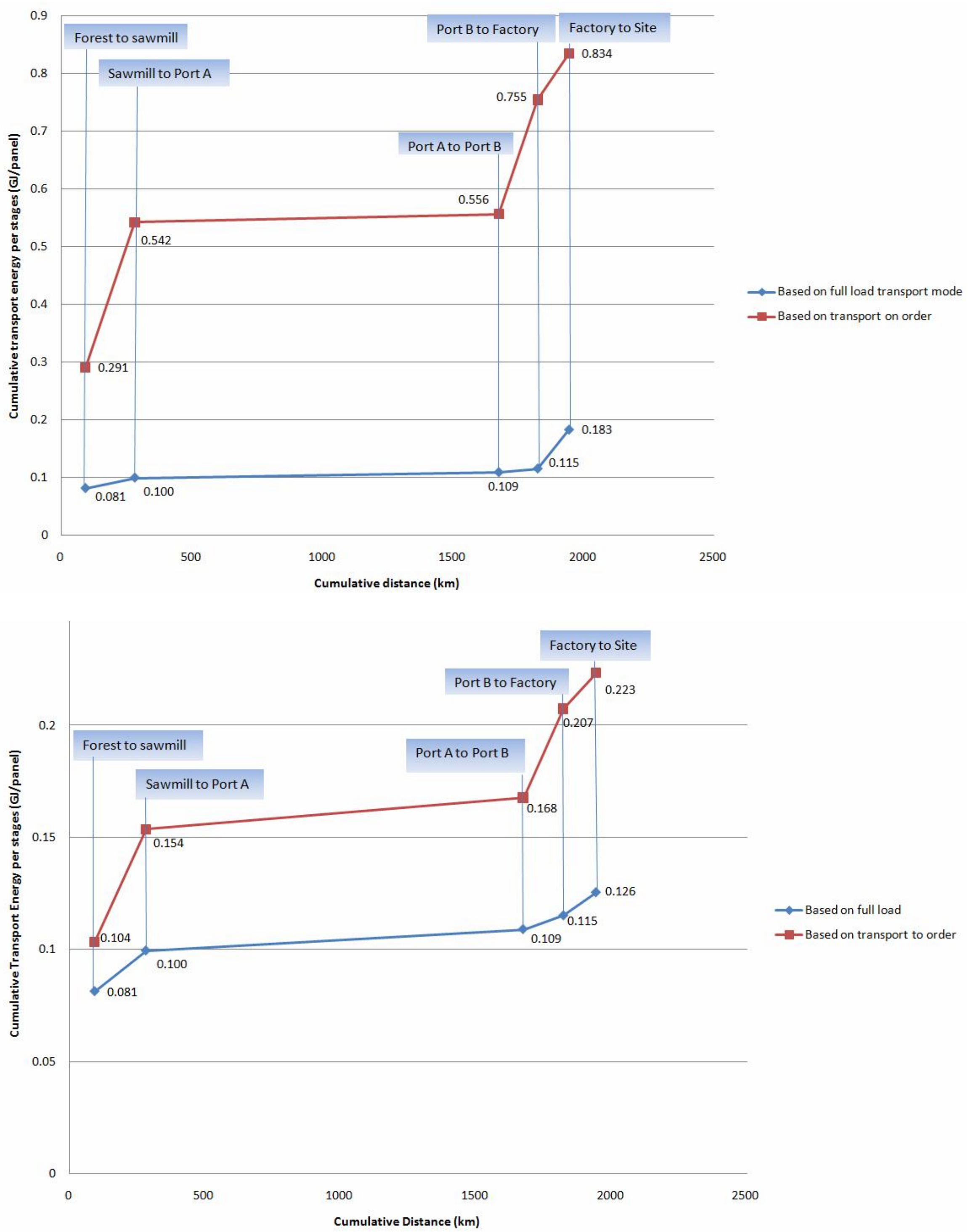


Figure 6.14 (Above) Comparison of cumulative transport energy per stages to transport 1 house. (Below) Comparison of cumulative transport energy per stages to transport 5 houses.

The first graph illustrated on Figure 6.14 (above) illustrates a comparison of cumulative transport energy for one house development based on cradle to site full load transport against cradle to site made to order scenario. The second graph (illustrated below it) shows a comparison of cumulative transport energy for five house development to compare the full load transport against made to order scenario.

Based on the one house development, there was a significant difference of 0.651GJ/panel if made to order scenario were chosen instead of full load transport method. The difference decreases to 0.097GJ/panel at the five house development. The graph indicated the point that the higher the number of house production per development is, the lesser the total transport energy per panel will be. Further details can be found in Appendix G and H.

Despite the huge difference in cumulative transport energy per panel between fully loaded transport mode and transport based on made to order scenario for a development which contain only one house, it can be seen on Figure 6.14 that the difference was narrowed down in transporting 5 houses. In this case, it can be explained that while fully loaded transport mode is still remain the lowest, the higher the demand for housing supply per development, the lower its transportation energy embodied will be.

An analysis was carried out in this research study to investigate how the total transportation energy per given functional unit may differ according to number of house supplied and constructed per development. This study used an assumption that the amount of wall panels transported to site is equal and direct throughout the cradle to site stages, which means that none were stored in the sawmills, manufacturing factory or any other holding depots.

Figure 6.15 shows the result of the analysis which illustrates the range of cumulative transport energy per panel based on made to order scenario on the average distance. The graphs demonstrates the total transport energy per given functional unit in a development ranges between one to 100 houses development.

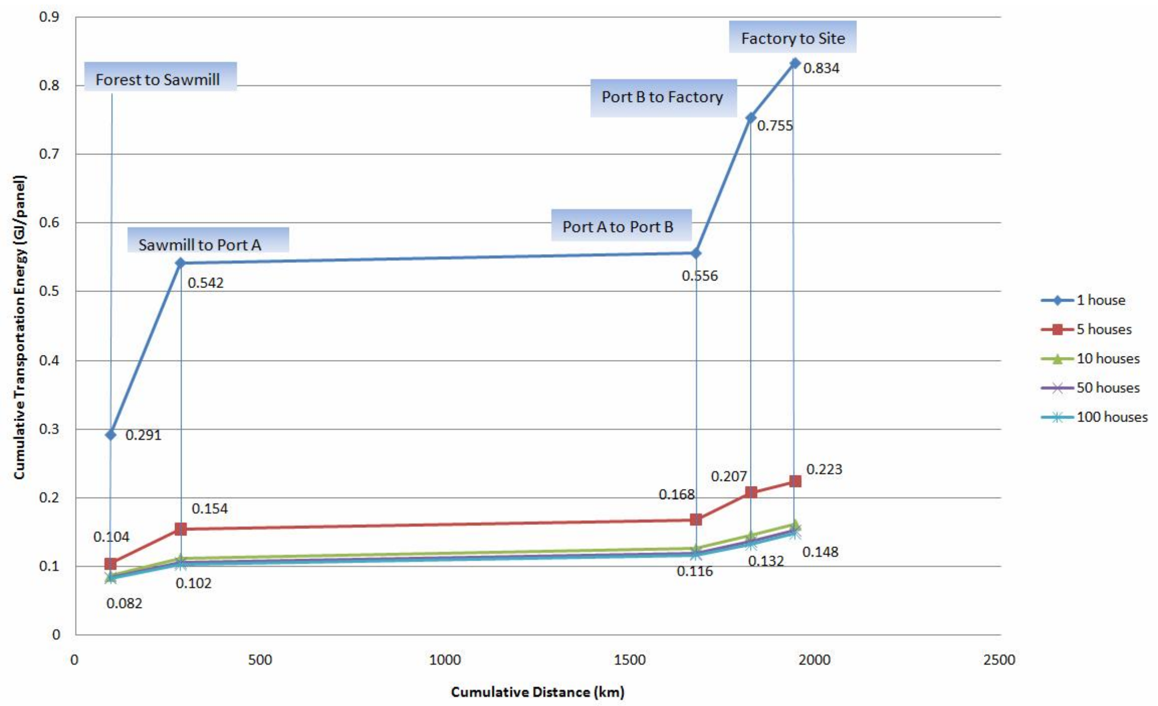


Figure 6.15 Cumulative transport energy per panel based on "made to order" – for average distance per stage.

As the graph illustrates the higher the demand of houses per development is, the lower the total transport energy per panel will be. The higher the number of houses demand per development also means a lesser difference in transportation energy per stages for the given functional unit.

Table 6.5 and 6.6 illustrates how transport energy per panel may differ based on one panel transport, number of house per development, and based on made to order scenario.

Table 6.5 Transport energy based on full load (GJ/panel), for different housing development quantity.

Stages	1 panel	1 house	5 houses	10 houses	50 houses	100 houses
Forest to Sawmill	0.08133	0.08133	0.08133	0.08133	0.08133	0.08133
Sawmill to Goteborg Port	0.01823	0.01823	0.01823	0.01823	0.01823	0.01823
Goteborg Port to UK Port	0.01438	0.01438	0.01438	0.01438	0.01438	0.01438
UK Port to Factory	0.01437	0.01437	0.01437	0.01437	0.01437	0.01437
Factory to Site	2.43626	0.10151	0.0203	0.0203	0.0203	0.0203
Total Transport Energy (GJ/panel)	2.57	0.23	0.149	0.1486	0.1486	0.1486

Table 6.6 Transport energy based on partial load scenario (GJ/panel)

Stages	1 panel	1 house	5 houses	10 houses	50 houses	100 houses
Forest to Sawmill	4.27045	0.29117	0.10353	0.08573	0.08347	0.08234
Sawmill to Goteborg Port	6.02975	0.25124	0.05025	0.02512	0.02147	0.01987
Goteborg Port to UK Port	0.01404	0.01404	0.01404	0.01404	0.01404	0.01404
UK Port to Factory	4.75361	0.19807	0.03961	0.01981	0.01693	0.01567
Factory to Site	1.91521	0.0798	0.01596	0.01596	0.01596	0.01596
Total Transport Energy (GJ/panel)	16.98	0.834	0.2234	0.1607	0.1519	0.1479

The results obtained from Table 6.4 and 6.5 above shows that for full load transport, assuming that all stages is based on direct transportation, has the range for transport energy per panel lower compared to made to order scenario. Full load transport has its transport energy per panel vary between 0.14861GJ/panel to 2.56457GJ/panel whereas for made to order scenario, transport energy per panel may vary between 0.147873GJ/panel to 16.98305 GJ/panel.

However, this research has acknowledged the difficulty in direct comparison between the fully loaded cumulative transport energy to those based on made to order. It is understood that the amount of timber materials transported per stages depends highly on the amount of timber materials available and stored on the sawmill and manufacturing factory before it is used to construct certain number of open wall panelling for a particular house development. It will also depend on the market demand of the particular size of plywood and studs.

This research also concludes that even though the energy requirement per panel per studied house has been established, it is not possible to multiply this transportation energy per panel as one lorry will be able to transport more than one house. Until it reaches the maximum loading, its energy consumption per panel will be different and this will also greatly depends on the number of houses needed to be constructed per development.

6.4 Summary and Discussion

6.4.1 Energy comparison between embodied transport energy and operational energy

Table 6.7 below shows the various calculated energy consumed on each process within the forest to site stage. Some of the energy consumption figures such as the timber logging as well as the plywood and studs production were obtained based on published data of which then converted further to represent the energy consumed per FU. The calculated figure of the operational stage, on the other hand, was based on an assumption that the site development is located in South East of England with degree days data taken based on the current year 2007. The transport energy figure compared here was based on three different situations: the first of which represents the worst case scenario where means of transport were carrying partial load throughout the journey which is an equivalent to one panel, the second which represents the transport energy for one house based on the full loaded means of transport throughout the forest to factory stage and the third of which represents the transport energy of fully loaded means of transport throughout the forest to site stage.

Table 6.7 Comparison of energy consumption from the forest to operational stage

	MJ/Panel	GJ/Panel
Timber logging	132.7	0.13
Manufacturing energy for plywood and kiln dried studs	4842.4	4.84
Manufacturing energy for plywood and air dried studs	4784.12	4.78
Total TE based on full load transport throughout (Scenario 1)	149	0.15
Total TE for one house development (Scenario 2)	230	0.23
Total TE for one panel throughout (Scenario 3)	16980	16.98
Operational energy over the 60 years lifetime	79994.73	80
Annual operational energy	1333.246	1.333246

Comparison graphs were generated based on the figure established in Table 6.7 above.

Figure 6.16 below illustrates energy comparison that includes operational energy based on the 60 years of the building lifetime. The graph revealed that the biggest energy consumption is on the operational energy consumed throughout the 60 years of the building lifetime. Nevertheless, because most of energy consumed during the first year of building life, the comparison of the energy consumed to the 60 years life of building could not, therefore, be considered as accurate.

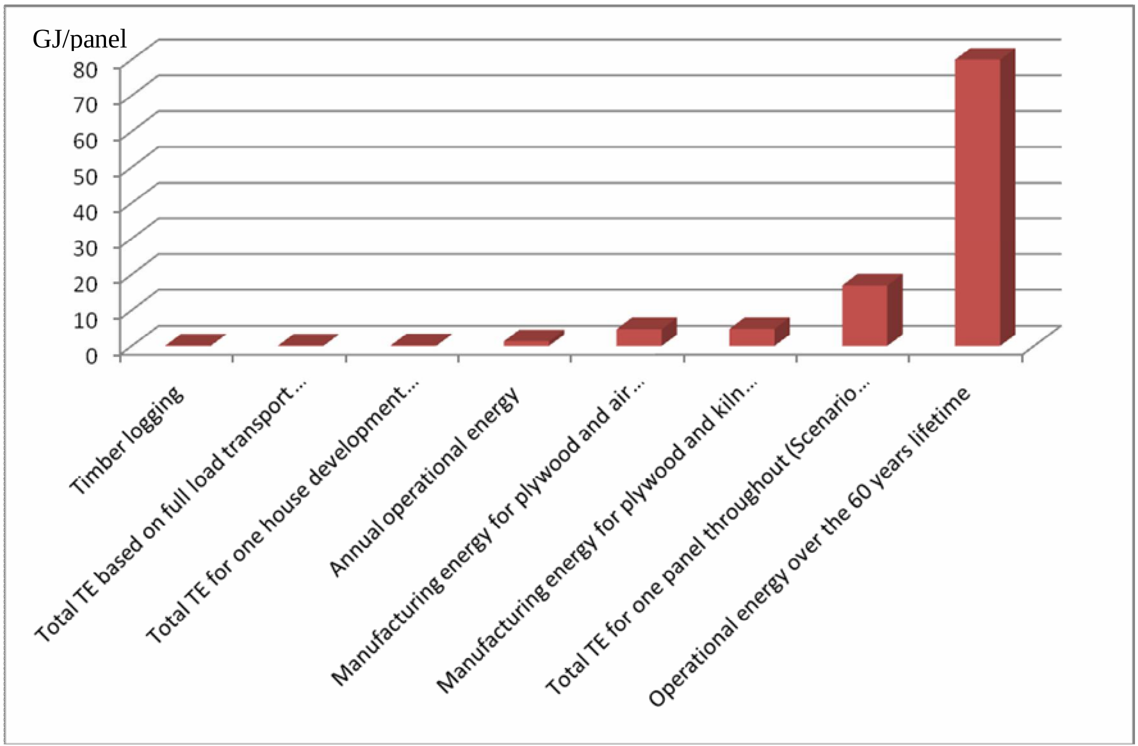


Figure 6.16 Energy comparison including the 60 years of the building's lifetime operational energy

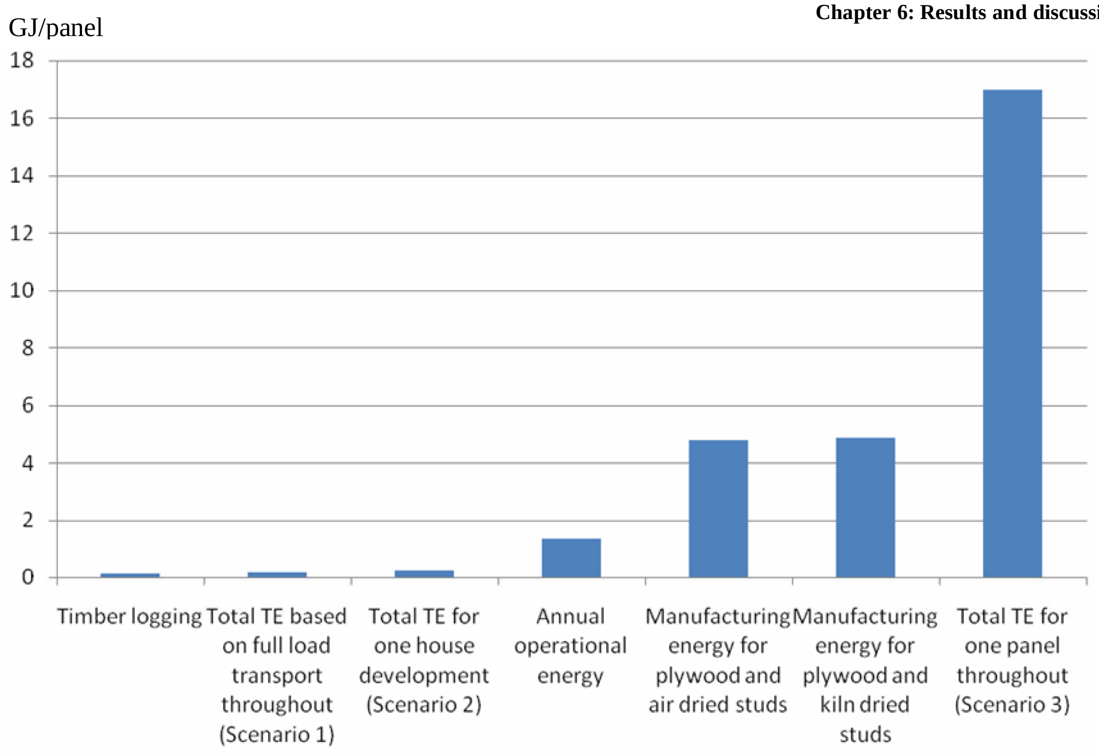


Figure 6.17 Energy comparisons excluding the 60 years of the building's lifetime operational energy

Figure 6.17, on the other hand, illustrates a comparison of energy consumption based on an annual operational energy. Based on the first year of the building lifetime, this graph demonstrates that the highest energy consumption occur in the worst case scenario as set within Scenario 3, with transport arrangement throughout the forest to site carries partial load that is an equivalent to one panel. This shows that transport energy plays an important role throughout the life cycle of prefabricated house. Careful consideration needs to be taken into account to make sure that means of transport will always carry full load and to ensure mass production rather than supply based on "made to order" request.

6.4.2 Variables affecting the transport energy consumption

Distances and the loading capacity per means of transport were considered to be the significance factors that mostly contribute to the output variability. The calorific values, fuel density and fuel consumption for both road and sea transport used within this research were drawn from published data sources and therefore their usage in the mathematical model to generate the embodied transport energy per functional unit could be relied on for the purpose of this investigation. Assuming that the range of distances used in this research remains the same, the impact on the model's output was found to be dependent highly on the loading per stage.

Three scenarios were established within this research earlier in the chapter. The first scenario represents the embodied transport energy per functional unit if full load transport were accommodated throughout the forest to site stage. The second situation was established based on a particular model house to signify the embodied transport energy consumed per functional unit if the means of transport were carrying full load up to the point of assembly factory but where the loading transport from the factory to site were based on the number of house required on site. When analysis was based on the particular model house, the flow output shows a high dependency of embodied transport energy per FU to the number of house required per site development.

For the first scenario, some of the figures presented earlier on table 6.1 displayed the minimum and maximum values for each of the stages depending on the shortest and longest possible distances gathered during the primary data collection which ranges between a total of 122-153MJ/panel. Analysis carried out based on this scenario were aimed to provide an idea of ranges of embodied transport energy to be expected with varying distance characteristics and when the means of transport were assumed to carry full load at all the stages from the forest to site.

The scenario set above provided the best possible transportation energy value for the given functional unit. Fully loaded lorry was noted to be able to transport around six houses per journey from the assembly factory to site. There is a case where a full load transport is not always possible especially at the assembly factory to site stage. This has driven the need to produce further case study to draw out the significance of it. Figures produced and presented on table 6.2 shows the total embodied transport energy for a case where there is only one house to be developed per site. Table 6.4 also shows that, for a one house development, there was about 0.604GJ/panel embodied transport energy difference just by having the loading capacity which is equivalent to one house from the forest to site compared to full load transport from forest to assembly factory.

The third scenario was based on the worst case scenario where it takes into consideration the possible low supply of plywood and studs for the particular open wall panelling unit assessed within this research study and hence the associated materials needed to be transported direct from the forest to the site. Assuming that this is the worst case scenario, transporting just one panel for replacement will consumed a total embodied transport energy of 16.98GJ/panel, whereas the for a one house development, there is a possible of 0.834GJ/panel embodied transport energy consumption. This is an additional of 16.831GJ/panel and 0.685 GJ/panel respectively compared to the means of transport carrying full load from forest to site. This scenario represents the significance of embodied transport energy when there is low supply of structural timber material to construct the open wall panelling unit.

Chapter 7

Conclusion and Future Work

CHAPTER 7: CONCLUSION AND FUTURE WORK

7.1 Introduction

Chapter seven is the concluding chapter, where the work accomplished through this research is reviewed. It started by firstly providing the summary of the research, followed by the examining the achievement of each objectives and finally establishing the key findings of research. Finally, the overall conclusion is drawn along with recommendations for further work.

7.2 The Research Process and Outcomes

This research aims to assess the embodied transport energy consumption within prefabricated timber wall panelling unit in order to provide better understanding on the effect of transport and loading pattern to the overall transport energy of a particular prefabricated element. The first objective in pursuing this aim is to review the technological advancement of prefabricated construction and its current status particularly within the UK construction industry. The review of the technological advancement and current available research in Chapter two revealed various benefits in the use of prefabricated construction techniques. Nevertheless, research on this construction method in the UK is currently limited. Attention was drawn to the lack of environmental studies within prefabricated construction techniques hence the importance of further exploration within this research area.

The second objective was to investigate and identify the major environmental factors within prefabricated timber wall element. The qualitative review suggested that the major environmental contributors within prefabricated construction techniques are material resources consumption, energy and transportation.

Transport energy is considered to be the most important environmental impact contributor among other fossil fuel dependent energy consumption within the construction industry. This is particularly significant within prefabricated timber wall construction due to the necessity and requirement of movement of prefabricated components such as timber (which are mainly obtainable from European sources) as well the lack of off-site manufacturing plants.

The factory assembled components also requires the transport of some additional volumes of air particular for volumetric system which gives rise to the possibility of a more frequent transportation to site resulting in a possibility of a higher embodied transport energy consumption.

The third objective of the research was to develop a process flow model to evaluate the significance of embodied transport energy of prefabricated timber wall element. Data associated with the generation of the transport and material process flow model was gathered primarily through questionnaire of which being distributed to a number of TRADA accredited prefabricated timber manufacturer.

The outcome of the questionnaire indicates prefabricated timber open wall panelling system as the most marketed prefabricated timber wall system in the UK. Questionnaire also reveals that most of the manufacturer tends to only involve one assembly factory and the average distance from a factory to site to be an average of 50-100 miles radius. But most importantly, the questionnaire also substantiates the high dependency on imported timber. The outcome of the questionnaire as the primary data has been used to define the boundaries and to act as a base to identify the components associated within the transport and material process flow model.

The significance of embodied transport energy in accordance to the transport loading capacity within prefabricated timber wall element was then established based on the process flow model. First, a Functional Unit (FU) was identified as a reference unit in order to quantify the performance of the process flow model. The FU was based on the most common prefabricated timber frame system used in the UK. In this case, the FU is defined as a 2.4 x 3.6m prefabricated timber open wall panelling and consists of seven numbers of studs that are 2.4m length (S24), two numbers of studs that are 3.6m length (S36) and three number of 12mm plywood sheet.

A set of mathematical equations were then formulated based on this FU. These mathematical equations were designed to represent the embodied transport energy per FU. The development of the mathematical equations was described further in Chapter five and the validation of the process flow model against the generated mathematical equations was described in Chapter six. When in use, the process flow model proven to function successfully. The effect on differing transport and loading patterns also provide further understanding on how the transport embodied energy may differ.

Results generated from the validation were based on three different scenarios and analysed to underline the significance of embodied transport energy in accordance to the differing transport loading capacity. This specific process flow model is then used to illustrate the significance of embodied transport energy based on the given FU. The significance of embodied transport energy of the given FU was carried out based on three different scenarios. The first was presented with an assumption that vehicles were fully loaded throughout the journey, whereas the second and third scenarios were based on an assumption where a particular development will require certain amount of two bedroom house. The second scenario is based on the assumption that transport from forest to the assembly factory is fully loaded whilst the transport from the assembly factory to site depends on the quantity of two bedroom house on construction per development. The third and worst case scenario where demand of prefabricated timber frame house is assumed to be low and represents the embodied transport energy per FU when partial-load transport is incorporated from the forest to site and of which are dependent on the number of two bedroom house required per development. This has been summarised further in table 7.1

Table 7.1 Three type of scenarios used within research

	Load from Forest to Assembly Factory	Load from Assembly Factory to Site
1st case	Full	Full
2nd case	Full	Partial
3rd case	Partial	Partial

From the evaluation of embodied transport energy based on the first case scenario, it is clear that the highest transport energy consumed per FU occurs at the forest to sawmill stage and that it contributes to 60% of the total embodied transport energy. It is believed that at this stage, the high transport energy figure per FU was due to high wastage factor during the conversion of logs to plywood.

Further evaluation and analysis was then carried out based on the second scenario and of which a two bedroom house was presented as the model house. Result shows that transport energy for a one house development is 6.5 times higher than transport energy of a fully loaded transport at the factory to site stage alone.

The third scenario was based on the worst case scenario where it takes into consideration of the possible low supply of plywood and studs required to construct open wall panelling units which resulted in the need to transport the associated timber material based on “made to order” scenario. The worst case scenario evaluation shows that transporting an equivalent of one panel per transport from the forest to site will consume a total embodied transport energy of 16.98GJ/panel, which is an additional of 16.83 GJ/panel compared to transport carrying full load from the forest to site stage. The third case scenario also shows total embodied transport energy for one house development which is an equivalent to 0.834GJ/panel (about 0.685 GJ/panel more than transport carrying full load from the forest to site).

Results generated based on the three different scenarios were then evaluated against a range of energy consumed at the manufacturing, sawmilling and logging stages to demonstrate the significance of transport energy to other embodied energy stages.

When comparing the embodied transport energy to other processes that also contributes to the total embodied energy of a typical prefabricated timber wall panelling unit, it was noted that the manufacturing processes of studs and plywood tends to be much higher than the total embodied transport energy figures generated within this research except for the worst case scenario where it represents the total embodied transport energy for transport load that is equivalent to one panel throughout the forest to site stage. The evaluation for this worst case scenario indicates that total embodied transport energy for an equivalent of one panel loading transport can be four times higher compared to plywood and studs manufacturing energy.

7.3 Conclusion and Outcomes of Research

With prefabricated housing considered to be reasonably new to the market, research carried out has so far been limited and incomplete, hence its impact on the environment merit investigation. Interest in this research lies specifically at examining and evaluating the significance of embodied transport energy within a generic prefabricated timber wall panelling unit. While it is understood that timber is known to have lower embodied energy consumption compared to other building material such as concrete and steel, timbers used by the UK construction industry tends to be imported from other countries. This further increases the embodied transport energy consumption within prefabricated timber frame house and highlights the importance of concentrating into this research area in greater detail.

This research aims to determine the embodied transport energy consumption associated within prefabricated timber wall panelling unit by means of process flow analysis. The processes involved were selected based on partial LCA approach. Due to the complexity, a systematic process flow model was generated to ensure transparency of the method applied in analysing the embodied transport energy associated within it.

Current literature review indicates that modern prefabricated construction techniques in the UK is at the early stage, hence there were very limited research available - especially those that focuses on its environmental implication.

Current literature review indicates that there have been various types of prefabricated timber frame construction associated with UK housing construction. Prefabricated timber wall element is adopted as a reference feature in this research as this type of wall construction is considered to be an alternative to traditional masonry wall construction.

Energy, transport and material resources were recognised as the major environmental impact factors associated with prefabricated timber wall. The divergence in prefabricated construction transportation pattern compared to traditional on site construction tightened the need to assess embodied transport energy of building constructed using prefabricated timber wall panel in order to enhance greater understanding of its environmental performance.

The complexity in evaluating the significance of embodied transport energy within prefabricated timber wall element necessitates the need to generate a generic process flow model. The components associated within this generic forest to site process flow model were identified with the aid of primary and secondary data collection. The generic process flow model was developed based on both material and transport process flow. This established process flow model was then evaluated further with the aid of mathematical formulae.

As demonstrated throughout the present study, the process flow analysis concluded that it is more environmentally friendly to deploy prefabricated timber frame construction into a large development where vehicles tend to carry full load. This study has also shown that there is a difference of 16.83 GJ/panel in the overall embodied transport energy per panel just by differing the loading amount from full load to partial load throughout the forest to site stage. Results indicate that transport and loading pattern are the significant factors contributing to transport energy associated with prefabricated element in general and prefabricated timber wall panelling in particular. Through this process flow model analysis, it can also be concluded that issue of transport energy is not simplistic and must not be overlooked especially when imported materials were used.

The developed process flow model analysis has proven to be an effective platform to provide a better understanding on the significance of embodied energy associated with the set variables. A robust process flow model has been developed based on the primary data obtained from UK existing practice. The process flow analysis was carried out in a clear and concise way for other professional to pick up and advance the environmental analysis in this area further and can also be used to aid in providing a better environmental decision making. In addition to that, the process flow model in this research can be served as a basis for future studies and may be applied to other prefabricated house system elsewhere in the world.

Given the magnitude of the implication for the environment, embodied transport energy of a prefabricated timber wall panelling unit used within prefabricated housing construction remains an issue of importance that needed to be explored further.

7.4 Recommendations for further work

This research has developed a system to enable the analysis of embodied transport energy consumption within prefabricated timber wall panelling unit in particular. The strength of the developed process flow model is in its flexibility to be used and adapted to a variety of situation which can be used to establish optimum outcome. The flow model was also designed and developed for use on site specific scenario and can be used to specific material, suppliers and efficiency of distribution and delivery route. It has also been identified as a valuable approach for improving environmental understanding by way of transport and loading pattern analysis. However, the full potential of the methodology has yet to be realised. It is recognised that although model and method has been applied to current practise, there may be a need for this process flow model to be further validated by using further in-depth case studies in a variety of transport patterns, locations and differing prefabricated construction element. Further research and development is therefore necessary of which are proposed as follow:

7.4.1 Complete environmental impact life cycle analysis

In the longer term, a full UK specific LCA procedure which also includes the end of life stage should be developed. Prefabrication method principles such as Design for Assembly” (DfA) and Design for Deconstruction (DfD) offer opportunities to extend building life spans and maximise the embodied energy invested. It was therefore important to investigate the possible amount of energy saved if this method is incorporated onto a life cycle assessment.

The lack of published research examining the LCA of prefabricated housing in the UK meant that there is further need in developing a comparison study of the various materials and types used within prefabricated housing construction. The assessment framework developed and used in this research would provide a comprehensive basis for gathering the range of data necessary and for quantifying the embodied transport energy of various prefabricated house construction types.

7.4.2 Comparison between transport energy of prefab timber transport energy to traditional masonry house

Transport energy for various materials varies widely depending on the source of raw materials, transport load, and location of supplier. Unfortunately due to limited research available, further research needed to be carried out in order to compare the transport energy of prefabricated timber wall panelling unit to a traditional masonry wall.

7.4.3 The inclusion of ancillary material

Ancillary material such as nails, screws and other connectors is highest for timber panel construction. It is therefore of importance to take this into consideration at the future work especially when comparing a prefabricated timber wall element to other type such as concrete wall panelling.

7.4.4 Development of automated mathematical model for a wider implementation

Chapter 5 describes the complex relationships between material consumption, means of transport and its loading capacity as well as geographical areas. It explains how loading capacity per means of transport and the demand for prefabricated timber open wall panelling unit having a direct impact on the overall total embodied transport energy of the particular prefabricated timber system. This relationship is explained in Chapter 5 and quantified further in Chapter 6. Nevertheless, the material flow and quantification established within this research is unique to that of open wall panelling unit and the choice of transport mode, as well as the geographical location set within the transport processes is unique to those open wall panelling unit produced by UK prefabricated timber frame house manufacturer.

A further development of mathematical model that can then be used for wider implementation is important. The anticipated tool would be software based and would follow the structure of the system framework and of which enabling the calculation of transport energy based on identified variables.

It was noted earlier in Chapter 1 that prefabricated system can be applied for various reason. In the UK, prefabricated construction used with automation can be implemented to tackle the lack of skilled labour. Whereas in developing country such as Indonesia, prefabricated construction can be implemented to provide new job opportunities and faster as well as better affordable housing supply.

The use of prefabricated timber techniques for housing construction in Indonesia, for example, seems to be beneficial at first glance due to the country's local timber source. Nevertheless its uses requires further evaluation in order to make sure that further strain isn't put onto the already depleting timber materials source in country. Rapid deforestation from the late 19th Century (in the form of slash and burn activities as well as illegal logging) in Indonesia were mainly caused by poor management. These has inevitably triggered not only an extensive air pollution, but also causing landslides and flash floods as well as disturbance in ground water level thus triggering the depletion of local timber resources in Indonesia. It would be interesting to assess the effects of prefabricated timber frame construction for house in Indonesia.

It is understood that the use of prefabricated construction techniques to accommodate housing demand in Indonesia will generate a different environmental impact compared to the UK. In Indonesia, the need for housing concentrates primarily in Jakarta as its capital city, whereas most of Indonesian forestry are located on another islands such as Sumatra and Borneo where its road infrastructure are still undeveloped fully. This may cause a difference in embodied energy consumption due to the use of other alternative means of transport, varying distances, the diversion routes or the limitation in certain material resources.

On that basis, it is noted that this research work could be extended further to improve the environmental knowledge in the use of other various types of prefabricated construction techniques for construction development in countries with different geography and socioeconomic background. These would establish a wider understanding to the causes and effects if certain types of prefabricated construction techniques were implemented in the UK and how it varied when it is being implemented in other countries with different socioeconomic and geographical background.

7.4.5 Expansion of the existing questionnaire

The questionnaire has been developed and compiled at the early stage of research and at the time when information of the life cycle of prefabricated element in the UK proven to be very limited. For future work, it is recommended to revise the questionnaire based on the knowledge that has been obtained through this research.

7.4.6 Integration of the developed process flow model with Computer Aided Design (CAD)

Design, technology and innovation play an important role in prefabricated construction and its element. Due to the inhomogeneous requirement and difficulties in incorporating design synthesis with qualitative information required within a particular LCA tool, it is understood that research concentrating in the integration of CAD and LCA software within the construction sector is very limited and many of them are still under development. It is believed that the integration of the developed process flow model with CAD will aid in providing an LCA decision making tool of which also taken into consideration the design, technology and innovation aspects.

7.4.7 Incorporate Multi-criteria Decision Analysis (MCDA) to the develop process flow model

MCDA methods are becoming increasingly relevant in assessing issues related to environmental assessment of products and processes. Similar to other LCA methodology tools, data stored and analysed in this developed process flow model often precise and straightforward, in spite of a huge amount of uncertainty and imprecision related to data, models and human judgments on which they are based. Therefore the use of uncertainty modelling formalisms and the building of decision support frameworks allowing the efficient interpretation of the assessment results and data in an uncertain environment are highly needed. This area is identified to be a potential further work from this research.

Finally, the main recommendation for future work from the present research is in providing a simple and user-friendly methodology that can be used to aid provide decision making within the construction industry. A series of real case studies approach will also provide a greater detailed results and sensitivity analysis of which can be used as a best practice benchmark.

REFERENCES

ADALBERTH, K. (1997) Energy use during the life cycle of single-unit dwellings: Examples. Building and Environment, 32, 321.

ADALBERTH K (2000) Energy use and environmental impact of new residential buildings. Department of Building Physics. Lund, Lund University.

ALCORN, J. A. (1998), Embodied energy coefficients of building materials. Wellington, New Zealand, Centre for Building Performance Research Victoria University of Wellington

ANDERSON J., & HOWARD N., (2000), The Green Guide to Housing Specification. Watford. CRC

ANDERSON J, EDWARDS S, MUNDY J & P, B. (2002) Life cycle impacts of timber. A review of the environmental impacts of wood products in construction, Building Research Establishment, BRE.

ANDERSON J, EDWARDS S (2000) Addendum to BRE methodology for environmental profiles of construction, materials, components and buildings. DETR Framework Project: support for government policies on sustainable development. Watford, UK, Centre for Sustainable Construction, BRE Building Research Establishment.

ANDERSON, L. M., ST. CHARLES, J., FULLILOVE, M. T., SCRIMSHAW, S. C., FIELDING, J. E. & NORMAND, J. (2003) Providing affordable family housing and reducing residential segregation by income: A systematic review. American Journal of Preventive Medicine, 24, 47.

ARGONNE NATIONAL LABORATORY (2005) Green transportation Technologies - Improving energy use in Heavy Duty Trucks and Diesel Locomotives. Chicago, The University of Chicago.

ARNOLD, D. (2004) Prefabs tagged with designers' numbers. Building Design. Building Design.

OVE ARUP. (2000) The Contribution that Technological change could make to meeting the Objectives of Rethinking Construction: The Product. IN CRISP (Ed.) CRISP Commission 99/17. London, Ove Arup and Partners.

AYRES R U (1995) Life Cycle Analysis: A Critique. Resources, Conservation and Recycling, 13, 199-223.

BAGENHOLM C, YATES A & I, M. (2001a) BRE Information Paper 16/01 Part 1 Prefabricated study in the UK. A case study - Murray Grove, Hackney IN BUILDING RESEARCH AND ESTABLISHMENT, B. (Ed.), BRE.

BAGENHOLM C, YATES A & I, M. (2001c) BRE Information Paper 16/01 Part 3 Prefabricated housing in the UK. A summary paper. IN BUILDING RESEARCH AND ESTABLISHMENT, B. (Ed.), BRE.

BAGENHOLM C, YATES A & MCALLISTER I (2001b) BRE Information Paper 16/01 Part 2 Prefabricated study in the UK. A case study - CASPAR II, Leeds. IN BUILDING RESEARCH AND ESTABLISHMENT, B. (Ed.), BRE.

BARKER, K. (2003) Review of Housing Supply: Securing our Future Housing Needs, Interim Report - Analysis. IN ODPM (Ed.) Norwich, HMSO.

BARKER, K. (2004) Review of Housing Supply. Delivering Stability: Securing our Future Housing Needs, Final Report - Recommendations. IN ODPM (Ed.) London, HMSO.

BARLOW, J., COCKS, R. & PARKER, M. (1994) Delivering affordable housing : Law, economics and planning policy. Land Use Policy, 11, 181.

BARLOW, J. & VENABLES, T. (2000) Housing and Construction: Identifying Missing Research Needs and Opportunities. CRISP Commission 00/01. SPRU, University of Sussex, Brighton, CRISP.

BATES J & WATKISS P (2006) Policy Coverage of Environmental impacts of Materials - A Research completed for the Department for Environment, Food and Rural Affairs. IN AEA TECHNOLOGY (Ed.) London, Defra.

BERG S & KARJALAINEN T (2002) Comparison of emissions from forest operations in Finland and Sweden. article manuscript.

BERG, S. & LINDHOLM, E.-L. (2005) Energy use and environmental impacts of forest operations in Sweden. Journal of Cleaner Production, 13, 33-42.

BERG, S. & LINDHOLM, E.-L. (2005) Energy use and environmental impacts of forest operations in Sweden [Journal of Cleaner Production 13 (2005) 33-42]. Journal of Cleaner Production, 13, 327.

BERG, S. V. & TAYLOR, C. (1994) Electricity consumption in manufactured housing. Energy Economics, 16, 54.

BERGDAHL A, ORTENDAHL A & D, F. (2003) The Economic Potential for Optimal Destination of Roundwood in North Sweden - Effects of Planning Horizon and Delivery Precision. International Journal of Forest Engineering, 14.

BERGE B (2000) The Ecology of Building Materials, Oxford, Architectural Press.

BERGSTROM, M. & STEHN, L. (2004) Matching industrialised timber frame housing needs and enterprise resource planning: A change process. International Journal of Production Economics, In Press, Corrected Proof.

BIZLEY, G. (2004) Four flats in a flash. Building Design.

BJORKLUND T & TILLMAN A M (1997) LCA of building frame structures: environmental impact over the life cycle of wooden and concrete frames. Technical Environmental Planning Report 2. Gothenburg, Chalmers University Technology.

BLAMEY M (2006) Terraces Have "Street" Appeal. NHBC.

BOEHM THOMAS, P. (1995) A Comparison of the Determinants of Structural Quality between Manufactured Housing and Conventional Tenure Choices: Evidence from the American Housing Survey. Journal of Housing Economics, 4, 373.

BONFIELD, P. (2004) Thoroughly modern mission. Building Design.

BOOTH, R. & HYAM, T. (2004) Less design, Peabody warned. Building Design.

BOS, A. J. M. (1998) Direction indirect: the indirect energy requirements and emissions from freight transport. Mathematics and Natural Science. Groningen, University of Groningen.

BOTTOM, D. E. A. (1996) Innovation in Japanese Prefabricated House Building Industries. London, Construction Industry Research and Information Association (CIRIA).

BRANSON, T. R., EISHENNAWY, A. K., SWART, W. W. & CHANDRA, S. (1990) Automation technologies for the industrialized housing manufacturing industry. Computers & Industrial Engineering, 19, 587.

BRE (2002) BRE Certification Scheme Document - Environmental Profiles of Construction Products. BRECertification Ltd.

BRIDGEWATER, C. (1993) Principles of design for automation applied to construction tasks. Automation in Construction, 2, 57.

BRIGHTON AND HOVE CITY COUNCIL (2005) Demand for different sizes of properties in Brighton and Hove over the next three years (2005-2008). Brighton and Hove, Housing Strategy Team.

BROWN, D. & JACOBS, P. (1996) Adapting environmental impact assessment to sustain the community development process. Habitat International, 20, 493.

BROWN, D. G. (1999) Design Guide and Innovation of Modular Units. SCI.

BUCHANAN A H & HONEY B G (1994) Energy and Carbon dioxide implications of building construction. Energy and Buildings, 20, 205-17.

Building Design. (2004) Minister looks to Europe for pre-fab model. Building Design. Building Design.

Building Design. (2004) Pioneering Robinson exits Peabody role. Building Design.

Building Design. (2004) Pre-fab housing gets 10% backing from government. Building Design.

Building Design. (2004) Rouse Rejects radical social housing. Building Design.

BUILDING SERVICES JOURNAL (2004) Buildings failing air tightness. Building services Journal: the magazine of CIBSE.

BURCH, J. (2004) Prefab dreams. Building Design.

BURSTRAND, H. (1998) Light-gauge steel framing leads the way to an increased productivity for residential housing. Journal of Constructional Steel Research, 46, 183.

BYNUM, R. T. (1999) Handbook of Alternative Materials in Residential Construction, London, McGraw-Hill.

CABE (2004) Design and Modern Methods of Construction. London, CABE.

CHEN T.Y., BURNETT J., CHAU C.K. (2001) Analysis of Embodied Energy Use in the Residential Building Envelope of Hong Kong, International Journal of Energy, 26, 323-340.

CHUDLEY R, G. R., BASSETT (1999) Advanced Construction Technology, Pearson Education.

CIRIA (1995) Environmental Impact of Materials, Volume A - Summary. London, Construction Industry Research and Information Association,.

CIRIA (1997) Snapshot - Standardization and Pre-assembly. Compiled by Gibb, A.G.F., GroaÂk, S. & Sparksman, W.G. Construction Industry Research and Information Association, London, pp. 1±8.

CIRIA (1999) Adding value to construction projects through standardization and pre-assembly. Compiled by Gibb, A.G.F., GroaÂk, S., Neale, R.H. & Sparksman, W.G. Construction Industry Research and Information Association, London, Report R176. ISBN 0-86017-498-0.

CIWMB (2000) Designing with vision: a technical manual for materials choices in sustainable construction. California, California Integrated Waste Management Board.

CLARK, M. (2001) Domestic futures and sustainable residential development. Futures, 33, 817.

CLARKE, L. & GOULD, N. (2000) Standardisation and skills: a transnational study skills education and training for prefabrication in housing. London, Westminster University.

COLE RJ (1998) Energy and greenhouse gas emissions associated with the construction of alternative structural systems. Building and Environment, 34, 335-48.

COLE RJ & PC, K. (1996) Life cycle energy use in office buildings. Building and Environment, 31, 307-17.

CRAIG, A., LAING, R. & EDGE, M. (2000) The social acceptability of prefabrication and standardisation in relation to new housing. "16th IAPS Conference" 21st century: Cities, social life and sustainable development. Paris, Scottish Centre for Environmental Design Research, Faculty of Design, The Robert Gordon University, Garthdee Road, Aberdeen, Scotland.

CLG (2007), Homes for the future: more affordable, more sustainable. p.22, Stationery Office, London.

Available fromwww.communities.gov.uk

CRAINE T & MASON A (2006) Who Buys New Market Homes. London, London Development Research Ltd.

CROFT, C. (2004) Constructive arguments. Building Design. London.

CROWTHER P (1999) Design for Disassembly to Recover Embodied Energy. PLEA (Passive and Low Energy Architecture). Brisbane, Australia.

DAVIES H, BOURKE K & LTD, C. A. (1997) Factors affecting service life predictions of buildings: a discussion paper. IN REPORT, B. (Ed.) BRE Report 230. Building Research Establishment, BRE.

DELVES, A., DRAYTON, R. & SHEEHAN, T. (2001) Faster construction on site by selection of methods and materials, London, CIRIA.

DEFRA (2004) Energy Efficiency: The Government's Plan for Action, Department of Environment, Food and Rural Affairs. Pg 7, April 2004

http://www.archive2.official-documents.co.uk/document/cm61/6168/6168.pdf

DEFRA, (2008) UK Climate Change Programme: Annual Report to Parliament, July 2008, p9. http://www.defra.gov.uk/environment/climatechange/uk/ukccp/pdf/ukccp-ann-report-july08.pdf

DfT (2006) Focus on Freight, London, Department of Transport, London, TSO.

DfT (2006) Transport Statistics of Great Britain. London, TSO.

DfT (2006) Transport Statistics Report - Maritime Statistics 2005. National Statistics. London, TSO.

DTI (2005) Digest of United Kingdom Energy Statistics 2005. DUKES. London, Department of Trade and Industry,.

DTI (2006) Digest of United Kingdom Energy Statistics 2006. DUKES. London, Department of Trade and Industry.

DETR (2001) Quality and Choice: A Decent Home for All. IN DETR HOUSING GREEN PAPER (Ed.) DETR Housing Green Paper,. DETR.

DETR (1998b) General Information Report 53: Building a sustainable future - homes for an autonomous community. London, DETR.

DETR (1998a) Opportunities for change - Consultation paper on a revised UK strategy for sustainable development. IN DETR (Ed.) London.

DETR (1999) Planning Policy Guidance Note 3: housing. IN DETR (Ed.) London.

DETR. (2000) Housing and Construction Statistic. IN DETR (Ed), HMSO.

DIAS, R. A., MATTOS, C. R. & P. BALESTIERI, J. A. The limits of human development and the use of energy and natural resources. Energy Policy, In Press, Corrected Proof.

DINEEN, M. (1987) Homes for the future. IN VISION (HALIFAX BUILDING SOCIETY BULLETIN) (Ed.) Vision (Halifax Building Society Bulletin),

EDGE, H., POLLOCK, R., AL-HAJJ, A. & SLAVEN, G. (2002) Overcoming Client and Market Resistance to Prefabrication and Standardisation in Housing. Aberdeen, Rober Gordon University, DETR and EPSRC.

EDGELL, G. J. (1998) House Wall Construction for the future. CERAM.

EGAN, J. (1998) Rethinking construction : the report of the Construction Task Force to the Deputy Prime Minister, John Prescott, on the scope for improving the quality and efficiency of UK construction. London, HMSO.

ELLIOTT, K. E. A. (1992) Precast Concrete Framed Buildings, Berkshire, British Cement

ENERGY INFORMATION ADMINISTRATION (EIA) (2006) International Energy Outlook 2006. Washington DC, National Energy Information Center.

ENTCHEV, E., GUSDORF, J., SWINTON, M., BELL, M., SZADKOWSKI, F., KALBFLEISCH, W. & MARCHAND, R. (2004) Micro-generation technology assessment for housing technology. Energy and Buildings, 36, 925.

ERLANDSSON, M. & BORG, M. (2003) Generic LCA-methodology applicable for buildings, constructions and operation services--today practice and development needs. Building and Environment, 38, 919-938.

EUROPEAN SUSTAINABILITY WORKING GROUP (2003)www.prepare-net.org.

EVANS, J. M. (1986) Measurement technology for automation in construction and large scale assembly. Robotics, 2, 87.

FICGB (1998) A Reference for the Forestry Industry. Stirling, Forest Industries Committee of Great Britain.

FINNFOREST (2002) Handbook of Finnish Plywood, Finnish Forest Industries Federation.

FIRMAN, T. (1998) The restructuring of Jakarta Metropolitan Area:: A "global city" in Asia. Cities, 15, 229.

FIRMAN, T. (2004) New town development in Jakarta Metropolitan Region: a perspective of spatial segregation. Habitat International, 28, 349.

FIRMAN, T. & DHARMAPATNI, I. A. I. (1994) The Challenges to Sustainable Development in Jakarta Metropolitan Region. Habitat International, 18, 79-94.

FLANAGAN, L. (2000). Environmental assessment of reuse and recycling of unplasticised polyvinyl chloride window profiles. Thesis in School of the Environment. University of Brighton

FORESTRY INSIGHTS (2005) Typical Sawmill Processes. New Zealand, Forestry Insights.

GALLENT, N. (1997) The alternative route to affordable housing provision: Experiences in rural Wales. Journal of Rural Studies, 13, 43.

GANN, D. & SENKER, P. (1993) International trends in construction technologies and the future of housebuilding. Futures, 25, 53.

GANN, D. M. (1990) High-technology buildings and the information economy. Habitat International, 14, 171.

GANN, D. M. (2000) Building Innovation: complex constructs in a changing world, London, Thomas Telford.

GAO, W., ARIYAMA, T., OJIMA, T. & MEIER, A. (2001) Energy impacts of recycling disassembly material in residential buildings. Energy and Buildings, 33, 553.

GARAS F.K., TAYLOR WOODROW CONSTRUCTION LTD & AL, E. (1994) Buidling the Future: Innovation in design, materials and construction, Spon Press.

GATES, C. (2004) Minister backtracks on modern methods. Building Design.

GIBB, A. G. F. (1999) Off-site fabrication : prefabrication, pre-assembly and modularisation Caithness, Scotland, J.W. Arrowsmith Ltd.

GIBB, A. G. F. (2000) Standardisation and pre-assembly: client's guide and toolkit. London, Construction Industry Research and Information Association (CIRIA).

GIBB, A. G. F. (2001) Pre-assembly construction: A review of recent and current industry and research initiatives on pre-assembly in construction. IN COMMISSION, C. C. (Ed.) CRISP Consultancy Commission - 00/19. CRISP.

GIBB, A. G. F. E. A. (1999) Standardisation and pre-assembly - adding value to construction projects. London, Construction Industry Research and Information Association (CIRIA).

GIELEN D J (1997) Building Materials and CO2: Western European emission reduction strategies. Petten, Netherlands Energy Research Foundation ECN.

GILHAM, A. (2001) Innovation and best practice in flexible and modular building solutions. Building Research Establishment, BRE.

GOLDBLATT, D. L., HARTMANN, C. & DURRENBERGER, G. (2005) Combining interviewing and modelling for end-user energy conservation. Energy Policy, 33, 257.

GOLDBLUM, C. & WONG, T.-C. (2000) Growth, crisis and spatial change: a study of haphazard urbanisation in Jakarta, Indonesia. Land Use Policy, 17, 29.

GOLDMAN, C. A. & RITSCHARD, R. L. (1986) Energy conservation in public housing: A case study of the San Francisco housing authority. Energy and Buildings, 9, 89.

GONZALEZ-URIEL, A. & ROANES-LOZANO, E. (2004) A knowledge-based system for house layout selection. Mathematics and Computers in Simulation, 66, 43.

GOODACRE, C., SHARPLES, S. & SMITH, P. (2002) Integrating energy efficiency with the social agenda in sustainability. Energy and Buildings, 34, 53.

GORGOLEWSKI MARK (SCI), MILER M (TRADA) & ROSS K (BRE) (2002) Off-site produced housing: a briefing guide for housing associations. Building Research Establishment, BRE.

GRANTHAM R et al. (2003) Multi-storey timber frame buildings a design guide. IN BRE (Ed.) BRE Report Building Research and Establishment, BRE.

GUSTAVSSON L & SATHRE R (2005) Variability in energy and carbon dioxide balance of wood and concrete building materials. Building and Environment, 41, 940-951.

HADIWINOTO, S. & LEITMANN, J. (1994) Jakarta. Cities, 11, 153.

HAKKINEN, T. (1994) Environmental Assessment of Building Materials. CIB Task Group 16 - First International Conference on Sustainable Construction. Florida.

HAKKINEN, T. (2001) A European Thematic Network on Construction and City Related Sustainability Indicators - Finnish State of the Art Report.

HALIFAX (2007) Terraced houses see biggest price rises over the last ten years. Halifax.

HAYGREEN JG & BOWYER JL (1996) Forest Products and Wood Science - An Introduction, Iowa, Iowa State University Press.

HENS, H., VERBEECK, G. & VERDONCK, B. (2001) Impact of energy efficiency measures on the CO_2 emissions in the residential sector, a large scale analysis. Energy and Buildings, 33, 275.

HERKOMMER, F. & BLEY, B. (1996) CAD/CAM for the prefabrication of brickwork. Automation in Construction, 4, 321.

HILLYER, C., BOLTE, J., VAN EVERT, F. & LAMAKER, A. (2003) The ModCom modular simulation system. European Journal of Agronomy, 18, 333.

HINCHCLIFFE P (2004) Gross and Net heating values and their significance for biomass energy. ROYAL COMMISSION ON ENVIRONMENTAL POLLUTION (RCEP),.

HODKINSON, R. (2000) Housing Issues Group. Final Report. Middlesex.

HONEY B G & BUCHANAN A H (1992) Environmental Impact of the New Zealand Building Industry. Christchurch, Department of Civil Engineering, University of Canterbury.

HOUSING CORPORATION (2004) The Housing Corporation: Sustainable Development.

HOWARD N, EDWARDS S & ANDERSON J (1999) BRE methodology for environmental profiles of construction materials, components and buildings, Watford, BRE Press.

HUNHAMMAR S (1995) Cycling Residues Potential for increased transportation demands due to recycling of materials in Sweden. Resources, Conservation and Recycling, 15, 21-31.

HURLEY J, ADAMS K, MCMINN A & A, T. (2003) Best practice of timber waste management, Building Research and Establishment, BRE.

HURLEY J, M. C. (2001) Deconstruction and reuse of construction materials. IN REPORT, B. (Ed.) BRE Report 418. BRE.

HURST, W. (2004) Prefab security slammed. Building Design.

IFEU AND SGKV (2002) Comparative analysis of energy consumption and CO_2 emissions of road transport and combined transport road/rail., Institute for Energy and Environmental research (IFEU) and Association for Study of Combined Transport (SGKV),.

ISHIHARA, O., ZHANG, Q. & YOSHIHARA, F. (1994) Development of a hybrid house with the photovoltaic system and earth heat storage system. Renewable Energy, 5, 339.

ISO 14040 (2006) Environmental management - Life cycle assessment - Principles and framework (AMD Corrigendum 16558), British Standards Institution.

JACKSON, P. (2004) Overview: Is building so many flats really the best answer to the housing shortage? The Independent Online Edition.

JAMES P & HOPKINSON P (2001) Virtual traffic: e-commerce, transport and distribution. IN WILSDON J (Ed.) Digital Futures. Living in a dot-com world. London, Earthscan Publications Ltd.

KALOGIROU, S. A. (2004) Environmental benefits of domestic solar energy systems. Energy Conversion and Management, 45, 3075.

KARKI, S. K., MANN, M. D. & SALEHFAR, H. (2005) Energy and environment in the ASEAN: challenges and opportunities. Energy Policy, 33, 499.

KEIVANI, R. & WERNA, E. (2001) Modes of housing provision in developing countries. Progress in Planning, 55, 65.

KEIVANI, R. & WERNA, E. (2001) Refocusing the housing debate in developing countries from a pluralist perspective. Habitat International, 25, 191.

KNECHTLE, N. (1997) Materialprofile von Holzerntesystemen – Analyse ausgewählter Beispiele als Grundlage für ein forsttechnisches Ökoinventar [Material profiles from forest harvest systems. Analyses of chosen examples as a base for forest

LCI]. ETH Zürich, Departement für Wald- und Holzforschung, Professur Forstliches Ingenieurwesen. Diplomarbeit, WS 1996/97.

KNECHTLE, N. (1999) Materialprofile von Holzerntesystemen als Ausgangspunkt für Ökoinventare [Material profiles from forest harvest systems as a basis for LCI]. Schweizerische Zeitschrift für Forstwesen 150(3):81-87.

KOBAYASHI, S. (2004) Landscape rehabilitation of degraded tropical forest ecosystems: Case study of the CIFOR/Japan project in Indonesia and Peru. Forest Ecology and Management, 201, 13.

KOCH P (1992) Wood versus non-wood materials in US residential construction: some energy-related global implications. Forest Products Journal, 42, 31-42.

KRAJNC, D. & GLAVIC, P. (2005) A model for integrated assessment of sustainable development. Resources, Conservation and Recycling, 43, 189.

LANG, S. (2004) Progress in energy-efficiency standards for residential buildings in China. Energy and Buildings, 36, 1191.

LAWSON, W.R. (1996), Building materials, energy and environment – towards ecological sustainable development, Canberra AU, School of Architecture, The University of New South Wales.

LAWSON, M. (2000) Performance Specification for Pre-Engineered modular construction. SCI.

LEE, A. D., ONISKO, S. A., SANDAHL, L. J. & BUTLER, J. (1994) Everyone wins! -- A program to upgrade energy efficiency in manufactured housing. The Electricity Journal, 7, 77.

LENSINK S M (2005) Capacity Building for Sustainable Transport. Mathematics and Nature Science.

Life-cycle assessment framework as laid down in ISO 14040:1997, Boustead Consulting, UK, viewed on 12th December 2007, <www.boustead-consulting.co.uk/images/figure2.gif>.

LIM, G.-C., FOLLAIN, J. J. & RENAUD, B. (1984) Economics of residential crowding in developing countries. Journal of Urban Economics, 16, 173.

LINDHOLM E L (2006) Energy use in Swedish Forestry and its Environmental Impact. Department of Biometry and Engineering. Uppsala, SLU.

LINDHOLM E L & BERG S (2005) Energy requirement and environmental impact in timber transport. Scandinavian Journal of Forest Research, V20, 184-191.

LITTLEFIELD, D. (2004) DIY for Architects. Building Design. Building Design.

LLOYD S (2000) Towards Responsible Swedish Timber Trade? A Survey of Actors and Origin of Timber from Russia and the Baltic States. Mattisudden, Taiga Rescue Network (TRN), WWF Sweden,.

LOETTERLE , F. (2004) Mass Housing Design Principles and Prototypes.

LORAINE R K , C. (1994) Construction management in developing countries, Thomas Telford.

LOVELL H (2003) Post note-Modern Methods of House Building. IN PARLIAMENT OFFICE OF SCIENCE AND TECHNOLOGY (POST) (Ed.), Parliamentary Copyright.

MAAS, G. & VAN EEKELEN, B. (2004) The Bollard--the lessons learned from an unusual example of off-site construction. Automation in Construction, 13, 37.

MACCARTHY, I. (1998) Prefabricated building method using cold-formed steel components. Journal of Constructional Steel Research, 46, 194.

MACE, L. (2000) Technological Change: The Next Leap Towards Lean Construction

A Report on the Contribution of Technological Change in Meeting the Objectives of Rethinking Construction. IN CRISP (Ed.) CRISP Commission 99/17. Mace.

MACGREGOR, J. J. (1956) Production in the Swedish Sawmill Industry (An examination of Dr Bertil Thunell's study). Forestry, 29, 119-136.

MATSUDOME, S.-I. (1990) Japanese prefabricated timber house construction. Habitat International, 14, 263.

MATTHEWS, A. (2004) Piecing the jigsaw to stand the test of time. Building Design.

MAYOR OF LONDON (2005) Housing - The London Plan Supplementary Planning Guidance, London, Greater London Authority.

MCALLISTER I, Y. A. (2000) The use of modular building techniques for social housing in the UK a market research report. IN REPORT, B. (Ed.) BRE Report 393. Watford, Building Research Establishment, BRE.

MCCUTCHEON, R. (1988) Industrialised house building, 1956-1976. Habitat International, 12, 95.

MCCUTCHEON, R. (1988) Major participants in the UK building industry, 1964-1977. Habitat International, 12, 105.

MCCUTCHEON, R. (1988) Technical and economic efficiency in the UK building industry, 1965-1977. Habitat International, 12, 117.

MCCUTCHEON, R. (1989) Industrialised house building in the UK, 1965-1977. Habitat International, 13, 33.

MCCUTCHEON, R. (1990) The role of industrialised building in low-income housing policy in the USA. Habitat International, 14, 161.

MCDONALD, J. R. & MEHNERT, J. F. (1990) A review of standards of practice for wind resistant manufactured housing. Journal of Wind Engineering and Industrial Aerodynamics, 36, 949.

MEYER, F.-M. & HARGER, J. R. E. (1996) Assessment of UN agency interest areas regarding environmental activities in Indonesia. Chemosphere, 33, 1841.

MIGUEZ, J. L., PORTEIRO, J., LOPEZ-GONZALEZ, L. M., VICUNA, J. E., MURILLO, S., MORAN, J. C. & GRANADA, E. Review of the energy rating of dwellings in the European Union as a mechanism for sustainable energy. Renewable and Sustainable Energy Reviews, In Press, Corrected Proof.

MIKAEL, R. (2003) Optimization in forestry. Mathematical Programming, V97, 267-284.

MILLER A.J (1996) Transportation Energy Embodied in Construction Materials. Embodied Energy:- The current State of Play. Deakin University, Australia, Australian Society for Sustainable Materials.

MILLER A.J (2001) Embodied Energy – A life-cycle of transportation energy embodied in construction materials. In: COBRA 2001, Proceedings of the RICS Foundation Construction and Building Research Conference, 05 September 2001, Glasgow.

MILNE, I. (2004) Lessons in Prefab. Building Design. London.

MITHRARATNE, N. & VALE, B. (2004) Life cycle analysis model for New Zealand houses. Building and Environment, 39, 483.

MUNICIPAL RESEARCH AND SERVICES CENTER OF WASHINGTON (MSRC) (1992) Affordable Housing Techniques A Primer for Local Government Officials. IN

MSRC - MUNICIPAL RESEARCH AND SERVICES CENTER OF WASHINGTON (Ed.), MSRC.

MULLENS, M. A., ARMACOST, R. L. & SWART, W. W. (1995) The role of object oriented CAD in a generic simulator for the industrialized housing industry. Automation in Construction, 4, 29.

NAEI (1999) UK Emissions of Air Pollutants 1970 to 1999 National Atmospheric Emissions Inventory.

NAIM, M. (2001) Innovation in standardised component systems in housing. Cardiff, Cardiff University.

NATIONAL ATMOSPHERIC EMISSIONS INVENTORY (NAEI) (2007) The UK Emissions Factor Database.

NEALE, R. H. E. A. (1993) Prefabricated Modules in Construction. Berkshire, The Chartered Institute of Building.

NEWTON J & VENABLES R (1995) Environmental Impact of building and construction materials - Volume E: Timber and timber products. London, Construction Industry Research and Information Association.

NICHOLSON, G. (1989) UK housing policy: transferring the burden. Land Use Policy, 6, 277.

NOURY, N., VIRONE, G., YE, J., RIALLE, V. & DEMONGEOT, J. (2003) Nouvelles directions en habitats intelligents pour la sante: New trends in smart homes. ITBM-RBM, 24, 122.

NOWAK, F. & HARLING, K. (1996) Evolution of Construction Process Research. Watford, BRE.

NYMAN, M. & SIMONSON, C. J. (2005) Life cycle assessment of residential ventilation units in a cold climate. Building and Environment, 40, 15.

ODPM (unknown) Planning and affordable housing. IN ODPM (Ed.).

Office of the Deputy Prime Minister (now the Department for Communities and Local Government). The Building Regulations for England and Wales, Approved Document L1A: Conservation of fuel and power (New dwellings) (2006 edition). London, DCLG, 2006. Also available fromwww.communities.gov.uk

O'NEILL, B. (1998) Good Practice for small builders. Building Research Establishment, BRE.

OPTIMA HOMES (2005) Optima House Type A4. IN AA_GIA_A4 (Ed.) http://www.optimahomes.co.uk/pdf/AA_GIA_A4.pdf Milton Keynes, Pace Timber Systems and Cartwright Pickard Architects.

ORAL, E. L., MISTIKOGLU, G. & ERDIS, E. (2003) JIT in developing countries--a case study of the Turkish prefabrication sector. Building and Environment, 38, 853.

OTTMAR, B., PATTANTYUS, A. A. & PETRO, B. (1970) Panel joints, prefabrication and placing tolerances. Building Science, 4, 229.

OZELTON EC & BAIRD JA (2006) Timber Designers' Manual, Blackwells Publishing.

PALMER PARTNERSHIP, T. (2000) A sustainable development centre (Cethus Centre) for the housing market.

PALMER S (2000) Timber Frame Housing, Sustainable HomesPALMGREN M (2005) Optimal Truck Scheduling – Mathematical Modeling and Solution by the Column Generation Principle, Division of Optimization, Department of Mathematics. Linkoping, Linkoping Universitet.

PASQUIRE, C. & GIBB, A. G. F. (1999) COMPREST: cost model for pre-assembly and standardisation in construction. Loughborough, Loughborough University.

PASQUIRE, C. & GIBB, A. G. F. (2003) IMMPREST: interactive model for measuring pre-assembly and standardisation benefit across the supply chain. Loughborough, Loughborough university.

PEARCE, J. M., JOHNSON, S. J. & GRANT, G. B. 3D-mapping optimization of embodied energy of transportation. Resources, Conservation and Recycling, In Press, Corrected Proof.

PHILLIPSON, M. (2003) DTI Construction Industry Directorate Project Report: Current Practice and Potential Uses of Prefabrication. Watford, BRE, Building Research Establishment.

PITTS, G. (2000) Factory pre-fabrication and construction: demonstration project. TRADA.

PITTS, G. (2000) Re-engineering timber frame affordable house construction: demonstration project. TRADA.

PLATO, N., KRANTZ, S., ANDERSSON, L., GUSTAVSSON, P. & LUNDGREN, L. (1995) Characterization of current exposure to man-made vitreous fibres (MMVF) in the prefabricated house industry in Sweden. The Annuals of Occupational Hygiene, 39, 167.

PORTER B & TOOKE C (2006) Carpentry and Joinery, Butterworth-Heinemann Ltd.

PRESS ASSOCIATION (2003) Land shortage fuelling house price rises, warns Treasury. The Guardian.

REBITZER, G., EKVALL, T., FRISCHKNECHT, R., HUNKELER, D., NORRIS, G., RYDBERG, T., SCHMIDT, W. P., SUH, S., WEIDEMA, B. P. & PENNINGTON, D. W. (2004) Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment International, 30, 701.

RICHARD, R.-B. Industrialised building systems: reproduction before automation and robotics. Automation in Construction, In Press, Corrected Proof.

RICHARD, R.-B. (2005) Industrialised building systems: reproduction before automation and robotics. Automation in Construction, 14, 442.

RIHANI, R. A. & BERNOLD, L. E. (1996) Methods of control for robotic brick masonry. Automation in Construction, 4, 281.

ROSS K, HONOUR J & K, N. (2004) An audit of UK social housing innovation. IN FBE (Ed.) FBE Report 7. Building Research Establishment, BRE.

SALVADOR S (2006) Information about Chain of Custody. IN HARDI, J. (Ed.) Bonn, FSC International Center.

SAMUELSSON BROWN G, PARRY T & C, H. (2003) Off Site Fabrication - UK Attitudes and Potential. BSRIA.

SANGER, D. (2007) Timber Ship in Goteborg Harbor. Alamy.

SARJA, A. (1998) Open industrialisation in building. Netherlands, CIB General Secretariat.

SCHARAI RAD M & WELLING J (1999) Biomass for Greenhouse Gas Emission Reduction - Sawn Timber and Wood Based Products as Building Materials. Hamburg, Institut für Holzphysik und mechanische Technologie.

SCHWEINLE, J (1996) Analyse und Bewertung der forstlichen Produktion als Grundlage für weiterführende forst- und holzwirtschaftliche Produktlinien – Analysen [Analysis and evaluation of forest production as a base for forest products]. Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft. Nr. 184, September 1996. Kommissionsverlag Buchhandlung Max Wiedebusch, Hamburg.

SEEDA (2001) The Regional Economic Strategy for South East England 2002-2012. London, South East England Development Agency.

SHEN, G. (2004) Location of manufactured housing and its accessibility to community services: a GIS-assisted spatial analysis. Socio-Economic Planning Sciences, In Press, Corrected Proof.

SMITH, D. C. (2003) Sustainable building: Building green. Refocus, 4, 62.

SMITH, M. (1999) Prefabrication and pre-assembly - applying the techniques to building engineering services. Berkshire, Building Services Research and Information Association (BSRIA).

SMITH R A, KERSEY J R & GRIFFITHS P J (2002) The Construction Industry Mass Balance: resource use, wastes and emissions. Viridis.

SMITH, R. R. (2004) Time is the essence for future of design. Building Design.

SPANGENBERG J H, FEMIA A, HITNERBERGER F & SCHUTZ H (1998) Material flow based indicators in Environmental Reporting. Environmental Issues Series. Luxembourg, European Environment Agency.

STALLEN, M., CHABANNES, Y. & STEINBERG, F. (1994) Potentials of prefabrication for self-help and mutual-aid housing in developing countries. Habitat International, 18, 13.

STEELE, A. & TODD, S. (2004) New developments for key worker housing in the UK. Structural survey, 22, pp.179-189.

SUSTAINABILITY WORKING GROUP REPORT (2001) Environmental Performance Indicators for Sustainable Construction". Movement for Innovation.

SWAMINATHAN, M. S. (2003) Bio-diversity: an effective safety net against environmental pollution. Environmental Pollution, 126, 287.

SWEDISH FOREST AGENCY (2000) Swedish Statistical Yearbook of Forestry, Jonkoping, Bokhandeln.

SWEDISH FOREST AGENCY (2006) Swedish Statistical Yearbook of Forestry, Jonkoping, Bokhandeln.

TARVAINEN V (2005) Measures for improving quality and shape stability of sawn softwood timber during drying and under service conditions - Best Practice Manual to improve straightness of sawn timber. Helsinki, VTT Technical Research Centre of Finland,.

TASDEMIROGLU, E., CHANDRA, S. & MOALLA, S. (1991) Savings from energy-efficient industrialized housing for the U.S. Energy, 16, 1119.

TATUM, C. (1987) Constructibility improvement using prefabrication, pre-assembly and modularisation. Texas, Construction Industry Institute, The University of Texas at Austin.

The European Council for Construction Research Development and Innovation (2000) http://ec.europa.eu/research/growth/gcc/projects/in-action-construct.html. European Commission.

THE HOUSING CORPORATION (2000) Sustainable Homes: Timber Frame Housing. Middlesex, Hastoe Housing Association.

THE OBSERVER (2003) Building booms. But where are the houses? The Guardian.

THUNELL B (1955) Sawmilling in Sweden. Unasylva, 9.

TIMBER TRADE FEDERATION (TTF) (2007) The UK Timber Industry Statistical Review 2007, access at 3rd February 2009, available at http://www.ttf.co.uk/industry/statistics/The_Timber_Industry_2007.pdf

TRADA (2005) Wood used in Construction: The UK Mass Balance and Efficiency of Use. Buckinghamshire, TRADA.

TRANSPORT RESEARCH LABORATORY (2007) Reducing the Environmental Impact of Transport. Berkshire, TRL.

Treloar, G.J. (1998) A comprehensive embodied energy analysis framework, Ph. D. thesis, Deakin University, Australia.

VEDRICKAS, G. (2002) Here's the lighter house. The independent - Online Edition.

VTT (2002) Unit emission. VTT.

WALKER, D. (2003) Plea for more public housing. The Guardian.

WEAVER, M. (2003) Affordable Housing. The Guardian.

WEAVER, M. (2003) Budget aims to boost house building. The Guardian.

WEAVER, M. (2004) Housebuilding plans need 'radical improvement'. Guardian Limited.

WEAVER, M. (2004) Poll shows conditional support for more housing. Guardian unlimited.

WEAVER, M. & HETHERINGTON, P. (2004) Millions wasted on homes no one wants. Guardian unlimited.

WWF (2003) One Planet Living in the Thames Gateway, World Wildlife Fund, UK, p.11

WEST J, ATKINSON C & HOWARD N (1994) Embodied Energy and Carbon Dioxide Emissions for Building Materials. CIB Conference: Buildings and the Environment. Watford, Building Research Establishment.

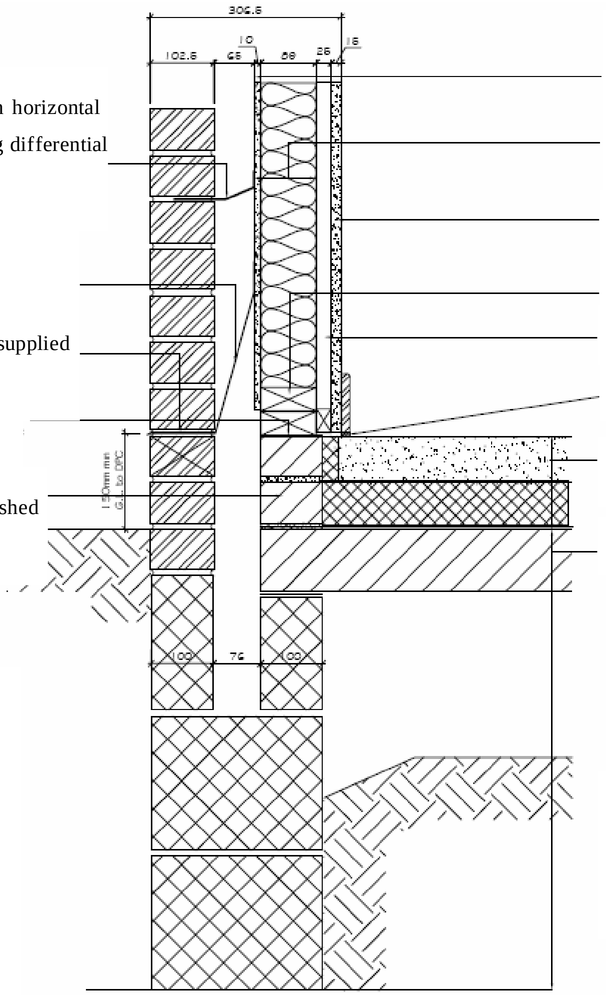
WHITE, R. B. (1965) Prefabrication A history of its development in Great Britain. IN STUDIES, N. B. (Ed.) Special Report 36. London, Building Research.

WHITEHEAD, C. M. E. & CROSS, D. T. (1991) Affordable housing in London. Progress in Planning, 36, 1.

YORKSHIRE AND HUMBLER ASSEMBLY (2004) Freight and logistics intelligence for the Regional Transport Strategy - A Regional Freight Strategy for Yorkshire and Humber. Yorkshire, Yorkshire Forward.

YRJOLA T (2002) Forest Management Guidelines and Practices in Finland, Sweden and Norway. IN PAIVINEN (Ed.) Joensuu, European Forest Institute.

APPENDIX A. TYPICAL EXTERNAL WALL CONSTRUCTION DETAILS FOR PREFABRICATED TIMBER FRAME HOUSE CONSTRUCTION



APPENDIX B. PRIMARY DATA COLLECTION

Appendix B1 Questionnaire design

1. Name of Company

____

____

2. Location of Company

____

____

____

3. Size of Company

____

4. Location of factories (if it is on different location to the head office)

____

____

____

____

____

____

____

5. Type of timber frame prefabrication provided

   (please circled as appropriate)

   a. (panelling) (Yes/No)

   b. (post and beam) (Yes/No)

   c. (modular) (Yes/No)

6. Type of timber used (please circle as appropriate)
    a. Softwood (Yes/No)
    b. Hardwood (Yes/No)
    c. Timber Species ____
    d. Technical Specification if applicable

    (i.e. CLS 140mm x 38mm for external wall studs)

    ____

    ____

7. Type of foundation used for the particular dwellings constructed (choose as appropriate)
    a. For Apartments
        i. Prefabricated Foundation Systems with the use of precast concrete piles (Yes/No)
        ii. Strip Foundations (Yes/No)
        iii. Pad Foundations (Yes/No)
        iv. Raft Foundations (Yes/No)
        v. Pile Foundations (Yes/No)
    b. For bungalows
        i. Prefabricated Foundation Systems with the use of precast concrete piles (Yes/No)
        ii. Strip Foundations (Yes/No)
        iii. Pad Foundations (Yes/No)
        iv. Raft Foundations (Yes/No)
        v. Pile Foundations (Yes/No)

8. Amount of house/apartment unit per production

(i.e equivalent to 3-5 manufacturing days per house or 1-2 manufacturing day per apartment unit)

____
____
____
____

9. Amount of timber used per production (m^3) (estimated)

a. Between ________(m^3) to ________m^3 per house

b. Between ________(m^3) to __________m^3 per apartment

10. Where does the timber being harvested from

a. If it's from another country, please state the country and the town name

____
____
____

b. If it's from the UK, please state the location

____
____
____

11. Processes undergone from acquiring the raw timber material into structures ready for manufacturing and produced as the final product

    a. From the forest to sawmilling

    ____

    ____

    ____

    b. From the sawmilling to factory(ies)

    ____

    ____

    ____

    c. In the factory(ies) to produce final product

    (i.e. cross cut to length, cut ends treated with preservative, etc)

    ____

    ____

    ____

    ____

12. Location for each process stages

    a. From the forest to sawmilling

    ____

    ____

    ____

    b. From the sawmilling to factory(ies)

    ____

    ____

    ____

c. In the factory(ies) to produce final product

(i.e. cross cut to length, cut ends treated with preservative, etc)

____

____

____

____

13. Routes, types of transport and average load of transportation used for each process stages

    a. Routes taken from timber sawmilling to factory(ies) and to the site assembly point

____

____

____

____

____

____

    b. Types of transportation used from timber sawmilling to factory(ies) and to the site assembly point

        i. Light Good Vehicles (Yes/No)

        ii. Rigid HGVs (Yes/No)

        iii. Articulated HGVs (Yes/No)

    c. Transport load for each process stages

____

____

14. Please state (if there is any) whether your company have a policy of only dealing with local client or whether there is any distance limitation on project you have received from clients

____

____

____

____

____

____

Appendix B2 List of the Participating Manufacturers

Space 4

Guildford Timber Frame

Acacia Timber

Thomas Mitchell Homes Ltd

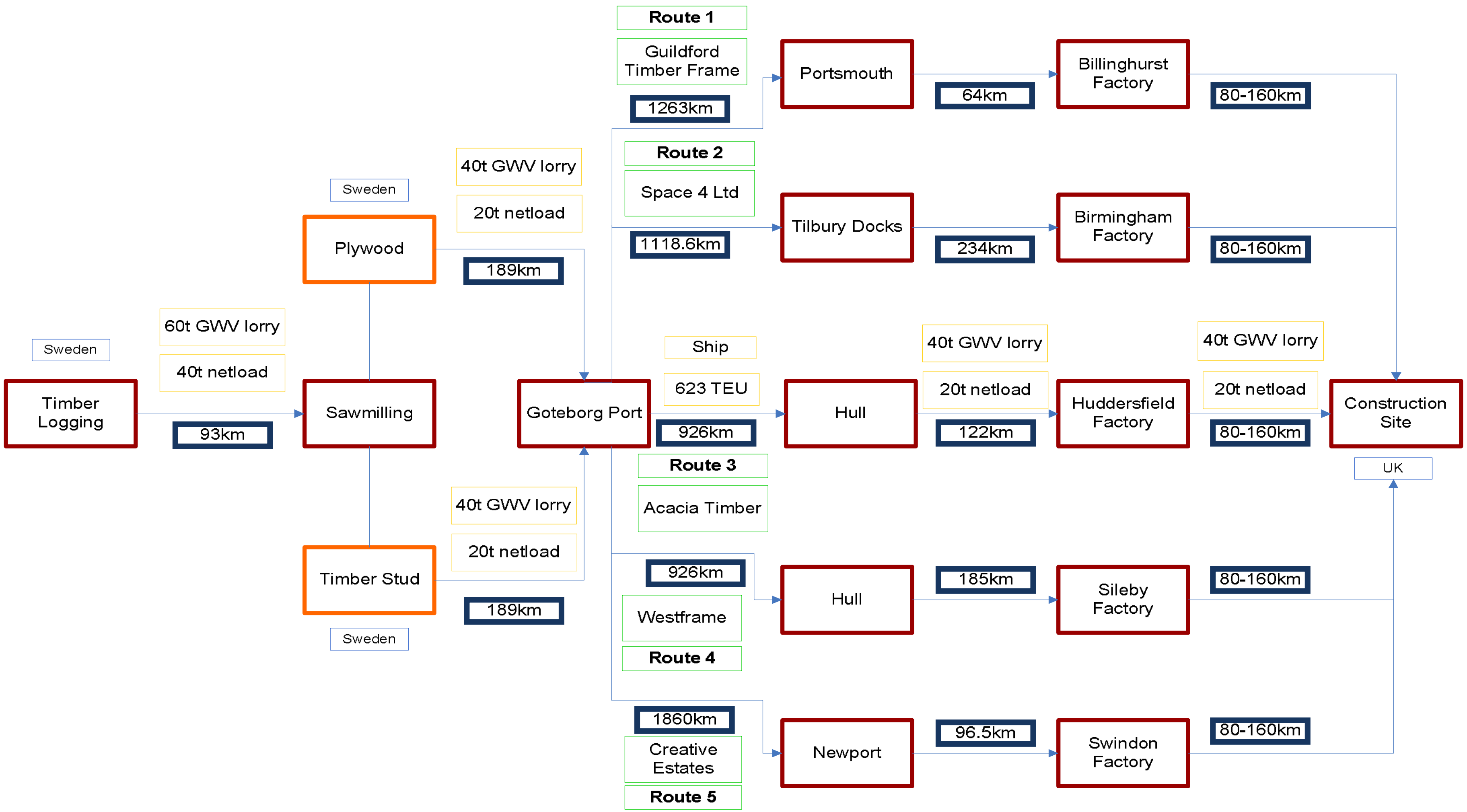
Timber Development Ltd

Westframe

Creative Estates

Custom Homes

Appendix B3 Distances on each stages of the transportation flow from the forest to site gate.



APPENDIX C. THE QUANTIFICATION METHODOLOGY FOR MATERIAL FLOW ANALYSIS

Appendix C1.0 - Definition

Log = lg

Panel = P

Plywood = ply

Studs = S

S24 = 89 x 38 x 2400 studs

S36 = 89 x 38 x 3600 studs

S60 = 89 x 38 x 6000 studs

1 panel = p = 7(S24) + 2 (S36) + 3 (ply)

ρ of plywood conifer sheet with thick veneer = 460kg/m^3

ρ of stud = 450kg/m^3

For a 12mm thickness plywood sheet, weight/area ratio = 5.5kg/m^2

weight	s24	3.65256	kg
	s36	5.47884	kg
	ply	0.1584	kg
	1panel	37.0008	kg
		0.037001	tonne

m^3 f pb = m3 solid volume including bark

m^3 f ub = m3 solid volume excluding bark

1m^3 f pb = 0.88m^3 f ub

1m^3 of sawnwood = 2.1m^3 f ub

1m^3 of plywood = 2.5m^3 f ub

Appendix C1.1 – Plywood

Plywood, also known as an engineered wood, is defined as a type of engineered wood made from thin sheets of wood veneer, called plies or veneers. The layers are glued together, each with its grain at right angles to adjacent layers for greater strength. There are usually an odd number of plies, as the symmetry makes the board less prone to warping. The grain on the outside surfaces runs in the same direction and the plies are bonded under heat and pressure with strong adhesives such as phenol formaldehyde resin, making plywood a type of composite material.

The outer layers of plywood are known respectively as the face and the back. The face is the surface that is to be used or seen, while the back remains unused or hidden. The centre layer is known as the core. In plywood with five or more plies, the inter-mediate layers are known as the crossbands. The weight of plywood panel is influenced by two main factors – the panel compression during the manufacturing process and the wood species. Due to variation between brands, the weight of plywood is not constantly proportional to thickness. Table 4 below shows the general amount of plies required for particular nominal plywood thickness necessitated.

Table 4.4 Number of plies per required plywood thicknesses and its weight/m^2 (TRADA, 2007)

Thickness (mm)	Number of plies	Weight/m^2
9	3	
12	4	5.5
15	5	6.9
18	6	8.3
21	7	9.7
24	8	11.0
27	9	12.4
30	10	13.8

Typical weights taken from Finnforest database (shown on Table 4.5) are divided into four different categories:

- Birch: which consists of birch veneer throughout the construction
- Combi: two birch veneers on each face and alternate inner veneers of conifer and birch
- Combi mirror: one birch veneer on each face and alternate inner veneers of conifer and birch
- Conifer: Conifer veneers throughout the construction. Face veneers of spruce or occasionally pine.

Table 4.5 Weight (kg/m2) of various sheet of plywood

Plywood	Birch		Combi, Combi Mirror		Conifer (thin veneers)		Conifer (thick veneers)	
Face	Birch		Birch		Conifer		Conifer	
Core	Birch		Birch and conifer		Conifer		Conifer	
Nominal thicknesses (mm)	No. of plies	Weight kg/m^2	No. of plies	Weight kg/m^2	No. of plies	Weight kg/m^2	No. of plies	Weight kg/m^2
6.5	5	4.4	5	4.0	5	3.4		
9	7	6.1	7	5.6	7	4.7	3	4.1
12	9	8.2	9	7.4	9	6.2	5/4	5.5

Lighter panel is always opted first. For the builder, a lighter panel means an easier handling requirement and installation. For the distributor, the heavier product will cost more to ship hence the lighter it is, the cheaper it will be.

Plywood weight is dependent highly on the type of wood used as its raw material[*]. The nominal thickness of birch and conifer veneer is 1.4mm and thick conifers veneers range from 2.0-3.2 mm thickness.

One example is spruce plywood production based on Finnforest products, constructed from 3mm thick structural veneer thickness, which will have different amount of plywood needed depending on the required nominal thicknesses, ways in which it was packaged for the distribution and the required panel sizes. Table 4.5 below shows the variety of plies needed per required plywood thicknesses and its weight per m^2.

[*] Density of Birch 680kg/m^3, combi 620kg/m^3, conifer (thin veneers) 520 kg/m^3 and conifer (thick veneer) 460kg/m^3.

Appendix C2.0 – Material quantification methodology from the forest to site

Appendix C2.1 - Material quantification from forest to sawmills

Assuming that maximum allowable net load per 60 tonne lorry = 40 tonne = 40,000kg

And if ρ of spruce = 450kg/m^3

Total volume of logs per 60 tonne lorry

$$= \frac{netload}{r}$$

$$= \frac{40{,}000\boldsymbol{kg}}{450\boldsymbol{kg}/\boldsymbol{m}^3}$$

= 88.9m^3 f pb

Due to de-barking in sawmill the total volume of logs per 60tonne lorry will be converted onto an equivalent volume of logs excluding the barks.

= total volume of logs per 60 tonne lorry un-barked x 0.88

= 88.9 x 0.88

= 78.2 m^3 f ub

<u>STUDS</u>

If volume of S60

= 0.089 x 0.038 x 6

= 0.02m^3

Amount of barked logs that a S60 will require

= 0.02 m^3 x 2.1 m^3 f ub

= $0.042m^3$ f ub

Therefore, the quantity of S60 if fully loaded onto a 60 tonne lorry

$$= \frac{78.2}{0.042}$$

= <u>1861</u> number of S60

<u>PLYWOOD</u>

If weight/area ratio of a 12mm thickness plywood sheet = $5.5kg/m^2$

The weight of 12mm thickness plywood sheet

= 5.5 x 12.2 x 2.4

= 16.1kg

If volume of the plywood sheet

= 12.2 x 2.4 x 0.01

= $0.288m^3$,

The amount of barked logs that the sheet of plywood requires

= 0.288 x 2.5

= 0.72 m3f ub

The quantity of plywood sheet able to be transported per 60 tonne lorry

$$= \frac{78.2}{0.72}$$

= <u>108</u> plywood sheet

Appendix C2.2 – Material quantification from Sawmills to Goteborg Port and from nearest UK port to Factory

This research has used an assumption that S60s and plywood sheets were transported from the sawn wood and plywood sawmill to Goteborg Port and from the nearest UK port to the factory in a 40feet containers (also known as FEU container) and on a 40 tonne GWV lorry.

The size and dimension of the FEU used in this research were based on the Hapag Lloyd's 40ft FEU standard container (Hapag Lloyd, 2006) as seen below:

Figure C1.0 40' (FEU) Standard Container from Hapag-Lloyd

General		Millimeters	Feet
Internal	Length	12032	39' 5 5/8"
	Width	2352	7' 8 5/8"
	Height	2395	7' 10 1/4"
Door Opening	Width	2340	7' 8 1/8"
	Height	2292	7' 6 1/4"
		Kilograms	Pounds
Weight	Max Gross	32500	71650
	Tare	3980	8774
	Max Payload	28520	62875
		Cube Meters	Cube Feet
Capacity		67.7	2390

Table C1.0 General details of the FEU standard container from Hapag Lloyd

STUDS

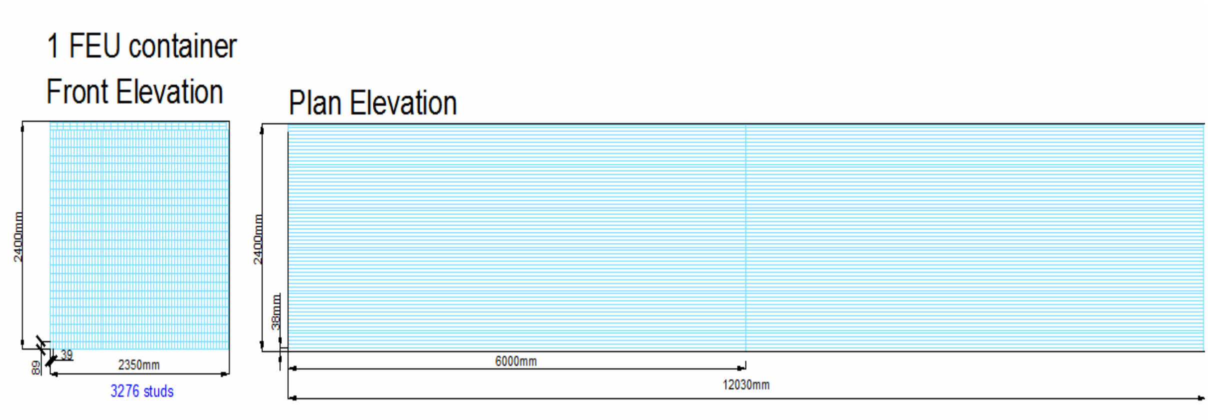


Figure C1.1 Estimating the quantity of S60 studs in an FEU container

Based on the Hapag Lloyd FEU standard container and with the use of rough estimation as seen earlier in Figure 4.8, an estimated of **3276 number of S60** can be carried per FEU container from the sawn wood sawmill to the Goteborg port.

If 1FEU 3276 number of S60 studs,

Wood density = 450kg/m3,

Weight per S60 = 450 x (0.038 x 0.089 x 6) = 9kg

Weight per FEU = 3276 x 9 = 29,812kg = 29.8 tonne **(≈30 tonne)**

PLYWOOD

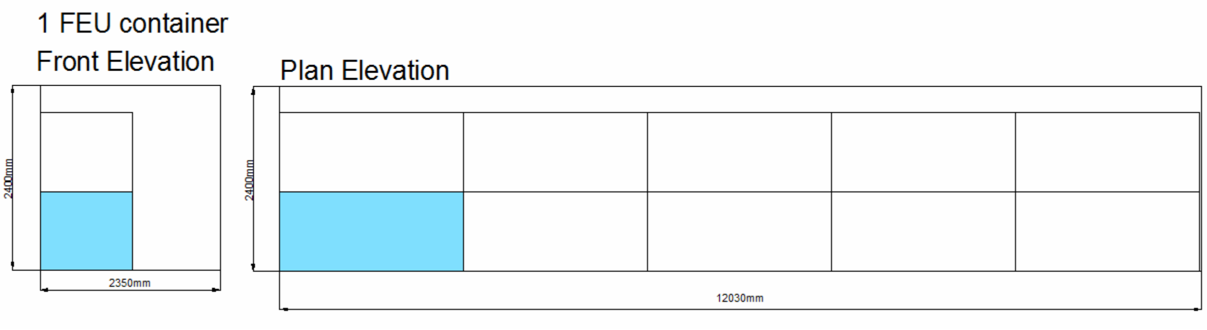


Figure C1.2 Estimating the quantity of plywood sheet in an FEU container

If each veneer assumed to be 3mm thick and each plywood thickness is 12mm, the number of veneer per 12mm thickness plywood will be 4.

Assuming that there are 85 number of 12mm plywood sheet per packaging and 10 packaging per FEU container, there is a possible of 850 number of 12mm thick plywood sheets on every FEU container being carried from the plywood sawmill to the Goteborg Port.

If 1 FEU = 850 number of 12mm plywood sheets,

And if weight per 1220 x 2400mm plywood sheet = 5.5kg/m2 x 2.4 x 1.2 = 16kg

Weight per FEU = 860 x 16 = 13,600kg = 13.6 tonne **(≈14 tonne)**

Appendix C2.3 – Material quantification from Goteborg port to a designated UK port

During shipping, a common measure of freight volume is TEU[†] which is the volume occupied by one ISO twenty foot container. Therefore 1 FEU = 2 TEUs.

This research has established the quantity of S60 and plywood sheets based on the assumption that a medium size container ship with net load of 1226TEU, as seen on Figure C1.0 below, was used to transport these timber materials from the Goteborg Port to the nearest UK port. The containerised ship has a maximum net load of 6720tonne and was assumed to be fully loaded and travelling at 18.5 knots.

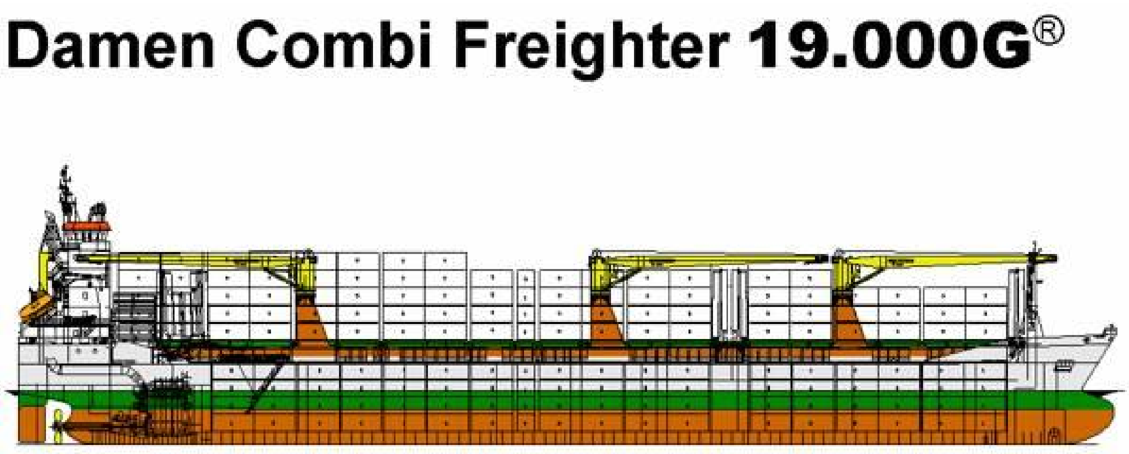


Figure C1.3 1226 TEU containerised ship

(taken from http://www.student-techniek.nl/bedrijven/damen_down.html, access date 21st March 2007)

Assuming that the ship is fully loaded and 25% of the load was allocated to transport S60 studs and another 25% of the load was assigned to transport 12mm plywood sheets, the number of FEUS containers holding S60 and 12mm plywood sheets are as follow:

[†] TEU is defined as volume equivalent to that occupied by one ISO twenty foot container.

Total loading weight of ship = 25% weight allocated for S60s + 25% weight allocated for 12mm plywood sheets + 50% weight allocated for others.

Assuming that ship is fully loaded,

6720tonne = 25% weight for S60s + 25% weight for 12mm plywood sheets + 50% for others

3360 tonne = x (S60) + y (Ply)

If x= number of FEU containers containing S60 and if 1 FEU container = 30 tonne,

Number of S60 FEU container = 1680/30 = **56 FEUs**

If y = number of FEU containers containing Ply and if 1 FEU container = 14 tonne,

Number of FEU container containing 12mm plywood sheets = 1680/14 =**120 FEUs**

APPENDIX D. THE QUANTIFICATION OF EMBODIED TRANSPORT ENERGY PER PANEL

Appendix D1.0 – Published data used in the embodied transport energy quantification

abbreviations	description	value	unit
Road Transport			
d	distance	vary	km
ρ of diesel fuel	density	0.831	kg/litre
c	calorific value	43.4	GJ/tonne
		0.0434	GJ/kg
Maritime Transport			
Fe	fuel efficiency	0.12	MJ/tonne km
		0.00012	GJ/ tonne km
	Full net load of ship	6720	tonne

Fuel consumption (FC)	**(Volvo 2006)**	Range of Fuel Consumption				
Type of vehicles	Loading Type		(litre/100km)	Average (litre/100km)	(litre/km)	Return Factor
60 tonne GWV arctic	Full Load	43	53	48	0.48	1.67
	Empty Load	29	35	32 l	0.32	
40 tonne GWV arctic	Full Load	29	35	32	0.32	1.73
	Empty Load	21	26	23.5	0.235	

Assuming that,

1 house = 24 panels

Maximum loading capacity per lorry from factory to site = 6 houses (an equivalent to 144 panels)

Te per stage (MJ/panel)= 7(*Te S24*) + **2**(*TeS36*) + **3**(*Te plywood sheet*)

Where,

Te S24 = 40% (Te S60)

Te S36 = 60% (Te S60)

Te S60 = total embodied transport energy per S60 calculated from forest to site stage.

Appendix D2.0 – Total embodied energy per panel based on fully loaded means of transport from forest to assembly factories

Based on average distance

				Amount of materials equivalent to (per vehicle)			Transport Energy (GJ)												
Stages	Means of Transport	d (km)	cum d (km)	S60 studs	Plywd	Panel	Full load	Per S60 studs	Per S24 studs	Per S36 studs	Per ply	Per Panel	Cum TE for 1 panel	Cum TE for 1house	Cum TE for 2 house	Cum TE for 3 house	Cum TE for 4 house	Cum TE for 5 house	Cum TE for 6 house
Forestry to Sawmill	60tonne GWV lorries	93	93	1861	108		2.718	0.00146	0.00058	0.00088	0.02516	0.0813	0.08133	0.08133	0.08133	0.08133	0.08133	0.08133	0.08133
Sawmill to Port A	40 tonne GWV lorries	189	282	3276	850		3.837	0.00117	0.00047	0.00070	0.00451	0.0182	0.09956	0.09956	0.09956	0.09956	0.09956	0.09956	0.09956
Port A to Port B	1226 TEU vessel	1393	1675	366912	204000		561.658	0.00153	0.00061	0.00092	0.00275	0.0144	0.11394	0.11394	0.11394	0.11394	0.11394	0.11394	0.11394
Port B to assembly factory	40 tonne GWV lorries	149	1824	3276	850		3.025	0.00092	0.00037	0.00055	0.00356	0.0144	0.12831	0.12831	0.12831	0.12831	0.12831	0.12831	0.12831
Assembly factory to site	40 tonne GWV lorries	120	1944			1	2.436					2.4363	2.5646	0.2298	0.1791	0.1622	0.1537	0.1486	0.1452
for 1 house						24	2.436					0.1015							
for 2 houses						48	2.436					0.0508							
for 3 houses						72	2.436					0.0338							
for 4 houses						96	2.436					0.0254							
for 5 houses						120	2.436					0.0203							
for 6 houses						144	2.436					0.0169							

Based on the shortest available distance

				Amount of materials equivalent to (per vehicle)			Transport Energy (GJ)											
Stages	Means of Transport	distance (km)	cum distance (km)	S60 studs	Plywood	Panel	Full load	Per S60 studs	Per S24 studs	Per S36 studs	Per plywood	Per Panel	Cum TE for 1 panel	Cum TE for 1house	Cum TE for 2 house	Cum TE for 3 house	Cum TE for 4 house	Cum TE for 5 house	Cum TE for 6 house
Forestry to Sawmill	60tonne GWV lorries	93	93	1861	108		2.718	0.0015	0.0006	0.0009	0.0252	0.0813	0.0813	0.0813	0.0813	0.0813	0.0813	0.0813	0.0813
Sawmill to Port A	40 tonne GWV lorries	189	282	3276	850		3.837	0.0012	0.0005	0.0007	0.0045	0.0182	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996
Port A to Port B	1226 TEU vessel	926	1208	366912	204000		373.363	0.0010	0.0004	0.0006	0.0018	0.0096	0.1091	0.1091	0.1091	0.1091	0.1091	0.1091	0.1091
Port B to assembly factory	40 tonne GWV lorries	64	1272	3276	850		1.299	0.0004	0.0002	0.0002	0.0015	0.0062	0.1153	0.1153	0.1153	0.1153	0.1153	0.1153	0.1153
Assembly factory to site	40 tonne GWV lorries	80	1352			1	1.624					1.6242	1.7395	0.1830	0.1491	0.1378	0.1322	0.1288	0.1266
for 1 house						24	1.624					0.0677							
for 2 house						48	1.624					0.0338							
for 3 house						72	1.624					0.0226							
for 4 house						96	1.624					0.0169							
for 5 house						120	1.624					0.0135							
for 6 house						144	1.624					0.0113							

Based on the longest available distance

				Amount of materials equivalent to (per vehicle)			Transport Energy (GJ)											
Stages	Means of Transport	distance (km)	cum distance (km)	S60 studs	Plywood	Panel	Full load	Per S60 studs	Per S24 studs	Per S36 studs	Per plywood	Per Panel	Cum TE for 1 panel	Cum TE for 1house	Cum TE for 2 house	Cum TE for 3 house	Cum TE for 4 house	Cum TE for 5 house	Cum TE for 6 house
Forestry to Sawmill	60tonne GWV lorries	93	93	**1861**	**108**		**2.717557315**	0.0015	0.0006	0.0009	0.0252	0.0813	0.0813	0.0813	0.0813	0.0813	0.0813	0.0813	0.0813
Sawmill to Port A	40 tonne GWV lorries	189	282	3276	850		3.837	0.0012	0.0005	0.0007	0.0045	0.0182	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996
Port A to Port B	1226 TEU vessel	1860	2142	366912	204000		749.952	0.0020	0.0008	0.0012	0.0037	0.0192	0.1188	0.1188	0.1188	0.1188	0.1188	0.1188	0.1188
Port B to assembly factory	40 tonne GWV lorries	234	2376	3276	850		4.751	0.0015	0.0006	0.0009	0.0056	0.0226	0.1413	0.1413	0.1413	0.1413	0.1413	0.1413	0.1413
Assembly factory to site	40 tonne GWV lorries	160	2536			1	3.248					3.2483	3.3897	0.2767	0.2090	0.1864	0.1752	0.1684	0.1639
for 1 house						24	3.248					0.1353							
for 2 house						48	3.248					0.0677							
for 3 house						72	3.248					0.0451							
for 4 house						96	3.248					0.0338							
for 5 house						120	1.624					0.0271							
for 6 house						144	1.624					0.0226							

Appendix D3.0 – Total embodied energy per panel with loading from forest to site dependent on "made to order" scenarios

BASED ON AVERAGE DISTANCE

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for required vehicles (GJ)			Te					Cum Te
For 1 house	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		168	72		1	1		2.718	5.435		0.01618	0.00647	0.00971	0.07549	0.29117	0.2912
Sawmill to port A	189	282	3276	850		3.837	3.837		168	72		1	1		3.837	3.837		0.02284	0.00914	0.01370	0.05329	0.25124	0.5424
Port A to Port B	1393	1675	366912	204000		1123.315			168	72		1			0.253	0.193		0.00150	0.00060	0.00090	0.00267	0.01404	0.5564
Port B to Factory	149	1824	3276	850		3.025	3.025		168	72		1	1		3.025	3.025		0.01801	0.00720	0.01080	0.04201	0.19807	0.7545
Factory to Site	120	1944			156			1.915			24			1			1.915					0.07980	**0.8343**

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for required vehicles (GJ)			Te					Cum Te
For 5 house	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		840	360		1	4		2.718	10.870		0.00324	0.00129	0.00194	0.03020	0.10353	0.1035
Sawmill to port A	189	282	3276	850		3.837	3.837		840	360		1	1		3.837	3.837		0.00457	0.00183	0.00274	0.01066	0.05025	0.1538
Port A to Port B	1393	1675	366912	204000		1123.315			840	360		1			1.264	0.963		0.00150	0.00060	0.00090	0.00267	0.01404	0.1678
Port B to Factory	149	1824	3276	850		3.025	3.025		840	360		1	1		3.025	3.025		0.00360	0.00144	0.00216	0.00840	0.03961	0.2074
Factory to Site	120	1944			156			1.915			120			1			1.915					0.01596	**0.2234**

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for required lorry			Te					Cum Te
For 10 houses	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		1680	720		1	7		2.718	19.023		0.00162	0.00065	0.00097	0.02642	0.08573	0.0857
Sawmill to port A	189	282	3276	850		3.837	3.837		1680	720		1	1		3.837	3.837		0.00228	0.00091	0.00137	0.00533	0.02512	0.1109
Port A to Port B	1393	1675	366912	204000		1123.315			1680	720		1			2.527	1.926		0.00150	0.00060	0.00090	0.00267	0.01404	0.1249
Port B to Factory	149	1824	3276	850		3.025	3.025		1680	720		1	1		3.025	3.025		0.00180	0.00072	0.00108	0.00420	0.01981	0.1447
Factory to Site	120	1944			156			1.915			240			2			3.830					0.01596	**0.1607**

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load			Amount of material transported			Number of vehicles needed			Te for required lorry			Te					Cum Te
For 50 houses	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		8400	3600		5	34		13.588	92.397		0.00162	0.00065	0.00097	0.02567	0.08347	0.0835
Sawmill to port A	189	282	3276	850		3.837	3.837		8400	3600		3	5		11.511	19.186		0.00137	0.00055	0.00082	0.00533	0.02147	0.1049
Port A to Port B	1393	1675	366912	204000		1123.315			8400	3600		1			12.637	9.628		0.00150	0.00060	0.00090	0.00267	0.01404	0.1190
Port B to Factory	149	1824	3276	850		3.025	3.025		8400	3600		3	5		9.075	15.125		0.00108	0.00043	0.00065	0.00420	0.01693	0.1359
Factory to Site	120	1944			156			1.915			1200			10			19.152					0.01596	**0.1519**

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load			Amount of material transported			Number of vehicles needed			Te for required lorry			Te					Cum Te
For 100 houses	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		16800	7200		10	67		27.176	182.076		0.00162	0.00065	0.00097	0.02529	0.08234	0.0823
Sawmill to port A	189	282	3276	850		3.837	3.837		16800	7200		6	9		23.023	34.534		0.00137	0.00055	0.00082	0.00480	0.01987	0.1022
Port A to Port B	1393	1675	366912	204000		1123.315			16800	7200		1			25.275	19.257		0.00150	0.00060	0.00090	0.00267	0.01404	0.1162
Port B to Factory	149	1824	3276	850		3.025	3.025		16800	7200		6	9		18.150	27.225		0.00108	0.00043	0.00065	0.00378	0.01567	0.1319
Factory to Site	120	1944			156			1.915			2400			20			38.304					0.01596	**0.1479**

BASED ON SHORTEST DISTANCE

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for full load vehicles (GJ)			Te					Cum Te
For 1 house	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		168	72		1	1		2.718	2.718		0.01618	0.00647	0.00971	0.03774	0.17794	0.1779
Sawmill to port A	189	282	3276	850		3.837	3.837		168	72		1	1		3.837	3.837		0.02284	0.00914	0.01370	0.05329	0.25124	0.4292
Port A to Port B	926	1208	366912	204000		746.726			168	72		1			0.168	0.128		0.00100	0.00040	0.00060	0.00178	0.00933	0.4385
Port B to Factory	64	1272	3276	850		1.299	1.299		168	72		1	1		1.299	1.299		0.00773	0.00309	0.00464	0.01805	0.08508	0.5236
Factory to Site	80	1352			156			1.624			24			1			1.624					0.06767	**0.5913**

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for required vehicles (GJ)			Te					Cum Te
For 5 house	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		840	360		1	4		2.718	10.870		0.00324	0.00129	0.00194	0.03020	0.10353	0.1035
Sawmill to port A	189	282	3276	850		3.837	3.837		840	360		1	1		3.837	3.837		0.00457	0.00183	0.00274	0.01066	0.05025	0.1538
Port A to Port B	926	1208	366912	204000		746.726			840	360		1			0.840	0.640		0.00100	0.00040	0.00060	0.00178	0.00933	0.1631
Port B to Factory	64	1272	3276	850		1.299	1.299		840	360		1	1		1.299	1.299		0.00155	0.00062	0.00093	0.00361	0.01702	0.1801
Factory to Site	80	1352			156			1.624			120			1			1.624					0.01353	**0.1937**

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for full load vehicles (GJ)			Te					Cum Te
For 10 houses	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		1680	720		1	7		2.718	19.023		0.00162	0.00065	0.00097	0.02642	0.08573	0.0857
Sawmill to port A	189	282	3276	850		3.837	3.837		1680	720		1	1		3.837	3.837		0.00228	0.00091	0.00137	0.00533	0.02512	0.1109
Port A to Port B	926	1208	366912	204000		746.726			1680	720		1			1.680	1.280		0.00100	0.00040	0.00060	0.00178	0.00933	0.1202
Port B to Factory	64	1272	3276	850		1.299	1.299		1680	720		1	1		1.299	1.299		0.00077	0.00031	0.00046	0.00180	0.00851	0.1287
Factory to Site	80	1352			156			1.624			240			2			3.248					0.01353	**0.1422**

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load			Amount of material transported			Number of vehicles needed			Te for required lorry			Te					Cum Te
For 50 houses	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		8400	3600		5	34		13.588	92.397		0.00162	0.00065	0.00097	0.02567	0.08347	0.0835
Sawmill to port A	189	282	3276	850		3.837	3.837		8400	3600		3	5		11.511	19.186		0.00137	0.00055	0.00082	0.00533	0.02147	0.1049
Port A to Port B	926	1208	366912	204000		746.726			8400	3600		1			8.401	6.401		0.00100	0.00040	0.00060	0.00178	0.00933	0.1143
Port B to Factory	64	1272	3276	850		1.299	1.299		8400	3600		3	5		3.898	6.497		0.00046	0.00019	0.00028	0.00180	0.00727	0.1215
Factory to Site	80	1352			156			1.624			1200			10			16.242					0.01353	**0.1351**

	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load			Amount of material transported			Number of vehicles needed			Te for required lorry			Te					Cum Te
For 100 houses	(km)	(km)	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		16800	7200		10	67		27.176	182.076		0.00162	0.00065	0.00097	0.02529	0.08234	0.0823
Sawmill to port A	189	282	3276	850		3.837	3.837		16800	7200		6	9		23.023	34.534		0.00137	0.00055	0.00082	0.00480	0.01987	0.1022
Port A to Port B	926	1208	366912	204000		746.726			16800	7200		1			16.801	12.801		0.00100	0.00040	0.00060	0.00178	0.00933	0.1115
Port B to Factory	64	1272	3276	850		1.299	1.299		16800	7200		6	9		7.796	11.694		0.00046	0.00019	0.00028	0.00162	0.00673	0.1183
Factory to Site	80	1352			156			1.624			2400			20			32.483					0.01353	**0.1318**

BASED ON THE LONGEST DISTANCE

For 1 house	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for required vehicles (GJ)			Te					Cum Te
	(km)	(km)	S60 needed	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		168	72		1	1		2.718	2.718		0.01618	0.00647	0.00971	0.03774	0.17794	0.1779
Sawmill to port A	189	282	3276	850		3.837	3.837		168	72		1	1		3.837	3.837		0.02284	0.00914	0.01370	0.05329	0.25124	0.4292
Port A to Port B	1860	2142	366912	204000		1499.904			168	72		1			0.337	0.257		0.00201	0.00080	0.00121	0.00201	0.01406	0.4432
Port B to Factory	234	2376	3276	850		4.751	4.751		168	72		1	1		4.751	4.751		0.02828	0.01131	0.01697	0.06598	0.31106	0.7543
Factory to Site	160	2536			156			2.554			24			1			2.554					0.10640	**0.8607**

For 5 house	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for required vehicles (GJ)			Te					cum Te
	(km)	(km)	S60 needed	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		1239.84	504		1	4		2.718	10.870		0.00219	0.00088	0.00132	0.02157	0.07347	0.0735
Sawmill to port A	189	282	3276	850		3.837	3.837		840	360		1	1		3.837	3.837		0.00457	0.00183	0.00274	0.01066	0.05025	0.1237
Port A to Port B	1860	2142	366912	204000		1499.904			840	360		1			1.943	1.286		0.00231	0.00093	0.00139	0.00357	0.01997	0.1437
Port B to Factory	234	2376	3276	850		4.751	4.751		840	360		1	1		4.751	4.751		0.00566	0.00226	0.00339	0.01320	0.06221	0.2059
Factory to Site	160	2536			156			2.554			120			1			2.554					0.02128	**0.2272**

For 10 house	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for required vehicles (GJ)			Te					Cum Te
	(km)	(km)	S60 needed	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		2479.68	1008		1	7		5.435	19.023		0.00219	0.00088	0.00132	0.01887	0.06538	0.0654
Sawmill to port A	189	282	3276	850		3.837	3.837		1680	720		1	1		3.837	3.837		0.00228	0.00091	0.00137	0.00533	0.02512	0.0905
Port A to Port B	1860	2142	366912	204000		1499.904			1680	720		1			3.375	2.571		0.00201	0.00080	0.00121	0.00357	0.01875	0.1093
Port B to Factory	234	2376	3276	850		4.751	4.751		1680	720		1	1		4.751	4.751		0.00283	0.00113	0.00170	0.00660	0.03111	0.1404
Factory to Site	160	2536			156			2.554			240			2			5.107					0.02128	**0.1616**

For 50 house	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for required vehicles (GJ)			Te					Cum Te
	(km)	(km)	S60 needed	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		12398.4	5040		5	34		13.588	92.397		0.00110	0.00044	0.00066	0.01833	0.05938	0.0594
Sawmill to port A	189	282	3276	850		3.837	3.837		8400	3600		3	5		11.511	19.186		0.00137	0.00055	0.00082	0.00533	0.02147	0.0809
Port A to Port B	1860	2142	366912	204000		1499.904			8400	3600		1			16.874	12.856		0.00201	0.00080	0.00121	0.00357	0.01875	0.0996
Port B to Factory	234	2376	3276	850		4.751	4.751		8400	3600		3	5		14.252	23.754		0.00170	0.00068	0.00102	0.00660	0.02658	0.1262
Factory to Site	160	2536			156			2.554			1200			10			25.536					0.02128	**0.1475**

For 100 house	Distance	c.d.	Amount of material equivalent to (per full loaded vehicle)			Te for full load (GJ)			Amount of material transported			Number of vehicles needed			Te for required vehicles (GJ)			Te					Cum Te
	(km)	(km)	S60 needed	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	S60	Plywood	Panel	Per S60	Per S24	Per S36	Per Plywood	Per Panel	Per Panel
Foresty to sawmill	93	93	1861	108		2.718	2.718		24796.8	10080		10	67		27.176	182.076		0.00110	0.00044	0.00066	0.01806	0.05857	0.0586
Sawmill to port A	189	282	3276	850		3.837	3.837		16800	7200		6	9		23.023	34.534		0.00137	0.00055	0.00082	0.00480	0.01987	0.0784
Port A to Port B	1860	2142	366912	204000		1499.904			16800	7200		1			33.748	25.713		0.00201	0.00080	0.00121	0.00357	0.01875	0.0972
Port B to Factory	234	2376	3276	850		4.751	4.751		16800	7200		6	9		28.504	42.756		0.00170	0.00068	0.00102	0.00594	0.02460	0.1218
Factory to Site	160	2536			156			2.554			2400			20			51.072					0.02128	**0.1431**

APPENDIX E. FUEL CONSUMPTION FIGURES

Fuel consumption is defined as the amount of fuel required to move a vehicle over a given distance and can be expressed in one of two ways:

- Based on the amount of fuel used per unit distance (L/100km). The lower the value, the more economic a vehicle is, as it means the less fuel it needs to travel a certain distance.
- Based on the distance travelled per unit volume of fuel used (either in km per litre - km/L or miles per gallon – mpg). In this case, the higher the value, the more energy efficient a vehicle is, as it means the more distance it can travel with a certain volume of fuel.

Fuel consumption varies considerably depending of the type of traffic, roads, driving behaviour, and many more.

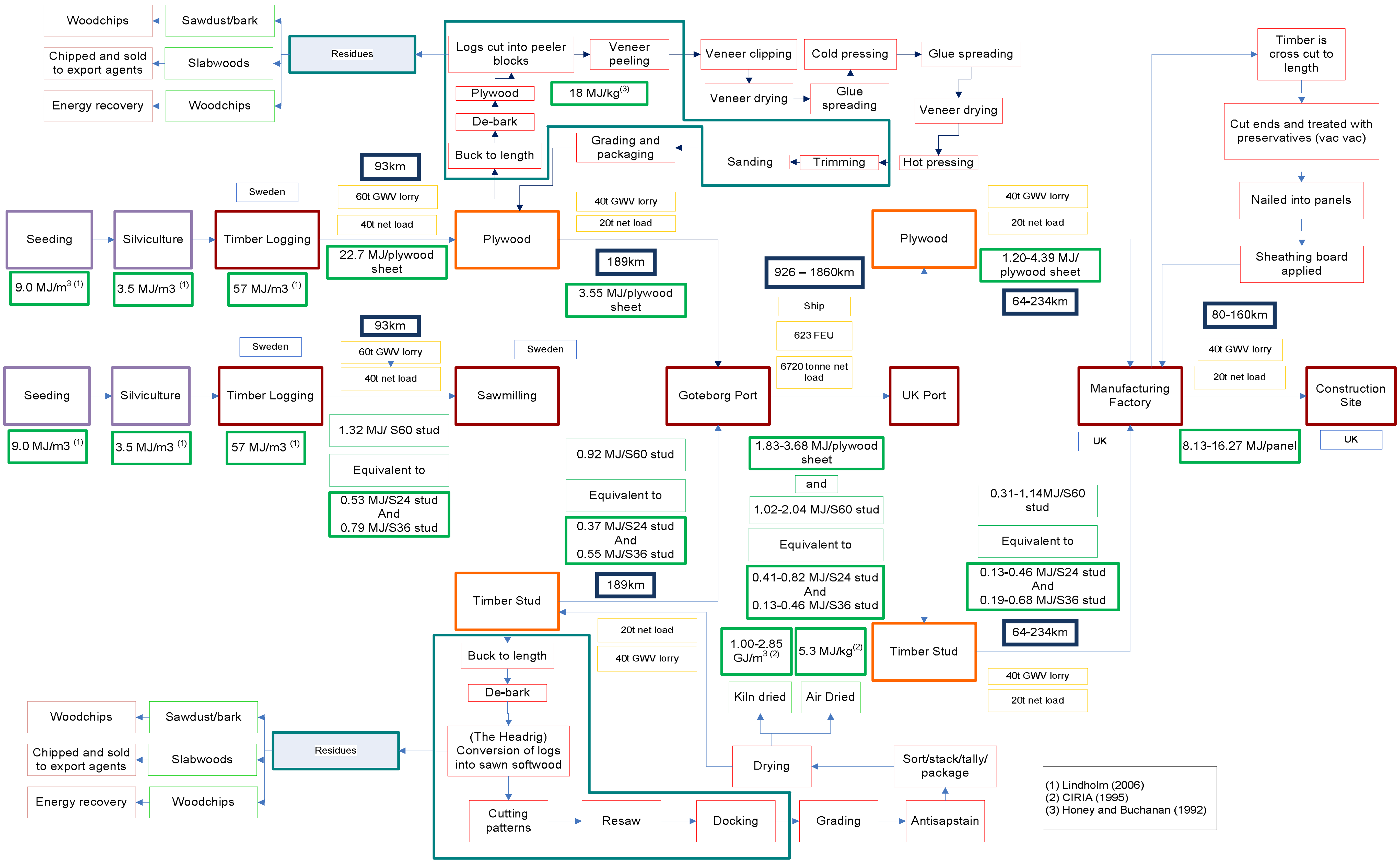
DETR (1997), for example, has differentiated the fuel consumption value based on the gross weight of the particular lorries and whether it was designed as a rigid or an articulated types. It ranges between 23.9-39.2litre/100km.

On the other hand, data published in 2002 by Institute for Energy (IFEU) and Association for Study of Combined Transport (SGKV) has differentiated that fuel consumption based on gross weight and whether it is hauling an empty or full load. Based on IFEU and SGKV (2002), a typical 40 feet lorry has a fuel consumption value of 39.2litre/100km when it is fully loaded and 29.3litre/100km when it is empty.

Table E.1 below shows the various fuel consumption values based on various references

Fuel consumption based on DETR (1997)								
	Rigid <7.5t	**Rigid 7.5-14t**	**Rigid 14-17t**	**Rigid 17-25t**	**Rigid 25t +**	**Arctic ≤ 30t**	**Arctic 30-33t**	**Arctic 33t**
Litres/ 100 km	23.9	26.4	31.7	41.5	43.5	35.8	35.8	39.2
Fuel consumption based on Volvo (2006)								
	Trucks, distribution traffic 8.5t	**Trucks, regular traffic 14t**	**Tractor and semi trailer, long haul traffic 26t**	**Truck with trailer, long haul traffic 40t**				
Litres/100km (empty)	20-25	25-30	21-26	20-32				
Litres/100km (full load)	25-30	30-40	29-35	43-53				
Fuel consumption based on IFEU and SGKV (2002)								
	Trucks/Lorry 40t							
Litre/100km (empty)	29.3							
Litre/100km (full load)	39.2							
Fuel consumption based on DTI (2006)								
	Trucks/Lorry 60t							
Litre/100km	46.9							

APPENDIX F. DETAILED BREAKDOWN OF THE EMBODIED ENERY CONSUMPTION PER STAGE



APPENDIX G. QUANTIFICATION OF OPERATIONAL ENERGY

Dwelling data

Ground floor area	58.32 m^2
Glazed openings	Assumed to be 25% of total floor area (=29.16m^2)
Wall area (net)	155.52m^2
Roof area	58.32 m^2
Volume of building	279.9 m^3

Standard U values of construction elements for domestic buildings (Building Regulations ADL1, 2002)

Building element	U Values (W/m^2K)
Pitched roof with insulation between rafters	0.2
Prefabricated timber Walls	0.3
Floors	0.25
Glazed openings	2.2

Assuming that passive vents and fans are installed on the particular dwelling, N (number if air changes) – 10m^3/hour

UA Calculation

Element	Area (m^2)	U-Value (W/m^2K)	UA (W/K)
Roof	58.32	0.2	11.664
Walls	29.16	0.3	8.748
Floors	155.52	0.25	38.88
Glazed openings	58.32	2.2	128.304
		ΣUA	187.6

Degree Day data for Year 2007 for South East England (source: Vilnis Vesma, Degree Days Direct, 2008)

January	268
February	258
March	260
April	124
May	109
June	38
July	31
August	39
September	67
October	166
November	248
December	332
Total DD	**1940**

The annual energy consumption (MJ)
= [(ΣUA x Degree days of the particular year x 24 x 3600) + (0.33NV x Degree days of the particular year x 24 x 3600)]/1,000,000

$$= [(187.6 \text{ x } 1940 \text{ x } 24 \text{ x } 3600) + \frac{0.33 \text{ x } 10 \text{ x } 1940 \text{ x } 24 \text{ x } 3600}{1,000,000}$$

= 31997.89 MJ = 32 GJ

Operational energy consumption during the house lifetime (60 years)

= (31997.89 x 60)/24 panel)

= 79994.7 MJ/panel = 79.99473 GJ/panel

≈ 80GJ/panel