DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

EVALUATION OF FIBER REINFORCED PLASTIC BOAT BUILDING TECHNOLOGIES SUSTAINABILITY BY MEANS OF LIFE CYCLE ANALYSIS

by
Mehmet ÖNAL

January, 2013
İZMİR

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We have read the thesis entitled **"EVALUATION OF FIBER REINFORCED PLASTIC BOAT BUILDING TECHNOLOGIES SUSTAINABILITY BY MEANS OF LIFE CYCLE ANALYSIS"** completed by **MEHMET ÖNAL** under supervision of **ASSOC.PROF.DR. GÖKDENİZ NEŞER** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

This thesis is designed on the basis of Life Cycle Assessment (LCA) and aims to quantitavely resize the controversial “sustainability” concept for all stages of supply chain for marine vehicles which are manufactered by using fiber reinforced plastic material. With LCA, supply chain carbon emissions, energy consumption, total weight difference between the first usage and recycling and potential contribution to global warming can be considered for the products’ cradle to grave life, even including the recycling processes cradle to cradle life.

In this study, the aforesaid parameters are presented in the context of the results of comparison for two boat building methods. The comparison of the sustainability of production the method differences for boats with the same material was done on the basis of Life Cycle Assessment by “Umberto” carbon footprint software which is specially developed and planned for all of the material life cycle processes (production, use, waste management) with flows. The obtained helpful results have been presented to the beneficial of the related stakeholders such as manufacturers, designers, suppliers and recyclers.

Keywords : Life cycle assessment, carbon footprint, fiber reinforced plastics, boat building methods, umberto

ELYAF TAKVİYELİ PLASTİK TEKNE ÜRETİM TEKNOLOJİLERİNİN SÜRDÜRÜLEBİLİRLİĞİNİN ÖMÜR DÖNGÜSÜ ANALİZİYLE DEĞERLENDİRİLMESİ

ÖZ

Elyaf destekli plastik (ETP) malzeme kullanılarak üretilen deniz araçlarının, tedarik zincirinin tüm aşamalarında tartışmalı hale gelen ‘sürdürülebilirlik’ kavramının nicel olarak boyutlandırılmasını hedefleyen bu çalışma, Ömür Döngüsü Değerlendirmesi (Life Cycle Assessment. LCA) temelinde tasarlanmıştır. LCA ile ürünlerin beşikten-mezara, hatta geri dönüşüm süreçleri de dahil olmak üzere beşikten-beşiğe tedarik zinciri içindeki karbon salımları, enerji tüketimleri, ilk kullanımdaki ve geri dönüşümdeki toplam ağırlıklarındaki fark ve küresel ısınmaya katkı potansiyeli parametreler olarak ele alınabilmektedir.

Bu çalışmada elle yatırma ve vakum infüzyon olmak üzere iki farklı metot ile imal edilmiş tekne gövdelerinin, yukarıda sözü edilen parametreleri bağlamında karşılaştırmalı sonuçları sunulmaktadır. Benzer mukavemete sahip tekne gövdelerindeki, üretim metodu farklılıklarından doğan üretimdeki sürdürülebilirlik kıyaslaması, Ömür Döngüsü Değerlendirmesi temelinde, özel olarak geliştirilmiş olan ve malzemenin tüm ömrü (üretim, kullanım, atık yönetimi) boyunca geçtiği tüm proseslerin belirli bir akış içerisinde planlandığı “Umberto” karbon ayak izi yazılımı ile yapılmıştır. Elde edilen sonuçların tasarımcı, üretici, tedarikçi ve geri dönüşümcü paydaşlar bakımından yararlı olabilecek sonuçları karşılaştırmalı olarak ele alınmıştır.

Anahtar sözcükler: Ömür döngüsü analizi, tekne üretim metotları, elyaf destekli plastik, karbon ayak izi, elle yatırma, vakum infüzyon.

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CHAPTER ONE
INTRODUCTION

Boat building is one of the oldest industries in nearly every coastal country throughout the world. For hundreds of years, people have depended on the reliability of different types of boats for fishing, and for the transportation of people and goods. Today, the industry has shifted to accommodate an increasing demand for personal sport and pleasure crafts (ICOMIA, 2007; Neşer, 2011).

Different materials have been used for all types of boats. The last 50 years have seen a sea change in the materials used in boat construction, with composites replacing wood or steel. During this time, the industry is faced with a two-important problem – the need to disposal vessels in a way that doesn't impact on the environment, and finding a way of designing new boats that will not leave future generations in the same predicament, which calls as "sustainability" (Bennet, 2011).

Sustainability is the ability to maintain a certain status or process in existing systems. The most popular definition of sustainability can be 1987 UN conference's are "*meet present needs without compromising the ability of future generations to meet their needs*" (WECD, 1987).

In this definition;

- the concept of "needs", in particular the essential needs of the world's poor, to which overriding priority should be given;
- the idea of limitations imposed by the state of technology and social organisations on the environment's ability to meet present and future needs.

Generally the application of the concept in engineering called " Sustainable Engineering". However, there is not any generally aggreed definition for Sustainable Engineering. In 2004, Centre for Sustainable Engineering has defined this kind of engineering as "*engineering technologies which deliver greater resource productivity or efficiency and fewer emissions of hazardous substances and/or* *emissions presenting lower hazards. This is distinct from most engineering research which majors on improving or increasing functionality and reducing cost.*" While this definition created some confusion, it also provided perception of engineers for this concept. This ranged from reducing energy use and waste to employing recycling and lowering emissions- and a belief among many that sustainable engineering is a trendy name for what used to be called "good engineering" (Brown, 2011).

For good engineering, in the first sight, it was necessary to look at the current best practice employed in all the major areas of sustainable design, production, operation and decommissioning. In order to encompass the widest possible solution envelope, enabling technologies were drawn from across all fields embracing concepts of sustainable engineering (Birmingham, et al. , 2006).

Sustainability requires making every decision with the future in mind. It is known that the production and the usage of products have significant impacts to their surrounding environment. The impact can be observed in all stages of the product life from the extraction of raw materials to the recycling of waste. Life cycle thinking can highlight trade-offs among different categories such as green-house gasses, water, energy and land use which helps to understand sustainability advantages, limitations and scalability (Milmo, 2011).

1.1 Life Cycle Assessment

Every year 2,8 millions tonnes of all categories of waste are produced in Western Europe. Assuming an average density of 2 kg/1, this waste would cover a surface area equivalent to that of Switzerland with a depth of three centimetres. One of the preconditions for further sustainable economic growth is that the implementation of new technology that should improve the efficiency of resource consumption and reduce waste output. To be the most effective, improvements should occur at all the stages of the life cycle of a product, from raw material extraction, manufacture and use to recycling or disposing (Lundquist, et al. , 2000).

Life Cycle Assessment (LCA) as defined in the International Standardization Organization (ISO) 14040 and ISO 14044 standards is the compiling and evaluation of the inputs and outputs of a product system and the potential environmental impacts of the related product system during product's lifetime(Parkinson & Bichard, 2000). Inputs have been considered as the needed resources and outputs are emissions to related media such as: air, water and soil (Waste & Central, 2006).

ISO (the International Organization for Standardization) is a world-wide indipendent organisation, including national bodies from both developed and developing countries, which aims to standardise a wide range of products and activities. One of its key activities is the development of the 9000 series of standards, which is aimed to integrate of quality aspects into business practice. The 14000 series of ISO standards includes the standard 14001 on Environmental Management Systems, as well as a series of standards relating to LCA (the 14040 series). These ISO activities began in 1994 and aim to produce the complete series of LCA standards. (Guinée, 2004)

The ISO LCA standards concern the technical as well as organisational aspects of an LCA project. The organisational aspects mainly focus on the design of critical review processes, with special attention to comparative assertions disclosed to the public. They also cover matters such as the involvement of stakeholders (Heijungs, et al. , 2012).

The following general standards and technical reports have been or are being produced by ISO in the 14040 series framework (Environmental management - Life cycle assessment):

- ISO 14040: A standard on principles and framework.
- ISO 14041: A standard on goal and scope definition and inventory analysis.
- ISO 14042:A standard on life cycle impact assessment.
- ISO 14044: A standard on life cycle interpretation.

- CD 14047: A draft technical report presenting examples for ISO 14042 on life cycle impact assessment
- CD 14048: A draft standard on data format
- TR 14049: A technical report presenting examples for ISO 14041 on the life cycle inventory phase.

In the other words, LCA is a technique to assess environmental impacts associated with a product over its life cycle; extraction of raw materials, manufacture, distribution, materials processing, manufacturing, transport, repair, maintenance, use, re-use and recycling (Charters, 2010).

The LCA is basically knowledge based comparative environmental assessment and managing tool for product systems (Schench, 2005). This comparison has been established on the concept of a functional unit which represents quantitative expression for the equal pay off of the systems compared. Since, this approach is “cradle to grave”, this process called as “Life Cycle Assessment” (Ayres, et al. , 1998). The interest of LCA, expanding from cradle to grave makes it unique (Hastak, et al. , 2003). From an environmental point of view, LCA has many benefits. LCA has the capacity to discover and keep a record of tradeoffs which represent the changing of environmental impacts, from one medium to the other or from one stage of the life cycle to another (O’Connor, et al. , 2012). Since LCA studies need carefully gathering and evaluation and verification of the data used, to carry on reliable significant amount of analysis takes time (Klpffer, 1998).

LCA has been developed as an analytical tool in order to assess the impacts not only products but also of services on the environment both of products and services (Parkinson & Bichard, 2000).

The environmental impact has been assessed by means of life cycle perspective for over fifty years. The early practitioners are related as early as the 1960s, with a multi-attribute quantitative approach to decisions regarding the beverage packaging (Hoffman & Schmidt, 1997).

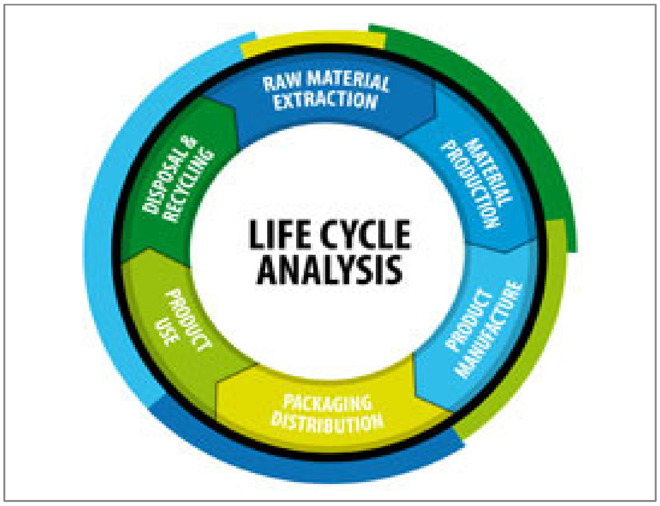

Figure 1.1 Stages of LCA (AIGMF, 2012)

Today, this study has been considered as first application made LCA become a worldwide common term. The first studies using a life cycle perspective on a process system has been done in the USA in the late 1960s and early 1970s, focusing on environmental impacts caused by different types of beverage containers (Klöpffer, 2012).

After the initial stage of the works which used LCA, until the 1980s, one cannot be found out concentrated efforts to use this tool. After this date, in Europe, a greater number of works on packaging of products can be found because of public awareness and governmental interest (Hauschild, et al. , 2005).

In the Netherlands in 1989, the first National Environmental Policy Plan (NEPP) was published. The objectives of this plan were to reach a sustainable development of the environment (O'Connor et al., 2012). The NEPP introduced the "product policy" which was to promote the use of products with a minimal environmental impact. In order to be able to evaluate the environmental impact a standardized methodology has been developed by the Centre for Environmentology of the (State) University of Leiden (CML). This project resulted as an order came from the Dutch Ministry for Housing, Physical Planning and Environment (VROM). The name of the methodology is "Environmental Life Cycle Analysis (or: Assessment) of Products", in short LCA (Schuurmans-stehmanna, 1994). Also there were international discussions about LCA and its methodology within the Society for Environmental Toxicology and Chemistry (SETAC). Which, various scientists, interest groups, policy makers, industrialists from different countries were involved in (Chubbs & Steiner, 1998).

Over the last two decades LCA methodology and the data that it provided became a sustainable and professional instrument to address and influence in a beneficial way the environmental aspects of sustainability of almost all anthropogenic activities (Wardenaar et al., 2012).

LCA is recognized as a scientific reliable approach regarding the environmental sustainability of human activities. That is why it is applied in many internal and external information supplies and for decision support. Nevertheless, the LCA application must fulfill three basic criteria (Krozer & Vis, 1998):

- It must be trustworthy so that it ensures the credibility of information and results
- It must fit with the present information routines and practices in business to ensure applicability
- It must give quantitative and important information to inform decision makers.

Briefly, LCA measures the material and energy flows to and from nature over the life time of a product or service, and assesses the potential impact of those flows on eco-systems, resources and the human health. LCA is science-based, quantitative and integrative (Schuurmans-stehmanna, 1994). The impacts which appears are in different segments of the manufacturing and through the life of a product. Often, the assessment is called as a cradle to grave evaluation. The most common reported impact metrics include: acidification (“acid rain”); global warming (“carbon footprint”); photochemical oxidant creation (“summer smog”), eutrophication (“algal bloom”) and ozone depletion (“ozone hole”). For a LCA makers the main interests are to identify the hot spots in the supply chain, identify and quantify alternatives, as well as exposing the environmental information (O'Connor et al., 2012).

In a LCA method, generally a product has its quantified life cycle effects on the environment. The processes of all life cycle stages form a so-called "process tree" (Ayres et al., 1998). However, to evaluate all of them in detail is not feasible. Therefore, for this method choices have to be made. As an example, capital goods such as machines, buildings are not taken into account. One can determine environmental hotspots of all processes of a product and use this information to improve the environmental performance at every stage of a product's life cycle with LCA (Mongelli, et al., 2005). LCA's are often used by decision – makers in industry for strategic planning, product development and marketing. The comparison of different products or process alternatives compiled with environmental legislations can be backed up with LCA (Charters, 2010). It is also a necessary tool for eco-labeling and the production of environmental declarations. Applications for LCA are used in:

- Planning Environmental Strategies
- Product Development
- Marketing
- Comparisons
- Follow Legislation
- Eco-labeling

The ISO has created the ISO 14044 as a guideline on how to conduct an LCA. LCA consists of four main stages (Figure 1.4).

In the first stage all general decisions for setting up the LCA system should made (M. Landamore, et al., 2006). This stage is called "Goal and Scope Definition". In the goal definition, the aims of the study as well as the main goal should be defined. In addition to this, the target group for the LCA report should be defined. At this stage, it should be determined that if LCA will be used for comparison purpose or not. In the scope definition the product itself and all assumptions have to be described. The system boundaries, impact categories, data quality requirements and the methodology used to set up the product system should be also described now. To describe the product, the function of it has to be defined as well as the demands which the product is supposed to fulfill. This becomes very important when products with a different range of functionalities are to be compared. For this a functional unit has been defined (Landamore, et al., 2005).

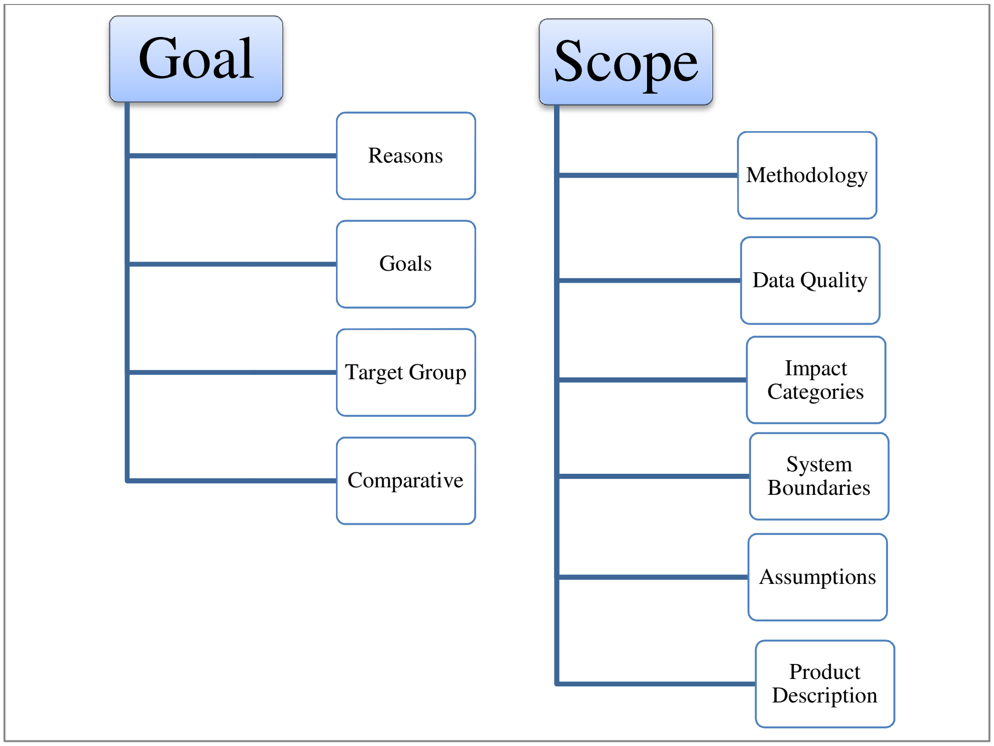

Figure 1.2 Elements of goal and scope

The functional unit is the quantified definition of a function of a product system with the related physical unit. The system boundaries are defined by the cut off criteria. Cut off criteria allow us to define which parts and materials of the product system will be included in or excluded from the total system and which are excluded from the system (Spatarb, et al., 2001). To consider the important processes, the cut off criteria have to be used in combination. For comparative LCA the processes used in both product systems can be eliminated because their comparison would not affect the overall results.

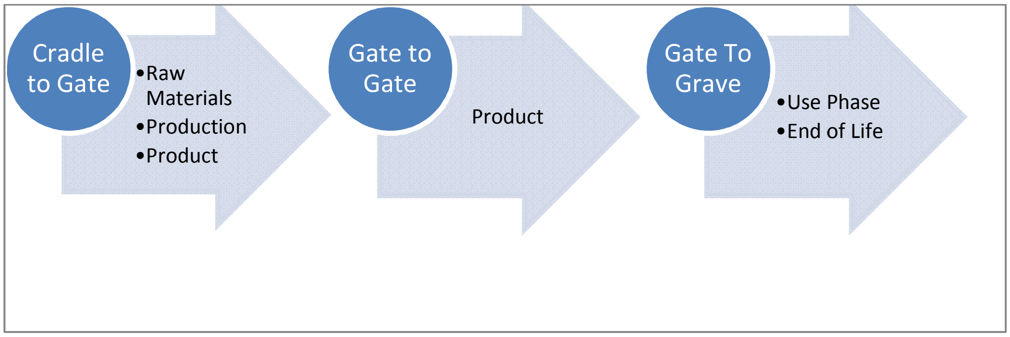

Figure 1.3 LCA flow from cradle to grave

In a LCA, the boundary types are; cradle to grave, cradle to gate, gate to gate and gate to grave. In the scope definition it is important to define if the LCA refers to the entire life cycle or to a part of a product systems life cycle. In majority of processes, more than one product is produced (Jönbrink & Wolf-wats, 2000). In such a case, the input and output data has to be shared according to their relative contribution to one product or the other. This activity is called "allocation". However, ISO 14044 advices to avoid from data sharing.

After the goal and scope of the project have been determined, the following phase in creating LCA is to model all the processes relevant to the system in order to calculate the life cycle inventory (LCI). This phase is maybe the most work intensive and time consuming among all the phases in an LCA (Landamore et al., 2005). Because of the need of data collection. Data collection involves collecting quantitative and qualitative data for every process in the system. This can be done by the collection of primary in situ data or by the collection of secondary data from literature or databases. The collected data must be related to the functional unit and validated while necessary allocation must be modeled. In some cases, the system boundaries maybe redefined. The model of the system can be built after the data has been collected (Hastak et al., 2003).

The LCI results allow the Life Cycle Impact Assessment (LCIA) to be calculated. LCIA identifies and evaluates the amount and significances of the potential environmental impacts of a product system (Guinée, 2004). The LCIA can be calculated using four steps. Two of these steps are mandatory: classification and characterization. The two optional steps are: normalization and evaluation (Baitz et al., 2011).

Each product has a relevant number of aspects selected. After the data are taken, the related environmental data are aggregated per environmental aspect with one identification number. Aggregation is possible when the data for one environmental aspect are given in the same unit; these types of units are called identification numbers. These numbers are calculated by means of indices and standards, called classification factors (Parkinson & Bichard, 2000).

Classification is a process where each resource and emission is assigned to one or more impact categories (Baitz et al., 2011). Impact categories are scientific definitions linking specific substances to a specific environmental issue. For example, the issue of global warming is represented by the Global Warming Potential (GWP) impact category. Any emission to air contributes to the GWP such as CO_2 or CH_4 (Guinée, 2004) .

The next step is the characterization of the results. This means that the results of the LCI should be converted in to the reference unit of the impact category. For example, for the GWP impact category all quantities are to be converted to "kgCO_2 Eq". The CO_2 is the reference substance for this impact category. To convert these to common units, every quantity will be multiplied by characterization factor. Characterization factors are determined by different scientific groups based on different methodologies and philosophical point of views of the environmental issues (Guinée, 2004). Two of the most widely used impact category methodologies are TRACI in the US and CML in Europe.

CML is an impact assessment method which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity) (PE International, n.d.).

Table 1.1 LCIA calculation example

Emission to Air	**Impact Categories**	**Factors**	**LCIA**
CH_4 7 kg	GWP	7 kg CH_4 x 25	175 kg CO_2 eq
CO_2 2 kg		2 kg CO_2 x 1	2 kg CO_2 eq

The impact of a product to the greenhouse effect is calculated while dividing the emissions per greenhouse gas by the global warming potential (GWP) of the gas. If, for example, a 100 mg of CO_2 emits equals to 100 GWP, the contribution to the greenhouse effect is one unit greenhouse effect contribution (Landamore et al., 2005).

The so-called environment measures have been created by reproducing these factors in identification numbers. Every environmental aspect corresponds to an environment measure. The environment measure provides information about the environmental impact of one specific aspect quantitatively. The set of environment measure is called the environmental profile, meaning a type of "environmental characteristic" of a product (Baitz et al., 2011).

For example, methane contributes The GWP so during the classification step we simply list methane with its quantity under the GWP. Methane has a GWP characterization factor of 25. This means the CML determines on the basis of Intergovernmental Panel on Climate Change (IPCC) reports that methane contributes the GWP 25 more than CO_2. Methane quantity should be multiplied with 25 to reveal its contribution in kgCO_2 Eq to the GWP (Baitz et al., 2011). After characterizing every substance that contributes to the system, all of the characterized quantities can simply be added together. This result in a final number represents the extend of this environmental impact.

The next step is to interpret the data. In this step the results are analyzed to determine where environmental hotspots exist and what conclusions can be drawn.

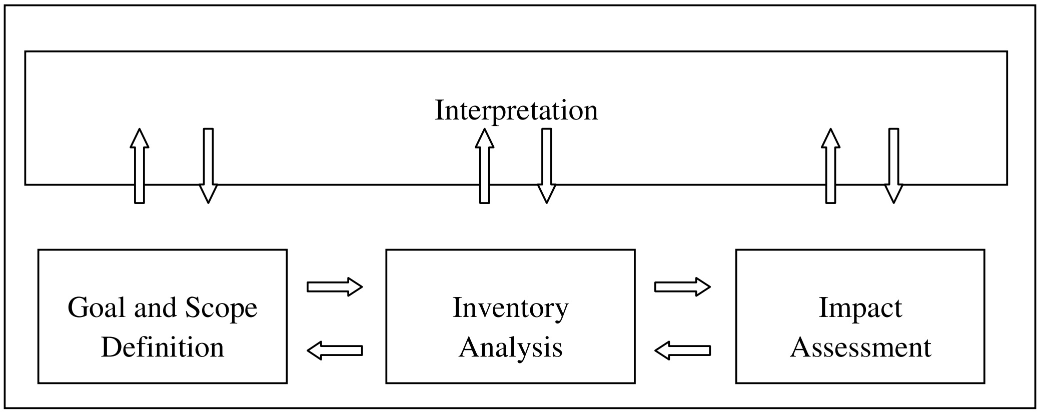

Figure 1.4 LCA Framework

It is obvious that it is important to think about the question for what purpose evaluations made by the help of a LCA will be used. There are possible a number of applications, each of them made for and corresponding with a specific target group in the boat building industry (Landamore et al., 2006). First of all, an LCA is an instrument which provides environmental – related information about a product. According to statistics in the Netherlands this information is used as:

- A basis for the certification of environmental aspects
- A basis for the eco – labeling of products
- A starting point to set up and study policy strategies, on behalf of the authorities
- A basis for product or process improvement or innovation having producers as a target group
- A management tool as part of the environmental management systems within a company
- A marketing instrument for producers and suppliers on behalf of their customers
- A comparison of products with standards, or the development of standards, useful for government institutions
- A means for product comparison on behalf of designers, clients, customers and users

- A starting point to set up and study policy strategies, on behalf of the authorities.

The idea to have life cycle assessments made initially by the government. Nowadays the environmental related information obtained by means of LCA’s is increasingly used in the promotion and communication policy of companies (Guinée, 2004).

Many users from industry, consultancy, and the academia from all over the world apply LCA in scientific, industrial, agricultural, societal, or political processes and use their discoveries. The different groups of authors are working in a proactive way in the LCA field, in data provision, methodology development, product optimization, data compiling and communication (Baitz et al., 2012). From the affiliations of the authors apply, assess and support LCA; they use it as a communication and a decision support tool in their organizations or along value and process chains and to talk to stakeholders. The foundation of their LCA work is to deal with technical boundaries and to identify realistic potentials according to scientific sound information.

The following are the key parameters that have been analysed as they have particular relevance for the study due to the particularities of the system, and follow the ISO regulations (Baumann et al, 2004):

- Fossil fuels
- Minerals
- Land use
- Carcinogens
- Climate change (global warming potential, GWP)
- Acidification / Eutrophication
- Radiation
- Respiratory organics
- Respiratory inorganic

- Ecotoxicity
- Ozone layer

A better industrial practice can be obtained after the understanding of the environmental impact of a product. The today's industrial practice can be encourage to become more adaptable and to surpass the present legislations which is becoming more strictly and ask manufacturers to take more responsibility for their production and products (Shenoi, et al., 2011).

The need for a sustainable boat building with fiber reinforced plastics (FRP), there should be analyses of LCA to ensure the sustainable future for boat building techniques.

CHAPTER TWO
MATERIALS AND METHOD

2.1 Fiber Reinforced Plastics

Plastic products are based on polymer based, materials which are omnipresent in nature (cellulose, proteins) or in synthetic form (textiles, adhesives, resins, etc.). In contrast to metals and other construction materials, polymers are organic materials with properties that depend strongly upon the environment in which they exist (Lundquist, et al., 2000). Plastics can be classified as thermoplastics and thermosetting. Both thermoplastic and thermosetting resins are used to manufacture fiber reinforced plastic products. (Environmental Protection Agency, 1991) Thermoplastic materials become fluid upon heating above the heat distortion temperature, and upon cooling, set to an elastic solid. The process of reheating and cooling can be repeated many times, although there may be some degradation in chemical or physical properties of the final product. Thermosetting materials on the other hand irreversibly polymerize and solidify at elevated temperature. The internal chemical structure of a thermosetting plastic material is permanently altered by heat, resulting in a product that cannot be re-softened (Jones & Simon, 1983). Thermoplastic resins were first used for industrial applications in 1889. Reinforced polyester resins were first utilized in 1944.

FRP is a general term used for all fiber reinforced plastics (Donald V. Rosato & Rosato, 2004). FRP is increasingly being used in construction due to their light weight, corrosion resistant, high strength to weight ratio, low thermal conductivity, longevity, adequate optical properties, low transportation costs, low installation costs, low resistance to flow, low electrical conductivity, dimensional stability, ease of installation, good energy savings, light in weight (Lundquist, et al., 2000). In one year, all around the world, the FRP industry produces millions of tones of components. (Conroy, et al., 2006) According to Turkish Statistical Institute’s annual manufacturing statistics report in 2001, the sales of goods produced by manufacturers of plastics in primary forms and of synthetic rubber is reached more than one billion Turkish Liras.

Their versatility has lead to the development of the approximately 20 thousands different types and grades of plastics presently on the market. Based on the major types of polymers, modification by copolymerisation, blending, alloying or mixing with additives means that plastics can be tailored to suit the requirements of individual applications. They can also be combined in complex assemblies to provide multiple functionality. Examples of this are multilayer packaging and automotive interior trimmings. The latter are triple layer structures composed of a rigid backing material, an intermediate tactile-enhancing layer and a surface material such as a textile or PVC for surface appearance. (Lundquist et al., 2000)

Nowadays there are many products manufactures by the FRP industry; bathtubs, spas, shower stalls, ladders, railings, tanks, pipes and vehicle parts.(Kong,et al., n.d.) The ship and boat building industry is one of the most common industry that fabricates fiberglass and composite plastics (Environmental Protection Agency, 1991). In the marine industry there has been a raising interest regarding the use of cheaper and lower performance polypropylene thermoplastics and glass reinforcements as a recyclable and durable structural material. This happens because the marine industry cannot use costly high performance materials which ask specialized curing cycles.

For about fifty years polymeric composite materials have been used in offshore structures, boats, ships, submersibles as well as in other marine structural applications (Shenoi et al., 2011). Boat building industry started to use FRP instead of wood in 1940s. With the 1940s some industries in the United States (U.S.) tried to produce fiberglass boats. However, these initial attempts were unsuccessful. Following these trials, in the 1950s the first fiberglass boats appeared in Europe. FRP boat building started to become popular and acknowledge all around the world especially after the 1960s. Also U.S. Navy and the Royal Navy tried to produce mine hunters in glass reinforced plastics (GRPs). Therefore during the 1970s a prototype was produced for the Royal Navy. In 1980 the high-speed trimaran Colt Cars GB was engineered in United Kingdom (UK) (Marsh, 2006). The demand for large high-speed marine vehicles such as passenger/vehicle ferries has been increasing in recent years. For these vessels of great importance is structural weight as light weight leads to greater speeds, fuel economy and payloads. In order to obtain savings in structural weight FRP materials have been used successfully in the construction of a variety of small ships and boats (Shenoi et al., 2011).

FRP materials have coefficients of thermal expansion similar to aluminum and steel and also for FRP material manufacturers need less cumulative energy than for steel and aluminum. FRP materials show good dimensional stability. Moreover, FRP materials have good process ability properties and can be shaped or molded to a very high degree into complex and intricate forms. (Nicholas & Paul, 1995a) These are the most widely used molding processes for FRP:

- Hand lay-up
- Vacuum Infusion
- Pressure bag
- Flexible plunger molding
- Matched dye
- Compression molding
- Transfer

For composites, especially when products such as boats and ships are made-to-order, each having a different specification and design and which are against extensive testing and prototyping, challenges such as the mechanism to manage variability and uncertainty can appear (Shenoi et al., 2011). That is why the building process type (spray-up, hand lay-up (HLU), vacuum assisted resin infusion molding (VARIM)) is of a great importance.

2.2 Polyester Resin

Polyester resins are unsaturated resins formed by the reaction of dibasic organic acids and polyhydric alcohols. Polyester resins are used in sheet moulding compound and bulk moulding compound (Gooch, 2007).

Polyester resins are the most widely used resin systems, particularly in the marine industry. By far the majority of dinghies, yachts and workboats built in composites make use of this resin system. Polyester resins such as these are of the 'unsaturated' type. Unsaturated polyester resin is a thermoset, capable of being cured from a liquid or solid state when subject to the right conditions. It is usual to refer to unsaturated polyester resins as 'polyester resins', or simply as 'polyesters'. There is a whole range of polyesters made from different acids, glycols and monomers, all having varying properties (Silvio & Sesto, 1973).

A manufacturer may supply the resin in its basic form or with any of the above additives already included. Resins can be formulated to the moulder's requirements ready simply for the addition of the catalyst prior to moulding. As it has been mentioned, given enough time an unsaturated polyester resin will set by itself. (Gurit, n.d.)

2.3 Gel Coat

Gelcoat is a material used to provide a high-quality finish on the visible surface of a fibre-reinforced composite material. The most common gelcoats are based on epoxy or unsaturated polyester resin chemistry. Gelcoats are modified resins which are applied to moulds in the liquid state (Genç, 2006).

They are cured to form crosslinked polymers and are subsequently backed with composite polymer matrices, often mixtures of polyester resin and fiberglass or epoxy resin with glass. The manufactured component, when sufficiently cured and removed from the mould, presents the gelcoated surface. This is usually pigmented to provide a coloured, glossy surface which improves the aesthetic appearance of the component. Gelcoats are designed to be durable, providing resistance to ultraviolet degradation and hydrolysis. Specialised gelcoats can be used to manufacture the moulds which in turn are used to manufacture components (Karapappas, et al., 2011).

Gelcoat has been produced by blending polyester Resin, titanium dioxide, silica and monomer (Bauchet, et al., 2005).

2.3.1 Monomer (Epoxy Resin)

For gelcoat production epoxy resin has been used as monomer. Epoxy resins are widely used in various industrial fields such as adhesive, surface coating, painting materials, laminates, semiconductor encapsulation, and insulating material for electric devices due to their advantageous properties of adhesion, excellent characteristics of solvent, chemical and moisture resistance, good toughness, low shrinkage on cure, and superior electrical and mechanical properties (Gao, et al., 2008) (Mimura & Ito, 2002).

Epoxy resins are polymeric or semi-polymeric materials, and as such rarely exist as pure substances, since variable chain length results from the polymerisation reaction used to produce them. High purity grades can be produced for certain applications, e.g. using a distillation purification process. One downside of high purity liquid grades is their tendency to form crystalline solids due to their highly regular structure, which require melting to enable processing (“Epoxy,” n.d.).

2.3.2 Silica

Silica plays an important role in nature, science and technical applications. The special advantage of silica is that various kinds of its morphology exist in natural sources or can be synthesized by various preparation techniques, e.g. nanoparticles, particles with random size, spherical hollow spheres, transparent films, mesopouros materials with narrow pore size distribution as well as solid materials without pores or flat surfaces of silicon wafers having a thin silica layer (Spange, 2000).

2.3.3 Titanium Dioxide

Titanium dioxide is a pigment for gel coat process. Titanium dioxide is the naturally occurring oxide of titanium, chemical formula TiO_2 (Gooch, 2007).

2.4 Methyl Ethyl Ketone

Methyl-ethyl-ketone (MEK) is an organic solvent that is characterized by satisfactory boiling point, good solubility, volatilization, and stability and is nontoxic. It is widely used as a solvent in paint, dye, pharmaceutical, and refining industries. MEK is also as an important raw material for organic chemical industries and is used for the production of MEK peroxide and oxime, as an intermediate in the perfumery industry, as an antioxidant, and for catalyst production (Zhenhua, et al., 2006)

2.5 Hand Lay-Up Method

Hand lay-up is the oldest and the simplest process for the manufacturing of FRP products. Even if it is slow and very labor intensive, hand lay-up is a very simple, low cost and easy to apply process for FRP products (Rosato, et al., 2004) Hand lay-up process consists of hand tailoring and placing one or more layers of FRP on a mold by saturating the reinforcement layers with a liquid plastic. All layers are applied to the molding by hand. Resin is sprayed or brushed on after each layer (Nicholas & Paul, 1995a). According to the resin preparation, the material in or around a mold can be cured with or without heat and without pressure. Inexpensive materials such as wood and plaster can be used as molds. The hand lay-up process is especially recommended for large and complex products which require high strength and reliability (Rosato & Rosato, 2004).

During the production of high performance, light weight, one-off racing boats it has been seen its biggest advance in the using of pressure while curing period took place. In a sandwich construction when pressure is applied to a curing laminate it allows a higher fiber to resin ratio through better consolidation, reduces void content and improves interlaminar shear, especially in the adhesive layer next to a sandwich core (Sleigh, 1985). It can be applied by the use of a vacuum bag, matched molds or an autoclave, the vacuum bag being the last complicated and most frequently used system in boat building.

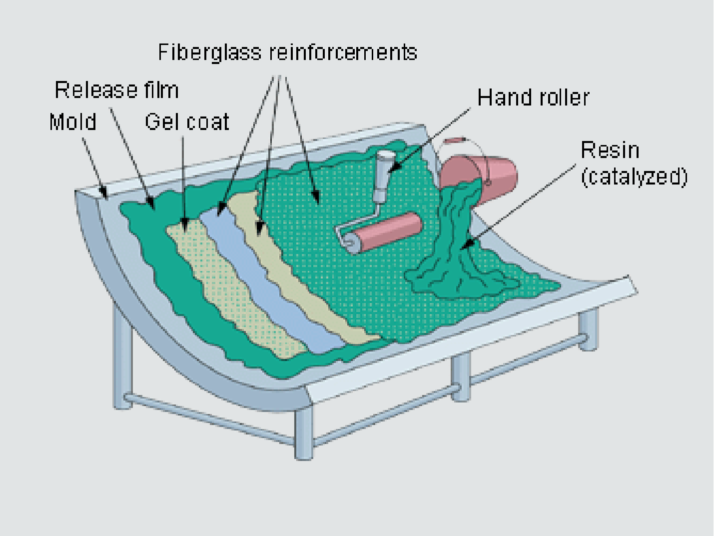

Figure 2.1 Hand lay-up technique (Wacker Company, n.d.)

2.6 Vacuum Infusion Method

Vacuum bag pressure is to enclose the wet liquid resin material and mold in a flexible membrane and draw a vacuum inside the enclosure. And atmospheric pressure on the outside presses the membrane uniformly against the wet lay-up. The vacuum directly helps to remove air in the wet lay-up (Rosato et al., 2004).

One method that provides greater laminate properties and shorter mould times is by using an autoclave. An autoclave is a big oven which can be pressurized. When using it, the laminate is laid up and put in the oven then, the temperature is raised to a level which will be accordingly with the resin system being used. Once done that the autoclave is pressurized. The pressure on the laminate makes it compact and it is bringing down the void content during which the raised temperature reduces the gel time and the hardening period. After that, as soon as the resin has hardened the temperature is usually increased again to give a post cure. This method requires a large production run or regular use for one off , specialized moldings, to warrant the cost of the equipment.

Another method which rarely justifies its usage in boat building is the matched mold method. In its least complex form, to matching male and female molds are clamped and put together. Then, once the laminate has been laid up in the female part, the hole is evacuated by vacuum pump and the two parts of the mold are forced into a unified structure by atmospheric pressure. The vacuum and the pressure diminish the voids produced by air entrapment, give a very good fiber- to- resin ratio and provide a molding with a good appearance on both sides. The molds can be heated or placed in an oven to give a fast cure and high temperature post cure. On one hand the matched molds are used for resin injection and vacuum injection molding and on the other hand can be used with pre-preg laminates.

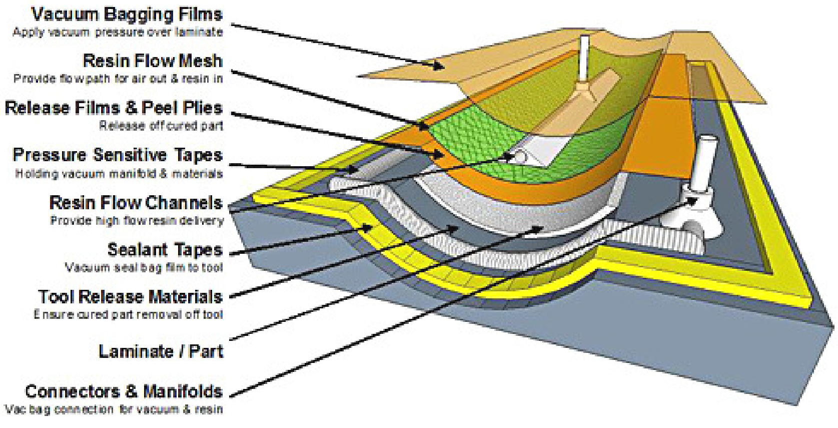

Figure 2.2 Vacuum infusion technique (Tygavac Ltd., n.d.)

2.7 LCA Software and Database

In this study, commercial software UMBERTO Carbon Footprint 1.2 and Ecoinvent v2.2 database have been used.

UMBERTO is the LCA software used in this study; it is a professional tool to store, analyse and monitor the environmental performance of products and services. By using this tool, complex life cycles can be modelled and analysed in a systematic and transparent way, following the ISO 14040 series recommendations.

Umberto Carbon Footprint has been launched in 2011 by Ifu Institut für Umweltinformatik Hamburg GmbH (ifu Hamburg). Umberto's features include (ifu Hamburg, n.d.):

- Graphical mapping of product life cycles in a network model.
- Network elements: process, input, output, content and Sankey arrow.
- Frame for structuring the life cycle model in phases.
- Gallery module with transport modules and for storing discrete areas of a life cycle model.
- Modeling of multi-product systems and allocation into individual products.
- Calculation of total flows, the product-related flows and CO_2 fluxes per product.
- Process specifications using input and output coefficients.
- Process specifications with the help of functions and parameters.
- Process specifications using generic materials.

The quality of input data is important for the credibility of the study. No matter how performant the methodology, it can never compensate for poor data input. The evaluation of data quality should (Lundquist et al., 2000):

- make as few assumptions and simplifications as possible;
- specify data sources, age and acquisition methods when possible;

- ensure that data on operations represent normal operating conditions;
- verify the reliability of in-house data by comparing to other sources;
- verify the reliability of externally-collected data by comparing several sources.

Special attention should be paid to conditions that are specific to the considered operations. As an example, very few industrial plants operate in isolation: some services, such as the treatment of water effluents and the provision of steam, are often common to several plants within the production site (Vidal, et al., 2008). If the distribution of these services is not well-defined, it can be very tricky to quantify the consumption of each plant or process. Furthermore, if a process produces several useful outputs, the consumption of energy and raw materials of the process must be distributed between these outputs in a rational and transparent.

2.7.1 Ecoinvent v2.2

The Ecoinvent v2.2 database was launched by the Ecoinvent Centre (originally called the Swiss Centre for Life Cycle Inventories). The Ecoinvent Centre, was created in 1997, is a Competence Centre of the Swiss Federal Institute of Technology Zürich (ETH Zurich) and Lausanne, the Paul Scherrer Institute (PSI), the Swiss Federal Laboratories for Materials Testing and Research (EMPA), and the Swiss Federal Research Station Agroscope Reckenholz-Tänikon (ART). Ecoinvent v2.2 database's features include (Swiss Centre For Life Cycle Inventories, n.d.):

- international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services.
- used by arround 4'500 users in more than 40 countries worldwide and is included in the leading LCA software tools as well as in various eco-design tools for building and construction, waste management or product design.

- a solution for data needs in Integrated Product Policy (IPP), Environmental Product Declaration (EPD), Life Cycle Assessment (LCA), Life Cycle Management (LCM), Design for Environment (DfE).

2.8 LCA Framework

The goal of the study is to define an LCA framework for boat building selection with FRP. The presented research aims to demonstrate how this framework can be used for boat building activity. This methodology incorporates the main processes for considered boat building methods. As stated before, the framework must be defined so that it can be used at an early stage of the conceptual design of a boat. To understand the potential impact of boat building to the environment when best implementedis another objective of the study.

The present study focuses on one material, Glass Reinforced Plastics (GRP) as FRP, and two boat building methods namely hand lay-up and vacuum infusion. For comparison the methods, a boat of 11 m, weighting almost 4000 kg hull has been considered. For the end of life scenarios: sanitary landfill, municipal incineration and granule extrusion processes have been assigned. All results calculated in CO_2kg Eq representing GWP_{100} (Global Warming Potential in 100 years).

The processes for the GRP hull in the LCA framework are:

- Gelcoat Manufacture and Transport
- Medium Density Fibreboard (MDF) Manufacture
- GRP Mould Manufacture
- GRP Hull Manufacture and Transport
- GRP Hull Consumer Use
- GRP Hull End of Life Scenarios

In the beginning of the analysis, IDs have been defined for each process in the related LCA framework (Table 2.1).

For input and output materials, a suitable data have been found in Ecoinvent v2.2 database. After this, desired amounts have been entered. The materials which couldn't be found in Ecoinvent v2.2 database, have been added manually (Table 2.2). With manual entry, the name, amount, unit and definition (indicate the product is an input or output) of material has been determined. Data from industry have been obtained from the boat builders in Izmir (Turkey). Because of this, while choosing the materials from Ecoinvent database the region has considered. For polyester resin, MDF, titanium dioxide, methyl ethyl ketone, transport lorry, glass-fiber reinforced hand lay-up and glass-fiber reinforced vacuum assisted moulding, the region of Europe has been chosen. Since Turkey purchases electricity from Bulgaria and disposal process of Trukey very simlar to Switzerland, these countries have been assigned in the related stage of the model.

Table 2.1 LCA process ID definition

Process Name	ID
Gel Coat Manufacture	T1
Disposal/Recycling	T2
Gel Coat Transport	T3
MDF Model Manufacture	T4
GRP Mould Manufacture	T5
GRP Hull Manufacture	T6
GRP Hull Transport	T7
Consumer Use	Use
GRP Hull (After Use) Transport	T8
Granule Cutting	T9
Granule Extruding	T10

Table 2.2 Database sources of materials

Source	**Material Name**	**Used For**
Ecoinvent v2.2	polyester resin, unsaturated, at plant [RER]*	Polyester Resin
	titanium dioxide, production mix, at plant [RER]	Titanium Dioxide
	silica sand, at plant [DE]**	Silica
	epoxy resin, liquid, at plant [RER]	Monomer (Epoxy Resin)
	liquid packaging , at plant [RER]	Barrel
	electricity mix [BG]	Electricity
	transport, lorry 3.5-7.5t, EURO4 [RER]	Transport
	medium density fibreboard [RER]	MDF
	glass fibre, at plant [RER]	Glass Fibre
	methyl ethyl ketone, at plant [RER]	Methyl Ethyl Ketone
	disposal, plastics, mixture, 15.3% water, to sanitary landfill [CH]***	Landfill
	disposal, municipal solid waste, 22.9% water, to municipal incineration [CH]	Incineration
	glass fibre reinforced plastic, injection moulding, at plant[RER]	Granule (Vacuum Infusion)
	glass fibre reinforced plastic, polyester resin, hand lay-up, at plant [RER]	Granule (Hand Lay-Up)
From the industry (Manually Entered)	GRP Hull(After Use)	GRP Hull
	GRP Hull	GRP Hull
	MDF Model (Disposal)	Disposal MDF Model
	Gelcoat (Disposal)	Disposal Gel Coat
	GRP Mould (Ready To Use)	GRP Mould
	Labor Force	Labor Force
	Gelcoat (Ready To Use)	Gelcoat
	Gel coat (Ready To Transfer)	Gelcoat
	MDF Model (Ready To Use)	MDF
*[RER] is the geographical code of Europe, **[BG] is the geographical code of Bulgaria ***[CH] is the geographical code of Switzerland		

2.9 LCA Framework : Hand Lay-Up Method

Table 2.3 Raw materials of the hand lay-up method LCA framework

Phase	Process	Material Definition	Material Name	Amount
Raw Materials	T1	Input	Polyester Resin (kg)	189
			Titanium dioxide (kg)	63
			Silica (kg)	9.45
			Monomer (kg)	53.55
			Barrel(kg)	36
			Electricity(kwh)	20
		Output	Gel coat (Ready To Transfer) (kg)	351
	T3	Input	Gel coat (Ready To Transfer) (kg)	351
			Transport (tkm)	228.15
		Output	Gel coat (Ready To Use) (kg)	351
	T4	Input	MDF (m^3)	4.5
			Electricity (kwh)	3909.30
			Labor Force (kcal)	2880000
		Output	MDF Model (Ready To Use) (m^3)	3.4
			Disposal MDF (m^3)	1.1
	T5	Input	MDF Model (Ready To Use) (m^3)	3.4
			Polyester Resin (kg)	1900
			Gel coat (Ready To Use) (kg)	151
			Electricity (kwh)	162.887
			Labor Force (kcal)	324000
			Glass Fibre (kg)	730
			Methyl Ethyl Ketone (kg)	10
		Output	Polyester Resin (Disposal) (kg)	19
			MDF Model (Disposal) (m^3)	3.4
			Gel coat (Disposal) (kg)	13.3
			Glass Fibre (Disposal) (kg)	14.6
			Barrel (Disposal) (kg)	18
			GRP Mould (Ready To Use) (kg)	2726.1

Table 2.4 Manufacture, distribution/retail and consumer use of materials

Phase	**Process**	**Material Definition**	**Material Name**	**Amount**
Manufacture	T6	Input	GRP Mould (Ready To Use) (kg)	2726.1
			Polyester Resin (kg)	2970
			Glass Fiber (kg)	1120
			Gel coat (Ready To Use) (kg)	200
			Methyl Ethyl Ketone (kg)	10
			Electricity (kwh)	325.775
			Labor Force (kcal)	1920000
		Output	GRP Hull (Ready To Transport) (kg)	4211.7
			Polyester Resin (Disposal) (kg)	29.7
			Gel coat (Disposal) (kg)	18.2
			Glass Fibre (Disposal) (kg)	22.4
			Barrel (Disposal) (kg)	18
			GRP Mould (Disposal) (kg)	2726.1
Distribution / Retail	T7	Input	GRP Hull (Ready To Transport) (kg)	4211.7
			Transport (tkm)	421.17
		Output	GRP Hull (Ready To Use) (kg)	4211.7
Consumer Use	Use	Input	GRP Hull (Ready To Use) (kg)	4211.7
		Output	GRP Hull (After Use) (kg)	4211.7

Table 2.5 Disposal/recycling of materials

Phase	Process	Material Definition	Material Name	Amount
Disposal /Recycling	T8 To Sanitary Landfill	Input	Transport(tkm)	2737.61
			GRP Hull (After Use) (kg)	4211.7
		Output	GRP Hull (Ready For Landfill) (kg)	4211.7
	Sanitary Landfill	Input	GRP Hull (Ready For Landfill) (kg)	4211.7
		Output	GRP Hull Landfill (kg)	4211.7
	T8 To Municipal Incineration	Input	Transport(tkm)	421.17
			GRP Hull (After Use) (kg)	4211.7
		Output	GRP Hull (Ready To Incinerate) (kg)	4211.7
	Incineration	Input	GRP Hull (Ready To Incinerate) (kg)	4211.7
		Output	GRP Hull Incinerated (kg)	4211.7
	T8	Input	Transport(tkm)	421.17
			GRP Hull (After Use) (kg)	4211.7
		Output	GRP Hull (Ready To Cut) (kg)	4211.7
	T9	Input	Electricity (kwh)	789.69
			GRP Hull (Ready To Cut) (kg)	4211.7
		Output	GRP Hull (Ready To Extrude) (kg)	4211.7
	T10	Input	Electricity (kwh)	280.78
			GRP Hull (Ready To Extrude) (kg)	4211.7
		Output	Granule (kg)	4211.7

2.9.1 Gelcoat Manufacture Process

Gelcoat produced by blending 60% Polyester Resin, 19% Titanium Dioxide, 2% Silica and 19% Monomer (Bauchet, et al., 2005). Industry data have considered for packaging barrel information and choosen two 220 kg of barrels (Poliya, 2012). One of the empty barrel’s weight is 18 kg (Ambalaj, 2003).

In Gelcoat production “Gelcoat (Ready To Transport)” product has become an output. Gelcoat (Ready To Transport) represents two unit of Gelcoat barrels which is ready to send to boat manufacturer.

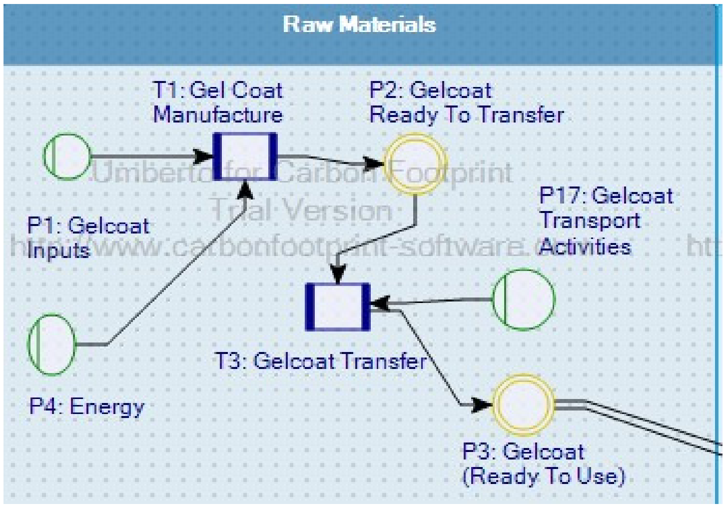

Figure 2.3 Gelcoat manufacture and transport process tree in software

2.9.2 Gelcoat Transport Process

In this study, for the transport scenario, the distance between gelcoat producer and boat manufacturer has been determined by considering a way of 650 km from producer to manufacturer. Euro4 lorryof 5t has been chosen for transportation (Panis, et al., 2007) Euro 4 has an emission rate according to 1970 Directive 70/220/EEC (Comission, 1970). To calculate the transportation amount a parameter has been defined with the variable "TDR" (Transport Distance Road). The quantity is 650 km for TDR. The formula for the road transportation is:

$$\text{Transport (tkm)}=\frac{\text{TDR x The Gel coat (Ready To Transfer)Amount}}{1000} \qquad \text{(Equation 2.1)}$$

$$\text{Transport (tkm)}=\frac{650 \text{ x } 351}{1000}$$

After production, gelcoat has been transported to boat builder and became a Gelcoat (Ready To Use) output.

2.9.3 MDF Manufacture Process

MDF Model Manufacture has been done by boat builder. MDF is a type of hardboard, which is made from wood fibres glued under heat and pressure (Design Technology, 2012). For this process, MDF, electricity and labor force is needed. According to literature, a worker uses 3000 kcal for the work in one day (8 hours) (Beyhan, 2008). Labor force (kcal) is calculated according to this rate. In this study, according to average industry values, the labor force has calculated for two workers and totally 3840 hours.

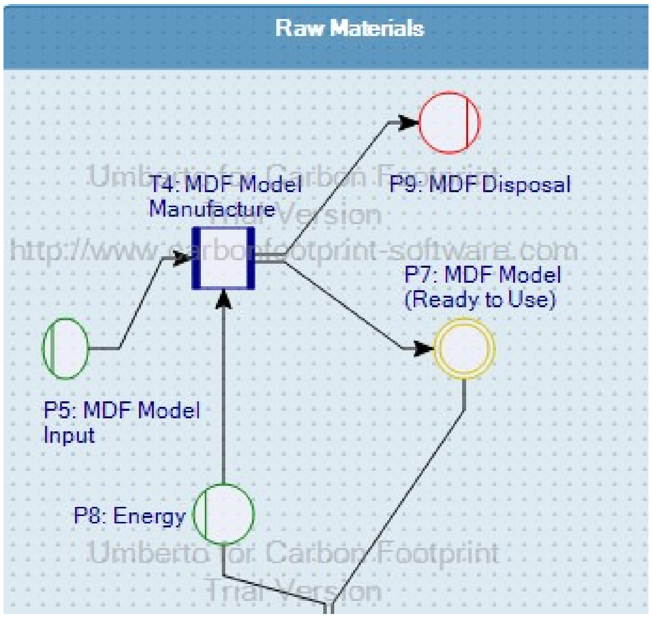

Figure 2.4 MDF manufacture process tree

$$\text{Labor Force (kcal)}=3000 \text{ x } \frac{\text{Working Hours}}{8} \text{ x Number of Workers} \quad \text{(Eq 2.2)}$$

$$\text{Labor Force (kcal)}=3000 \text{ x } \frac{3840}{8} \text{ x } 2$$

From MDF Manufacture process, 1.1 m^3 of MDF disposal and 3.4 m^3 of MDF model has become as outputs. MDF Model is being used for the GRP mould manufacture.

2.9.4 GRP Mould Manufacture Process

GRP mould manufacture is also a hand lay-up process. By using polyester resin, glass fibre and gelcoat, GRP mould has been produced by using MDF model. For this process, methyl-ethyl ketone (MEK) has been used to separate the GRP mould from the MDF model. MEK is a sharp, colorless, liquid ketonehas with sweet odor of reminiscent of butterscotch and acetone. It is produced industrially on a large scale, and also occurs in trace amounts in the nature. It is soluble in the water and is commonly used as an industrial solvent (Lacovara, et al., 1997) For this process 6 workers have been worked for 144 hours (Eq. 2.2).

$$\text{Labor Force (kcal)}=3000 \text{ x } \frac{144}{8} \text{ x } 6$$

After GRP mould manufacture process, 1% of polyester resin, 2% of glass fibre, 1% of gel coat, 100% of MDF Model and one of gelcoat barrel of 18kg have been become disposal (Ambalaj, 2003).

2.9.5 GRP Hull Manufacture Process

This process is the main process for the hand lay-up boat building method. After this process, the GRP hull is prepared for transport. Similar to the GRP mould manufacture outputs, 1% polyester resin, 2% glass fibre and 1% gel coat and one empty barrel of 18 kg have become disposal. Although, there are chances to re-use GRP mould but for this study this product has been accepted as a disposal after production.

For this process, 4 workers have worked for 1280 hours (Eq 2.2).

$$\text{Labor Force (kcal)} = 3000 \text{ x } \frac{1280}{8} \text{ x } 4$$

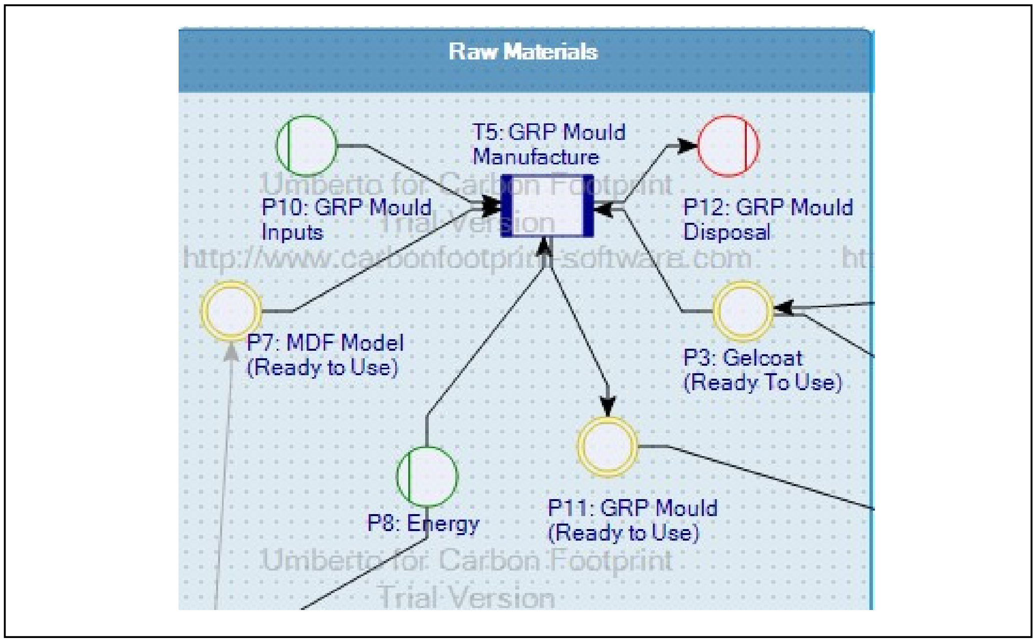

Figure 2.5 GRP mould manufacture process tree

2.9.6 GRP Hull Transport Process

Now the 4211.7 kg of GRP hull is ready to transport. To calculate the transport amount a TDR parameter has defined. The quantity is 100 km for TDR. The formula for the road transport is (Eq. 2.1):

$$\text{Transport (tkm)} = \frac{100 \text{ x } 4211.7}{1000}$$

For transport, a Euro 4 lorry vehicle of the 3.5 – 7.5 tof capacity has been choosen.

2.9.7 Consumer Use Process

In this study GRP hull is the only focused part of a boat. The GRP hull consumer use process is the process where the functional unit (reference unit) is assigned. To calculate the total CO_2 kg Eq. for the all manufacture processes for the GRP hull, GRP hull (ready to use) is defined as functional unit. To define the functional unit as GRP hull (ready to use) means the all LCA framework is set for this product.

After GRP hull consumer use process, the same amount of the GRP hull will be an output for the process. Because, for its life time, GRP hull is a material that cannot be consume by the consumers. GRP hull consumer use process output material is a reference flow for this study. "*The reference flows translate the abstract functional unit into specific product flows for each of the compared systems, so that product alternatives are compared on an equivalent basis, reflecting the actual consequences of the potential product substitution. The reference flows are the starting points for building the necessary models of the product systems*" (Wenzel & Petersen, 2004).

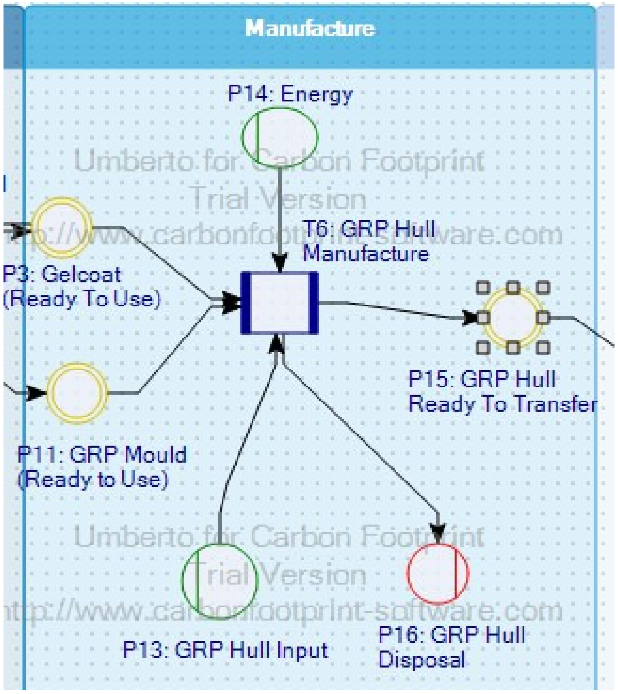

Figure 2.6 GRP hull manufacture process tree

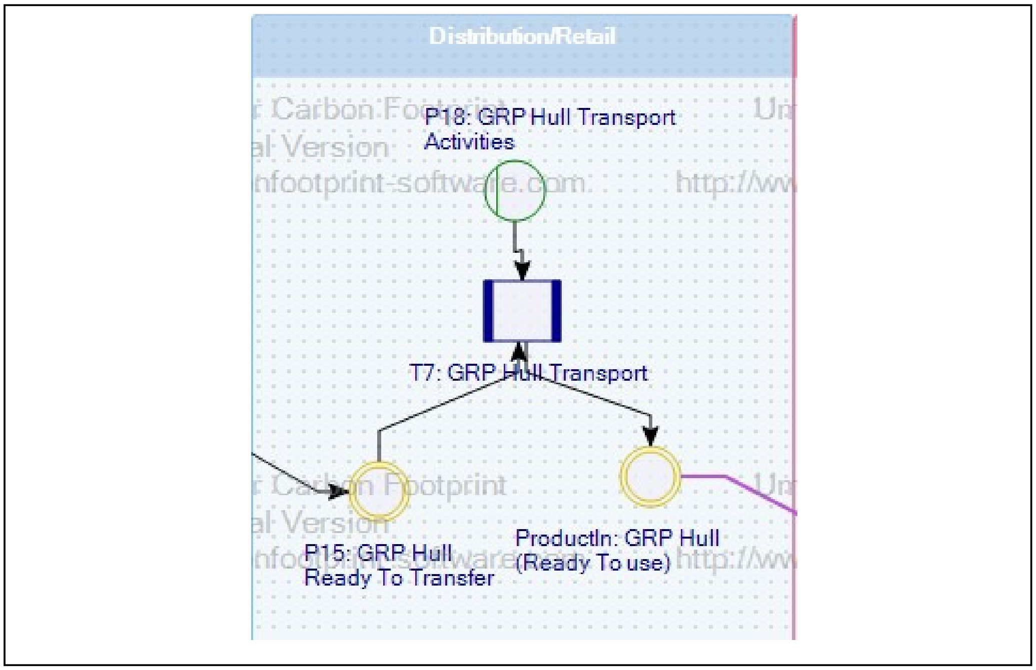

Figure 2.7 GRP hull transport process tree

For the GRP hull, three end of life scenarios has considered.

- To the sanitary landfill
- To the municipal incineration
- To the extrusion facility

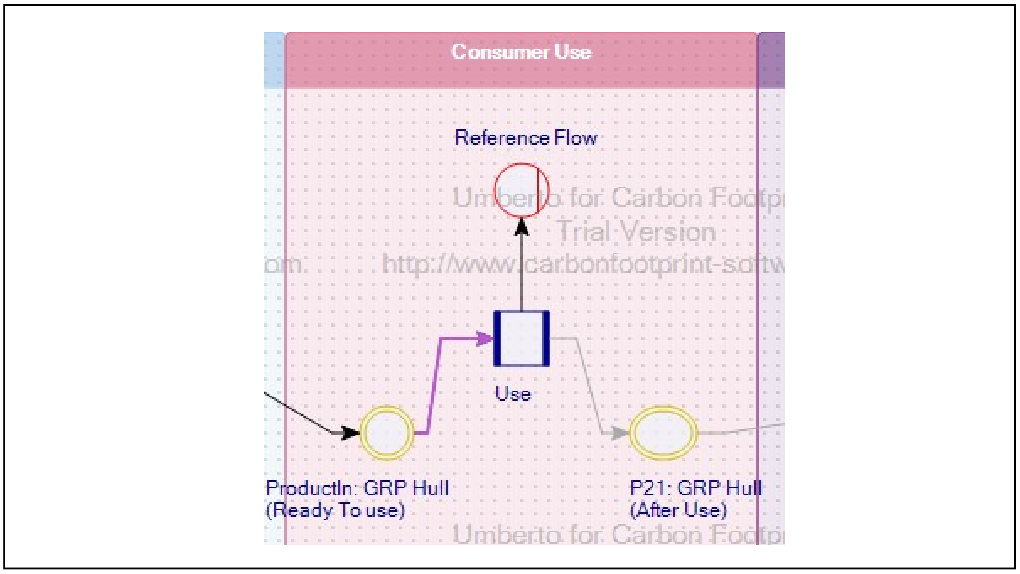

Figure 2.8 Consumer use process tree

2.9.8 GRP Hull (After Use) Transport To Sanitary Landfill Process

For the transport of the GRP hull (after use) to the sanitary landfill, the transport amount a “transport distance waste” (TDW) parameter has defined. The quantity is 650 km for TDW. The formula for the road transport is (Eq. 2.1):

$$\text{Transport (tkm)} = \frac{650 \text{ x } 4211.7}{1000}$$

For transport, a Euro 4 lorry vehicle of the 3.5 – 7.5 tof capacity has been choosen.

2.9.9 Landfill Process

After 650 km road, GRP hull (after use) has become available for the landfill process.

For the sanitary landfill process from the Ecoinvent v2.2 database “disposal, plastics, mixture to sanitary landfill” material is used. In the end of this “end of life scenario” the landfill emission calculation is done for the 4211.7 kg of GRP hull.

2.9.10 GRP Hull (After Use) Transport To Incineration Process

For the transportation of the GRP hull (after use) to the municipal incineration facility, the transport amount indicating by a TDW parameter has defined. The quantity is 100 km for TDW. The equationa for the road transport is (Eq 2.1):

$$\text{Transport (tkm)} = \frac{100 \text{ x } 4211.7}{1000}$$

For transport vehicle a 3.5 – 7.5 t Euro 4 lorry has choosen.

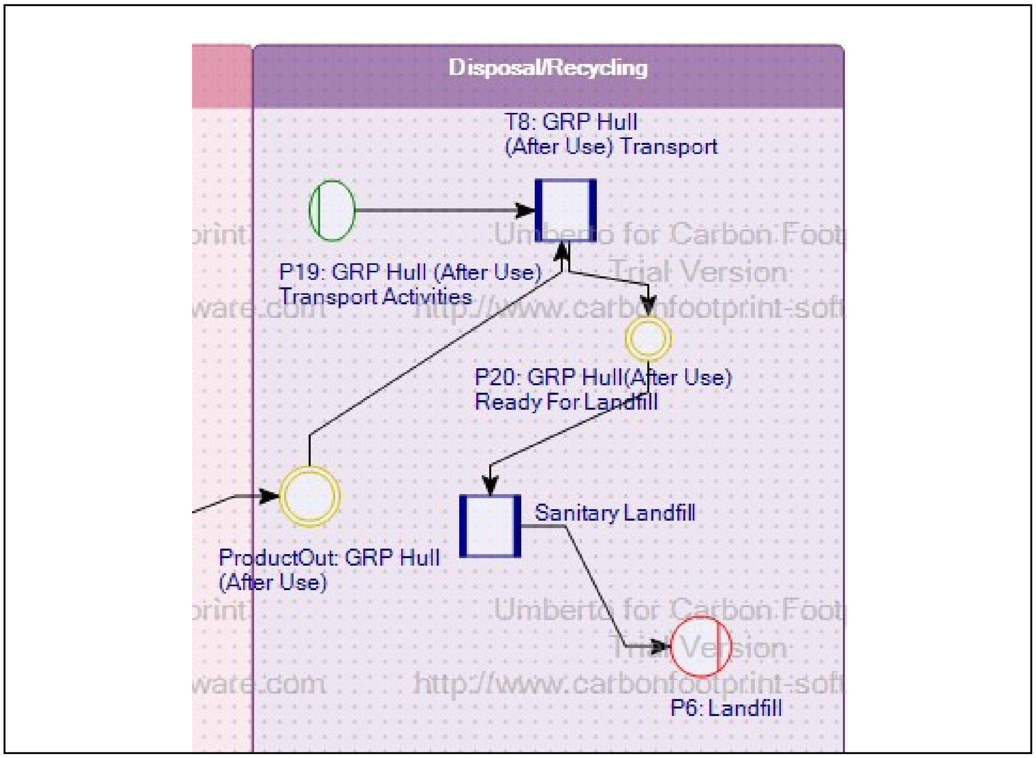

Figure 2.9 GRP landfill process tree

2.9.11 Incineration Process

After 100 km transport, GRP hull (after use) has become available for the incineration process.

For the municipal incineration process from the Ecoinvent v2.2 database “disposal, municipal solid waste to municipal incineration” material is used. In the end of this “end of life scenario” the incineration emission calculation is done for the 4211.7 kg of GRP hull.

2.9.12 GRP Hull (After Use) Transport To Extrude Process

For the transport the GRP hull (after use) to extrude the transport amount a TDW parameter has defined. The quantity is 100 km for TDW. The formula for the road transport is (Eq. 2.1):

$$\text{Transport (tkm)} = \frac{100 \times 4211.7}{1000}$$

For transport, a Euro 4 lorry vehicle of the 3.5 – 7.5 tof capacity has been choosen.

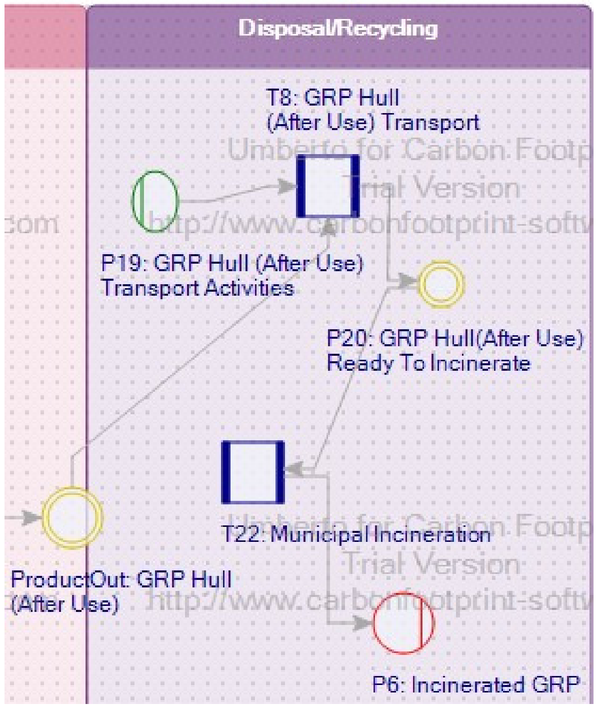

Figure 2.10 GRP incineration process tree

2.9.13 Cutting Process

GRP hull is become ready to cut after extruding process. For cutting process a granule cutting machine is used which has 1500 kg/h capacity and uses 100 kw per hour (Makina, 2004).

2.9.14 Extruding Process

After 100 km transportation, GRP hull (after use) has become available to extrude. For extruding process, a granule extruder machine is used which has 800 kg/h capacity and uses 150 kw per hour (Makina, 2004). For the granule extruding process from the Ecoinvent v2.2 database “glass fibre reinforced plastic, polyester resin, hand lay-up, at plant [RER]” material is used.

In the end of this “end of life scenario” the extruding and cutting emission calculation is done for the 4211.7 kg of GRP hull.

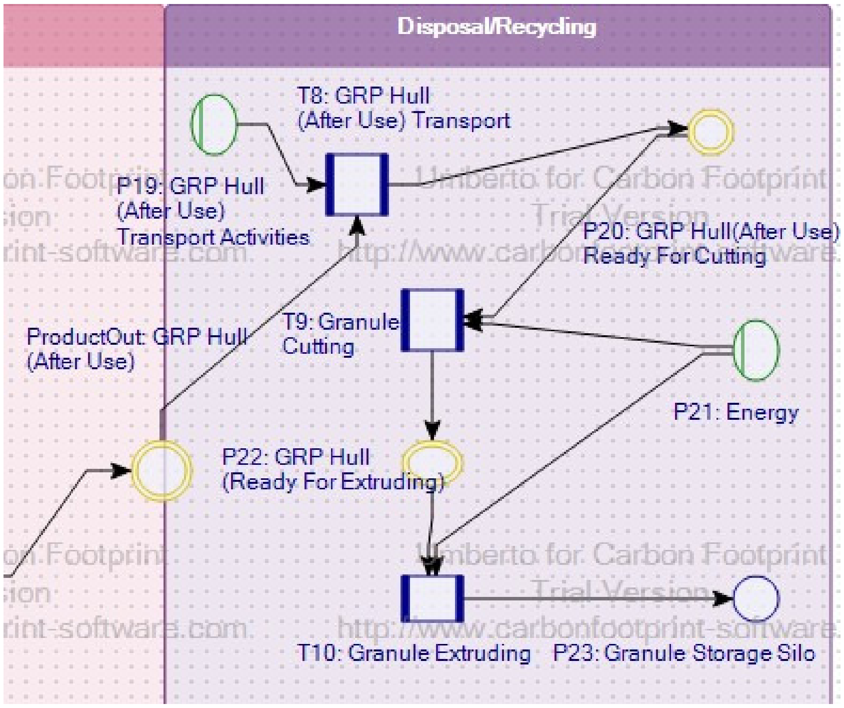

Figure 2.11 GRP cutting&extruding process tree

2.10 LCA Framework: Vacuum Infusion Method

In this study to compare the boat building methods, same material has chosen. Because of this, except the main hull manufacture process previous processes are same as in the hand lay-up method.

Table 2.6 Manufacture, distribution/retail and consumer use phases of the vacuum infusion method LCA framework

Phase	Process	Material Definition	Material Name	Amount
Manufacture	T6	Input	GRP Mould (Ready To Use) (kg)	2726.1
			Polyester Resin (kg)	1227
			Glass Fiber (kg)	2863
			Gel coat (Ready To Use) (kg)	200
			Methyl Ethyl Ketone (kg)	10
			Electricity (kwh)	1303.1
			Labor Force (kcal)	120000
		Output	GRP Hull (Ready To Transport) (kg)	4194.27
			Polyester Resin (Disposal) (kg)	12.27
			Gel coat (Disposal) (kg)	18.2
			Glass Fibre (Disposal) (kg)	57.27
			Barrel (Disposal) (kg)	18
			GRP Mould (Disposal) (kg)	2726.1
Distribution / Retail	T7	Input	GRP Hull (Ready To Transport) (kg)	4194.27
			Transport (tkm)	419.42
		Output	GRP Hull (Ready To Use) (kg)	4194.27
Consumer Use	Use	Input	GRP Hull (Ready To Use) (kg)	4194.27
		Output	GRP Hull (After Use) (kg)	4194.27

2.10.1 GRP Hull Manufacture Process

For the GRP hull manufacture by using the vacuum infusion methods 1303.1 kwh electricity has been used and 2 workers have worked for 160 hours (Eq 2.2).

$$\text{Labor Force (kcal)}=3000 \text{ x } \frac{160}{8} \text{ x } 2$$

This process is the basic one for the vacuum infusion boat building method. After this process the GRP hull is prepared for transport. 1% polyester resin, 2% glass fibre and 1% gelcoat and one empty barrel (18 kg) have become disposal. There are chances to re-use GRP mould but for this study it is accepted as a disposal after production.

Table 2.7 Disposal/recycling phase of the vacuum infusion LCA framework

Phase	Process	Material Definition	Material Name	Amount
Disposal /Recycling	T8 To Sanitary Landfill	Input	Transport(tkm)	2725.62
			GRP Hull (After Use) (kg)	4194.27
		Output	GRP Hull (Ready For Landfill) (kg)	4194.27
	Sanitary Landfill	Input	GRP Hull (Ready For Landfill) (kg)	4194.27
		Output	GRP Hull Landfill (kg)	4194.27
	T8 To Municipal Incineration	Input	Transport(tkm)	419.42
			GRP Hull (After Use) (kg)	4194.27
		Output	GRP Hull (Ready To Incinerate) (kg)	4194.27
	Incineration	Input	GRP Hull (Ready To Incinerate) (kg)	4194.27
		Output	GRP Hull Incinerated (kg)	4194.27
	T8	Input	Transport(tkm)	419.42
			GRP Hull (After Use) (kg)	4194.27
		Output	GRP Hull (Ready To Cut) (kg)	4194.27
	T9	Input	Electricity (kwh)	787.81
			GRP Hull (Ready To Cut) (kg)	4194.27
		Output	GRP Hull (Ready To Extrude) (kg)	4194.27
	T10	Input	Electricity (kwh)	280.11
			GRP Hull (Ready To Extrude) (kg)	4194.27
		Output	Granule (kg)	4194.27

2.10.2 GRP Hull (Ready To Use) Transport Process

Now the 4194.27 kg GRP hull is ready to transport. To calculate the transport amount a TDR parameter has defined. The quantity is 100 km for TDR. The formula for the road transport is (Eq. 2.1.):

$$\text{Transport (tkm)}= \frac{100 \text{ x } 4194.27}{1000}$$

For transport, a Euro 4 lorry vehicle of the 3.5 – 7.5 tof capacity has been choosen.

2.10.3 Consumer Use Process

After 100 km road, GRP hull reached to consumer and became ready to use.

As mentioned in hand lay-up method (2.12.7 Consumer Use) GRP hull is also a functional unit for vacuum infusion method LCA framework.

To compare the end of life scenarios for the GRP hull same processes have been considered with hand lay-up method.

2.10.4 GRP Hull (After Use) Transport To Sanitary Landfill

For the transport of the GRP hull (after use) to the sanitary landfill, the transport amount a TDR parameter has defined. The quantity is 650 km for TDR. The formula for the road transport is (Eq. 2.1):

$$\text{Transport (tkm)}= \frac{650 \text{ x } 4194.27}{1000}$$

For transport, a Euro 4 lorry vehicle of the 3.5 – 7.5 tof capacity has been choosen.

2.10.5 Landfill Process

After 650 km road, GRP hull (after use) has become available for the landfill process.

For the sanitary landfill process from the Ecoinvent v2.2 database “disposal, plastics, mixture to sanitary landfill” material is used. In the end of this “end of life scenario” the landfill emission calculation is done for the 4194.27 kg of GRP hull.

2.10.6 GRP Hull (After Use) Transport To Incineration Process

For the transportation of the GRP hull (after use) to the municipal incineration facility, the transport amount indicating by a TDW parameter has defined. The quantity is 100 km for TDW. The equation for the road transport is (Eq. 2.1.):

$$\text{Transport (tkm)}= \frac{100 \text{ x } 4194.27}{1000}$$

For transport, a Euro 4 lorry vehicle of the 3.5 – 7.5 tof capacity has been choosen.

2.10.7 Incineration Process

After 100 km road, GRP hull (after use) has become available for the incineration process.

For the municipal incineration process from the ecoinvent v2.2 database “disposal, municipal solid waste to municipal incineration” material is used. In the end of this “end of life scenario” the incineration emission calculation is done for the 4194.27 kg of GRP hull.

2.10.8 GRP Hull (After Use) Transport To Extrude Process

For the transport the GRP hull (after use) to extrude the transport amount indicating by TDW parameter has defined. The quantity is 100 km for TDW. The formula for the road transport is (Eq. 2.1):

$$\text{Transport (tkm)} = \frac{100 \times 4194.27}{1000}$$

For transport, a Euro 4 lorry vehicle of the 3.5 – 7.5 tof capacity has been choosen.

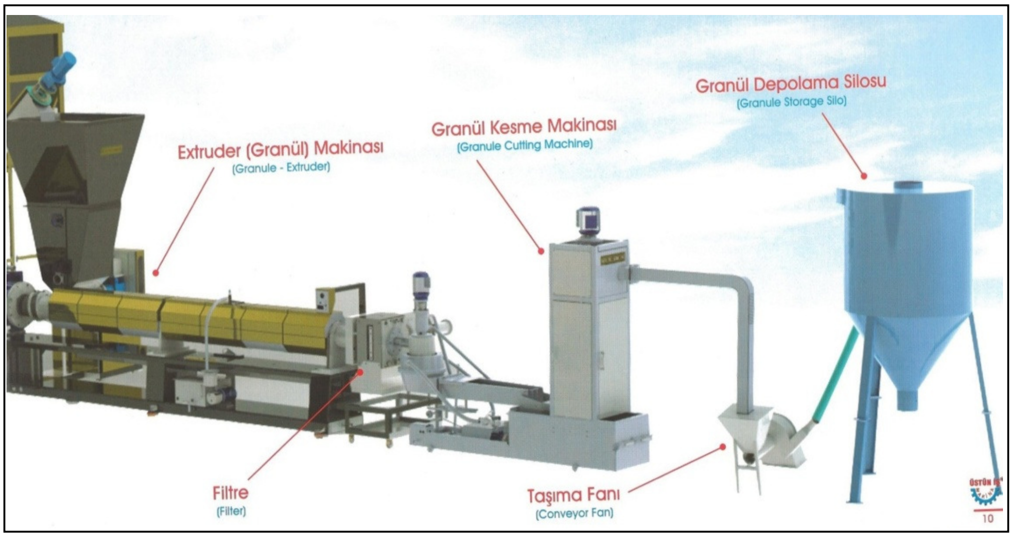

Figure 2.12 Extruding and cutting processes of GRP

2.13.1 Cutting Process

GRP hull is become ready to cut after extruding process.

For cutting process a granule cutting machine is used which has 1500 kgh capacity and uses 100 kw electricity per hour (Makina, 2004).

2.13.2 Extruding Process

After 100 km road GRP hull (after use) has become available to extrude.

For extruding process a granule extruder machine is used which has 800 kg/h capacity and uses 150 kw per hour (Makina, 2004).

For the granule extruding process from the Ecoinvent v2.2 database “glass fibre reinforced plastic, polyamide, injection moulding, at plant [RER]” material is used. In the end of this “end of life scenario” the extruding and cutting emission calculation is done for the 4193.27 kg of GRP hull.

After this process GRP hull stored in a granule silo to re-use in different areas.

CHAPTER THREE
RESULTS

3.1 Hand Lay-Up Method Results

Table 3.1 Emissions from one kg of GRP hull

Emissions for one kg of GRP Hull				
Phase	Emission Source	Process Place	Material Name	Quantity (kg CO_2 –eq)
Raw Materials	Resources and Energy Consumption	T1	Electricity	3.04E-03
			Monomer(Epoxy Resin)	0.09
			Silica	4.72E-05
			Polyester Resin	0.34
			Barrel	5.09E-03
			Titanium Dioxide	0.07
		T3	Transport	0.03
		T4	MDF	0.54
			Electricity	0.59
		T5	Methy Ethyl Ketone	4.19E-03
			Polyester Resin	3.3
			Glass Fibre	0.46
			Electricity	0.02
	Waste of Disposal	T4	MDF	0.13
		T5	Barrel	0.03
			Glass Fibre	9.14E-03
			Polyester Resin	0.03
Manufacture	Resources and Energy Consumption	T6	Electricity	0.05
			Polyester Resin	5.27
			Methyl Ethyl Ketone	4.19E-03
			Glass Fibre	0.70
	Waste of Disposal	T6	Polyester Resin	0.05
			Glass Fibre	0.01
			Barrel	2.55E-03
Distribution/ Retail	Resources and Energy Consumption	T7	Transport	0.05

Table 3.2 Input and output material quantities for one kg of GRP hull

	Process Place	Material Name	Landfill Quantity	Incineration Quantity	Extruding Quantity
Input Materials	T1	Electricity(kwh)	4.75E-03		
		Monomer(kg)	0.01		
		Barrel (kg)	8.55E-03		
		Polyester Resin (kg)	0.04		
		Silica (kg)	2.24E-03		
		Titanium Dioxide (kg)	0.01		
	T3	Transport (tkm)	0.05		
	T4	Electricity(kwh)	0.93		
		Labor Force (kcal)	683.81		
		MDF (m^3)	1.071E-0.3		
	T5	Electricity(kwh)	0.04		
		Glass fibre(kg)	0.17		
		Labor Force (kcal)	76.93		
		Methyl Ethyl Ketone(kg)	2.37E-03		
		Polyester Resin (kg)	0.45		
	T6	Electricity(kwh)	0.31		
		Glass fibre(kg)	0.68		
		Labor Force (kcal)	28.61		
		Methyl Ethyl Ketone (kg)	2.37E-03		
		Polyester Resin (kg)	0.29		
	T7	Transport (tkm)	0.10		
	T8	Transport(tkm)	0.65	0.10	0.10
	T9	Electricity(kwh)	-	-	0.19
	T10	Electricity(kwh)	-	-	0.03
Output Materials	T2	Disposal,sanitary landfill (kg)	1	-	-
	Use	GRP Hull(kg)	-	-	1
	T2	Disposal,municipal incineration(kg)	-	1	-
	T4	MDF(m^3)	2.61E-04		
	T5	Gelcoat(kg)	3.16E-03		
		Glass fibre(kg)	3.47E-03		
		Barrel(kg)	4.27E-03		
		MDF Model(m^3)	8.07E-04		
		Polyester Resin (kg)	4.51E-03		
	T6	Gelcoat(kg)	4.32E-03		
		Glass Fibre(kg)	0.01		
		Barrel(kg)	4.27E-03		
		GRP Mould(kg)	0.65		
		Polyester Resin (kg)	2.93E-03		

The GRP hull is the functional unit of this study. Because of this, for all results "one kg of GRP hull" is defined as the reference unit. Table 3.1 shows all emission quantities has shown for functional unit.

To get the kg CO_2-eq emission results, all input and output materials have scaled for the functional unit. Table 3.2 shows the total required quantities.

The disposal/recycling phase calculations have been done for the three different end of life scenarios.

Table 3.3 Emission quantities for the end of life scenario

Phase	Emission Source	Process Place	Material Name	Quantity (kg CO_2 –eq)
Landfill	Waste Disposal	T2	GRP Hull Landfill	0.09
	Resources and Energy Consumption	T8	Transport	0.30
Incineration	Waste Disposal	T2	GRP Hull Incineration	0.50
	Resources and Energy Consumption	T8	Transport	0.05
Extruding	Resources and Energy Consumption	T8	Transport	0.05
		T9	Electricity	0.12
		T10	Electricity	0.02

Figure 3.1 shows the shares of GWP_{100} results, for different end of life scenarios.

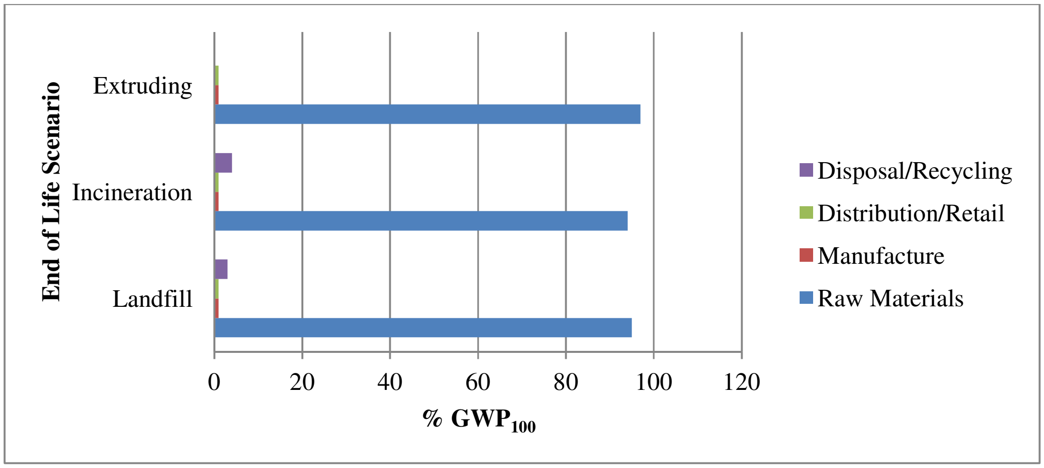

Figure 3.1 Shares of GWP_{100} impacts for different end of life scenarios

Figure 3.2 shows the comparison of the GWP_{100} results for the all LCA framework according to different end of life scenarios.

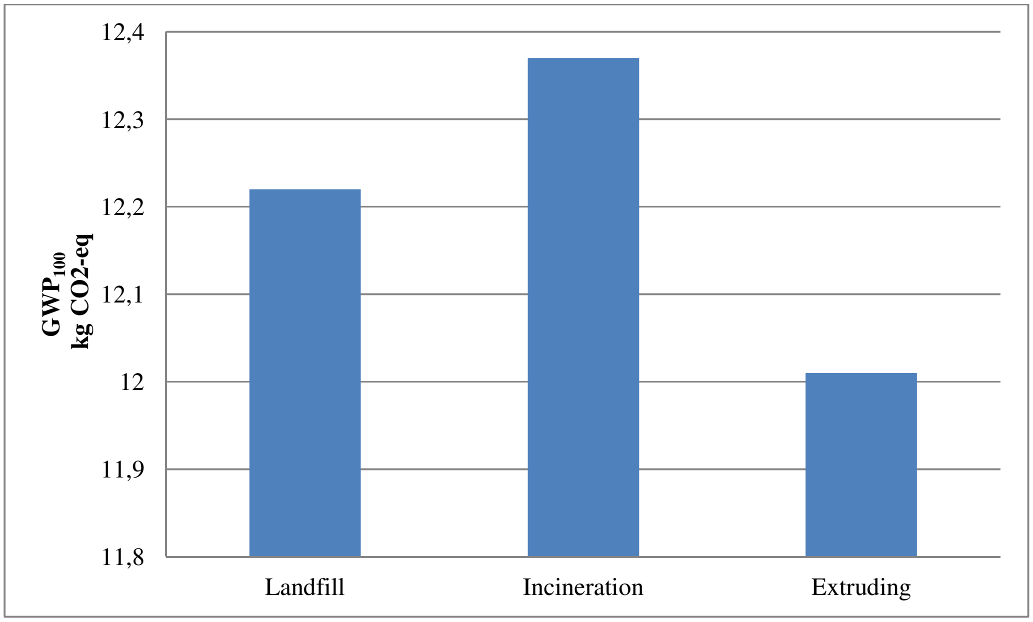

Figure 3.2 Hand lay-up method LCA results for different end of life scenarios

Figure 3.3 shows the comparison of the GWP_{100} results for the disposal/recycling phase in LCA framework for hand lay-up method, according to different end of life scenarios.

Figure 3.4 shows the comparison between two GRP hulls. One of the GRP hulls is calculated in this study and its weight is 4211.7 kg. The other one is 3000 kg (Landamore et al., 2006).

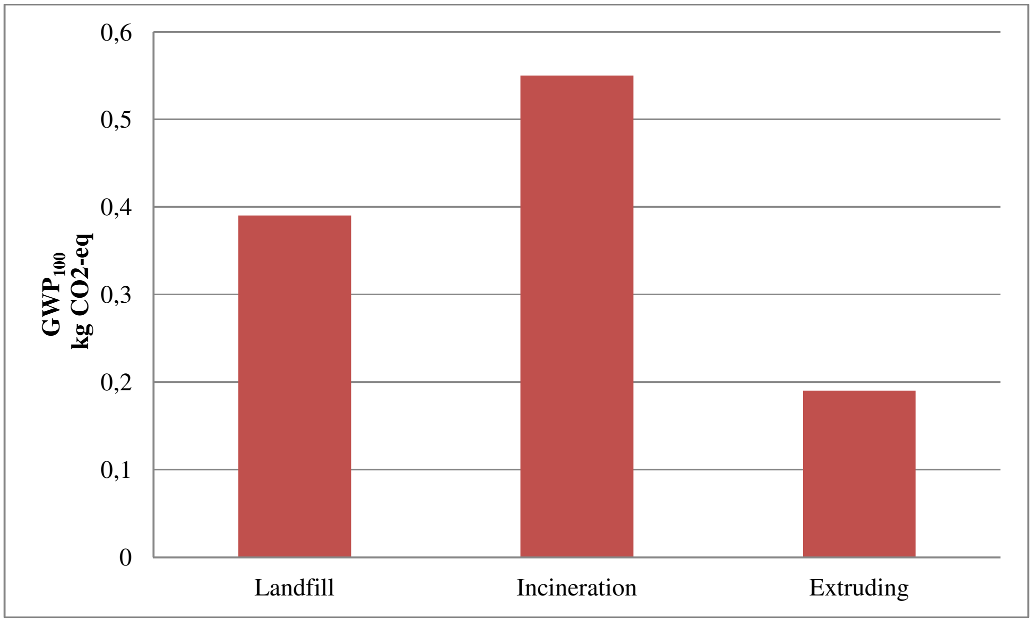

Figure 3.3 Disposal/recycling phase results for hand lay-up method

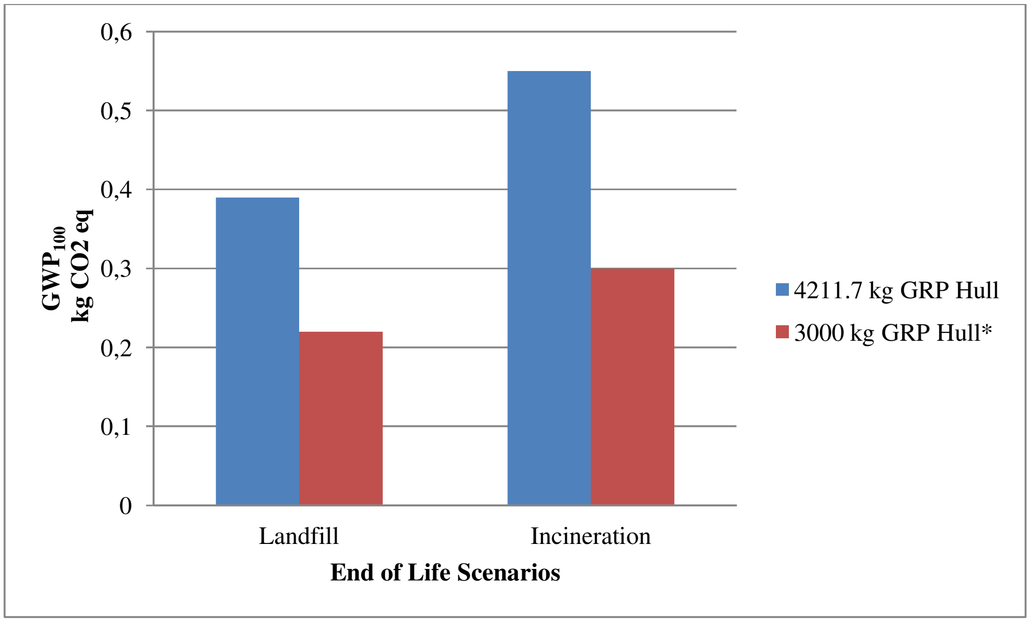

Figure 3.4 Comparison of GWP_{100} results according to the different end of life scenarios between this thesis and (*) life cycle and cost-benefit analysis of selected technologies for sustainable inland boating study (M. Landamore et al., 2006)

3.2 Vacuum Infusion Method Results

Table 3.4 Emission quantities for one kg of GRP hull

Emissions for one kg of GRP Hull				
Phase	Emission Source	Process Place	Material Name	Quantity (kg CO_2 –eq)
Raw Materials	Resources and Energy Consumption	T1	Electricity	3.06E-03
			Monomer(Epoxy Resin)	0.09
			Silica	4.74E-05
			Polyester Resin	0.34
			Barrel	5.12E-03
			Titanium Dioxide	0.07
		T3	Transport	0.03
		T4	MDF	0.54
			Electricity	0.59
		T5	Methy Ethyl Ketone	4.19E-03
			Polyester Resin	3.3
			Glass Fibre	0.46
			Electricity	0.02
	Waste of Disposal	T4	MDF	0.13
		T5	Barrel	2.56E-03
			Glass Fibre	9.17E-03
			Polyester Resin	0.03
Manufacture	Resources and Energy Consumption	T6	Electricity	0.20
			Polyester Resin	2.19
			Methyl Ethyl Ketone	4.21E-03
			Glass Fibre	1.80
	Waste of Disposal	T6	Polyester Resin	0.02
			Glass Fibre	0.04
			Barrel	2.55E-03
Distribution/ Retail	Resources and Energy Consumption	T7	Transport	0.05

Table 3.5 Input and output material quantities for one kg of GRP hull

	Process Place	Material Name	Landfill Quantity	Incineration Quantity	Extruding Quantity
Input Materials	T1	Electricity(kwh)	4.75E-03		
		Monomer(kg)	0.01		
		Barrel (kg)	8.55E-03		
		Polyester Resin (kg)	0.04		
		Silica (kg)	2.24E-03		
		Titanium Dioxide (kg)	0.01		
	T3	Transport (tkm)	0.05		
	T4	Electricity(kwh)	0.93		
		Labor Force (kcal)	683.81		
		MDF (m^3)	1.071E-0.3		
	T5	Electricity(kwh)	0.04		
		Glass fibre(kg)	0.17		
		Labor Force (kcal)	76.93		
		Methyl Ethyl Ketone(kg)	2.37E-03		
		Polyester Resin (kg)	0.45		
	T6	Electricity(kwh)	0.31		
		Glass fibre(kg)	0.68		
		Labor Force (kcal)	28.61		
		Methyl Ethyl Ketone (kg)	2.37E-03		
		Polyester Resin (kg)	0.29		
	T7	Transport (tkm)	0.10		
	T8	Transport(tkm)	0.65	0.10	0.10
	T9	Electricity(kwh)	-	-	0.19
	T10	Electricity(kwh)	-	-	0.03
Output Materials	T2	Disposal,sanitary landfill (kg)	1	-	-
	Use	GRP Hull(kg)	-	-	1
	T2	Disposal,municipal incineration(kg)	-	1	-
	T4	MDF(m^3)	2.61E-04		
	T5	Gelcoat(kg)	3.16E-03		
		Glass fibre(kg)	3.47E-03		
		Barrel(kg)	4.27E-03		
		MDF Model(m^3)	8.07E-04		
		Polyester Resin (kg)	4.51E-03		
	T6	Gelcoat(kg)	4.32E-03		
		Glass Fibre(kg)	0.01		
		Barrel(kg)	4.27E-03		
		GRP Mould(kg)	0.65		
		Polyester Resin (kg)	2.93E-03		

Table 3.6 Emission quantities for the end of life scenarios

Phase	Emission Source	Process Place	Material Name	Quantity (kg CO_2 –eq)
Landfill	Waste Disposal	T2	GRP Hull Landfill	0.09
	Resources and Energy Consumption	T8	Transport	0.30
Incineration	Waste Disposal	T2	GRP Hull Incineration	0.50
	Resources and Energy Consumption	T8	Transport	0.05
Extruding	Resources and Energy Consumption	T8	Transport	0.05
		T9	Electricity	0.12
		T10	Electricity	0.02

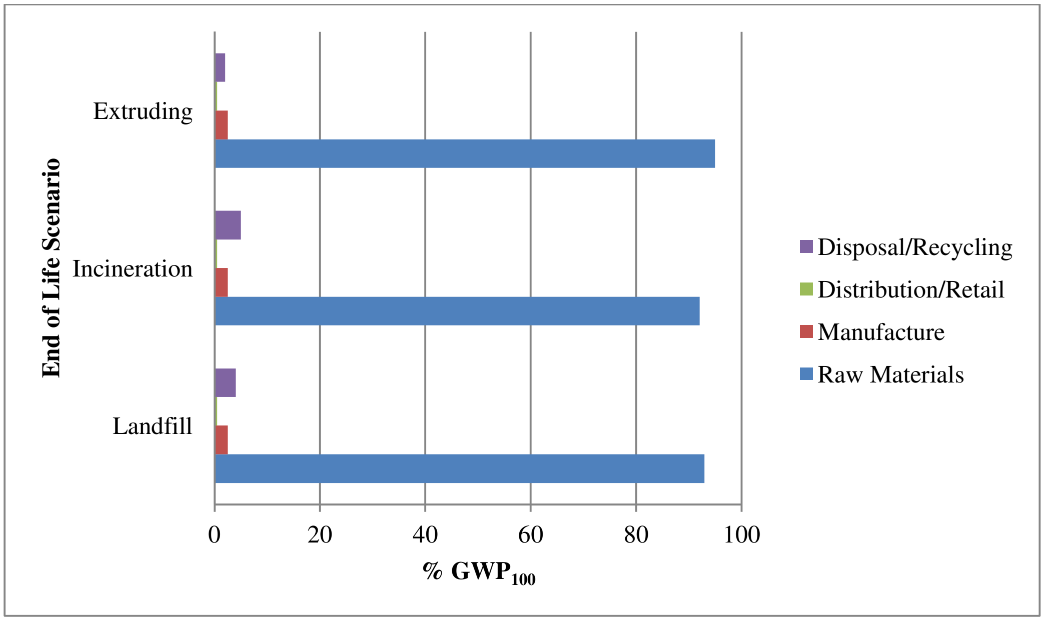

Figure 3.5 Share of GWP_{100} impacts for different end of life scenarios

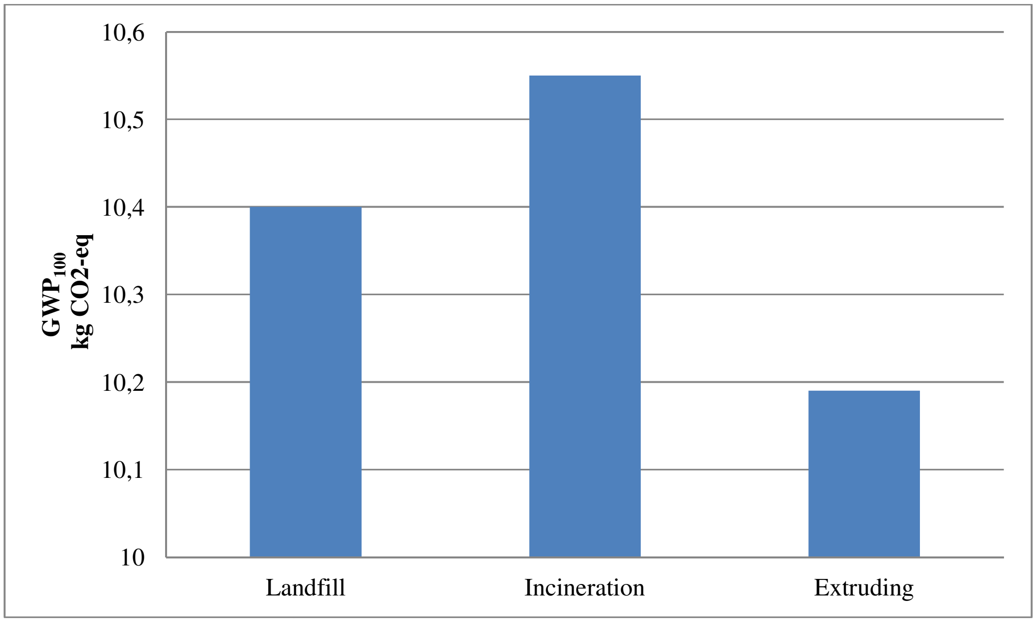

Figure 3.6 Vacuum infusion method LCA results for different end of life scenarios

In this study, three different end of life cycle scenarios(landfill, incineration and extruding) have been calculated for hand lay-up and vacuum infusion boat building methods. Figure 3.7 shows the comparison of the GWP_{100} results for these scenarios.

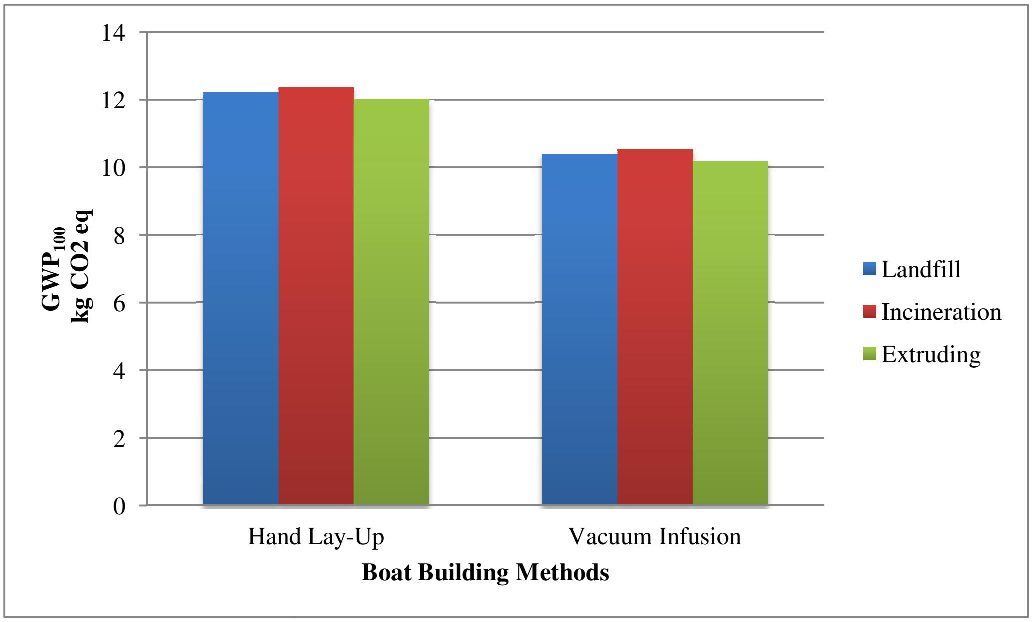

Figure 3.7 Comparison of GWP_{100} results between hand lay-up and vacuum infusion method

CHAPTER FOUR

DISCUSSION AND CONCLUSIONS

The objective was to develop a proper framework for deciding boat building method by using LCA. In this study these system boundaries have been used for LCA framework: Glass Reinforced Plastics(GRP) as FRP and two boat building methods: Hand Lay-Up and Vacuum Infusion. For comparison between boat building methods, a hull of 11m in length and almost 4000 kg in weight has been considered. For the end of life scenarios: sanitary landfill, municipal incineration and granule extrusion processes have been choosen. All results have been presented in CO_2kg eq for GWP_{100}.

In this study emissions recorded for the raw materials, manufacture, distribution/retail and the disposal/recycling phases. There are no emissions or impacts recorded for the hulls during the consumer use phase; it could be stated that the hulls are inert objects in the environment during their life time. Therefore, raw materials and disposal/recycling phases, which have the main impact on GWP_{100} emissions, are of importance of this study.

Table 3.1 and 3.4 show all emissions quantities for one kg of GRP hull, which is functional unit for this study, for raw materials, manufacture and distribution/retail phases. Figures 3.1 and 3.5 shows that raw materials phase have the biggest percentage on emissions for all the end of life cycle scenarios for both methods. It is observed that in raw materials part polyester resin and glass fibre usage percents effect the result more than 2 kg CO_2 eq. This could be reduced if the polyester resin percentage could be determined in an optimum level with glass fiber.

Figure 3.7 shows the difference of GWP_{100} results between hand lay-up and vacuum infusion method for the three different end of life scenarios. The difference is manily coming polyester resin in raw materials and manufacture phases. Polyester resin's CO_2 footprint is equal to 7,47 kg CO_2 eq for glass fibre it is 2,64 kg CO_2 eq.

The figure clearly shows that to use less polyester resin will cause low CO_2 emissions.

Overall, this analysis demonstrates that production with vacuum infusion is a better boat building method than hand lay-up. Because less polyester resin has been used in vacuum infusion method for all end of life scenarios the GWP_{100} quantity is lower than hand lay-up method.

4.1 Conclusions

The goal of the study was to obtain the environmental impacts of boat building methods for same material. The LCA methodology was chosen to provide a solid and well documented framework upon which to build the study. The literature on LCA is rich and the approach chosen for the present research could be compared with work from other authors.

FRP composites offer tremendous potential to be used as multifunctional structures in boat building industry. The main disadvantage of these materials in terms of their value after disposal is really the same as their main advantage, that is, their complex, heterogeneous, anisotropic characteristics.These characteristics make re-use and recycling, in part or in whole, very challenging problems. Efforts are already underway to address these challenges, but more needs to be done to design materials by keeping end-of-service in mind and to improve the overall eco-footprint of composites (Nicholas & Paul, 1995).

It is widely accepted that boat building industry need to form a strategy to make its supply chain more environmentally friendly in order to keep competitiveness and to be prepared new legislative pressures.

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APPENDICES

Table Annex.1 GWP_{100} factors for characterizing climate gases

Substance	CAS number	GWP_{100} (kg CO_2 eq)
1,1,1 – tricloroethane	71-55-6	110
Carbon Dioxide	124-38-9	1
CFC-11	75-69-4	4000
CFC-113	26523-64-8	5000
CFC-114	1320-37-2	9300
CFC-115	76-15-3	9300
CFC-12	75-71-8	8500
CFC-13	75-72-9	11700
Dichloromethane	75-092	9
Dinitrogen oxide	10024-97-2	310
Halon – 1301	75-63-8	5600
HCFC- 123	306-83-2	93
HCFC-124	63938-10-3	480
HCFC-141b	27156-03-2	630
HCFC-142b	75-68-3	2000
HCFC-22	75-45-6	1700
HCFC-225ca	422-56-0	170
HCFC-225cb	507-55-1	530
HFC-125	354-33-6	2800
HFC-134	811-97-2	1000
HFC-134a	811-97-2	1300
HFC-143	430-66-0	300
HFC-143a	420-46-2	3800
HFC-152a	75-37-6	140
HFC-227ea	431-89-0	2900
HFC-23	75-46-7	11700
HFC-236fa	690-39-1	6300
HFC-245ca	679-86-7	560
HFC-32	75-10-5	650
HFC-41	593-53-3	150
HFC-43-10mee	138495-42	1300
Methane	74-82-8	21
Perfluorobutane	355-25-9	7000
Perfluorocyclobutane	115-25-3	8700
Perfluoroethane	76-16-4	9200
Perfluoroexane	355-42-0	7400
Perfluoromethane	75-73-0	6500
Perfluoropentane	678-26-2	7500
Perfluoropropane	76-19-7	7000
Sulphur hexafluoride	2551-62-4	23900
Tetrachloromethane	56-23-5	1400
Trichloromethane	67-66-3	4

Source : Houghton et al., 1994 & 1996

Table Annex.2 GWP_{20} & GWP500 factors for characterizing climate gases

Substance	CAS number	GWP_{20} (kg CO_2 eq)	GWP_{500} (kg CO_2 eq)
1,1,1 – tricloroethane	71-55-6	360	35
Carbon Dioxide	124-38-9	1	1
CFC-11	75-69-4	5000	1400
CFC-113	26523-64-8	5000	2300
CFC-114	1320-37-2	6900	8300
CFC-115	76-15-3	6200	13000
CFC-12	75-71-8	7900	4200
CFC-13	75-72-9	8100	13600
Dichloromethane	75-092	31	3
Dinitrogen oxide	10024-97-2	280	170
Halon – 1301	75-63-8	6200	2200
HCFC- 123	306-83-2	300	29
HCFC-124	63938-10-3	1500	150
HCFC-141b	27156-03-2	1800	200
HCFC-142b	75-68-3	4200	630
HCFC-22	75-45-6	4300	520
HCFC-225ca	422-56-0	550	52
HCFC-225cb	507-55-1	1700	170
HFC-125	354-33-6	4600	920
HFC-134	811-97-2	2900	310
HFC-134a	811-97-2	3400	420
HFC-143	430-66-0	1000	94
HFC-143a	420-46-2	5000	1400
HFC-152a	75-37-6	460	42
HFC-227ea	431-89-0	4300	950
HFC-23	75-46-7	9100	9800
HFC-236fa	690-39-1	5100	4700
HFC-245ca	679-86-7	1800	170
HFC-32	75-10-5	2100	200
HFC-41	593-53-3	490	45
HFC-43-10mee	138495-42	3000	400
Methane	74-82-8	56	6.5
Perfluorobutane	355-25-9	4800	10100
Perfluorocyclobutane	115-25-3	6000	12700
Perfluoroethane	76-16-4	6200	14000
Perfluoroexane	355-42-0	5000	10700
Perfluoromethane	75-73-0	4400	10000
Perfluoropentane	678-26-2	5100	1100
Perfluoropropane	76-19-7	4800	10100
Sulphur hexafluoride	2551-62-4	16300	34900
Tetrachloromethane	56-23-5	2000	500
Trichloromethane	67-66-3	14	1

Source : Houghton et al., 1994 & 1996

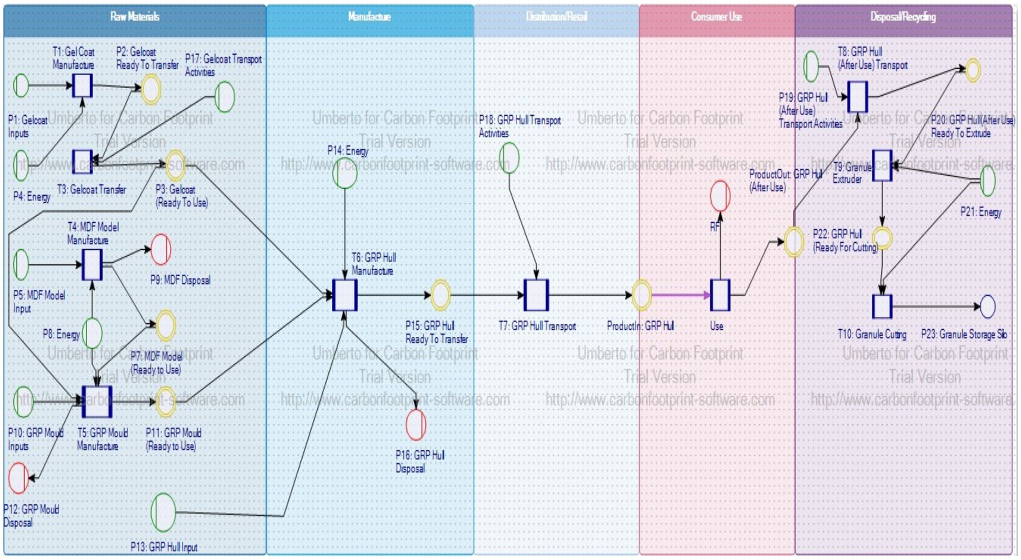

Figure Annex 3. Process tree of the extruding end of life