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Environmental Impacts of Fiber Composite Materials

Study on Life Cycle Assessment of Materials used for Ship Superstructure

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Acknowledgements

Though fiber composites have been in use for many years but still there is little information available on their environmental impacts. This work is another effort to study these impacts.

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Abstract

This thesis was conducted to investigate the impacts of fiber composites on the environment. Composition, properties and application of fiber composites were also studied. On the basis of its application, taking into account previous studies information was gathered related to impacts of these fiber composites. In order to study impacts of fiber composites in marine application a detail study was conducted where using the LCA method and Sima Pro software three ship superstructures of the ship Stena Hollandica were compared. These were steel superstructure, balsawood core superstructure and PVC foam superstructure. The results showed that over the lifecycle the impacts of PVC and balsawood superstructure were almost the same and were better than the steel superstructure. The main contribution of impacts over the lifetime was due to the fuel consumed. When only the superstructure was considered separately from the life cycle the best choice was balsawood and the PVC foam superstructure had the most impacts. Overall it was found that balsawood could be considered as the best alternative as a material for the construction of this ship superstructure.

Keywords

Fiber composites, Life Cycle Assessment, ship superstructure, balsawood core sandwich superstructure, PVC foam superstructure.

1. Life Cycle Assessment of Fiber Composites

This chapter presents a brief introduction to the thesis and its structure. It also has the purpose, goal and objectives of this study.

1.1. Introduction

Presently the world population is 6.5 billion people and it is increasing at a fast pace everyday. With this increase in population a lot of emphasis is made in order to produce better products and to sustain this growing population. Everyday, every second in different part of the world new products are being produced in order to improve livelihoods of people. When we talk about sustainability of human population we come across the sustainability of the environment, which has to play a great role in human sustainability. Deterioration of the environment is one of the threats to the human race. Advancement in life and increased production of goods to meet the growing needs of people has lead to the environmental deterioration, which is one of the threats to human race.

Recently with the increased awareness of environmental degradation among the people has led the producers as well as consumers towards achieving environmental sustainability. Today the producer is aligned towards producing more environment friendly products and the consumer is more interested in products that bear a green label. With this awareness more tools are being introduced that study the impact of various products on the environment, one such tool is Life Cycle Assessment. Life Cycle Assessment is cradle to grave assessment of a product or service. It analyzes the impact of any product over a lifetime from the extraction of raw materials to the waste disposal of its various components. (ISO, 2006)

Life Cycle Assessment is focused on studying the whole product system, as it is not only studying one single process but also the complete chain of production and lifetime. It also helps in studying various alternatives and making the right decision in order to make the most environment friendly choice. This tool studies all possible environmental impacts of the product such as acidification, climate change, global warming, toxicity etc.

Today, with the increasing consumer market recently new products have been introduced in order to replace material such as metals, cement etc that are very heavy, corrosive and less environment friendly. One such material is fiber composites. In the past 30 – 40 years fiber composites have been competing with materials such as steel, aluminum and concrete in cars, aircraft, buildings, bridges, bicycles and everyday sports goods. It has such a wide range of application due to its possibility to combine high strength and stiffness with low weight it is non-corrosive and is considered to be less expensive in cost when compared to other material in some cases. They are also cheaper because they reduce the cost over the product's lifetime as they have very low maintenance cost. A lot of work is being done in order to make them more environmental friendly.

Fiber composites have also found their way into the ship building industry. LASS (lightweight construction application at sea) is a project, which has tried to improve the efficiency of marine transport and to improve the competitiveness of the Swedish shipbuilding industry. They have used fiber composites and other material for this purpose. They also conduct cost and environmental analysis to make cheap and more environment friendly ships.

The Life Cycle Assessment (LCA) of Stena Hollandica is also a part of this project. Stena Hollandica is one of the ships of Stena Line, which is one of the biggest cruise companies in the world. It is a Ro Pax ferry that means it carries passenger with basic emphasis on freight. Stena Lines has great interest in reducing the impact of its ships on the environment, marine and land resources. They are also certified by ISO 14001. With their efforts they have been able to reduce various impacts of energy consumption, emissions etc.

1.2. Research Objective:

The purpose of this study is to investigate impacts of fiber composite on the environment. It will provide a platform for industries to choose a material, which is better from an environmental point of view for the manufacturing of various products. This study comprises of present applications of composites and data, which can be used for future LCAs. It will help in selection of the most suitable material for Stena Hollandica superstructure as it includes a comparative analysis where PVC foam sandwich, balsawood core sandwich and steel super structure would be compared. This study will be a source for information and data for Stena Lines, LASS project, ship designers, fiber composites manufacturers, ship industry, and researchers.

The overall goal of this study was to investigate the environmental impacts of fiber composites by conducting LCA of Stena Hollandica super structure.

The objective of this study is to

- study the application of fiber composites and use previous LCAs to study impacts of fiber composites
- collect data on fiber composites and enter it in to Simapro 6.4 database which is the software used to conduct Life Cycle Analysis (Pre consultants, 2006)
- study the impacts of fiber composites on the environment emphasizing on its marine application and by using comparative life cycle assessment of Stena Hollandica superstructures.

1.3. Research Methodology

The methodology used for this study is firstly data and information was gathered through literature review on fiber composites. Present and future applications were also studied along with impacts of some of these applications. The literature collected on impacts of fiber composites was based on various LCA. The impact data gathered of these fiber composites was also entered into Simapro for future studies. In order to further study the impacts of fiber composites in marine applications an LCA of Stena Hollandica superstructure is conducted where sandwich fiber composite material has been used. This LCA helped in order to study the impacts these fiber composites and it would help in the future to choose most environment friendly structure. Simapro 6.4 software was used to model the superstructure and study its impact.

1.4. Structure of the thesis

This thesis comprises of 5 chapters. The second chapter consists of fiber composites and their properties. It describes which are the classes of fiber composites and why and how do fiber composites compete with so many other materials. It also has the existing and future application of fiber composites. This part looks into all research work done on different applications of fiber composite and also focuses on what are the future applications of fiber composites and impacts of fiber composites on environment for which various previous LCAs conducted have been used.

The third chapter is on the comparative LCA of superstructures of Stena Hollandica ship, which is a part of the LÄSS project that specializes in developing lightweight ship structures. This will be studied in order to look into the environmental impacts of fiber composites in marine applications.

The fourth chapter presents information on the data and flow charts of the superstructure models. It also discusses the data and calculations made to model these superstructures.

Fifth chapter is based on life cycle interpretations, results and discussion where the results from this LCA study have been discussed. At the end it has the list of references.

2. Fiber composites

This chapter gives a detailed introduction on the history of composites, their main properties, composition and classification, types of fiber reinforcements and one important type of structure is presented which is the sandwich structure and has been used in the LCA of Stena Hollandica. In this chapter present and future application of fiber composites are also discussed and it has information on impacts of fiber composites from previous LCAs. These LCAs has been used to show impact of various fiber composite applications on the environment. This study also has data sheets created in the Simapro from these LCA.

2.1. History of Fiber Composites

The concept of fiber composites is very old as it dates back to the 800 B.C when Israelites and as Egyptian pharaohs in third millennium BC used straw in bricks manufacturing as a reinforcement. Later on the Chinese used to do this as well. The papyrus is another such example where papyrus reed was placed parallel to each other and stacked on perpendicular layers and pressure was exerted on it in order to form papyrus paper. In 108 AD Chinese invented the paper, as we know it in the similar fashion. (Åstrom, 1997) In 1930s a more advanced version of fiber composites came into being in United States where they used short glass fiber reinforcement in cement and fiber enforced composites were developed in 1940. Composites were also used in World War II when glass fiber and polyester resin composites were used to make boat hulls and radomes (radar cover) In 1950s for the first time composites were used in cars because of desirable properties. With time the research conducted on studying more characteristics and improving the manufacturing process has increased. Composites began to be used more and more in everyday commodities like bath tubs, railings, electrical goods, sports equipment cars etc. aerospace and ship industry also started using composites initially for some of the parts and later on for the whole structure. For the first time in construction they were used to build a dome structure in Benghazi in 1968. Now their application in construction has enhanced four folds. (Tang, et.al. 1997)

2.2. Composites:

A composite is usually made up of at least two materials out of which one is the binding material, also called matrix and the other is the reinforcement material (fiber, kevlar and whiskers). There are many composite products with more than two raw materials. Those materials are not miscible together and are of a different nature (EADS, 2000). In composites both the matrix and reinforcement are distinguishable and holds their distinctive characteristics, which enhance the characteristics of the final product. This is unlike alloys where a combination of two metals produces an alloy that has totally different properties and makes both metals indistinguishable. Another example of a composite most widely used for construction is known as concrete that has cement as binder and gravel or steel rod as reinforced solid. In the case of fiber composites it is the reinforcement that basically determines their properties while the matrix holds the reinforcement in place and helps to transfer loads along the reinforcement. The matrix may be metallic, ceramic, or polymeric in origin (Åstrom, 1997). In the case when the reinforcement is a fiber it yields composites known as the fiber composites.

2.3. Characteristics of Composites

The composite's characteristics that have made them useful and unique are:

2.3.1. Strength

One of the most important characteristics of the composites is their strength. As they are very hard and rigid they provide the required strength for all structures that they are used for such as buildings, ships in combination with low weight. Tensile strength, which is the capacity to bear stress, is four to six times greater than that of steel or aluminum (Biswas et. al., 2002). Structures made of composites are 30-40% lighter than similar ones made of aluminum. The high strength, low weight and excellent design flexibility allows them to be easily molded into structures that have such requirements.

The strength of composites may be hindered as a result of different environmental interaction. As recent study shows that the tensile and transverse strength of composite resins demonstrate lower values after storage and test in water as compared to dry condition due to its water absorption. (Tani, 2002)

2.3.2. Stiffness

Another characteristic of composites that has made them popular is their stiffness to density ratio. The stiffness helps in building various structures. This is the reason that fiber composites have various structural applications. The stiffness can be tailor made and usually depends on the spatial configuration of the reinforcements. It also depends on the type of fiber used, as the synthetic fiber composites are stiffer than the natural fiber ones.

2.3.3. Expense

A lot of composites are manufactured at a lower cost as compared to other material such as steel, concrete etc. As for the fiber composites, they may be competitive at initial cost that includes manufacturing cost, they are substantially less expensive in terms of installation cost, and are far less costly to maintain. Fiber composites have been found to be responsible for setting up cost effective structures.

2.3.4. Environmental Sustainability and Sustainability of composites

A lot of research is being conducted in order to see which plants can provide raw material for composites and how to make them more environmental friendly. The use of composites have reduced the impacts on the environment as it has reduced the use of various toxic compounds and increased that of environment friendly products. It helps in various natural disasters such as earthquakes. Houses may be built in earthquake zones using lightweight composites and therefore may help in reducing the impact on human life when disaster strikes. Indeed most earthquake related deaths occur due to the fact that people are being buried under heavy concrete and metal beams. Lightweight structures have increased fuel efficiency in cars, buses, ships, etc., thus saving on fuel consumption and increased payload.

2.4. Classification of Composites

Composites can be classified into the following categories:

2.4.1. Blends

A blend is a mixture of two or more substances. These materials can be polymers, metals, or other components. There is no chemical bonding between the components in the blends rather links are created as a result of intermolecular forces that do occur. This blend can be quite homogenous in some cases. Some blends are mixed on the order of 1 millionth of a meter (molecular) while some are just homogenous to the naked eye.

2.4.2. Inter-penetrating networks

Inter penetrating networks is a type of composites which can produce synergistic properties which means that the material produced has better characteristics than that of the separate components. Most composites do not display properties that exceed the sum of the properties of its components.

2.4.3. Nanocomposites

Composites in which the fiber reinforcement is on the extremely small nano scale ($1x10^{-9}$ meters) are known as nanocomposites. Clay particles are a common nanocomponent in composites that offers a selection of applications not seen in other large fiber composites (PSLC, 2005).

2.4.4. Fiber Composites

Composites, which contain fibers as reinforcement material, are used for many applications. A common fiber-containing composite is fiberglass, which has polyester polymer matrix and glass fiber fillers for reinforcement. The glass fibers strengthen the resin and make it more impact resistant. Many boat hulls are made of fiberglass that must withstand the constant beating of waves and other hard objects in water such as wood and rocks. These are the composite, which we will be studying in detail.

2.5. Constituents of Composites

The constituents or materials that make up the composites are resins, fillers, additives and reinforcements (e.g. fibers).

2.6. Resin Systems

The resin is an important constituent in composites. The two classes of resins are the thermoplastics and thermosets. A thermoplastic resin remains a solid at room temperature. It melts when heated and solidifies when cooled. The long-chain polymers do not form strong covalent bond. That is why they do not harden permanently and are undesirable for structural application. Conversely, a thermoset resin will harden permanently by irreversible cross-linking[1] at elevated temperatures. This characteristic makes the thermoset resin composites very desirable for structural applications. The most common resins used in composites are the unsaturated polyesters, epoxies, and vinyl esters; the least common ones are the polyurethanes and phenolics.

2.6.1. Epoxies

The epoxies used in composites are mainly the glycidyl ethers and amines. The material properties and cure (hardening) rates can be formulated to meet the required performance. Epoxies are generally found in aeronautical, marine, automotive and electrical device applications. Although epoxies can be expensive, it may be worth the cost when high performance is required. It also has some disadvantages, which are its toxicity and complex processing requirements. Most of the epoxy hardeners cause various diseases.

2.6.2. Vinyl Esters

The vinyl ester resins were developed to take advantage of both the workability of the epoxy resins and the fast curing of the polyesters. The vinyl ester has better physical properties than polyesters but costs less than epoxies. A composite product containing a vinyl ester resin can withstand high toughness demand and offer excellent corrosion resistance. Its properties are considered the best and it can adhere to reinforcements very well.

2.6.3. Polyurethanes

Polyurethanes are mainly used without reinforcements or in some case with fiber reinforcement. They are desired due their low cost, low viscosity and rapid hardening. They have less mechanical and less temperature tolerance as compared to the above mentioned thermoset resins. Polyurethanes are also related with resin toxicity. Most of their applications are in the car industry.

[1] covalent bonding of polymers

2.6.4. Phenolics

The phenolic resins are made from phenols and formaldehyde, and they are divided into resole (prepared under basic conditions) and novolac resins (prepared under acidic conditions). The phenolics are praised for their good resistance to high temperature, good thermal stability, and low smoke generation. They have a disadvantage due to their brittleness and inability to be colored until now. (Åstrom, 1997)

2.6.5. Unsaturated Polyesters

The unsaturated polyester amounts to about 75% of all polyester resins used in USA. The advantages of the unsaturated polyester are its dimensional stability and affordable cost as well as the ease of handling, processing, and fabricating. Some of their special properties are high corrosion resistance and fire retardants. These resins are probably of the highest value for they have a balance between performance and structural capabilities. They have low cost and have good properties such as low viscosity. One disadvantage of unsaturated polyesters it has an impact of light and UV light. In this study the LCA that has been conducted uses polyester as a resin that, forms glass reinforced composite skins of the balsawood core and PVC foam sandwich structures.

2.7. Fillers

Since resins are very expensive, it will not be cost effective to fill up the voids in a composite matrix purely with resins. Fillers are added to the resin matrix for controlling material cost and improving its mechanical and chemical properties. Some composites that are rich in resins can be subject to high shrinkage and low tensile strength[2]. Although these properties may be undesirable for structural applications, there may be a place for their use.

The three major types of fillers used in the composite industry are the calcium carbonate, kaolin, and alumina trihydrate. Other common fillers include mica, feldspar, wollastonite, silica, talc, and glasses. When one or more fillers are added to a properly formulated composite system, the improved performance

[2] Strength to bear stress

includes fire and chemical resistance, high mechanical strength, and low shrinkage. Other improvements include toughness as well as high fatigue and creep resistance. Some fillers cause composites to have lower thermal expansion. Wollastonite filler improves the composites toughness for resistance to impact loading. Aluminum trihydrate improves on the fire resistance or flammability ratings. Some high strength formulations may not contain any filler because it increases the viscosity of the resin paste.

2.8. Additives

A variety of additives are used in the composites to improve the material properties, aesthetics, manufacturing process, and performance. The additives can be divided into three groups -- catalysts, promoters, and inhibitors; coloring dyes; and, releasing agents. The additives can alter the processing ability, mechanical properties, electrical properties shrinkage, environmental resistance, crystallization, fire tolerance and cost.

2.9. Reinforcements

It is the reinforcements that are the solid part of the composites, which are reinforced in to the matrix. They determine the strength and stiffness of the composites. Most common reinforcements are fibers, particles and whiskers. Fiber reinforcements are found in both natural and synthetic forms. Fiber composite was the very first form of composites, using natural fiber such as straw was reinforced in clay to make bricks that were used for building. Particle reinforcements are cheaper and are usually used to reduce the cost of isotropic material[3]. Whiskers are pure single crystals manufactured through chemical vapor deposition and are randomly arranged in the matrix. They are also isotropic but this type of reinforcement is very expensive. Among these reinforcements the long glass fiber (12 to 50 mm) are the ones most commonly used. There four kinds of fiber reinforcements, which are:

2.9.1. Carbon fibers

[3] as they do not have to be directionally aligned or reinforced

They were invented in 1878 by Thomas Alva Edison with cotton fiber and later on were made up of bamboo. Carbon fibers were used in high temperature missiles. They are made using rayon, Polyacrylonitrile and petroleum pitch (Åstrom, 1997). The carbon fiber are not organic even tough they are formed from organic components. They are the strongest of all reinforcements and work is being done in order to increase their strength. They have resistance to high temperatures, and corrosive environment and lack moisture sensitivity. They also have disadvantages that they are brittle and are expensive. They are used in racing vehicles, ships, spacecrafts and sports goods. Though the carbon fiber reinforcement is high temperature resistant it has been seen that carbon fiber reinforced in thermoplastic matrix at low temperatures collapse and fracture of the beam that is initiated by inter laminar shear[4] and delamination[5]. At high temperatures large-scale inelastic deformation was observed by Ningyun et.al (1994).

2.9.2. Aramid Fibers

They are the most common form of organic fiber used in composites and were introduced in 1971. They are also known as Kevlar. Kevlar aramid is an aromatic organic compound of carbon, hydrogen, oxygen, and nitrogen. Kevlar fibers are produced by spinning long-chain polyamide polymers using standard textile techniques (Åstrom, 1997). The low-density, high-tensile strength, low-cost fiber produces tough, impact-resistant structures. Kevlar fibers, which were originally developed to replace steel in radial tires, have found increasing use in the belts of radial car and truck tires, where it saves weight and increases strength and durability compared to steel belts. The disadvantages of aramid fiber in epoxy matrix are that deformation occurs when used in distilled or saline water (D'Almeida, 1991).

2.9.3. Natural Fibers

Natural fibers have come into use after centuries. They have been around a decade that natural fibers have started to be used again. Now they are being highly recommended because of being naturally derived from plants and due to their characteristics of being lightweight compared to glass. These reinforcements are reusable, good insulator of heat and sound, degradable and have a low cost. They also have their disadvantages as they are more prone to

[4] Force is exerted parallel to layers in the composites
[5] The layers separates as a result

catching fire, their quality can not be maintained equally, moisture causes swelling of fibers and its price may fluctuate according to the yield of the crop etc. It is being used widely for building purposes, in cars etc. The natural fibers used for composites are jute, hemp, flax, china grass etc

2.9.4. Glass fibers

Glass fiber reinforcements were produced for the first time in 1893. Now it is one of the most appealing reinforcements due to its high performance, good properties and low cost. It is made up of silicon oxide and some other oxide. Glass fibers are resistant to high temperatures and corrosive environments and they also have radar transparency.

There are two main types of glass fibers: E-glass and S-glass. The first type is the most widely used, and takes its name from its good electrical properties but is prone to fractures in case of acoustic emissions, (Cowking, 1991). The second type is very strong (S-glass), stiff, and temperature resistant. Reinforced glass fiber composite are an ideal material to make boat hulls, swimming pool linings, car bodies, roofing and furniture. Glass fiber reinforcement and polyester matrix has been used in this LCA for construction of the skin for the sandwich structures of the PVC foam and balsa wood core for the super structure of Stena Hollandica.

2.10. Metal Matrix Composites (MMC)

Another important class of fiber composites is metal matrix composites. In this type of fiber composites one of the constituents is a metal. For e.g. carbon fiber can be reinforced into aluminum matrix. They are used in car brakes, aircrafts, sports goods, cycles etc. MMC are very expensive and are being used only in case where cost is not the basic concern but properties and quality is and where there is a margin of how much can be spent on the product. These MMC have strong properties of thermal and electrical conductivity, they are resistant to environmental conditions, are strong, fire and heat resistant.

2.11. Sandwich Structures

A sandwich-structured composite is a special construction that is fabricated by attaching two thin but stiff skins to a lightweight but thick core. The core material is normally low strength material, but its higher thickness provides the sandwich composite with high bending stiffness with overall low density.

Open and closed cell structured foam, balsa wood and syntactic foam, and composite honeycomb are commonly used core materials. Glass or carbon fiber reinforced laminates are widely used as skin materials. Sheet metal is also used as skin materials in some cases. They are commonly being used in ship construction, building, bridges, trains, car doors, panels etc. In construction new green sandwich structures are also being introduced where the core is usually made from the natural materials (wood) and the skin is made form earth (clay) instead of cement. Thus making it more environment friendly

2.12. Application of Fiber Composites

Today with all the advancement in life, growing population and its increasing needs we have to consider how to meet those needs by producing the best and making it available for all. Fiber reinforced composites are helping to fulfill the needs of this growing population. They have been and are being studied in order to maximize their utilities in different fields. This part of the chapter will look into the various fields that fiber reinforced composites are being used and what are their environmental impacts.

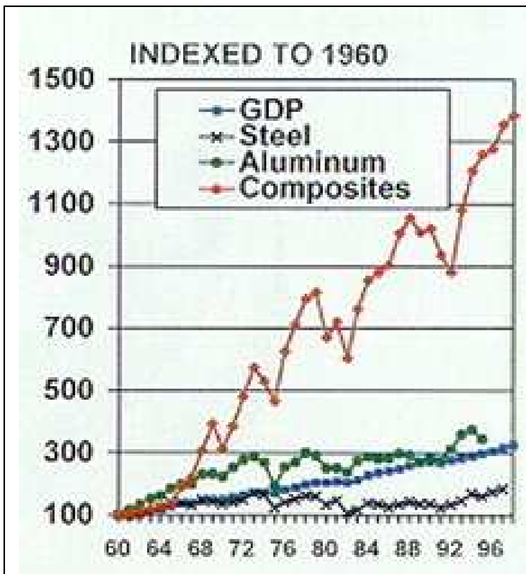

Fig 1.1. Composite shipment in US

This graph shows the US shipment of composites over the years. Fig 1.1 shows the increasing demand resulted in increased shipment of composites and how it's competing with steel and Aluminum. Fiber composites have the property of being light weight and strong which is the property that man has trying to achieve for a long time. Wherever composites are being applied they tend to increase the performance or quality four folds. More and more efforts are being put on increasing its efficiency and for looking at new ventures where this technology can be applied. Some of these findings would be discussed in this part of the chapter.

Application of fiber composites are represented by the following groups which are 70% of the total market value: automotive (23%), building and public works

(21%), aeronautics (17%) and sports (11%), (JEC, 2005). North America represents 40% of the composites industry's total market value, with 35% for Europe, 22% for the Asia-Pacific region and 3% for the rest of the world.

2.12.1. Fiber Composites in Construction

The very first known application of fiber composites was in construction. Straw reinforced clay bricks were used by the Egyptian Pharaohs, Israelites and Chinese centuries ago. Nowadays the construction is the field of greatest application of fiber composites. The property of composites of being strong and resistant to environmental impacts makes them good building material. Its weight helps only in case of transportation of this material as they are lightweight and can easily be transported. Its light structure may help in earthquake prone region. The fiber composites being lightweight and strong and has an ability to absorb and reduce seismic wave unlike heavy stones, bricks, mortar, granite etc. Being lightweight and fixed with nuts and bolts help in lateral movement and in case of collapse reduces threats to human life. In Gujrat India such fiber composite houses have been installed in an earthquake prone region in order to reduce the impacts of future earthquakes (Biswas. et .al, 1992). Flexible concrete is also made using fiber reinforcements that can withstand earthquakes (Shelly, 2006). Foldable structures have been introduced and are available due to the fiber composites otherwise making of foldable structures out of cement and a bricks is a difficult task. As mentioned earlier, the first application of glass fiber reinforced composites was in a dome structure in Benghazi in 1968 (Tang, 1997).

Today glass fiber reinforced composites are used in footbridges as well as Highway Bridge in Bulgaria. The first fully instrumented all-composite two-lane vehicle bridge, with an extensive health-monitoring system, was installed in US. Nearly four-year long continuous monitoring was carried out to demonstrate the performance of the bridge. Field monitored information was studied to evaluate the behavior and durability of composites in the harsh infrastructure environment. This evaluation showed the level of confidence in the long-term field benefits of composite materials and technology (Farhey, 2006). Since the early 1990s, there has been an increase in the use of small pultruded[6] structural shapes for the construction of industrial platforms, pedestrian bridges, latticed transmission towers, and for other applications. Fiber reinforced to concrete is widely used in building and construction since 1980s.

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[6] formed through the process of pultrusion in which reinforcement is infused with resin and then is continuously consolidated in to a solid composite

Katz (2004) studied the impacts of fiber composites, two materials were compared. Fiber reinforced polymer and steel reinforced pavement. The environmental load of FRP reinforced pavement was found to be significantly lower than that of steel reinforced pavement. This result mainly from the fact that FRP reinforced pavement requires less maintenance, its cement content and concrete cover over reinforcement can be reduced, and the reinforcement itself generates a smaller environmental load.

During construction one of the important things to consider is insulation nowadays. It helps in reducing energy losses helps retain the internal temperature. Therefore an LCA on insulation materials was used to study the impacts of fiber composites used in construction. This LCA was conducted where three insulation material were compared to see which had the least environmental impacts. The three materials that compared were paper wool, stone wool and flax fiber. According to this LCA in general, paper wool had the lowest global and regional environmental impacts, and flax insulation the highest, with stone wool falling in between. A notable exception is the total energy use, where stone wool had the lowest consumption followed by cellulose and flax. The study also addressed occupational health issues using an approach similar to that for risk assessment. Here, the less bio persistent HT stone wool products was seen to be the safest alternatives, because of a low potential for exposure, sufficient animal testing, and the obvious absence of carcinogenic properties, (Schmidt, 2003). The functional unit used in this case was 1.26 kg of the insulation. The impacts were also studied per kg. The analysis included all process from the growing of flax to the production of flax insulation and to the end of life. Similarly the functional unit for stone wool was 1.84kg of insulation and for paper wool was 1.280kg. This was a complete life cycle that had consumed energy based on European data, it did not include the use phase and paper and flax were considered CO2 neutral.

2.12.2. Fiber Composites in Aerospace and Military

As mentioned before, the quality of fiber composites of being lightweight and strong has been put into use in the aircraft, rockets, and other equipments used in aerospace. A new low cost resin system has been used to produce a composite elevator. It is widely used because of stiffness to density ratio and exceptional strength. The use of fiber composites in the transport has provided 15-30% weight saving thus increasing fuel efficiency and lowering maintenance and operation costs. Boeing 777 was built ten years ago, which had saved 680 kg of weight by using 20% of composites as building material. Fiber composites are easier to shape according to aerodynamic rules and are therefore being widely used in rockets and spaceships. First passenger carrying spaceship was made used fiber composites it has 24.8 m wingspan.

Ballistic composites are materials with superior properties being lightweight and durable under environmental conditions, (water and chemicals) with high performance (high strength, impact and ballistic resistance, damage tolerance). Lightweight ballistic composites are used in a wide range of lightweight vehicles, watercraft and aircraft armor giving high performance and lightweight protection against bullets and fragments. They also have exceptional insulating properties in high temperature environments. They are being used in missiles, tanks, fighter planes and retractable bridges. They can receive and send radar signals. And they are not magnetic thus help in wars from being easily targeted.

2.12.3. Fiber Composites in Transportation

Fiber composites are being used is car industry. The reason for their increasing demand in this industry is because the strength and stiffness in combination with low weight decreases the fuel consumption. It is said to save up to 27% of the weight in most of the structures (Nangia et.al, 2000). All vehicles from train to cars as well as bicycles are now using fiber composites. They are not only being used in the exterior but a lot of car parts are also being made from composites which include radiators, ignition components, spoilers, door panels, hoods, hatchbacks, roof panels, bonnets, wing mirrors, rear light units, brake linings, ignition components. Internal parts and trim where they are the solution to lightness, freedom of shape, freedom of design, matching internal décor and providing thermal and sound insulation. They are used to mould interior components for buses, seat squabs and bases, car door liners, back panel of seats, parcel shelves.

Composite materials are increasingly being used in the train industry, which has resulted in high performance and lower costs. Weight savings of up to 50% for structural and 75% for non-structural applications brings associated benefits of high-speed, reduced power consumption, lower inertia, less track wear and the ability to carry greater pay-loads. Composites also provide greater versatility in train design and optimization of train performance (e.g. lowering the centre of gravity to enhance stability). High stiffness from structural materials reduces (even eliminates) supporting framework, increases passenger room, carries fittings readily. The construction of composites (interchangeable panels) is easy to handle and install and offers rapid fitting. Due to fire resistant characteristics, it also allows full safety to the entire system. Components of coaches are generally made of glass fiber reinforced with polyesters/epoxies phenolic resins. (Nangia, et.al, 2000)

Fiber composites are being used in Formula 1 cars as new and improved materials are being introduced that are fireproof.

An LCA conducted on materials used for side panel of Audi Car showed impacts on the environment. This LCA was a comparison between hemp reinforced fiber composite side panels and Acrylonitrile butadiene styrene (ABS) copolymer composite side panel. It is a complete lifecycle from cultivation to the recycling (Wotzel, et.al. 1999). This LCA showed that in case of ABS copolymer composite side panel was more energy consuming. It was also noted that in the case of hemp growing a lot of fertilizers were used which would have a significant impact on the environment. The impacts of carbon dioxide were reduced considerably because of the use of hemp fiber.

2.12.4. Fiber Composite in Medical Sciences

Fiber composites have found their way into medical sciences where they have provided new alternative in the field of science for other materials. Previously broken bones were supported with metal rods surgically, which in some cases would cause problem such as bending, corrosion etc thus causing a threat to the patient. Similarly in the case of amputees they had to use artificial limbs that were very heavy, they were a cause of sores in diabetics. Thus making movement difficult. With the introduction of composites in this field it has been found to be a new and improved replacement for metal rod for bone surgery. Polysiloxane-based[7] composites with carbon fiber reinforcement have mechanical properties that are adequate from viewpoint of bone surgery requirement for load-bearing implants. They have also been studied to be more biocompatible (Gumula, et.al, 2004). In the case of artificial limbs new lightweight and cheaper artificial limbs have been introduced. This has made mobility for amputees easier. It has also benefited the diabetic patients. Now amputees are also able to compete just like other athletes with artificial limbs that have shocks. In 1896 there were no Olympics for those with prosthetic limbs but in 1992 they could not only participate but were considered to be equally good as those with full limbs, (Froes, 1997)

Application of fiber composite in the spinal surgery is also remarkable. One of such is the spinal fusion that means surgical immobilization of the spine by

[7] silicon oxygen polymer resins

joining two or more vertebrae, creating a bony union. The disk space may also be replaced by medical implants called interbody fusion devices (IBFDs) such as fusion cages, which holds the bone graft material within them. Recent study show creation of composites which can be applied for spinal fusion different types of material were tested along with polylactide[8] fiber reinforced composites The goal of the study was to create a composite material, which is much stronger in compression than cancellous[9] bone or vertebrae. This material developed may also have use as a bone substitute or as a material for bone fixation devices, such as plates, pins, screws, etc., in applications where high strength is required. (Huttunen. et.al, 2006)

Recently fiber reinforced composite have made their way into dentistry. Their mechanical properties can be tailor-made to correspond the properties of tooth substance and bone, an increased interest has rose in their use in dentistry and medicine. Multiphase mono- and dimethacrylate polymers are matrices for composites made of inorganic and organic reinforcing fibers. These result in enhanced adhesive bonding properties in cementing of appliances such as dental bridges to tooth substance. (Vallittu et.al, 2001)

2.12.5. Fiber Composites in Sports goods

Another application of fiber composites is in sports goods. Nowadays wooden racquets and fishing rods are almost history. Wood is rarely being used for sports goods. In sports where the time and strength is what is required fiber composites are playing a great role. When designing sport equipment most important things to consider are strength, ductility[10], density, fatigue resistance, toughness and cost.

With introduction of new materials in sports new records have be set. Initially bamboo stem was used for pole vaulting then came the aluminum and now sophisticated fiber composites are being used. These have layers of different fibers, which optimize the performance with an outer layer of high-strength carbon fiber providing high stiffness and an intermediate webbing of fibers together with an inner layer of wound-glass fiber building resistance to twisting. The glass fiber consists of 80% longitudinal and 20% radial fibers. (Froes, 1997)

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[8] thermoplastic resin

[9] where most of the veins and arteries are. Cancellous bone is the spongy interior layer of bone that protects the bone marrow.

[10] capable of being shaped

Cycling is not limited to the Olympics or sports but has become one of the modes of transportation. China manufactures 10 million cycles per year. Since the first cycle that was built in 1817 a lot of advancements have taken place in the bicycle. The most important of these changes are that made in the frame and tires. In addition to the carbon-fiber-reinforced composite frames, frames have recently been produced from magnesium, aluminum, titanium, and metal-matrix composites. In addition, hybrid frames such as carbon-fiber-reinforced composites combined with titanium have been produced. Wheels with increased stability and rigidity for off-road bikes constructed from glass-fiber-reinforced nylon and disc wheels have been introduced. In disc wheels, discs made of aluminum alloys or carbon-fiber-reinforced composites replace the spokes in conventional wheels. Developments also include three- or five-spoked wheels for rigidity and crosswind aerodynamics. (Froes. 1997)

Tennis elbow is a condition in which the jerk as result of shot may lead to damaging blood capillaries in the tendons or muscles around the elbow. But with the composite racquets the sweet spot has been increased, stiffness and shape of the frame and handle has also been improved. This results in less vibration and less impact on the elbow. Similarly in golf the weight has been reduced of the clubs from 165grams to 115grams and the length has been increased from 109 to 114 cm, which has resulted in better and straighter shot.

2.12.6. Fiber Composites in Musical Instrument

One of the finest musical instruments is manufactured by fiber composites. They are lightweight and have astonishing sound properties. A silent piano[11] is a composite keyboard musical instrument fabricated on the basis of an acoustic piano, and a pianist can play a tune by piano tones or electronic tones. Carbon fiber and epoxy resin is being used to make guitars and violins, as it is lightweight and resistant to environmental impacts, and damage. It has resonating properties similar to that of wood and has lower construction time and cost. First fiber composite flute was made in Finland. It is a carbon fiber flute with synthetic rubber pads and titanium keys.

2.12.7. Fiber Composites in Household Products

[11] where the pianist can only listen to the music he plays

Fiber Composites have also made their way in to our homes on the basis of their useful properties. Manufacturing of the fireproof core of fire resistant doors and screens, insulating and fire-resistant materials with different characteristics are being used, including a large number of materials comprised of insulators based on different silica compounds, e.g. fly ashes, which can be reinforced by fibers and produce fire resistant products with good thermal stability at high temperatures. Furniture is now being produced which is made of fiber composites. They are being used because they can easily be shaped into various beautiful and fashionable shapes. With the help of additives they can easily be colored according to our taste. Being lightweight it is preferred over heavy wooden and steel furniture.

Various appliances in our homes are made from fiber composites such as vacuum cleaners, food processor etc. Bathtub swimming pools and other toiletries are also made from fiber composites. Children swings, joyride, water slide are another application of fiber composites.

Waste management through land filling has caused great problem of leakage. The layer of fiber composites is used to secure the landfill waste from leaching toxins into the environment. This is possible because of the strong structure of this layer, which is non-corrosive.

One common application of fiber composite is in packaging. In this LCA, comparison was carried out between china reed pallets and glass fiber pallets, which are reinforced into plastics and is used for transportation. It was found Transport pallets reinforced with China reed fiber proved to be ecologically advantageous if they had a minimal lifetime of 3 years compared with the 5-year lifetime of the conventional pallet. The energy consumption and other environmental impacts are strongly reduced by the use of raw renewable fibers, due to three important factors: (a) the substitution of glass fiber production by the natural fiber production; (b) the indirect reduction in the use of polypropylene linked to the higher proportion of China reed fiber used and (c) the reduced pallet weight, which reduces fuel consumption during transport. Considering the whole life cycle, the polypropylene production process and the transport cause the strongest environmental impacts during the use phase of the life cycle. Since thermoplastic composites are hardly biodegradable, incineration has to be preferred to discharge on landfills at the end of its useful life cycle. The potential advantages of the renewable fibers would be effective only if a purer fiber extraction is obtained to ensure an optimal material stiffness. China reed biofibers are finally compared with other usages of biomass, biomaterials, in general, can enable a three to ten times more efficient valorization of biomass than mere heat production or bio fuels for transport. (Corbiere, et.al., 2001)

2.12.8. Fiber Composites in energy production

Composite flywheels are currently being developed for energy storage. The energy stored in the flywheel can be retrieved to supply power for electrical drive machinery. To satisfy the high performance and low-weight constraints, high-strength carbon fiber composites are the materials of choice for flywheel construction. Recently, several composite flywheels have been developed for commercial power generation and vehicles, such as buses and trains (Tzeng. et.al, 2006). Wind turbine blades are made up of fiber composites are another application recently introduced.

Environmental impacts were studied using LCA of composite rotor blade where three types of rotor blade of the wind energy converter were considered in flax fiber reinforced epoxy, carbon fiber reinforced epoxy and glass fiber, reinforced polyester. The functional unit for this LCA was a wind rotor blade to be applied in a 250 kW wind energy converter. The energy production of a wind energy converter was not taken into account. This study concluded with the least impacts by glass fiber reinforced rotor blade and most impacts caused due to carbon fiber rotor blade. It showed in general the overall energy consumed was almost similar but carbon fiber consumed more energy during manufacturing. As for the flax fiber it plays a great role in reducing carbon dioxide emissions but on the other hand it may also contribute to magnification of impacts caused due to use of pesticides and fertilizers. It was also found that carbon fiber rotor blade contributed a lot to smog and acidification when compared to flax and glass fiber rotor blade (DeVegt, 1997).

2.12.9. Fiber Composites in Marine

Before composites and light aluminum structures were available, all boats and ships were made from wood. Therefore were very costly, vulnerable to environmental impacts and had a lot of maintenance problems. With complex structures such as ship wood was found to be very hard to shape as well. Fiber composites boats are now much more famous because of their new interesting shapes, less cost, less maintenance etc. Similarly in Navy ships steel was used previously but it was heavy thus increased the fuel consumption and were slower. It was easily detected due to magnetic properties and was easily exposed to mines. Its maintenance was very costly thus forcing high budgets to the Navy. With the advents of fiber composites new light weight structures of Warfare ships have been introduced which are fuel efficient, fast, fire resistant, non magnetic and with a minimum cost of maintenance. These ships can easily receive and send radar waves. Key fixtures and fittings of the boat are now being made from these materials. Steering wheels and wind transducers are some of the most recent areas of application (Micheal, 1999).

With the increase in worldwide need for improving fire standards in ships fiber composites are playing greater role. Fiber reinforced composites based on thermosetting polymeric resins offer many benefits over traditional materials but have typically suffered from poor fire performance. Phenolic resins have resistance to heat and combustion. When phenolic composites do burn, a carbon char is rapidly formed which insulates and protects underlying material. An additional valuable property derived from the resin is the ability to retain its physical properties at high temperatures. All the outstanding fire performance of the phenolic matrix is achieved without the use of additives other than reinforcing fibers. (Borden, 1993)

Nowadays tug boats, passenger boats, cranes, yacht, ferries fishing boat all are being built in fiber composites.

Another application of fiber-reinforced composite is its offshore application. It has provided with an alternative and solution to the materials used in this corrosive environment. It has good strength to weight ratio and is lightweight. Use of fiber composite pipes for transportation of oil, sewerage, drilling etc has helped as they are resistant to corrosion and has less cost for maintenance compared to other material, which are easily corroded and have to be replaced regularly on corrosion. They are easier to transport.

In order to study the impacts of fiber reinforced composites in marine applications we have conducted a study on materials used in the superstructure of Ro Pax vessel. LCA has been used to study these impacts. The next chapters would study LCA and impacts of fiber composites in marine application in detail.

3. Life Cycle Assessment

This chapter is an introduction to LCA methodology and how it has been applied to this case study. It discusses the goal and scope of this LCA. It describes functional unit, system boundaries and impact categories.

As we are becoming aware of our environment we have concerns regarding it's retaining. Previously many had the belief of Cornucopian that everything in this world is infinite and everything can be destroyed and used without bringing it to an end. It was considered that the earth's resources are never ending. Dirty water was poured into massive rivers as they had the capacity to dilute its impurities but later on humans started to understand the sensitivity of the environment. They started to realize what is one mans dumping site is another mans drinking water supply. How one liter of toxic solution could harm thousands of people, how some gas emissions adds to the global warming, how a simple refrigerant or a deodorant affect the ozone? Keeping these concerns 191 countries met at the World Summit for Sustainable Development in 1992 in Johannesburg. There they agreed on eight Millennium Development goals and one of which is to ensure environmental sustainability. This conference was a platform, which streamlined 191 countries towards ensuring environmental sustainability. So today the world is working towards a sustainable environment. People are tend to be aware are of their environment and want to know more. A lot of tools have been designed in order to study the impacts on the environment and to help producers, decision makers and consumers to decide what to choose as the most environmental friendly product and bring it into use. Similarly like Environmental Impact assessment is a tool use to assess present and future impacts of any construction etc Life Cycle Assessment is used to study the overall impact of any product or service on the environment. It has a cradle (extraction of raw material) to grave (final waste disposal) perspective. LCA is now a part of International Standards series ISO 14040-14044 which was issued in 2006. According to ISO 14040- 14044 the goal of LCA is defined as

> "The goal of LCA is to compare the environmental performance of products in order to be able to choose the least burdensome. The term 'life cycle' refers to the notion that for a fair, holistic assessment the raw material production, manufacture, distribution, use and disposal (including all intervening transportation steps) need to be assessed. This then is the 'life cycle' of the product. The concept can also be used to optimize the environmental performance of a single product (ecodesign) or that of a company" (ISO, 2006).

LCA has been used now for the past 10-15 years. It has helped to provide grounds for decision makers, political bodies and consumers to make the right choice, which is more sustainable and safe for the environment in the long run. It tries to gives a complete in depth study of all processes involved and all materials used for manufacturing and their possible impacts on the environment. It helps us to decide where, to change what, in order to reduce the impact on the environment. Though a lot of assumptions have to be taken into consideration while making an LCA, it gives the producer almost a complete information of what impacts a product can have thus he would keep himself within the limitations of environment.

3.1. LCA Framework

The LCA process is divided into four phases according to ISO 14040-14043. These four steps include goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006).

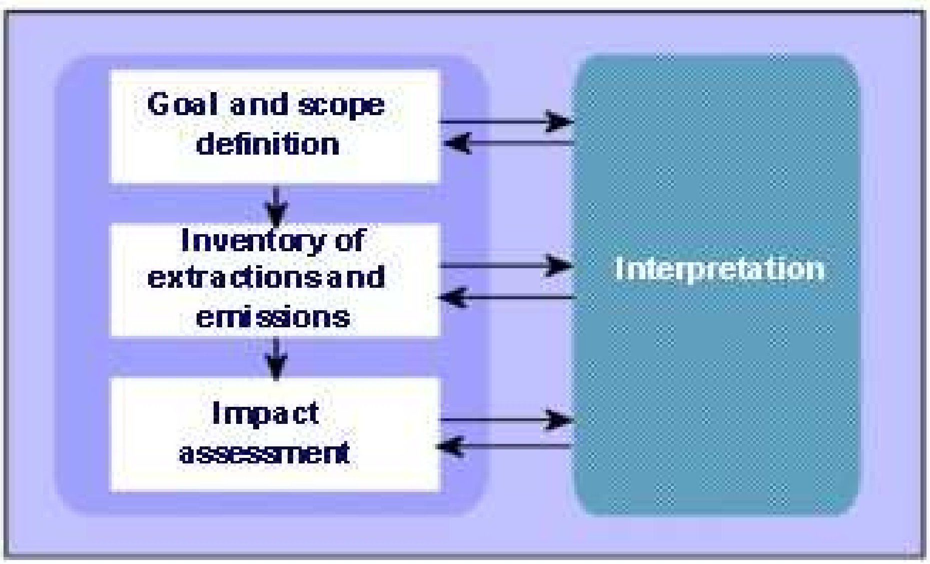

Fig 3.1. LCA Framework (ISO, 2006)

3.1.1. Goal and Scope Definition

This part of the LCA emphasizes on the purpose of the study. It takes into account limitations of the study and what are the parameters included and excluded form the LCA. The intended audience is identified. Boundaries for the study are set. The functional unit is decided which is the unit to study the impact of any product as the impact is not studied per product but per function of the product. For e.g. functional unit can be impact per liter of packaged beverage. In this phase the impact categories and methods that will used to study the impact are also discussed.

3.1.2. Inventory Analysis

In this phase the data inventory is made where the data is collected of raw materials used and emissions. Data is entered into Sima Pro software, interpreted and presented.

3.1.3. Impact Assessment

This phase the inventory is presented into environmental relevant information. It includes three steps which are classification which mean sorting inventory parameter according to the impact categories they contribute to, characterization where potential contribution to each impact is studied and the last step is weighing where total impact over the lifecycle is assessed this is usually an optional step. It can also be known as the combination of the above two mentioned steps of classification and characterization.

3.1.4. Interpretation

This is the last phase where all the results from the impact assessment are discussed and the impact is analyzed keeping in mind the goal and functional unit. This is the last step in a LCA where we can analyze all data and come to conclusion as to what are the impacts of the a specific product over a lifecycle, which should be the best choice when considering different product (comparative LCA) etc.

3.2. The LASS project

Sweden has a huge transportation industry and the shipping industry is one of them. Sweden has been trying to work on all possible efforts in order to improve the efficiency of marine transport and increase the competitiveness of the Swedish shipping industry. The LASS project is targeted towards achieving this target through the development and demonstration of techniques for using lightweight materials for ship construction. It has combined traditional and modern knowledge of shipbuilding in order to produce ships that are lighter in weight is more energy efficient, faster and with less impact on environment. It is also involved in capacity building of research institutes, shipping industry in this regard. (LASS, 2006)

The LASS project will be involved in carrying out studies and analyzing the impacts of these ships on the environment. Introduction of lightweight materials would be considered in order to reduce the impacts. As the cost of fuel over a ship's lifetime has a decisive effect on its total life cycle environmental impact, shipping lines are constantly looking for more efficient propulsion systems and greater cargo capacities for the same underwater profile. Lightweight construction of ships can thus make a significant contribution to greater sustainability of transport systems. (Hertzberg, 2005)

3.3. LCA of Stena Hollandica

As a part of sub project of LASS project an LCA would be conducted on the super structure of the ship STENA Hollandica. One of the objectives of this sub project is to

- To develop economic lightweight composite sandwich design concept for (a part of) a superstructure on a passenger ship. Weight reduction of 50-70% at only a slight manufacturing cost increase compared to traditional designs.

A comparative LCA has been conducted to study the impacts of the super structure of this RoPax vessel[12]. The three structures that would be compared are steel, balsa wood sandwich structure and PVC foam sandwich structure.

This Ro Pax vessel is 200m in length and deadweight is 7500T (tonnage i.e. cargo capacity) 33000GT, 3100 lane meters and 500 PAX[13]. The superstructure is approximately 75 m long and 29 m wide and 13 m high. In this LCA we would compare a reference steel superstructure with balsa and PVC sandwich composite structures.

[12] a ship/ferries that carry passenger but its basic emphasis is on carrying freight

[13] passenger capacity

3.4. Goal of the LCA

The goal of the LCA is to study environmental impacts of fiber composites. We conducted a comparative LCA to study the impacts of one of its marine applications where we studied the Stena Hollandica superstructure. The three superstructures that have been compared are the steel, balsawood core and PVC foam superstructure.

This LCA would target the huge shipping industry of Sweden and provide them with a platform for decision-making on the use of most environmental friendly lightweight structures. It would help generate income by building of such spacious and environment friendly ships.

3.5. Functional Unit

In LCA the impact is not studied impact per unit of product but its functionality. Therefore, every LCA has a functional unit, which is very important, as this is the unit of the impact of the function of the product. It is the quantified performance of a product system and is used as a reference unit in a life cycle assessment study.

The functional unit of this LCA would be to study the environmental impact of 1 tkm (tonkm) of unit transported by Stena Hollandica. The life of this ship is 25yrs thus a complete lifecycle is being considered in this case. All impacts in this LCA are related to 1 tkm of transported goods.

3.6. Type of LCA

This would be a comparative LCA in which we would compare the superstructure of Stena Hollandica. The three structures that would be compared are made up of, steel, balsa wood sandwich composites and PVC foam sandwich composites.

3.7. System Boundaries

3.7.1. Time Boundaries

This LCA would study the impacts of Stena Hollandica with three different superstructures. The ship operates twice a day each time it travels for 6 hours (one trip) and operates 350 days per year. The lifetime of the ship is 25 years.

3.7.2. Geographical Boundaries

The ship is constructed in Cadiz in Southern Spain. This Ro Pax ship would be moving and transporting in the Northern Part of Europe. This ship travels between UK and Holland. It has two routes one is form Hoek Van Holland to Harwich and Killingholme and the other is from Rotterdam to Harwich (shown in fig 3.2). It is taken to the South Asian countries at the end of its life to be cut down and managed accordingly.

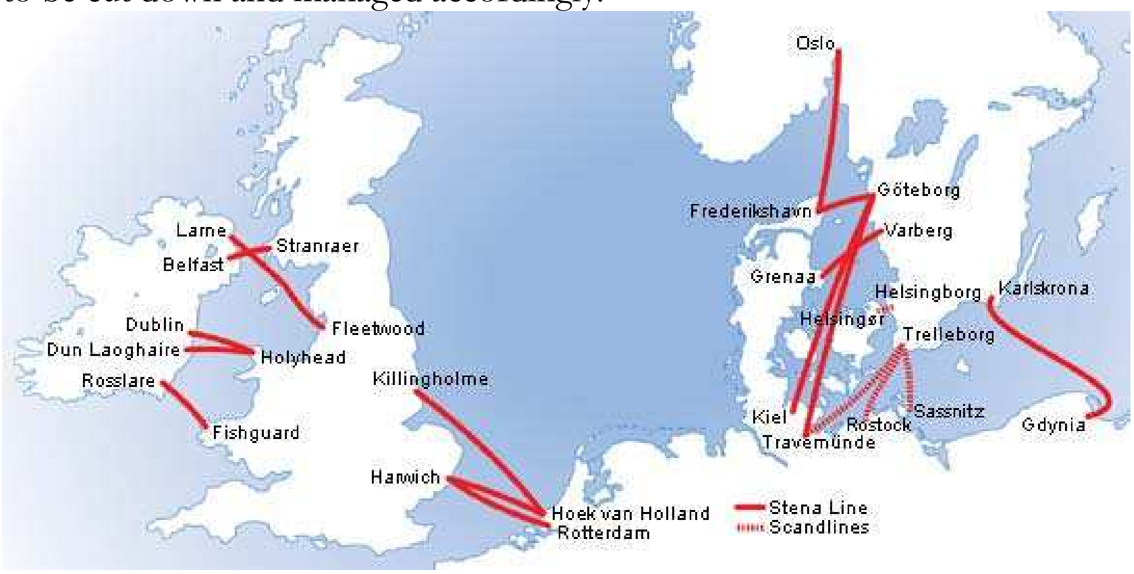

Fig 3.2. Route of Stena Hollandica

3.7.3. Technical Boundaries

In this LCA we have considered the cradle to grave impact of the ship but some parts have not been discussed. Among which one is how the structure weight would influence fuel efficiency. The painting and other such processes have been kept out of the system. The hull of the ship that is the same for all three superstructures have also been kept out of the system. Work environment has not been considered in the lifecycle. Three alternative waste scenarios have been modeled; recycling, land filling and incineration. Incase of the steel only recycling has been considered as that is what is the fate of steel in real scenario but for the other sandwich structures various end of life scenarios can be taken into account. The manufacturing of sandwich composite by vacuum infusion[14] has been kept out of the system due to unavailability of data. Welding of the steel (processing of steel structure) is taken into consideration. The energy for the construction of the three super structures has been taken into account.

3.8. Allocation and Cut Off criteria

Allocation problem arises when the same material or process is used for multiple productions; this impact is divided or allocated over the various products produced from that particular material or process. All materials and procedures used and shown in the lifecycle were used for and by separate processing (single process for single product) and manufacturing. Therefore there was no need for allocation

Similarly Cut off criteria has not been used as the whole process has been taken into consideration in the lifecycle except for what has been excluded in system boundaries.

3.9. Assumptions and Limitation

Various assumptions have been made throughout the process, which will be discussed, in the next chapter where the data will be described. On the whole the main assumptions that have been made were due to unavailability of data on composites and LCA of ships in general. Assumptions have been made in the case of maintenance. It has been assumed that in overall life cycle in the case of sandwich structure no maintenance would be required but in case of steel we would be considering 10 % of total steel would be replaced, (Jiven et.al. 2004). All assumption but has been supported by relevant data. All data and energy sources have been taken from European data and have been assumed to be the same for this ship, which would be constructed and maintained in Europe. It has been assumed based on information of Stena lines previous operation that the ship will be operating mostly in Northern European waters.

[14] method used to make these sandwich structures used in this ship

3.10. Impact Assessment Method

The three categories that would be taken into account are global warming, acidification and abiotic depletion. The method that has been used to analyze the impacts is CML 2 baseline 2000. This method is an update from the CML 1992 method. This version is based on the spreadsheet version 2.7 (April 2004) as published on the CML web site. (Sima Pro 6.4) This method was selected as it shows an overall picture of the specific impacts that we are studying. It takes into account global warming, acidification and abiotic depletion.

3.11. Choice of Impact Categories

As mentioned earlier the impact categories that will be taken into account are global warming, acidification, and abiotic depletion since they all play and important role in the lifecycle of Stena Hollandica. These are some of the areas where Stena lines are interested in reducing the environmental impacts. It is also some of the common problems related to the ship industry in Sweden.

3.11.1. Global warming

Over the year's emissions from industries, car, fuel combustion, deforestation has led to the phenomena called as the global warming. This is caused due to the greenhouse effect. Gases as carbon dioxide, NO_X, SO_X and methane cause the heat to be trapped with in the earth and stop it from moving into the space. This has led to increased temperature of earth and has led to climate change. In this LCA we will study the impact of the superstructure on these phenomena, as we believe because it will be consuming a lot of energy especially in the operation phase where fuel is being used which will lead to various emissions into air. Therefore it is necessary to study this impact category. The other reason we have considered is as lighter weight structure leads to faster moving vessels and more fuel efficiency therefore it would be interesting how the weight and material of the structure could help in reduction in global warming.

3.11.2. Acidification

Acidification is another process where, SOX, ammonia and NOX produced due to combustion of fuel may result of acid rain (fog, snow) on reaction with water vapors. This results in acidification, which is a threat to fresh water organisms and marine life. It also has negative impacts on rivers, lakes and forests.

3.11.3. Abiotic Depletion

Abiotic depletion is another term used for resource depletion. As this LCA takes into consideration the fuel consumption over the life of the ship therefore it is important to study the impacts on natural resource depletion.

4. Life Cycle Inventory Analysis

In this chapter the data collected and how it was used for modeling the three super structures will be discussed. It takes into account all calculations made and all assumptions made in order to construct, operate and maintain the superstructures. It also studies the various waste scenarios in each case.

4.1. Process flow chart

The three life cycles are broken down into 4 phases that are

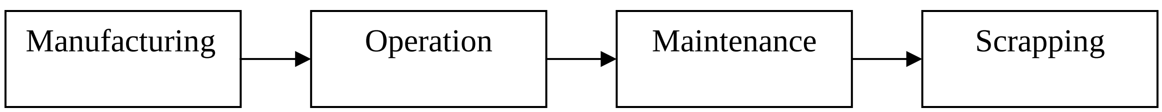

Fig 4.1. Flow Chart of Life Cycle of Stena Hollandica

The three comparative life cycles have been divided into four basic steps. First step that is the manufacturing, which includes all the materials, used and energy consumed for manufacturing of the superstructures this also includes data of emission from extraction of raw material to the use stage. Second stage would have data for operation of the ship where we would study the total tons transported and fuel consumption. Fuel and transported weight are materials that would be added in this part of the lifecycle. All three ships are assumed to travel the same distance and have the same fuel consumption, but would vary with regard to the amount of cargo transported, which causes the difference in impact per ton kilometer (tkm) during operation. It would also vary in regard that the fuel per ton would be different for different structures. For e.g. a lighter weight structure would carry more weight per ton of fuel. In maintenance we consider the material that is used or replaced in the maintenance stage. At the end is where the ship is broken down and waste is sent to different place where they could be incinerated, land filled or recycled according to the designed scenario

4.2. The life cycle Steel Super Structure

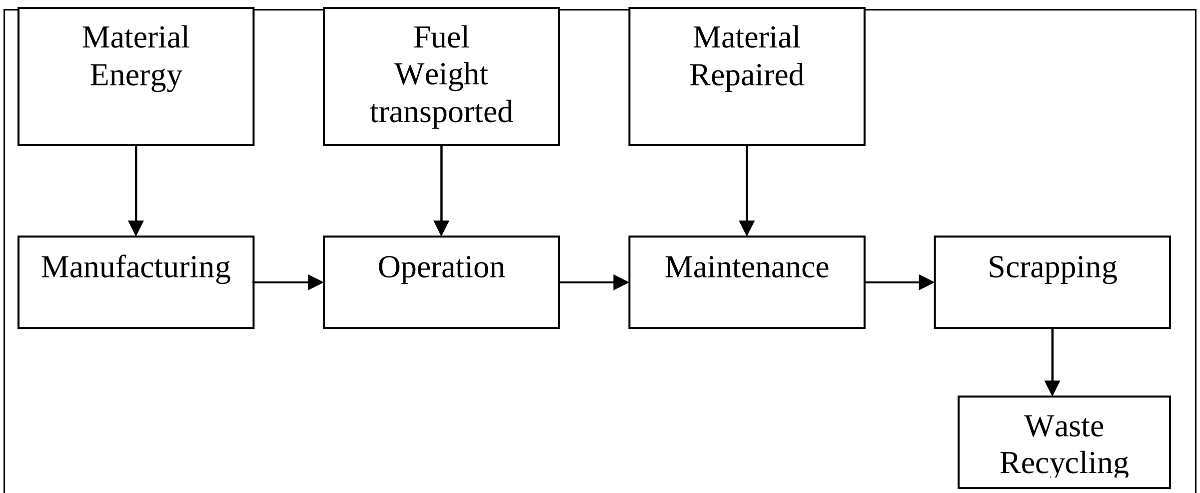

Fig 4.2. Life cycle of Stena Hollandica with steel super structure

This Fig 4.2 shows the life cycle of the ship with the steel super structure. In this case manufacturing would include materials and energy consumed, operation will include the fuel and weight being transported, maintenance would have all the amount of material that would be replaced and at the end scrapping is taking place and the steel is sent for recycling.

4.3. Life Cycle for Balsa Core and PVC Foam Sandwich Super Structure

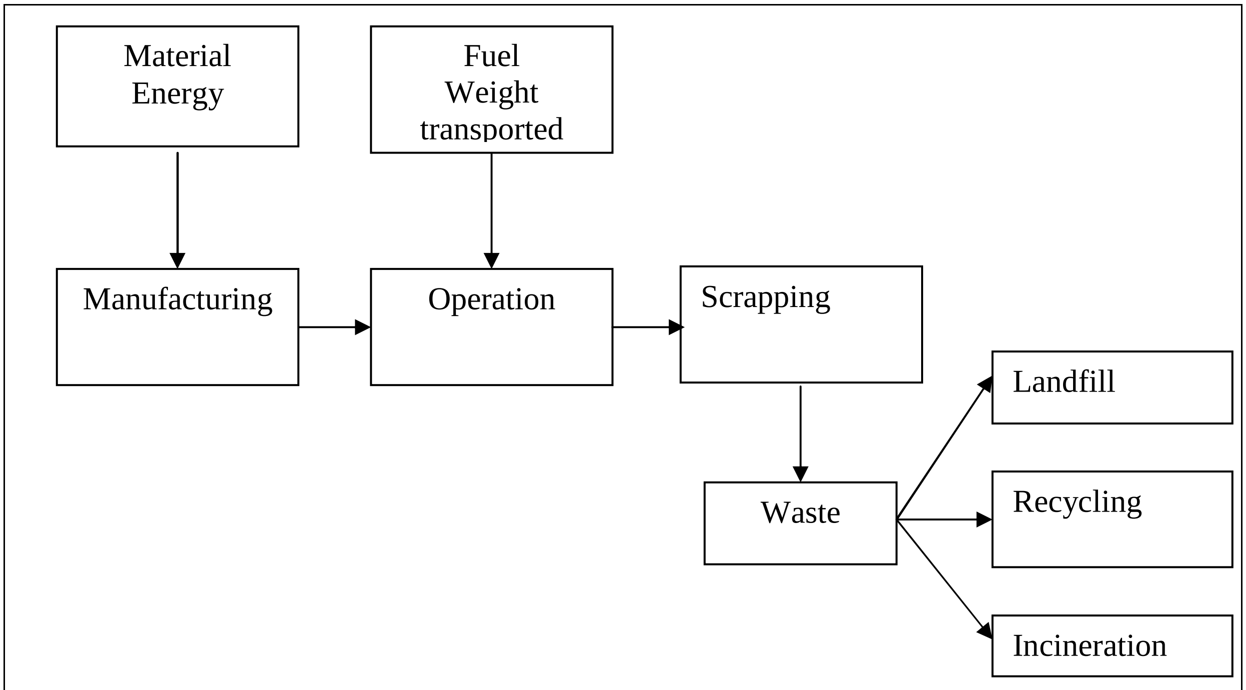

Fig 4.3. Life Cycle of Stena Hollandica with balsawood core and PVC foam sandwich superstructure**.**

In Fig 4.3 again the manufacturing would include materials and energy consumed. Operation would include the fuel and weight transported over a lifetime. The end of life scenario in this case would be considered using three different alternatives that is recycling, land filling and incineration. The flow chart is similar for balsawood structure and PVC foam structure the difference would be of the weight transported and the material used. As the PVC being much lighter than the balsa wood would be able to carry much weight over its lifetime thus reducing the overall impact per tkm.

4.4. Data

4.4.1. Data for Steel Structure

Table 1. Data for manufacturing steel superstructure

Material/processes	Amount	Name of Database	Comment
Steel	800 tons	ETH ESU 1996 process	Complete emissions taken into account
Glass wool for	50 tons	Created	It was created using

insulation			Glass wool mat from Eco invent Database to match the density of our glass wool that would be used for insulation
Deck Covering (fiber cement facing tile)	100 tons	Ecoinvent process	It includes complete manufacturing and transportation data.
Electric welding 5mm	1600m		The two welding processes have been taken as to assume it would have equal impact 6-7mm welding as we do not have data for exact 6-7mm thickness steel welding data.
Electric Welding 2mm	800m		
Energy [15]	37003.8GJ	Ling , 2003.	Energy used for manufacturing steel structure.

This table 1 shows the data that has been taken from the Sima pro and used to design the Steel structure of this ship. The welding of two different thicknesses is taken and is assumed that their collective emission data would be equivalent to the emissions for a 6-7mm^2 thick steel plate. The fiber reinforced cement tiles have been used as it has the same composition as the deck coverings. The insulation being used is glass wool which has a density of 100 kg /m^3. In this case glass wool that has a 40 kg/m^3 has been used.

In the case of steel structure of the ship

Table 2. Calculations for steel superstructure

The weight of the Structure is = 950 tons (Safedor, 2003)
Total weight carried per year = 1750000 tons/year (Anna Hedlund)
Over a lifetime it would be carrying = 43750000 tons (1750000x25)
The ship travels = 308000 km/year (880 km/day x 350 day/yr) (Anna Hedlund)
Over a lifetime it is 7700000 km. (308000 x 25)

[15] The energy used here was taken as a resource input from the nature as unspecified energy because exact energy source was not mentioned otherwise other and exact forms of energy could have been taken from technosphere for modeling. Though this does not have any impacts on the lifecycle so it can be assumed that we can use this energy from the nature than the technosphere. This would be the case with all three superstructures.

Total tkm over lifetime= 336875000000000 tkm
Per ton km impact of the total weight of the steel super structure would be (functional unit) = 1 unit of super structure/ Tons carried over lifetime x distance covered over lifetime = 2.968E-15

In the operation phase the heavy fuel oil data was used from the Sima pro database. Its emission during combustion (Altmann et.al., 2004) of heavy fuel during operation was entered into the Simapro. To give exact picture of how much emission are given out in the atmosphere during operation of the ship and combustion of fuel.

Table 3. Data for operation steel superstructure

Material/ processes	Amount	Name of Database	Comment
Heavy Fuel oil For Stena	1.324E-9	Created Combustion data (Altmann, 2004) Fuel oil (IDEMAT)	All diesel ships use this fuel.

The consumption of fuel during operation a mean value is taken per day consumption from the following data which is 51 ton per day on a an average speed of 20 knots and per hour consumption of 2.8 tons

Table 4. Data for fuel consumption by Stena Hollandica. (Anna Hedlund)

Speed in knots	Tons/hour	Ton /day
19	2.3	42
20	2.8	50
21	3.4	61

Table 5. Fuel consumption over lifecycle

The fuel consumed on the basis of above taken mean values per year is = 17850 tons (51 x 350)
Over a life time the fuel consumed would be = 446250 tons (17850 x 25)
Per tonkm consumption of the fuel for steel structure would be = 1.32E-9 (unit / tons transported lifetime x distance covered over lifetime)

In the maintenance of the steel super structure we are assuming over a lifetime 10 percent of the steel would be replaced by new steel. (Jiven. et.al. 2004)

Total steel used for maintenance is = 80 tons

Table 6. Data for maintenance of steel superstructure

Material	Amount	Name of Database	Comment
Steel	80 tons	ETH ESU 1996 process	Complete emissions taken into account

At the end of the ship lifecycle the steel superstructure will be cut down and will be recycled to recover the 90% of the steel.

Table 7. Data for recycling of steel superstructure

Material	Amount	Process	Comment
Steel waste	237E-12	Recycling steel and iron/RER S	Complete data from collection to recycling

4.4.2. Data for Balsa Wood Sandwich Super Structure (BWSSS)

Table 8. Data for balsawood core sandwich superstructure (Safedor 2003)

Material / Processes	Amount	Name of Database	Comment
Glued laminated timber.	920m3	Ecoinvent process	Data for any glue laminated wood that can be used for core material.
Glass wool for insulation	50 tons	Created	It was created using Glass wool mat from Eco invent Database to match the density of our glass wool that would be used for insulation
Mineral Wool	64 tons	Eco invent process	
Polyester	88 tons		
Glass fiber, at plant	88tons	Eco invent process	Complete database from extraction to manufacturing.
Energy	13783.4GJ	(Ling, 2003)	Energy used for manufacturing composite structure.

The table 8 shows the data for the BWSSS. The glue laminated structure is taken as the balsa core is made from balsa wood and wood is cut, glued and laminated so it can be assumed that this data is equally valid for the balsa core. It is a general data for any kind of wood that is processed just like the balsa core. Rest of the data is taken from Sima pro according to the requirement of the ship structure.

Table 9. Calculations for BWSSS of the ship

The weight of the BWSSS is = 440 tons (Safedor , 2003)
Total weight carried per year = 2107000 tons/year
Over a lifetime it would be carrying = 52675000 tons (2107000x25)
The ship travels = 308000 km/year (880 km/day x 350 day/yr)
Distance covered over a lifetime it is 7700000 km. (308000 x 25)
Total tkm over lifetime = 405597500000000 tkm
Per ton km impact of the total weight of the BWSSS would be = 1 unit of super structure/ Tons carried over lifetime x distance covered over lifetime = 2.465E-15
In the case of operation per ton km consumption of the fuel for BWSSS would be = 1.100 E-9 (unit / tons transported lifetime x distance covered over lifetime)

In the case of maintenance it is assumed that because the sandwich structures are strong and have no impact of environment upon them so effects like corrosion etc cannot be seen and therefore they have no maintenance problem (Jiven, et.al 2004). The maintenance is not considered for both the BWSSS and the PVC Foam Super Structure.

At the end we have considered three waste management scenarios have been considered which are

Table 10. Data for Recycling of BWSSS

Material	Amount	Process
Wood waste	3.40E-10ton	Recycling wood(sub)
Glass waste	2.16E-13ton	Recycling glass/RER S
Glass waste	1.40E-13 ton	Recycling glass (sub)
Plastic waste	2.16E – 13 ton	Recycling plastic (excluding PVC) B250

The data for recycling of mineral wool was not available.

Table 11. Data for Incineration of BWSSS

Material	Amount	Name of process

Wood waste	3.40E-10ton	Incin.Wood (sub) T
Glass waste	2.16E-13ton	Incin Glass
Glass waste	1.40E-13 ton	Incin Glass Wool T
Plastic waste	2.16E-13 ton	Incin Plastics (Excluding PVC)
Mineral wool waste	1.577E-13 ton	Incin Mineral Wool T

Table 12. Data for Land filling of BWSSS

Material	Amount	Name of Process
Wood waste	3.40E-10ton	Landfill Wood T
Glass waste	2.16E-13ton	Landfill Glass wool T
Glass waste	1.40E-13 ton	Landfill Glass B250
Plastic waste	2.16E-13 ton	Landfill Plastics
Mineral wool waste	1.577E-13 ton	Landfill Mineral Wool T

4.4.3. Data for PVC Foam Super Structure (PVCFSS)

Table 13. Data for Manufacturing of PVCFSS

Material/ processes	Amount	Name of Database	Comment
Divinycell	64 tons	Created using data (Baczynska, 1996)	
Steel	22 tons	ETH ESU 1996 process	
Glass wool for insulation	160 tons	Created	It was created using Glass wool mat from Eco invent Database to match the density of our glass wool that would be used for insulation
Polyester	110.5 tons		
Glass fiber	125tons	Eco invent process	Complete database from extraction to manufacturing.
Energy	13783.4GJ	(Ling, 2003)	Energy used for manufacturing composite structure.
Mineral wool	64 tons		

In this case the Divinycell or PVC foam process data sheet was created in the Sima Pro (Baczynska, 1996). The rest of the data has been taken form Simapro according to the requirement of the PVCFSS.

In this case there would be some manufacturing waste that has been entered to model, which is

Table 14. Data for manufacturing waste

Material	Amount	Name of Database
Divinycell	9.6 tons	Landfill PVC
Glass waste	16ton	Recycling Glass wool T
Glass waste	18.75 ton	Recycling Glass B250
Plastic waste	24.31 ton	Landfill Plastics (except PVC)
Steel waste	1.1 tons	Recycling Steel

Table 15. Calculations for PVCFSS

The weight of the PVCFSS is = 487.5 tons
Total weight carried per year = 2073750 tons/year Over a lifetime it would be carrying = 51843750 tons (2073750x25)
The ship travels = 308000 km/year (880 km/day x 350 day/yr)
Distance over a lifetime it is 7700000 km. (308000 x 25)
Total tkm over lifetime = 399196875000000tkm
Per ton km impact of the total weight of the PVCFSS would be = 1 unit of super structure/ Tons carried over lifetime x distance covered over lifetime = 2.505E-15
In the case of operation per ton km consumption of the fuel for PVCFSS would be = 1.117E-9 (unit / tons transported lifetime x distance covered over lifetime)

At the end we have considered three scenarios have been considered which are

Table 16. Data for Recycling of PVCFSS

Material	Amount	Name of Database
PVC Waste	1.69E-13 tons	Recycling PVC
Glass waste	4.008E-13 tons	Recycling glass sub
Glass waste	3.13 E-13 ton	Recycling glass sub
Plastic waste	2.76E–13 ton	Recycling plastic (excluding PVC) B250
Steel waste	5.51 E-14 ton	Recycling steel

Table 17. Data for incineration of PVCFSS

Material	Amount	Name of Database
PVC Waste	1.69E-13 tons	Incin PVC
Glass waste	4.008E-13 tons	Incin Glass Wool T
Glass waste	3.13 E-13 ton	Incin Glass
Plastic waste	2.76E–13 ton	Incin Plastics (Excluding PVC)
Mineral wool	1.60 E-13	Incin Mineral Wool T

Table 18. Data for Land filling of PVCFSS

Material	Amount	Name of Database
PVC Waste	1.69E-13 tons	Landfill PVC
Glass waste	4.008E-13 tons	Landfill Glass wool T
Glass waste	3.13 E-13 ton	Landfill Glass
Plastic waste	2.76E–13 ton	Landfill Plastics
Mineral wool	1.60 E-13 ton	Landfill Mineral wool T

5. Results and Discussion

This chapter is based on results and discussion and also has some suggestion in order to reduce the impacts of the structure

5.1. Results

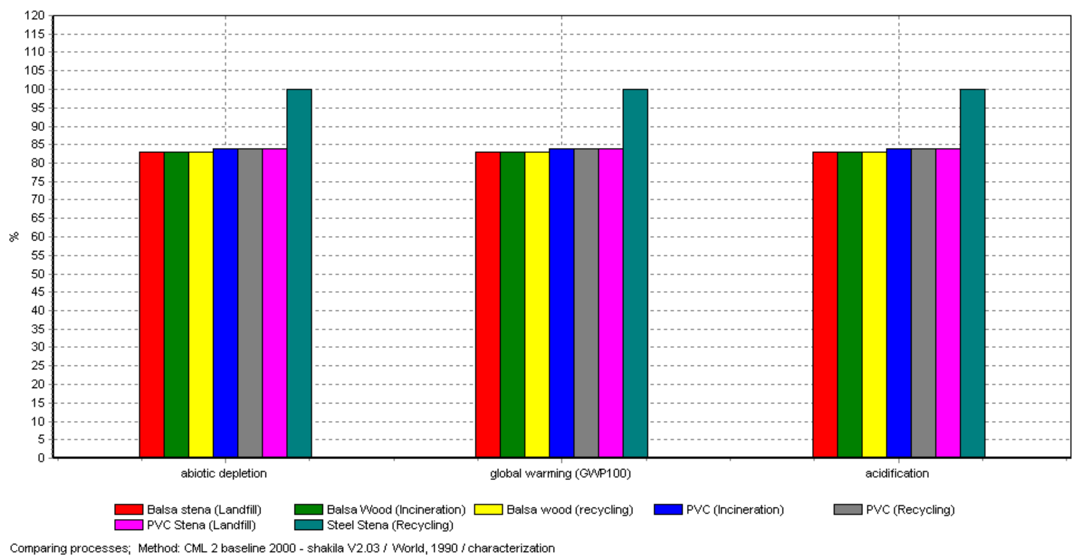

Fig 5.1 Comparison complete Lifecycle with various waste scenarios

When comparing all three super structures with different waste scenario it can be seen that there is a minor difference that between them. Overall it can be seen that the balsawood and PVC superstructure are almost the same and we can opt for any one of the two superstructures when compared to steel. Here we can see that there is not much difference of impacts caused by different waste scenarios.

Table 19. Impact data on comparison of the three superstructures with different waste scenarios

Impact Categories	BWSSS			PVCFSS			SSS
	Landfill	Incineration	Recycle	Incineration	Recycle	Landfill	Recycle
Global warming (in kg CO_2 eq)	0.127	0.127	0.127	0.128	0.128	0.128	0.152

Acidification (in kg SO_2 eq)	0.000943	0.000943	0.000943	0.000951	0.000951	0.000951	0.00113
Abiotic Depletion (in kg Sb eq)	0.0111	0.0111	0.0111	0.0112	0.0112	0.0112	0.0133

It can be seen that on the whole the highest impact is that of the Steel Super Structure, second highest impact is that of the PVC and the third one is of BWSSS. The waste scenarios do not show any difference in the reading for the reason this could be that the impact of the waste generated over the lifetime per functional unit is negligible. It can be assumed that in general over the lifetime all of the three choices can be used when considering the waste management of these structures. The result does not show a very high over all impact with a little difference between the structures. This is also because the operational phase when the fuel is consumed makes up most of the impact, which is also the highest. The fuel consumption leads to abiotic depletion, which will be discussed further when we look at individual structure results. During the operation phase the fuel used over the lifetime by each superstructure is the same, while the ton transported over the lifetime is higher for the PVC and balsa. As they can carry more the impacts are reduced when divided per ton km. The table above shows that steel has the highest impact on acidification, global warming and eutrophication. When considering incineration some energy could be retrieved in the case of balsawood and PVC structure. In the case of steel structure 90% of the steel would be recycled thus it can be used again for ship building, but obviously energy would be consumed for recycling but however it was seen through the model that it had positive impact.

We also looked into the waste scenarios individually to see the impact that might be caused over the lifetime. When considered per tkm over a lifetime the impact seems to be almost negligible compared to operational phase therefore show very little difference. The results of individually compared waste scenarios are

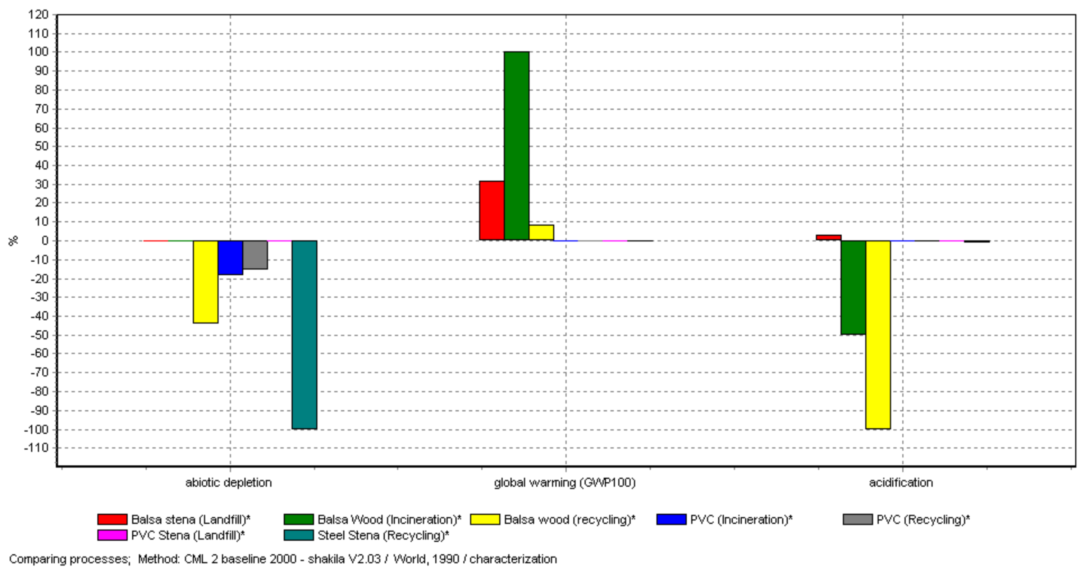

Fig 5.2. Comparison of waste scenarios

The fig 5.2 shows that recycling of steel is the best choice, especially in case of abiotic depletion as it results in complete reuse and thus reducing the impacts over the lifetime. Similarly it has a minor impact on global warming and acidification. Balsawood recycling is a good option as it reduces the impacts on acidification and abiotic depletion. In case of incineration of balsawood though it produces energy it also has a high impact on global warming, as it would release carbon dioxide. In case of PVC could again be a good option when we look into waste scenarios because PVC structure recycling has very little impact on all three categories, and incineration and recycling of PVCSS has a positive impact.

Impact Categories	BWSSS			PVCFSS			SSS		
	M[16]	Op[17]	LC[18]	M	Op	LC	M	Op	LC
Global warming (in kg CO_2 eq)	9.09E-09	0.127	0.127	5.15E-09	0.128	0.128	5.2E-09	0.152	0.152
Acidification (in kg SO_2 eq)	1.86E-10	0.000943	0.000943	2.94E-11	0.000951	0.000951	2E-11	0.00113	0.00113
Abiotic Depletion	1.45E-10	0.0111	0.0111	3.21E-11	0.0112	0.0112	5.03E-11	0.0133	0.0133

[16] Manufacturing,
[17] Operation phase
[18] Complete Lifecycle

(in kg Sb eq)									

The table above shows the contribution of impacts by the manufacturing, operation and the complete lifecycle. It can be seen that in every superstructure the impacts caused during manufacturing are very small compared to the operation phase. It can also be seen that the impacts are almost the same over the total life cycle and the operation phase. That shows that the operation phase contributes the most to the lifecycle.

5.2. Comparison of the three superstructure

The results of the comparison of the three superstructures are given below in fig 5.3. This is the comparison of the superstructure only not of the complete lifecycle. In this comparison the operation phase and waste scenarios have been eliminated so that a clear picture of the impact of the superstructure itself can be seen. From the fig 5.3 and table 20 we can see that the PVC structure has the highest overall impact, which is followed by steel super structure and then is the balsawood super structure. The most prominent impact of these super structures can be seen in the case of acidification. In the case of global warming that is one of our main impact categories we can see that the steel structure and PVC structure has an impact as for the balsawood wood structure does not have much impact due to the biogenic carbon dioxide. Similarly in case of acidification we can see PVC as main contributor. The steel structure has significant impact in the case of abiotic depletion where as it has less impact on acidification

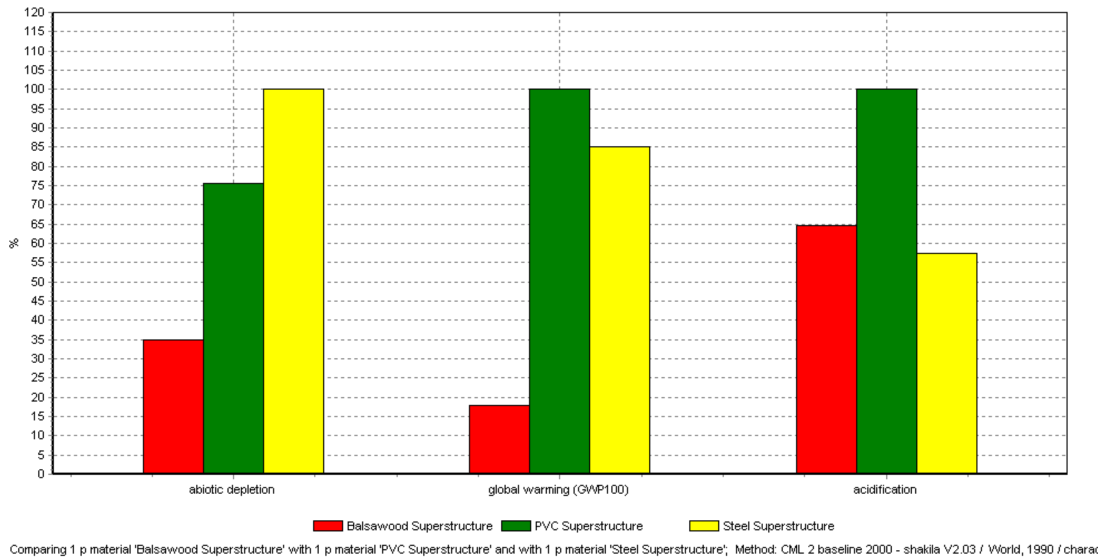

Fig 5.3 Impacts of the Superstructures

Table 20. Impacts of the super structures

Impact	BWSSS	PVCFSS	SSS
Global warming (in kg CO_2 eq)	370000	2060000	1750000
Acidification (in kg SO_2 eq)	7570	11700	6740
Abiotic Depletion (kg Sb eq)	5900	12800	16900

This table 20 shows contribution of the three super structures in the impacts that are under discussion in this LCA. It shows the steel structure has considerable impact on the resource depletion.

When we looked into individual superstructures we found that for the PVC superstructure the most impacts were caused due to PVC foam used, glass wool and polyester (fig 5.4). It can be seen that glass fiber and polyester used as skin for this sandwich structure may also contribute highly to these impacts. It can also be seen that the manufacturing waste may help in reducing the impact of overall structure. It can be seen in the graph that it gives some negative values which are contributed by manufacturing waste thus it results in a positive impact.

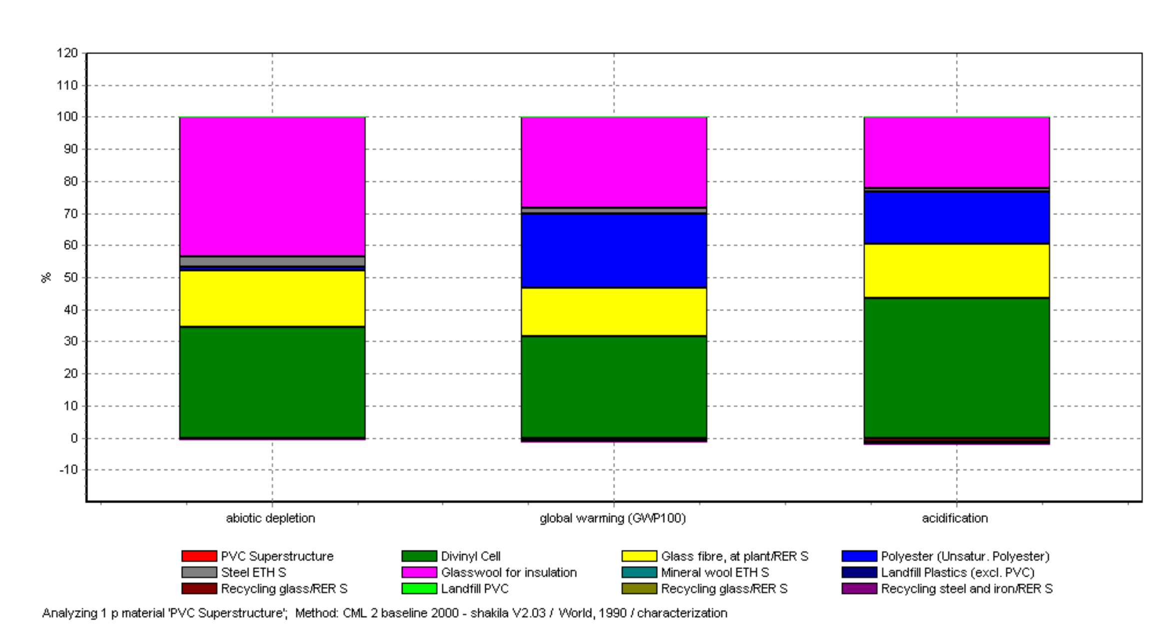

Fig 5.4. PVC superstructure

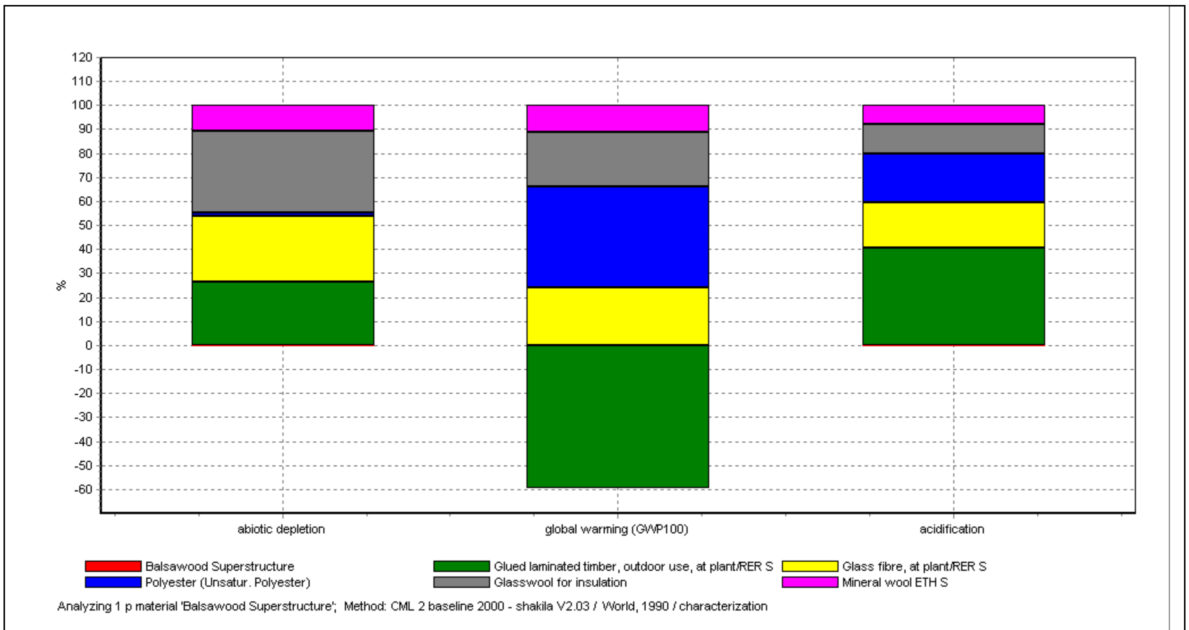

Fig 5.5. Balsa wood structure

The balsawood superstructure here shows that the balsawood would capture carbon dioxide thus reducing the impact on global warming. This carbon dioxide is however released if the balsa wood is incinerated in waste management. Balsawood structure also has impacts on abiotic depletion and acidification. In this case again it can be seen that glass wool and the skin of the superstructure are main contributors of the overall impact.

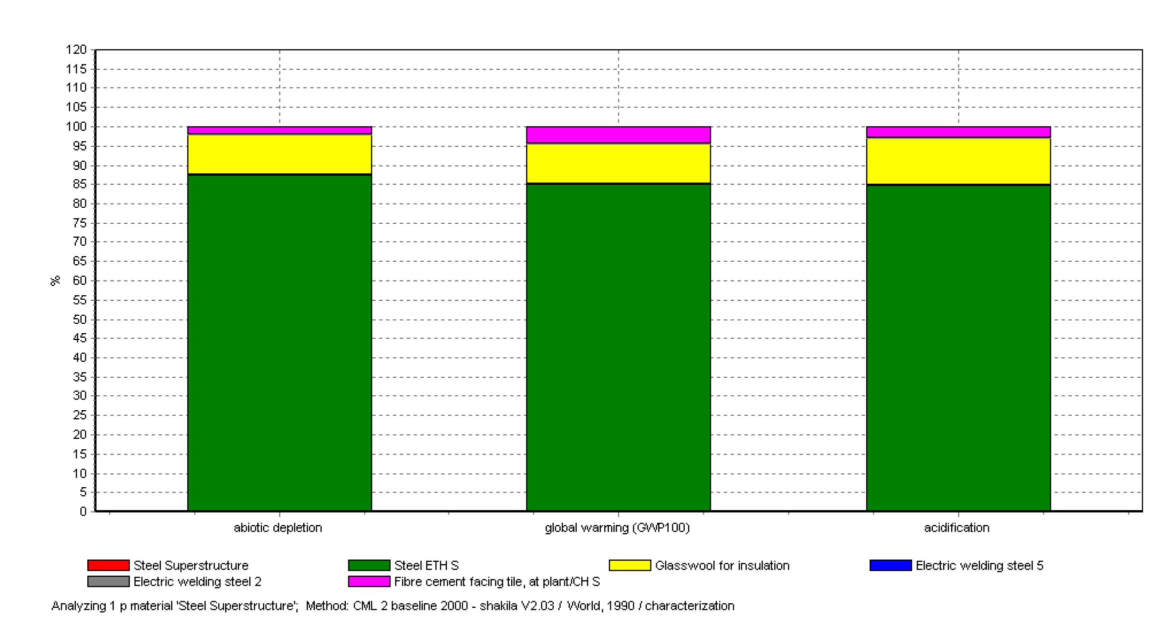

Fig 5.6 Steel superstructure

In the fig 5.6 it can be seen that the steel is main culprit followed by glass wool.

5.3. Discussion and Conclusions

On comparison we have found the balsawood alternative to be the best overall though when compared over lifetime the impacts are almost same as PVC. It was also seen that the operation phase contributed mostly for the overall impact of the lifecycle. Recycling in general can be the best scenario for all the superstructures. As for management of PVC a good choice could be incineration.

The over all results show that in manufacturing the highest impact is that of glass wool used for insulation and due to the skin of the balsawood and PVC sandwich structure. This could be reduced if the glass wool insulation could be replaced by other natural fiber insulation. As mentioned in chapter 2 there was study conducted on insulation types that included paper wool, stone wool and flax fiber insulation and paper wool was the best option. In this case we can study the possible of replacing it with more environmental friendly or natural fiber insulation.

Similar case is with polyester and glass fiber skins can be replaced with less harmful material than these super structures could be made more environment friendly. New research is being done on introducing more organic polyester. The impacts of the polyester skin can be reduced using bio polyester but a lot of work would have to be done in order to study the possible impacts of the environment in which it would be used. The impact of the operation phase is very high on abiotic depletion and this is because of the use of fuel results in depletion of resources. If other renewable resource could be brought into use this could reduce the impact of the operation phase. The balsawood super structure has least impact on abiotic depletion, which shows that being lightweight it consumes less fuel per tkm thus reducing the impact on resources. Therefore it shows that lighter weight materials contribute to fuel efficiency and reduce resource depletion. Also if we look at the fig 5.3 it shows that PVC structure showed the highest impact but when we study it over a lifetime we see that PVC impacts are reduced compared to the steel structure (in fig 5.1). This again shows that because PVC is lighter than the steel structure thus less fuel is consumed per tkm, which results in reducing abiotic depletion. Another solution to reduce impact on abiotic depletion could be to see into fuel cell it has been studied to be more environment friendly when compared to heavy fuel (Altmann, 2004). Decreasing the weight of the balsawood could further improve the per ton impact of the superstructure. Therefore the other Balsawood alternative should also be studied which is lighter in weight. When looking into the waste scenarios the best option would be to recycle these superstructures. The impact of the steel structure is very high but considering the fact that 90 percent of the steel can be recycled it is one positive thing about it. When accounted for, the energy required for the process does result in higher impacts when comparing it with land filling but it would avert the impact of reducing the capacity of landfills. Thus the recycling could reduce the load on landfills and the recycled steel could be put use.

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5.4. Suggestion

Some of the suggestions that can be made to improve the superstructure are

- Replace glass wool insulation with an environmental friendly insulation
- Use of lighter alternative for the Balsawood Superstructure
- Detailed study on fuel efficiency and renewable source that can used in this ship

- More lighter weight sandwich structures should be used to ensure fuel efficiency
- Recycling of the sandwich structures should be done in order to reduce over all environmental impacts.
- A detail study should conducted in order to investigate the impact on lives of thousands of people involved in ship cutting and breaking.
- Explore possibilities of using fuel cell technology for these ships.

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