A life cycle assessment method for alternative material selection strategies in boat structures.

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ABSTRACT

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A LIFE CYCLE ASSESSMENT METHOD FOR ALTERNATIVE MATERIAL SELECTION STRATEGIES IN BOAT STRUCTURES.

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In general the use of composites results in shorter production time, lightweight and lower maintenance costs to the marine industry in the leisure, fast and fishing boats sectors. The social and economic benefits of using composite materials have made users complacent about the pollution and the health and safety issues associated with these materials. As the perception of environmental problems changes with time, alternatives with lower emissions allowing for cleaner production and easier disposal must be investigated. Glass Reinforced Thermoplastics (GRTP) have been in use for many years in the automotive industry and aerospace. These materials are fast to process, solvent free, have an unlimited pot life and demonstrate better mechanical properties such as improved toughness compared to aluminium and Glass Reinforced Thermoset (GRTS). However, building boats with GRTP requires massive investment in equipment that ship builders do not currently undertake, such as curing ovens, autoclaves and plastic welding equipment. It is, thus, necessary to define a method to measure the environmental performance of this material in the context of marine structure. The present research presents a comparative study of four materials, namely steel, aluminium, GRTS and GRTP, in the above context . The outcome of the research defines a material selection framework for marine structures focusing primarily on environmental performance. The study focused on life cycle energy and material flows to represent environmental impact over the entire life of a boat and the methodology used respects Life Cycle Assessment (LCA) standards. The influence of the conventional marine structure design approach on LCA results was highlighted by the result of a grillage and a boat design study. These two studies also showed that the contribution of in-service fuel consumption to the life cycle energy has the most significant environmental impact. This impact is two to three orders of magnitude larger than the manufacturing environmental impact of the candidate materials. A boat study taking into account the results of the two above mentioned studies overcame this limitation. This boat study, referred as a boat synthesis, uses a constant fuel consumption as a design constraint for each material. It demonstrated that in some part of the studied design space, GRTP could offer the best material alternative, whereas in some other part, aluminium is the best alternative. In addition, the study also showed that steel could also be the least environmentally damaging material under some conditions, which goes against the common practice to build all small boats in GRTS.

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Chapter 1

Introduction

Material selection is an important stage in any design. However, small boats are almost exclusively made out Glass Reinforced Thermoset (GRTS). Composite materials are very popular in ship building with applications such as sailing boats, sport boats, rigid inflatable boats (RIB), underwater vehicles, passenger vessels, fishing vessels, pilots or hovercrafts but also in marine components such as pipes, masts or offshore structure modules [1, 2, 3]. GRTS is the most common choice for small boats and other material such as steel or aluminium are rarely considered.

The development of the glass fibres and resin in the 1930s [1] preceded the introduction of composites in ship building in the 1950s. It led to an increase in number and market share of small composites boats which in return increased the confidence and understanding of the material. As a result, new application developments and larger structures were built [2]. The vast majority of small boats (less than 15 metres) are currently built in composites since composites allowed the transition from custom built, labour intensive wood sailing boats to repetitive production. The low starting investment attracted new entrepreneurs to respond to the demand of a vigorous and growing market of first owners [1]. It is in the 1960s that production of GRTS boats accelerated with, for instance, the first Janneau GRTS hulls and a fleet of South African GRTS fishing vessels being built. Since then composite material technology developed fast. Technology first used for high performance boats transferred soon to mass production market and from small to large boats [1]. Naval minehunter building illustrates the scale increase e.g. the 46.6 metres HMS Wilton (1973) was the first mine hunter entirely built in composites [2], followed by other large volume production mine hunter such as the hull of the 51.5 m Tripartite class used in several countries [2]. The composite superstructure of the Lafayette class [2], and more recently the super yacht Mirabella V [1] show the adaptation of composites to large scale. During the same time, composite small boats, more generally non-ocean going ships, pleasure and working boats, boats usually produced in large number, held the vast majority of the market share in marine composites.

Marsh [1] argues that most of the composite boats ever built have yet to be disposed. It is clear that boats were overdesigned in the past. The marine industry is therefore left with the huge task of disposing several generations of composite boats, recent as well as old. GRTS composites currently do not have a clear recycling path making the disposal of boat, an even harder task. In addition, GRTS production releases volatile organic compounds for which increasingly severe regulations exist. There is a need for cleaner and more versatile alternatives to traditional materials such as wood, steel or aluminium but maintaining the advantages of composites. Thermoplastic resins are an alternative to thermoset resins. The advantage of thermoplastics over thermoset resins is that thermoplastic are melted at high temperature, bond to fibres and harden while cooling without the need of manipulating reactive and potentially harmful chemicals such as in the curing of thermoset resins. Thermoplastics are recyclable, do not release solvent and are not toxic in their raw material form. Cogswell [4] reviewed Glass Reinforced Thermoplastic (GRTP) successfull applications in domains such as aeronautics, biomaterials and the automotive industry as a replacement to thermoset composites. GRTP demonstrated [4] mechanical capabilities for a large number of applications, with additional properties such as fast processing, chemical inertia and temperature toughness in cryogenic applications. The automotive industry is a mature market where cars are regularly renewed and scraped, thus much could be learnt from experiences in this industry sector.

GRTPs are considered in the present research as a possible alternative to conventional materials such as steel, aluminium or GRTS because GRTP will reduce future disposal problems. It will be more easily disposable whilst keeping most of the advantages of traditional thermoset based GRTS. In order to assess whether it is worth investing in GRTP, one must assess the traditional materials of boat building i.e. steel, aluminium, GRTS. These four candidate materials are all implemented with the same objective to minimise environmental impacts. Material selection strategies have been widely studied and will be used in the current research in order to compare the performance of materials at the conceptual stage of a design taking into account the life cycle performance of material. This new design paradigm itself must be compared with traditional approaches in order to assess whether the new approach brings a decrease of life cycle impact. Life cycle impact will be studied using the definition of Life Cycle Assessment (LCA) from ISO 14040 [5].

Chapter 2

Aims and Objectives

The aim of the present research is to develop a methodology for material selection using LCA. This research focuses on the issues of material selection at the conceptual stage of marine structural design. The research is concerned with the understanding of the interaction between boat structures and the material in a design for life cycle approach. This will be achieved through the following objectives:

A The development of a mathematical model including life cycle assessment, material selection and the design of marine structures. The model aims to understand what the design requirements are and the design complexity needed to select a material when comparing GRTP with GRTS, steel and aluminium. The model will aim to understand how LCA can influence the design approach of marine structures, i.e. a grillage using first principles (Chapter 5), a boat with a fixed topology using Lloyd's Register rules (Chapter 6) and a boat study with a free topology using Lloyds Register rules and taking into account the results of the two previous chapters. This study is referred as a boat synthesis (Chapter 7).

B The collation of the life cycle information for four candidate materials in order to define the best life cycle practice, e.g. for manufacturing, in-service, etc. The definition of these life scenarios for each material will be achieved by critically reviewing the literature. The research will focus on the life cycle of composites qualitatively in section 3.2 and quantitatively in Appendix A along with the two other materials, i.e. steel and aluminium. This is will be the basis of the LCA impact inventory.

C The development of a material selection strategy. Its aim is to lower the life cycle environmental impact of boat structures. This material selection strategy will ensure that the possible benefit of one candidate material compared to the others will be highlighted. The same design objectives and constraints will be used for the four candidate materials.

D The boat synthesis uses the outcome of the critical review of a grillage and a boat with a fixed topology studies. These outcomes definet new constraints such as the boat fuel consumption in order to fulfil environmental objectives for the four candidate materials. It is considered as an approach to design to life cycle. The model developed in Chapter 7 aims to define the working principles of this approach to design to life cycle.

Chapter 3

Critical review of previous research

The present research covers a wide range of disciplines from *material science*, which is at the very core of mechanical engineering, to *environmental impact assessment* which is more at the margins of mechanical engineering. Previous research has explored much of these areas but independently. The paper of Hedlund-Astrom et al. [6] studied material science and impact assessment independently. The authors compared the life cycle assessmnet (LCA) result of two boats sharing the same topology but built with two different materials. However, the authors focus mainly on the life cycle impact characterisation rather than on material selection at the conceptual design stage. Their paper lacked consistency because:

- It ignored the implication of the material change on the design. Indeed the material change lead to a decrease in weight. The authors reported that they kept the same topology for the two materials. The variation in weight could have lead to a variation in loading which in return could have lead to a change in the internal geometry of the boat such as spacing between stiffeners.
- It used LCA as a material selection criterion but the authors mentioned that they did not take any advantage of the LCA result to optimise the design.

The present research aims at developing a LCA based material selection framework. In this selection process, the LCA results for each material influence the design. In addition, the LCA results depend on the design implementation of each material.

The literature review has been grouped into the following areas:

The role of material selection in design : This section explains the benefits of material selection at an early stage of a design, the possible methods and the common practices in material selection with environmental perspectives. It also defines the requirements to conduct a well argumented selection strategy. These requirements are used in the present chapter as well as in the entire thesis (section 3.1)

The current use of thermoplastic composites : The review focuses on an introduction to the current structural applications of GRTP, the suitability of the current manufacturing processes to boat building and a comparison between the thermoset and thermoplastic composites in a life cycle perspective. This section is a qualitative evaluation of the readiness of GRTP technology to be applied to boat building, the possible area of the life cycle of boats where benefit can be gained with GRTP being a candidate material for ship building (section 3.2).

Critical review of life cycle approach for environmental impact assessment : The review of the current practice in life cycle analysis for environmental impact management. This section shows qualitative results on the best practices in composites technology and performance measurement with a thorough analysis on how the LCA can be used in the present research (section 3.3)

A theoretical foundation of boat ship design : The presentation of the specifics of ship design and all the definitions required for later stages of the research (section 3.4). It also covers the topic of optimisation using genetic algorithms.

3.1 The role of material selection in stuctural design

Material selection is an important stage of any structural design as each material has specific functionalities, physical properties and manufacture possibilities. Any design has constraints and objectives. The **constraints** can be regarded as function which should be accomplished by the design e.g. maximum deflection, quantity of heat to evacuate, conduction of electricity, while the **objectives** are the level of performance to be attained e.g. minimizing cost or weight. The best solution (therefore the best material) would be the most effective with regards to the objectives. It is not possible to test all these materials to a given set of design requirements, but it is possible to extract from the design requirement some mechanical / physical model or principle by which it is possible to chose a set of materials that fulfil the constraints or function and which can be ranked by mechanical properties (e.g. specific strength).

It is necessary to understand the interaction between material and life cycle environmental impact in order to optimise structural design to better environmental impact. The working principles of the material / environmental life cycle model derives from the understanding of this interaction. The following critical review of the literature attempts to highlight:

- The good selection practices and the reasons for selecting materials, the possible approaches and required stages of material selection (section 3.1.1).
- An overview of some selection practices with emphasis on the most popular (section 3.1.2).
- The current state of the art of material selection with environmental considerations (section 3.1.3).

3.1.1 Good selection practices

Deng and Edwards [7] described the material screening stage of a design. Screening aims at selecting the possible candidate materials at an early stage of design, namely the conceptual stage. A good screening allows a greater number of possible solutions to a problem as these possible solutions depend on (1) 'the design specification', (2) 'material domain knowledge' and (3) 'working principle' [7]. The knowledge on material functional capability e.g stiffness, thermal insulation, chemical resistance, piezzo electricity properties, etc. and level of performance e.g. young modulus, etc. forms a domain of knowledge which size derives directly from the screening extensivity. This domain influences the possible answers the design problem.

Deng and Edwards [7] cited Kota and Lee [8] who stated that 70% of the cost of a product is decided in the early stages of the design. It is the best time to gather the material information needed to conduct the design. The working principle and design concept depend on the functions, e.g. thermal insulation, which have to be fulfilled by candidate materials.

Deng and Edwards [7] described five situations under which materials have to be selected:

1. **Design with functionality** when a function needs to be fulfilled by the material e.g. conducting electricity
2. **Design with physical requirement** when a particular physical properties is required e.g. smart material, piezo electric material, etc. The design takes advantage of these phenomena to achieve a functionality.
3. **Design requiring a material solution** when a material solution is sought as an alternative to a complex system. For example, a piezo electric material implementation may be preferred to a system with structural and electronic components.

4. **Design with functional integration** when the interaction between the structure and the material is studied in order to achieved a sum of function

5. **Design with tailored material** when several materials can be combined in order to achieved a compromise between their properties e.g. composites material such as GRTS.

The authors [7] claim that it is more cost efficient to achieve a function with a material solution than a mechanical or electronic system because the later is more complex to build and maintain. Therefore, it is important to note that point 3 and 4 are 'material oriented' design solutions and are potentially cheaper than 'structure oriented' solutions.

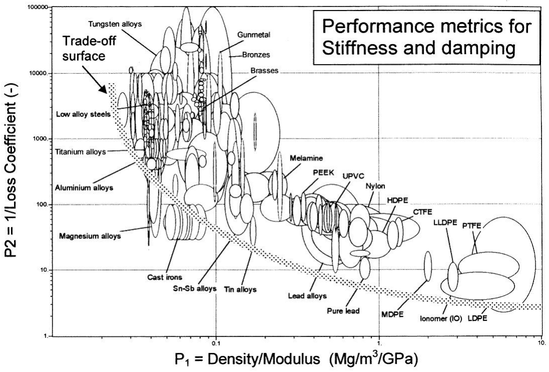
The first four points draw attention to the fact that a material solution can be used in place of a structural system. Therefore it is essential to intensively gather all the properties of the material. The examples mentioned are very specific to engineering, mixing physical phenomenon such as electrical conduction, vibration damping, insulation, electronics, smart material, etc. In the present research, materials must carry a structural function. The candidate materials are implemented using classification society rules. These rules are not purely mathematical and are the result of years of experience resulting in empirical rules. Therefore the environmental performance of these material is measured from the environmental performance of artefacts designed using these rules.

The last case (5) is a more familiar situation of material selection in boat design as it may be regarded as the adaptation of composite materials to a given application. For example Zehnder et al. [9] studied the optimum composition and lay up configuration of composites for a sail boat. In the present research, the present focus is on a family of materials such as GRTP rather than the composition or architecture of the material itself.

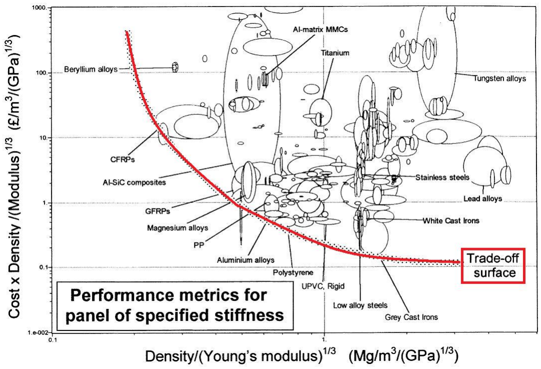
It has been discussed that there is a need for a strong interaction between the material functional capability and the design working principle. Therefore good practice in material selection should highlight the functional capability of material and design working principle. Section 3.1.2 is concerned with how the methods in the literature can answer the problem of making sure that a large material candidate pool can help in finding a solution.

3.1.2 Material selection methods

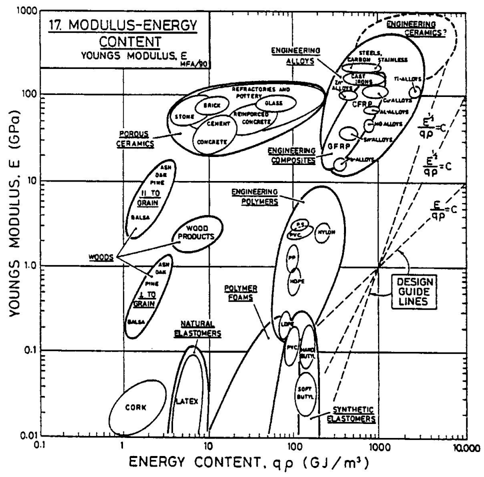
This section aims at reviewing methods of material selection. Material selection methods have been widely studied and are still the subject of numerous publications. Ashby is one of the most influencial authors in this area with several of his publications on material selection being cited more than 70 times.



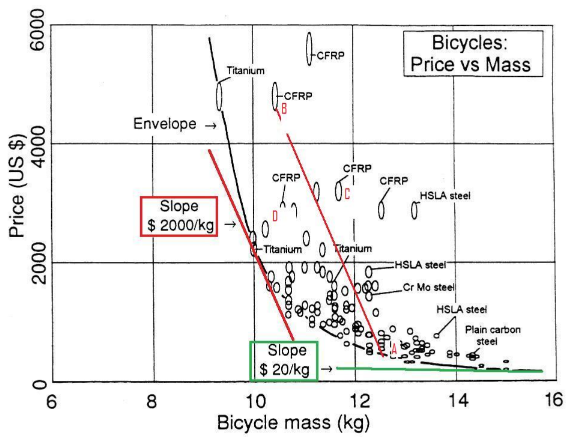
(a) Performance metrics stiffness and damping [10]



(b) Performance metrics with cost [10]



(c) Performance metrics with environmental impact Holloway [11]



(d) Value function [10]

Figure 3.1: Example of Ashby method

Figure 3.1 shows some examples of graphs at the core of Ashby's material selection method [10]. Each of the graphs (a) to (d) are examples of his selection methods. Each material or material family is presented in the graph in an ellipse highlighting the performance of the material for a given pair of parameters. In (b) the red line is the trade off surface. When one parameter is fixed it is not possible to find a material with better performance on the other parameter than the material in contact with the trade off line at the level of the fixed parameter. For a parameter P1, e.g.

$Density/Young'smodule^{1/3}$ fixed at 1.2, it is not possible to find a material with a lower value of the parameter P2 e.g. $Cost * Density/Modulus^{1/3}$, than grey cast irons. Therefore the trade off line is where the best possible performance can be achieved. If the selection is based on only one parameter performance e.g. best P1 or P2 there is no optimisation and the best solution is chosen regardless of the other parameter. However the parameters tend to be in conflict and the cheapest bike might not be the lightest as seen in (d). The concept of *value function* is added in order to select the best possible material.

Graph (d) shows the cost value function and shows the best material for any given application. It highlights the value for money of a given upgrade in material for a potential customer. As being shown by the red line, a 'passionate' cyclist would find it easy to justify the payment of $2000 for a one kilogramme reduction in bike weight. Therefore the titanium grade at the tangent point of the trade off line and the red value function would be the best solution. The other red line, parallel to the red line tangent to the trade off line has the same value function. On this line a 10.5 kg CFRP (B) option for $5000 will have the same value as an 11 kg steel (A) bike as this latter bike would cost $4000 less. However each material above this line and on the right of the steel (A) such as the CFRP (C) would demonstrate a far too modest decrease in weight for the additional cost, but any material below the line on the left of (A) such as (D) would show a greater weight decrease for a smaller amount of money than any other solution on the line increasing therefore its value to the eye of the 'passionate' cyclist. This demonstrates why the tangent to the line is the best solution as no other solutions can have a better value for money than this one as there is no material below the line. For an 'average' cyclist (green line) for whom any expense greater than $20 for kg lost on his bike would be too high, steel is therefore the best material.

In addition with this method Ashby [10], also presents some examples of cost value function in several industrial areas. Although this method does not give ambiguous results, the material choice being obvious, it still requires a strong expertise in materials as well as an even stronger insight on several industrial sectors. The work of collecting the value function is, by itself, a big challenge. Ashby [10] presented the value function for several sectors of industry. For family cars, the fuel saving of a lighter car is estimated as being between $0.5 and 1.5 per kg added or substracted. In comparison, in the aircraft industry each kg would worth between $100 and 500.

Apart from Ashby other methods have also been used for instance Zhou et al. [12] used a neural network and genetic algorithm and the authors cited the following three works. Sirilee et al. [13] used a pareto set to search for the best solution. Beiter et al. [14] documented an expert system approach which performs reasoning for the selection of the best material. Yang et al. [15, 16] presented a genetically optimized neural network helping the decision making. All these methods are based on pure mathematical models.

Zhou et al. [12] and Yang et al. [15, 16] demonstrated that neural networks are flexible because they can be applied to any objective function. Neural networks produce a great accuracy in the modelling of the potential performance of material. It is limited by the candidate material pool in input. Flexibility and accuracy are the advantage of neural network. Ashby's method is less flexible as it cannot be applied to multidisciplinary optimization. It is however easier to implement. In addition it is readily available in the material selection software package CES. Ashby's method is largely documented in books, articles and CES. It provides an extensive source of information for material selection. It is possible to select material from a very large pool of candidate material already stored in CES database.

3.1.3 Material selection for environmental impact

Deng and Edward [7] argue that further investigation is needed in the area of material selection with a life cycle environmental perspective. The authors referenced only two papers, a 1998 paper from Holloway [11] and 2005 papers from Guidice et al. [17]. These papers are both highly cited, 16 and 26 times [18] respectively. These two papers have several limitations in their implementation of material selection to environmental impact. A solution to these limitations have been suggested in this thesis.

Holloway [11] further developed Ashby's methodology (see section 3.1.2 for detail on Ashby's work), in order to include in the graph several environmental impact factors, and applied it to drink containers. The author highlighted that Ashby mostly focused on material energy use and Holloway supported this view and considered it the most important factor. However he also reviewed more impact parameters. Indeed a range of environmental information is readily available and can be used to provide a more precise impact picture. The author recognized that collecting the information for one impact type is a complex task but it is even more difficult when it comes to the *overall environmental impact*. The limitations pointed by the author stressed that the sources for environmental information are an average for many manufacturing processes and may not be completely representative for a very specific process.

In this thesis, the environmental impact information collection sometimes deals with manufacturing processes which have never been studied with respect to environmental impact before, such as aluminium laser welding or friction stir welding as well as all the processes related to GRTP manufacture. In this case focusing on energy is necessary because no impact information is available. The issues on information inventory and quality are treated in more depth in section 3.3.

Guidice [17] used an LCA methodology to compare materials for a car brake disk application (Section 3.3 defines thouroughly LCA). The design of the disk is adapted to the material as the geometry is changed for each material to the best of their physical properties. This is contrary to a general tendency to ignore the topology in the specific implementation of a material such as in Hedlund-Astrom's paper [6], already commented on in the introduction of this thesis. On the other hand the number of materials is limited to cast iron and squeeze cast aluminium alloy. The output shows that producing the aluminium brake is more expensive, requires more energy to be produced but it is lighter and therefore over a long time saves car fuel consumption. Each cast iron disc is 6kg and each aluminium disc is less than 4kg, saving more than 8kg per car. Cars (as well and aircraft and boats) are extremely sensitive to weight saving as it acts directly on the fuel consumption. Therefore any sensible decrease in weight for any part of a vehicle will result in a better environmental impact in the long run whatever the initial energy requirement, however there are problems, namely:

- **Cost equality**: The extra initial cost for the aluminium alloy disc could be better spent on design change.
- **Studied system limit**: In this case studying the disk as part of the entire car system shows a lack of consistency between the detailed modelling of the brake and the more shallow modelling of the car. Indeed the disk is a minor part of the car and the same kind of weight decrease could have been achieved in many ways such as smaller tank with less fuel. The uncertainties on the life of a car for such a small gain are very very large. In this case a 1% change in weight (8kg saving for a car of 1000kg) is not significant at the car scale and such small variation should be excluded from the system boundary.

Numerous other papers can be found on material selection and environmental impact analysis. Huang et al. [19] studied the air conditioner support plate to illustrate environmental design.

Ljundberg [20] focussed on the development of sustainable design and design management systems. He emphasised on the need to reduce material and energy consumption, increase recyclability and reusability and move forward to a more function-oriented business model. Manufacturing company can product as both services and products. By doing so, they may reduce production need for the same income as they are not so dependant to selling hardware product only. The author of the paper also drew attention to the properties of composite materials to decrease impact as each constitutive material of the composite is implemented in an optimal way.

Xu et al. [21] studied the LCA of wood fibre reinforced polypropylene. The authors compared material with several fibre weight contents and pure polypropylene. They used LCA to support material selection. The main outcome of the study is the definition of a material selection criterion called *material service density*. It is used as the functional unit of the presented LCA. In an LCA, the functional unit is the measure of the performance for which the input and output of the system are measured. It serves as a reference for comparing solution. In the present research, the functional units are defined in details in chapter 4. Xu et al. [21] defined the functional unit or performance of a material as the mass or volume of material required to perform a task. Therefore a different mass for each candidate materials can be used in the LCA when calculating the overall impact. The authors used eco indicator 99 to assess the impact. The result of the study demonstrated that impact is mostly influenced by the PP content. Indeed PP has a much larger specific impact than wood fibres. The comparison of composites with polypropylene shows that less material (in weight and volume) is required to withstand the same mechanical constraints. The environmental impact of PP solution is therefore higher than the composite alternatives because it requires more material of a higher specific impact. The study is also of particular interest because it provides a reference for comparing the result of the present study (see Chapter 5 and 6). The paper is reviewed in greater details in the conclusion of these chapters and compared with the result of the present research.

Song et al. [22] studied the LCA of fibre reinforced composites. The authors applied LCA to a truck and a bus component. They compared the relative performance of composites with recycled steel and recycled aluminium. The authors presented and extensive collection of energy values for the life cycle of the candidate materials. These values are used in the present research to validate the results. The author showed that the composite and aluminium components were much lighter that the steel. As a result the in service energy was much lower for the lightweight materials thanks to lower fuel consumption. The manufacturing energy difference between steel and composites is negligible in comparison with the in service. The aluminium and composite structure are close in weight. The aluminium structure is lighter than the composites structure. It generates a small saving in service. The composite structures require less energy than aluminium to be manufactured. The authors clearly highlighted the influence of the length of use. Indeed the truck life is small and the saving during manufacture of composites compensates largely the extra in service energy consumption. The coach life is long and the extra energy consumed mile after mile by the composite structure is larger than the saving from manufacturing. The aluminium structure has therefore better results. The study also showed that composites end of life treatment required more energy that the metal alternatives. In the present research it is important to carefully consider the in service life length in order to have the correct balance between in service and manufacturing impact.

Zhou et al. [12] studied multiobjective optimization of material selection for beverage containers. The author used LCA with the Eco-indicator [23] as an impact measurement and a genetic algorithm and neural network for the optimization. Although the study is rather intensive the limitation to beverage containers gives little insight for a large structural application such as a boat. The design is very simple and the information on readily available and commonly used materials and processes is very accessible. In the present research on structural grade GRTP, the information availability is considerably lower.

Rydth et al. [24] summarized and grouped the environmental information from Eco-Indicator 99 [23] for several materials. The work focused on grouping materials in families and provides more accurate information than energy for the environmental impact. The Eco indicator 99 is a measure of the impact providing information reflecting the state-of-the-art in impact measurement for several phenomena such as climate change, resource depletion and eutrophication (the detail on LCA impact information inventory is detailed in section 3.3.2). Although the information is very accurate in comparison with energy as extensively used by Ashby [10], it must be mentioned that it is difficult to get this level of accuracy over a wide range of industrial processes. This has been the case in the present research for instance for processes such as composite boat recycling. One of the motivations for the study of GRTP is recycling potential compared with GRTS and little is known about the processes associated with GRTP. One objective of the research is therefore to balance the need for an accurate impact parameter but also to insure a consistency in the quality of data. Section 3.3.2 covers both the issue of data quality as seen in the ISO standard for LCA and section 3.3.4 provides an insight into the consequence of the inacuracy on LCA results.

In terms of applications, Weaver et al. [25], Bovea et al [26] and Vidal et al. [27] studied respectively fridge insulation, wood configuration for furniture and a bio composite for aquaculture application. These three papers showed three material studies where material selection tended to be of minor importance in comparison with impact assessment. The first paper highlighted the balance between material insulation and energy consumption over the life of the fridge. The thickness of the insulation is fixed therefore the issues are to balance life cycle and manufacturing cost. The second work dealt with the wood configuration such as plywood or compressed wood. While it shows the impact differences between the products are relatively different, it fails to compare alternatives having similar mechanical properties. The second issue with this study is that that the environmental impact of natural materials is very controversial especially for land use. It is extremely difficult to find a measure of the environmental consequence of land use. Vidal et al.'s [27] paper highlighted this fact well in doubting the benefit of bio composites to traditional oil based composites, for which processes are much more optimized than the bio composites and on which it is difficult to assess the real cost in terms of land use.

3.1.4 Conclusion and opportunities for research

As seen in the introduction of the thesis, composite materials are by far the most common material in small boats. A large amount of work has been done in order to design composite materials and enhance the laying up for instance, as discussed in the paper of Zehnder [9]. However, the focus here is on the life cycle as a whole and therefore aspects other than the manufacture should be taken into account such disposal and materials can be compared using a larger family such as steel, aluminium or GRTP each having different qualitative properties in terms of weight, recycling and implementation in the Lloyd's Register special service craft rules and regulations.

3.2 Current use of thermoplastic matrix composites

Glass Reinforced Thermoplastic matrix composites (GRTP) are considered in the present study as an alternative for Glass Reinforced Thermoset matrix composite (GRTS). As presented in the first section 3.1 the possible structural design depends on the knowledge of the material. As a first approach, the advantage of GRTP over GRTS is the recycling potential and the clean production. Indeed, the environmental performance of thermoset composites is impaired by the presence of Volatile Organic

Compounds (VOC) and regulations aim at lowering VOC emissions. European legislations on VOCs are becoming increasingly strict. Some major directives such as the one of 1999 on the global use of VOC (1999/13/EC) and the directive on paints and coatings (2004/42/EC) illustrates the banning of products with high organic solvent content. The elimination of VOCs by using thermoplastic composites and the desire to consider the life cycle of a product, including manufacture is a key focus of the present research.

3.2.1 Composites life cycle

Studying composite life cycle means to study the entire life of the materials i.e. from raw material manufacture to complete disposal. The best way to improve a system is to identify, at the earliest stage, all the useful mechanical and material requirements. The present through life study has the same aim. It has to take into account, very early, the issues which are not service issues such as the manufacturing wastes, dismantling, recycling and repair.

The life cycle properties of the thermoplastic need to be investigated in order to evaluate the real cost (economical and environmental) of the final product. The final goal of this action is to decrease the negative impact of the product economically, socially and environmentally. From an engineering point of view, this deals with the selection of:

- the resin and the matrix
- the raw material configuration e.g. fibre configuration, prepreg, commingled yarn of thermoplastic and glass fibre, etc.
- the processing variables
- the processes and the elimination of consumables as it counts for a non negligible material flow in the LCA
- the use
- the reuse or refurbishment
- the recycled material production method
- the suitable recycling alternatives
- the monitoring method

- the suitable time for landfill

The properties of the resin make the main difference between the GRTS and GRTP. There is a large number of resins available and used in the manufacture of fibre reinforced composites. Table 3.1 provides the qualitative properties of a selection of the most commonly treated thermoplastics as seen in literature. The GRTP resins need to have a structural grade i.e. virgin, be cheap, and as easy to implement as thermoset resin. It must be mentioned that the quality of the finished product depends on the processing. The control of the process should tend to an optimum quality of GRTP final product that balances cost with crystallinity requirement versus residual stress and void content. The slower the cooling, the higher is the crytallinity but increasing time in the oven makes it more expensive. The quicker the cooling the higher the residual stress.

Table 3.1: List of GRTP resin

Resin	detail	PRO	CON	ref.
PP	Poly propylene. Extremely current in a variety of consumer application	Large range of manufacture temperature Available in a large variety of configuration (GMT, commingled yarn,consolidated tape, etc.) Price	Low heat resistance	
PET	Poly ether terephthalate. Technical thermoplastic. Extremly current in a variety of consumer application.	High mechanical properties	Relative difficulty to process due to higher melting point	
PA	poly amide. Also known as nylon	Good wettability and manufacturability	Heat sensitive	
PEEK	Poly ether ether ketone. Mostly used in high performance application such as aerospace and bioengineering	Highly studied in aeronautical and aerospace application	Difficult to process due to high melting point Very high cost (in comparison to PPS for instance)	[28, 29, 30, 4]
PEKK	Poly ether ketone ketone. Very close to PEEK but easier to process. Gardiner considered it has potential[30]	Heat resistance High mechanical properties Relative ease to process	id PEEK	[30]
PES	Poly ether sulphide	Heat resistance Suitable for sandwich core material	difficult to process	
PEI	Poly ether imide. PEI is an amorphous thermoplastic	Heat and fire resistance Toughness suitable for sandwich core material	Low chemical resistance	[28, 29, 30, 4]
PPS	Polyphenylene sulfide. High performance resin. The higher chemical resistance of PPS in comparison with PEI for relatively similar properties will probably increase its use in the aircraft industry [30]	Heat resistance Higher chemical properties in comparison with PEI		[28, 29, 30, 4]
PBT	Poly butylene terephthalate	Good wettability		
POM	Also known as Acetal. Technical resin.	High mechanical properties		

PEI (polyetherimide), PPS (polyphenylene sulfide) and PEEK (poly ether ether ketone) are the most commonly reviewed in the literature [28, 29, 30, 4]. These matrices have as a common point, a very complex chemical structure compared to the linear structure of low performance thermoplastics. Their aromatic and/or imide rings and crystallinity give them very good chemical inertia (PEI is an amorphous imide thermoplastic), improved toughness and excellent fire resistance. These properties are not common to all thermoplastics. Offringa[28] stated that PEI is the most used matrix due to its ratio of price to performance but predicted that the utilization of PPS will increase because of the future need of chemically resistant material in aircraft applications (resistance to hydraulic fluid for instance). Gardiner[30] cited Offringa from Stork Fokker, who found that PEEK is attractive because of its high temperature resistance but too expensive to purchase and process. However he considered that PEKK (poly ether ketone ketone, relatively similar to PEEK but with easier processing) revealed a better potential[30]. Even with these drawbacks, PEEK remains intensively studied in academic literature because of its outstanding thermomechanical and chemical properties[29, 4]. PEEK applications can be found in engineering applications as varied as cryogenic tanks for aerospace, satellite structures and hip prosthesis[4].

3.2.2 Current application

Table 3.2 shows a selection of application of GRTP in the aeronautical, automotive and ship industries highlighting the reason for the introduction of GRTP in these areas.

Table 3.2: Summary of the material selection literature review

Case nb	Application	Details	PRO	CON	Ref
1	Stork Fokker: landing gear door	PEI/glass compressive moulding	Reduced assembly time Dramatic weight gain in comparison with aluminium	High temperature cost of manufacture	[28]
2	Stork Fokker: flooring for airbus A310 (cargo)	PEI sandwich with welded edge	Improved edge toughness		[28]
3	Stork Fokker leading edge Airbus A340	PEI /carbon Leading edge in autoclave with welded GRTP stiffener	No complex ply sequence for locally reinforced part Welded stiffener	Custom made Cetex carbon / pps Need for autoclave High curing temperature	[31, 30, 31, 32]
4	Stork Fokker: leading edge Airbus A380	Same as 3 but with glass fibre allowing greater flexibility and lower cost	id	id	[28, 30, 31, 32]
5	Lockheed Hercule C 130 door	PEEK / carbon fibre as an alternative to aluminium	Weight reduction Reduced number of fastener	Cost of raw material	[29]
6	Lockheed Hercule C 130 radome (1)	PES film stacked to glass yarn	Reduced manufacturing time	High viscosity High manufacturing pressure part size limit to less than $1m^2$	[4]
7	Lockheed Hercule C 130 radome (2)	PEEK /glass	Easier impregnation than PES		[4]
8	BWM M3 CSL bumper	Nylon based GRTP award winning component. The individual components are welded together	High toughness Lightweight		[33, 34]
9	BMW M3 CSL seat	Twintex / PES foam sandwich	Lightweight	Difficult to recycle	[35]
10	PP/glass car bonnet	compressive moulding part. PP is showing the best wettability, heat resistance, price in comparison with PA and PBT	Improved shock absorption preventing the catastrophic failure observed on steel bonnet Good corrosion	Cost effective for range of production lower that steel (GRTP: 10,000 - 100,000 vs Steel > 100,000)	[36]
11	Stork fokker technology transfer	The sandwich panel used in the Airbus A310 and Fokker 100 was used in the plating of the Carmac Voyager pilot boat.			[37]
12	Resin design for paddle boat	Young et al. [38] presented the struggle to find a resin as easy to mould as ABS, with an increased weatherability and with a top grade gloss as GRTS. A paddle boat with skin glass reinforcing blend of ABS with a PMMA protecting layer with urethane core	Good manufacturability Intermediate gloss between PP with bright colour and high gloss finish of GRTS	Difficulty to compete with GRTS in small boat range Extremely customised resin Suitable mainly for leisure Lower gloss Recyclability	[38]
13	CETMA Twintex boat	Vaccum bagged Twintex sailboat. The study highlighted the relationship between high manufacture temperature and the wettability of the resin but failed to demonstrate any influence of the cooling rate on the mechanical properties although showing an increase in crystal size. The component of the boat are welded			[39]
14	VT Halmatic	Award wining boat. Vacuum bagged Twintex boat	Recyclability + clean production Dramatic weight decrease in comparison with aluminium alternative high impact resistance Reduced laminating time of thick Twintex Cost efficiency		[40]
15	Large in-situ consolidation	Some large component especially cylindrical can be manufactured with in situ consolidation	High mechanical properties Cost effective	Suitable only for simple geometry	[41]

In the aircraft industry the consolidation potential, increased toughness and weight decrease potential in comparison with aluminium makes GRTP an attractive alternative to aluminium [28]. The fuel saving due to its lightweight and the manufacturing cost decrease due to the decrease of fastening operation time makes it easy to overcome the high investment requirement and the cost of raw material. In the automotive industry the potential cost decrease was the main trigger for the introduction of GRTP. GRTP compressive moulding is a fast processing method [42, 43, 44, 45]. It is cost effective for series between 10,000 and 100,000 parts a year. For similar components, steel is cost effective for series larger than 100,000 parts a year and GRTS is most cost effective for series inferior to 10,000 [36].

The consolidation properties of GRTP allow a decrease in the need of fasteners. This is a major advantage in the aircraft industry in comparison with aluminium structure but brings little benefit to boat hull building as the thermoset structure uses few or no fasteners in the manufacture of a hull.

Fast processing is one of the most important aspects of GRTP which influence its introduction in the automotive industry through the higher productivity due to compressive moulding. In the case of boat building, the decrease in the actual consolidation time is not such a big advantage as the number of boats built is much lower than vehicles in the automotive industry. Higher productivity can however be gained through easier lay up as seen in table 3.2 line 14. This can be an advantage as it makes up for the extra investment required for the introduction of GRTP in the boat industry. The same application also showed that extra toughness can be expected from the introduction of GRTP

Although GRTP is recyclable[40], no marine application of recycled material was found in past literature. The recycling of GRTP should therefore be treated in the same way as the recycling of GRTS to provide a fair comparison between the two materials.

It has been shown in this section that GRTPs have been used in a large number of applications and there are no indications that the possibility of a larger GRTP structure is not feasible. In addition, improved toughness and lower laminating time will be of great benefit to manufacturers of boats if GRTP is introduced. GRTP will therefore be considered as a candidate material in the selection process at the conceptual design stage of a boat.

3.2.3 State of the art of GRTP manufacturing process

The industries using GRTP, such as automotive industries or aircraft industries have objectives such as aiming for faster and cleaner processing. In the following section the manufacturing processes dealing with GRTP is studied. One objective is to identify what processes can use a recyclate from boat dismantling and the conditions in which this recyclate will have some value for another company.

Table 3.3 shows the manufacturing processes that can be used in a recycling perspective. Each composite material and raw material configuration require a different method of recovery and disposal. Each recyclate, resulting from a specific recovery method, can be of interest for reuse by another company's specific processes. Marine application of GRTP studied in the present research are structural which means the primary material would have a high reinforcement content and long fibres. As a result only the matrices suitable for engineering applications are considered.

Composite material properties are largely influenced by their manufacturing conditions. This section presents the manufacturing processes suitable for marine structures. This study considers only the influence of the manufacturing process of composites on the quality of the final laminate rather than its cost efficiency and focuses on continuous fibres composites. The peculiarity of thermoplastics is that they are very viscous melting and the flow of the resin through the reinforcement is difficult without high pressure. Such pressures are quite difficult to reach for large parts and need a suitable mould. These specialised moulds can be very expensive and not very economically suitable for the small volume production of large parts.

The configuration of the material can be as a sheet or tape, of uni- or multi-directional consolidated material, tissues of commingled yarn of thermoplastic and reinforcement fibres or separated thermoplastic and fibre sheets. The raw material can be pre- or post- consolidated. The main idea is that the raw composite configuration must minimise the flow distance of the matrix[42] during the melting and consolidation. The material selection has to consider the implicit pressure needed for each kind of material by looking how intimately the matrix and the fibre are in contact with each other and how the raw material can be fitted in the mould. For example a commingled yarn process requires less pressure to be manufactured than a separated film stacked process[4] (vacuum moulding, compressive moulding, autoclave...) because the resin and fibres are intimately in contact. It is also expected that consolidated tape requires less time to be consolidated as the matrix flow does not have to wet the reinforcement fibres as they are already preimpregnated.

Table 3.3: Manufacturing processes for GRTP. SLP: suitable for large component, SR: suitable for smaller recyclate, RMC: raw material configuration

Process	Definition	SLP	SR	RMC
Vacuum mouling	The raw material is pressed into a mould thanks to vacuum made in a airtight bag. It takes place in an oven	Y	N	Commingled yarn, tape, on site mixing
Autoclave moulding	Same process as vacuum moulding but extra pressure is applied with the use of an autoclave	Y	N	Commingled yarn, tape, on site mixing
Compression moulding	The most versatile. The cost of the mould however limits the size of the component	N	Y	All compound (virgin raw material or recyclate) can processed through compression moulding
Injection moulding	A screw mixes, heats and injects the melted material in a mould. Complex components are possible but the size is limited.	N	Y	The injection uses pellets
Pultrusion	Fibres and the resins are injected through a die and cooled off. Creating straight or moderately curved beam. The reinforcement is only in one direction. This process is related to the granulation	Y	Y	This process is best used with long fibre tape or TP and glass fibre roving can be used
RTM	The melted resin is injected in the reinforcement in a closed mould.	N	N	It is the only GRTP process which does not use prepreg but separated resin and fibre. Only few resins specially treated can be considered for this process. Recycled resin cannot be considered
Filament winding	Filament of fibre and resin or tape of preconsolidated materials are winded.	N	N	
Welding	The assembly of material through local heating	Y	Y	Resistive mesh (This local contamination of the material results in difficult recycling)
Shredding	The waste material is shredded in case of smaller chips in order to be repocessed, shipped or incinerated.	-	Y	
Compounding	This process converts a material to a raw material configuration suitable for a given process i.e. granulating	Y	-	

It is advantageous to chose a matrix for which mature composite recycling route exists i.e. a thermoplastic matrix use extensively in car industry such as PP. The legislation on car recycling [46] should push car manufacturers to develop methods for their composite material disposal. As PP is probably the most common thermoplastic matrix in the car industry and the recycling route for car component exists, making it of major interest for ship building.

The most extensively studied material used for large thermoplastic parts is commingled yarn and TWINTEX from St Gobain Vetrotex is the best example. TWINTEX is PP/E-glass composite which raw unconsolidated configuration is a fabric made of interwoven fibre of E-glass and PP. This material is consolidated under pressure and temperature. It is easy to implement and lay up [40] in the context of a large hull manufacture compared to consolidated tape. The use of vacuum bagging is the only possible process for the building of a boat. The mould is not loaded and as the matrices fibres are closely mixed with the thermoplastic fibres the flow of melted resin is small. The process for laying up and bagging TWINTEX is similar to that used for thermoset composites.

The production of thermoplastic structures generates waste: vacuum bag, breather, sealant, mould, mould backing structure. The backing structure may be in steel and is recyclable. The mould can be recycled through fluidised bed and the fibres recovered. The resin is subject to repeated heating and cooling cycle that can damage the integrity of its properties. The other consumables are composed of several layers of thermoplastic, thermoset, glass fibres and contaminated by chemicals such as release agents and adhesives such as sealant. Their disposal is complex but represents a relatively low volume of material. The effort for collection (in term of impact) may be very high for little recovery. Suitable incineration process could be considered.

The recycling depends on the quality and contamination of the recovered material. The massive use of the exact same material for the entire structure could contribute to an easy and automatic dismantling (e.g. press and automatic crushing). Non permanent joint has to be implemented when joining dissimilar materials. The sandwich can be easily recycled if the core is PP (honeycombe or foam). PP/E glass skin with PP honeycomb material has been recycled on a laboratory scale in order to produced new pellets[47]. Monolitique composites need to be shredded.

The mechanical recycling has the advantage over 'glass only recovery' by not deteriorating the mechanical properties of the glass fibre. The drawback of glass fibre recovery from heating process is that mechanical properties are lost at high temperature. Pickering et al.[48] demonstrated a 67% recovery of tensile strength. Surface treatment and washing are undesirable and can be avoided by reusing the resin in the same configuration. Indeed recyclate can be considered as prepreg.

When recovery is not possible the value of the scrap is very low. This is the case when the recyclate glass fibres are short, the resin has already been reprocessed and therefore cheap processes of recovery are to be used. Incineration can be used with city waste and takeing advantage of the high calorific value of the recyclates and energy recovery in the output. The remaining product is mainly made of non organic waste ashes which must be suitably disposed in a landfill.

3.2.4 Comparison between GRTS and GRTP recycling

Thermoset composites cannot be remelted and reprocessed. The problems related to thermoset composite recovery, and the state of the art of the technology related to their recycling, is addressed in the following section. In the context of boat recycling, two strategies can be found which are, the development of dedicated recovery equipment for composites specific to the needs of the boat building industry, and the adaptation of the boat building industry to new materials more suited to recycling. Using a material such as GRTP could be beneficial to the disposal strategy. Much can be learnt from the automotive industry and automotive component recycling. At the same time, the boats are much larger than automotive components and need to be partially dismantled. Dismantling methods are similar for both GRTS and GRTP.

Table 3.4 shows the possible route for the recycling of thermoset and thermoplastic matrix composites. The processes dealing with composite recycling in general deal with low volumes of reinforcement and resin and large volumes of filler.

Energy recovery is another alternative for the disposal of composites. In general the reinforcement and fillers in composites have a low heat release during incineration compared to the relatively high value obtained from the plastic resins. This works against composite materials, as higher performance composites tends to contain higher fibre volume fractions effectively reducing the amount of energy per tonne of material. Glass fibres, calcium carbonate and other fillers are responsible for a high amount of ash. Fire retardants have a relatively low impact on heat release[49]. Recycling

Table 3.4: Comparison between thermoset and thermoplastic matrix composites recycling

Process	Definition	subproduct	Ref.
Mechanical recycling (GRTS powder)	GRTS scraps are shredded in small fraction	The recyclate is used as a filler	[49]
Mechanical recycling (GRTS large chip)	GRTS Scrap are shredded	The result is used as a reinforcement	[49]
Mechanical recycling (GRTP shredded scrap compressive moulding)	GRTP scraps are shredded in small fraction and directly reused as prepreg	The recyclate is a prepreg readily available	
Mechanical recycling (GRTP shredded scrap recompounding)	GRTP scrap are shredded and mixed with in a screw and the material can be injected. Main application would be to blend new raw material that can be used in standard conditions	Pellets can be obtained.	
Pyrolysis (GRTP and GRTS)	Heating under controlled atmosphere of the composites and separate resin and fibre	Fibre can be recovered. Monomer are theoretically possible to be separated but very difficult in reality	[50]
Fluidised bed	Temperature controlled combustion of the composites	Short glass fibres are recovered with an average of 67% recovery in tensile strength	[48]
Chemical recovery	The matrices is dissolved in a special solvent and is separated from the fibre	Resin and fibre can be recovered but the separation of monomer is difficult.	
Incineration	The scraps are burnt in regular incinerator. Less pollution is expected from GRTP, especially for simple linear carbonated chain such as PP	Energy	[49, 50]
Cement Kiln (of calcium carbonate charged GRTS)	Highly filled composites generate high level of ash due to the calcium carbonate content. This filler can be valorised as a desulphurisation agent for coal in cementery	Energy and desulphurisation	[49]

can appear as the best solution to reduce the environmental impact of material of a structure and reduce the consumption of new materials. Recycling is a high adverse environmental impact process especially for composite materials. The level of ash is very high and moreover the resulting materials have low mechanical properties. At the early stage of recycling, the amount of recycling material used in a new product (fibre and matrix) is commonly close to 20% and the question of using a large volume of recycled material is an important issue. Reuse is the best solution for waste prevention. A suitable reuse depends on the calculation of the property loss (after aging, repair, re-melting, etc.). Heldung-Aström[51] referenced K.A. Olson et al. [52] who demonstrated that reshaping thermoplastic matrix composites resulted in better properties than virgin GRTP. This could be explained by better impregnation of the fibres after re-heating and re-shaping.

In order to ensure ease of recycling the materials should be clean and separated, i.e. having no mixed materials. Easy dismantling can be achieved by the following [53] :

- Implementation of a modular solution.
- Application of material with more pronounced recyclability.
- Using alternative assembling technique such as clips and avoid permanent joints and mechanical fasteners.
- Avoiding hybrid structures.

the last two points go against some composite adavantages. Indeed, weight efficient design with composites is based on consolidation, sandwich structures and permanent structural joints. These types of structure have poor recyclability potential but result in lighter more efficient structures. The impact on fuel consumption may be larger with design for recycling therefore not being the most environmental friendly method overall.

The recyclability heavily depends on screening. One way to ensure recycling is to reference components. The British Standard 22628-2002[54] presents a method for the accounting of the recyclability and recovery rate of automotives. It takes into account the design, the material properties and the existing technologies for recycling and recovery. The evaluation has to be conducted before the arrival of the vehicle on the market. It also gives the mass of material which could be recycled for one given method. Jankovic et al.[53] introduced in his paper an initiative with the same purpose, from GRUNDIG, which labels every part bigger than 100 grammes with recycling information.

Boat disposal in Japan has been implemented and documented in Hedlung Astrom[55] where the shredding of an 8 metre long boat has been presented. In addition, Hedlung Astrom[50] studied different ways to recycle polymer composites using a case study consisting of a sandwich construction for a Royal Swedish Navy vessel. Every single feature of the boat is included in the model from the bulk material recycling to wire recovery. Some parts of this study are based on the Swedish VAMP 18 project which deals with the recycling and recovery of polymer composite materials. In this project five materials have been investigated for the recycling and recovery potential including a GMT (Glass Mat Thermoplastic usually polypropylene/glass composites), a GRTP relatively close to TWINTEX. The other studied materials are carbon fibre reinforced plastic, sandwich with GRTS skin and PVC core, a SMC (thermoset/glass fibre), and polypropylene/flax fibres (flax is a natural fibre). This study provided a good evaluation of a thermoplastic (reinforced with glass or flax) for aspects including, such as the ease of grinding (tool specification and energy consumption) or energy recovery (high [energy recovered/ash] rate).

Several possible life cycle 'scenarios' are presented. One of them showed that 'material recycling of GMT results in both cost gains and decreased environmental impact'. In the present research, the design has to be sensitive to possible scenarios, design paradigm and duly consider their environmental impact. Therefore, the question is what is the best boat design approach: Design for low weight, low investment, ease to manufacture, ease to dismantle, etc.

The end of life model should take into account EU legislations imposed on industry to process waste treatment as close as possible to the production site. Composite materials are not on the "green list" for shipment (1999/816/EC) and so permission is needed to allow waste to travel from one country to another[50]. The present research focuses on the UK and takes into account the global laws that highlight the responsibility of the waste producer, the amount of waste that needs to be recovered by law and the current state of the facilities.

In the case of thermoset composite materials, mechanical material recycling can be considered as the most obvious and effective way of recovering material. Scrap is ground or cut and the resulting recyclate is used as reinforcing material. Pickering [49] highlighted the fracture mechanic issues because large recyclate particles create hard points in the new material. Powder reinforcement makes the resin more viscous and lowers the mechanical properties[49]. If the waste management is the main cause of recycling and the mechanical properties are a lower concern, possible reuse can be new automotive parts, telephone kiosks, or cable boxes. It has to be noted that, some small leisure boats containing 40% recycled material[50] have been investigated.

Evidence of the application of recycling outside packaging is sparse and the general level of landfill in UK is very high. According to DEFRA (Department for Environment, Food and Rural Affairs) [56] industrial waste represents 13% of the total waste in the UK to compare with the household waste (8%) or commercial waste (29%). 44% of industrial and commercial waste is landfilled and 45% are recycled. In general, plastics are recycled at a rate of 10% in the UK which is much lower than more expensive material such as lead (60%) or paper (38%). Recycling figures include a high portion of composting which makes the actual recycling of plastic low. However, composite materials are not considered as a material in the same way as plastic or lead.

Energy recovery reduces the volume to landfill while releasing some energy. Landfilling companies have to limit the landfilling of biodegradable waste and carbon based waste and incineration is a good solution as composting composites is not possible. However in the case of composite materials, the higher the fibre and filler content, the higher the ash content. For instance the ash of SMC (Sheet Moulding Compound) is almost 70 - 80% of the material and the question is whether the pollutant emission is worth the energy and volume recovered. In the case of structural thermoplastic and thermoset materials, it is less critical because the energy recovery is higher thanks to a lower filler content. It is possible to blend the composites with municipal waste to keep a limit on the pollutant in the smoke. The cleaning of contamination (oil, fuel etc.) is not required. Only 8% of British municipal waste is incinerated including a low proportion of industrial and commercial waste[56].

For both energy recovery and chemical recovery recycling methods, the main aim is to remove the matrix from the fibre. The heating in absence of oxygen (pyrolysis) decomposes the matrix into liquid and gaseous components which can be used as fuel or as a basis for new polymers. The cost of the fibre obtained is 80% of the price of virgin fibre. 20% of recycled fibres can be introduced in BMC (Bulk Moulding Compound) without significant loss of properties. Hydrolysis, alcoholysis and glycolysis are the chemical routes for monomer recovery. The fluidized bed technique is similar to pyrolysis. A hot flow separates the resin from the fibre and the gas is burnt releasing energy for sustaining the burning and creating some energy [49, 48]. Separation and burning at lower temperatures allows a decrease of smoke and avoids overheating of the fibres, which may reduce their physical properties. These fibre are suitable for low performance, long term applications and large volume applications such as city furniture (bus stops, phone kiosks) and cements [50]. These kinds of applications have potential in terms of cost and volume of recycled material.

Recycling of matrices by monomer recovery for virgin matrix manufacturing while keeping the fibre mechanical qualities is difficult. The solution would ensure the recycling loop of the material but is very expensive and may cause substantial pollution due to the use of chemicals for the matrix digestion.

This section has dealt with thermoplastic usage, production and recycling, that latter two aspects are part of the life cycle and will therefore have an impact. Quantification of these processes is a key aspect of life cycle analysis and will be considered in the present research.

3.3 Critical review of life cycle approaches

3.3.1 Introduction to the life cycle approach of materials

Y. Leterrier[57] presented the life cycle of composites. He introduced a *closing loop of composite materials* concept in which he demonstrated that a loop could be based on waste minimisation and resource efficiency. Figure 3.2 shows this loop. Several loops can be found such as (raw material – refining – material – recycling – raw material). Reducing the impact implies the time extension of the last loop (product – use – waste – cleaning – product). It shows for instance that a designer can optimize the resource consumption and the waste production by decreasing the weight of a system. In the same way, the waste minimisation by recycling has an impact on the resource, keeping in mind that 'recyclable' does not imply 'recycled' and 'recycled' does not imply 'environmentally friendly' [57].

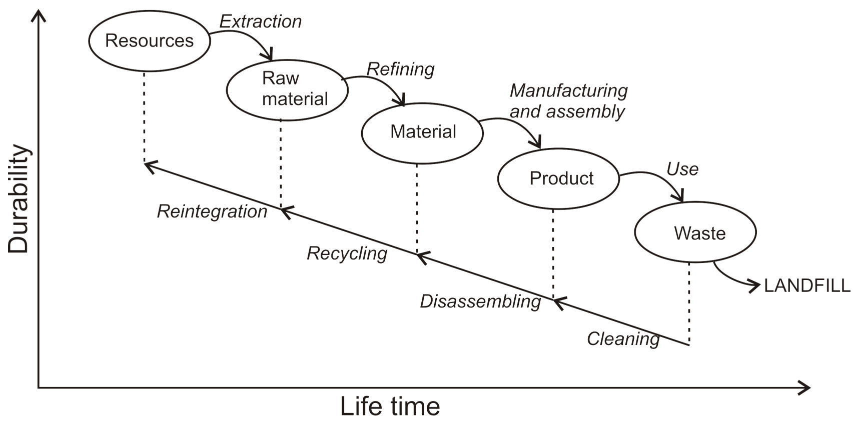


Figure 3.2: Life cycle of composites [57]

In order to improve environmentaly the life cycle of a material, Y. Leterrier[57] presented and ranked a list of actions beneficial to a more environmentaly friendly life cycle (table 3.5). This study made the link between Design, Composites Material Science and Environmental Science. Durability and waste prevention could be considered as key aspects. In other words, the longer the system is used, the smaller the volume of waste and therefore easier the treatment, and thereby reducing the impact of the system on the environment.

Table 3.5 shows that it is possible to improve product life cycle. However as seen in the present section, the relationships are qualitative more than quantitative and depend mostly on the goodwill of the stakeholders to be implemented. For example, dematerialization and reuse require users and manufacturers a lot of efforts in order to move toward a business model based on selling services e.g.

Table 3.5: Hierarchy of action lowering life cycle impact (Leterrier [57]

Action	Comments
Dematerialization	This process tries to limit the material consumption in different ways such as consolidation. It is difficult to implement.
Life extension	This is the core of the durability aspect, the more a system is used the less important the manufacturing impact will be. Nevertheless this is also quite difficult to achieve because it demands a strong preliminary study to avoid the limiting factor such as aging, degradation, improper design, manufacturing cycle and obsolescence.
Maintenance	Maintenance and upgrading are useful tools to increase the life of system in normal service conditions.
Repair	In addition to maintenance the repair can avoid the problems due to accidents.
Reuse	When the system is too degraded or if no upgrade can be done the reuse of parts or the total system in another application is a good solution. The dismantling or some disposition for a further reuse has to be taken into account during the design.
Recycling	It may be surprising but recycling is not really the best solution because of its technical aspects, the loss in properties of most of the recycled material and energy consumption required. It acts mainly on resources.
Energy recovery	The incineration with energy recovery is a less interesting method for the waste management. The large amount of ash and pollutant emission limits its use for composites. It includes also resin recycling in fuel
Incineration / landfill	These last two solutions have to be used only if no other solution can be used. Landfilling would be probably very difficult for bulk material in the future and it should be considered as an increase in cost.

maintenance rather than products. Material selection strategies widen the possible solution pool of a given problem by increasingly taking advantage of each material's characteristics, as presented in section 3.1.1. In the following section Life Cycle Assessment (LCA) is presented as it is a way to compare different solutions with an environmental impact emphasis. Application of LCA to material selection were reviewed in section 3.1.3).

3.3.2 The Life Cycle Assessment (LCA) methodology

The Life Cycle Assessment (LCA) is a technique for assessing the environmental aspect and potential impact of a product by compiling an inventory of the relevant input and output of a system, evaluating the impact and interpreting the results. LCA has been examined by a wide range of organisations. This methology is at the boundaries of design, science, legislation and trade. This section presents the LCA according to ISO standard 14040[5].

Most of the time the design focuses on the in service life. Environmental impact measurement also

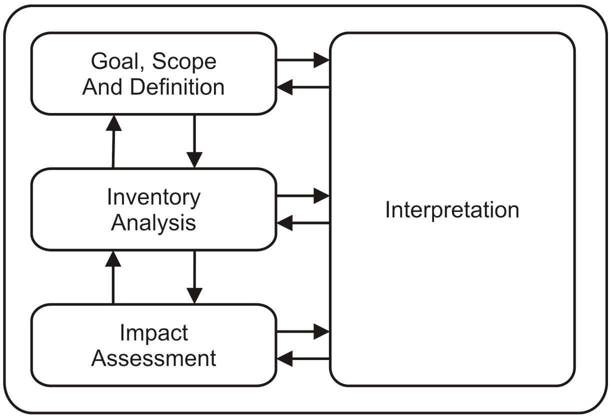


Figure 3.3: Phases of the LCA (from ISO14040)

reflects complex interrelated phenomena (green house gas emission, global warming and biodiversity for example). The accumulation of environmental damage over a product's life is also an important input to design decisions. A product can be acceptable to people for a variety of reasons (technical or not) and material selection can play a great role. The life cycle understanding of a given material integrates every environmental damage created over the life of the structure, from resource consumption to complete disposal. Designs that integrate life cycle understanding would benefit from significant environmental advantage over traditionally designed alternatives, as environmental impact is a key parameter in societal decision making. There are two approaches to deal with material selection: Ashby [58] considered that it is generally the design that dictates the material choice, however the new properties of the ever growing number of new materials can make design improvement possible from an existing product / material design.

Recycling is a specific stage in the life of an industrial product. The life cycle understanding can assess the benefit of recycling in comparison with virgin material production. At any stage of the life of a product, its performance should be assessed. The Life Cycle Assessment (ISO 14040) is a standardised tool which can assess the potential environmental impact of a manufactured product. Its framework is presented in figure 3.3 which shows the recursive process and flexibility of the framework as the interpretation at each stage of the study may change the way the problem is considered. LCA has the advantage of focusing on a product (or a function) over its entire life and tries to encapsulate a selected number of environmental damages into an impact score. The damage selection is a compromise between a large number of parameters that give an accurate image of the environmental impact and the time and effort allocated to the LCA study. The major advantage of LCA over other environmental tools, such as Environmental Impact Assessment (EIA) or environmental auditing, is that by focusing on the product over its life, it may deal with information from outside the design office or manufacturing company [59] i.e. the material shipping from mining source, to recyclate stockholder, and through material manufacturer, product manufacturer, repair contractor, etc. It can be applied in design whereas the environmental management system (ISO 14001-4) is more related to firm management, environmental auditing (ISO 14010-12) and environmental performance (ISO 14031) are oriented to organization assessment [59]. These 3 ISO tools miss the interrelation of life induced impact. Using LCA in design can be adapted to the current state of the art of production tools with a life cycle point of view. EIA cannot be considered because it tends to assess accurate, local, possible environmental consequences of projects and presents mitigation to an existing design. It is not suitable as a design tool because it is not as flexible as LCA for measuring the impact and it does not include a critical review highlighting design corrective actions.

LCA can be used for material selection, whose intrinsic properties may have an impact on how they are implemented in the design. Recyclability shows an increasing interest whereas landfilling is viewed quite negatively. Waste management has been a key societal concern for a long time. The 1970s saw an increase of awareness on the topics of waste treatment due to a number of serious pollution events[60]. The 1972 cianide leakage at Nureaton[60] UK, is one example of the needs for emission treatment, leakage control and constant monitoring of hazardous waste over a long term and in some cases long after the closure. In order to reach a sustainable waste management, effort has to be made on the reduction, reuse, and recovery (via recycling, composting and energy recovery) of waste before disposal in landfill. The societal input in design with respect to the customer and the manufacturer is a key concept of sustainable development. The use of new materials has to be in accordance with landfilling regulation, recyclate demand and efficient use of existing waste treatment equipment such as incineration plants. Even if recycling is desirable, as it saves primary resources and prevents waste, it does not necessarily mean environmentally friendly, demonstrating that any positive or negative points should be forecasted. The material selection and its disposal process as well as the life cycle understanding need to be investigated at an early stage of design. It can be related to 'design for production' by Balwing and Niebel, 1957, and described by Ring [61], separating design into two functions: "the product design function" fulfilling customer requirement and the "process design function" developing the manufacturing in a cost effective, timely and good quality way. Both of the concepts are linked together. The present study aims to extend the concept of the process design function to include raw material and end of life issues, incorporating the views of the finished product manufacturer, customer and community.

LCA is a relatively recent method that measures environmental performance and has increased in popularity and has gained wider acceptance as a management tool [62]. It has been applied in many sectors for materials, complete systems or components. The literature reviews application in the process industry, nuclear, water, electronic [62], aluminium [63], composites [64, 6] , boats [64], and also discusses paper recycling vs incineration assessment [65].The LCA derived from the 'net energy analysis' aimed to report the entire energy consumption related to a product[62]. Later action tends to standardise the approach and includes more inflows and outflows, impact characterisation and normalisation measurement. The Society for Environmental Toxicology and Chemistry (SETAC) created a LCA framework in the nineties[62], later ISO created another framework [62]. Embodied energy remains a very important parameter for LCA study and is always included in every LCA study [65]. As presented before energy was the approach to life cycle assessment in the 70s [62]. However the LCA frameworks modernised it in order to benefit the decision making process.

The 4 main aspects of the life cycle assessment are (see figure 3.3):

- Definition of the problem and the objective by defining the function, the functional unit and the reference flow.
- Inventory of relevant inputs and outputs of a system.
- Potential environmental impacts of those outputs.
- Interpretation of all this information in relation with the study.

The result of such an approach has to be used to improve the design through the life of the product. It is also very relevant to decision making, marketing issues (ecolabel, environmental communication, etc...).

The global framework of LCA given by the standard ISO 14040 emphasises the necessity to define the function and functional unit, reference flow, system boundaries and data quality requirements, with a sufficient accuracy in goal and scope definition. Assumptions and limitations of the study have to appear clearly at this early stage. The next stage is the data collection and the impact evaluation on the designs. The life cycle interpretation is the final stage of the study and is vital in decision making. It is not an easy process but at this stage, social and economic aspects can be introduced in order to make conclusions easier.

The key aspects of the critical review of an LCA in accordance with ISO 14040 are verified if:

- The strategy is valid.
- The data is appropriate and reasonable for the goal of the study.
- The results reflect the goals and the limitations are identified.
- Comprehension is easy enough and the study is credible.

The main difficulties are related to impact assessment because of subjectivity and data interpretation. The scale of the study must be suitably chosen to limit interpretation difficulty. LCAs may have to incorporate several environmental damages. It results in a composite score which is difficult to interpret because they are highly dependent on the weighting factor applied to each damage. The difficulty of weighting individual results is especially true when damage is as varied as biodiversity depletion, green house effect, etc. and are presented in a single score. One adverse effect could be the consequence of another impact and weighting them individually is difficult. There is no absolute value of damage hence comparative studies are the most effective way to ease the decision making process.

3.3.3 Environmental impact and characterisation factor

One essential advantage of LCA is it brings to light the issue of multicriteria comparison study and helps to bring about a single value result. The calculation of the impact follows a complex approach which is going to be detailed hereafter using an example taken from [66].

The first step is to decide the physical flow the user will focus on. In reference [66] the physical flow is the emission of NO_x, NH_3 and SO_x. The second step is the selection of the physical phenomenon. The two most noticeable effects of these emissions are eutrophication and acidification. These are the two phenomena the authors used in their LCA study. It highlights the large influence of author's choices on the LCA conduction by selecting the focus. The model for the impact calculation is the loss of biodiversity using models from Eco indicator 99. The final step in this LCA is to weight the results by applying a conversion method to monetary value. In this case it is possible to assess the cost for the reconversion of damaged area.

In conclusion it must be noted that the models are extremely complex and require a high level of expertise. On one hand, it has been seen in section 3.1.2 that the level of expertise for the determination of value function is high. On the other hand, while being extremely insightful on the material selection side, Ashby [58] focused mainly on energy for environmental impact leaving aside the LCA driven method as presented in section 3.1.3. LCA is heavily dependent on information and model availability. Mature technology benefits from the better information availability and are sometime selected over newer technology due to this reason [66].

If material selection and environmental assessment is to be used together the level of data quality requirement on both side needs to be equivalent and therefore simplification is needed. Another requirement would be to have complete access and control over all the information used in the research model therefore the collection of fewer but well trusted information. This might be a way to overcome the difficulty presented in the previous paragraph.

3.3.4 Treatment of uncertainties in LCA

In her survey Bjorklund [67] reviewed the possible causes of uncertainties and inaccuracies in LCA. The main causes of uncertainties are:

- Data gaps, unrepresentative data
- Model uncertainties
- Uncertainties due to choice
- Spatial and temporal variability
- Variability due to sources and objects
- Epistemological uncertainty
- Mistakes
- Estimation of the uncertainties

From the above problems it is noted that 3 are of particular interest in the present research, they are data gaps and unrepresentative data, model and epistemological uncertainties.

The selection of embodied energy as an impact parameter solves the problem of data gaps and unrepresentative data. There is little missing information on this parameter and most of the time, it is possible to estimate the energy consumption for a given process. The representativeness of energy as an impact is however subject to discussion [68, 69], but the energy variability between information sources is lower than any other physical flow such as NO_x or CO_2. This is shown by Finnveden [65] in its review of data quality for PVC. Moreover the use of commercial databases on environmental impact can show significant variation [70] even if their impact results are a compound of several pieces of information.

3.3.5 Case studies

The analysis of some case studies illustrates the use of the LCA. The first case study presents the advantage of the use of LCA for well defined alternatives comparison. This is not the case in the present research where the GRTP boat is not designed yet. However it presents the approach and tools used in situations where the LCA is very effective and their relevancy to the present research.

The first example can be the simple case of the use of expanded polystyrene or recycled paper in egg packaging from Zabaniouto and Kassidi[71]. It is summarized in table 3.6. It is relatively simple because the product is made of one single material roughly in one operation but on a country scale, it can demonstrate a non negligible impact. It has to be noticed that paper and expanded polystyrene are very different materials creating very different types of pollution and the correct use of LCA can be used for the comparison. Eventually it also clarifies the affirmation of Letterrier[57] about the environmentally friendliness of recycled material.

Zabaniouto and Kassidi[71] presented their study on packaging and used an impact assessment database to assess the environmental impact. Table 3.6 gives the global result of the study. The conclusion on this study is that the impact for egg packaging is that the recycled paper showed a lower pollution potential. In this case the result on the advantage of paper over plastic is straight forward because the case study is simple, in a domain where the data is readily available. The data for the egg packaging study was obtained from the software “Simapro” which contains a database of information from Pré Consulting, a specialist company in LCA tools. The result of the LCA study was almost entirely based on this data for the polystyrene boxes. In the case of the recycled paper a large amount of data was provided by a paper industry company who was directly involved in the research project. The authors commented that "quality of the LCA can only be as good as the quality of data". However, one drawback of the study is that data came from several sources but the author do not review critically if they are consistent with one another in term of accuracy, collation methodology, etc.

On a more specific point of view the targeted audience and the use of the result are not presented. It is said that this is only a comparative study. This is the main drawback of this kind of study where the alternatives are relatively well documented and the result can only be obtained for impact comparison. There is no possibility to assess the possible action as there is no information about the needs of the study which is a requirement of the ISO 14040. In addition, there is no assumption on the cost which pushes the reader to consider that both of the alternatives have the same price.

For the second case study, Lenzen et al.[72] presented what can be indirect variability in the case of the wind turbine LCA. The authors compared two identical types of wind turbine produced in Germany and Brazil. The towers and nacelles were in steel, the blade in epoxy/glass composites. The study was carried out with a focus on the energy and CO_2 emission. Three alternatives of manufacture and operation are taken into account for the comparative study:

1. The wind turbine is manufactured in Germany and produces electricity in Brazil
2. The wind turbine is manufactured in Brazil and produces electricity in Brazil
3. The wind turbine is manufactured in Brazil and produces electricity in Brazil (assuming a large proportion or recycled steel)

The function is production of electricity and the functional units were the primary energy needed for the production of one kilowatt-hour of electricity.

The result of this study showed that the production and operation of the wind turbine in Brazil provided the lowest impact. This was possible because the authors[72] collected information on the structure of the industry, the energy structure and supplies in both of the countries. Steel production industry structure gave Brazil an advantage over Germany because of its larger secondary steel made using electric arc furnaces (further detail on steel structure in Appendix A). Furthermore in Brazil the electricity is produced from hydroelectric sources decreasing the CO_2 emission result. The energy requirements to build the wind turbine per unit of electricity produced are lower in Brazil than in Germany.

Table 3.6: Zabaniotou LCA study

Polystyrene (PS)	**Recycled paper**
BACKGROUND	
The PS gives a good protection to shock and has a good resistance to moisture. However there is some concern about some styrene transfer to the eggs, the amount of waste created, the rain acidification potential and about the amount of energy needed to manufacture the material	The protection of paper is much lower than the PS box. However the production does not require as much energy as the PS and is a solution to some paper waste. There is some concern about the carcinogen material used in the process.
GOAL AND SCOPE	
FUNCTION AND FUNCTIONAL UNIT: packaging 300,000 eggs (in 50,000 boxes) BOUNDARY OF THE SYSTEM: the study focuses on the production and excludes transportation of the box, use and maintenance of the production site. For simplification reason both of the boxes are disposed in landfill. The study takes place in Greece. The energy data are based on the European energy mix because of lacking data in this domain. (there is no comment on the targeted audience but that it is in Greece) The production requires 750kg of PS and 1,100kg of Paper whose transportation is taken into account	
DATA INVENTORY	
Data used: BUWAL 250, ETH Energy version 2 and Simapro 4, various papers on the impact of transportation and a company producing recycled paper boxes. These databases are dealing with the energy production, transport solid, liquid and gas emissions and waste. The OUTPUT is a complete review of the physical flow for both of the alternatives according the calculation condition	
IMPACT ASSESSMENT	
eco-indicator95 is the impact assessment methodology used. It is available in Simapro. Both of this tools are release by Pré consulting, The Netherland. It brings along normalisation coefficient for the comparison between the value of different unit and weighting coefficient for the perception of the targeted audience for a given type of result (ozone depletion, acidification, etc). The following numbers are the most relevant results normalised and weighted (no unit)	
Green House Gas: 0.4	GHG: 0.3
Acidification Potential: 10.5	AP: 1
Winter Smog: 5	WS: 1
Heavy Metal: 0.3	HM: 0.4
CRITICAL REVIEW	
The paper boxes have a lower environmental impact than the PS in the framework of the study. It is however difficult to assess which one is really the most environmentally friendly. The result depends mostly on the quality of data and most data are not easily available	

In conclusion, this paper shows that it is relevant to consider fewer parameters but to describe them with the integration of heavy industry and electricity production local policy. The product is assumed not to have a significant impact on the heavy industry and electricity production.

The third case study presents the use of LCA by Alcan[73]. Alcan applied the LCA with a management point of view. Alcan is a leading company in aluminium packaging and in aluminium composites. The authors presented the application of LCA in Alcan for the impact assessment of manufacturing procedures and took the example of an aluminium floor.

At first it is important to present how the author[73] (and so Alcan) considers the utility of LCA. The first statement is that the LCA should be able to help management, be practical and stop being an academic "one time study". It should make a clear statement of the actual pollution problem. In addition, the statement of Lenzen et al.[72] showed that geographic considerations must be included. Alcan followed the recommendation of the ISO 14040, "the LCA study should be as detailed as needed and as simple as possible". The depth of an LCA study can be very large and this has to be decided in accordance to its relevancy to the audience, decision maker, resources available and delivery time.

The experience of Alcan in LCA and its involvement to make this tool a key aspect in their life cycle management policy lead to the following conclusions:

- The results must be delivered in a timely way and the goal, scope and data quality must be chosen to meet this aim.
- The results must be usable by a decision maker and so easy to interpret. Very detailed studies which can be understood only by LCA specialists are irrelevant because they are not decision makers. It is important to choose output parameters easy to understand for a non-specialist.
- Commercially available database software provides a single number result as output in order to help non specialist to assess the impact after the data inventory. This is nevertheless difficult to interpret and Alcan chose internally, a set of parameters in a commercially available database (eco indicator 95) and from bulk data from internal databases of flow and emission to assess best procedures.

The presented case study[73] is a comparison of two sandwich structures with honeycomb cores (skin and core are in aluminium) with two different manufacture procedures and a wood floor for an automotive application. The new procedure was the cutting of the skin and core before the assembly. It avoided the problem of sandwich sawing wastes which are difficult to recycle. The parameters selected are primary energy, greenhouse potential, Eco indicator 95 (excluding greenhouse gas effect, and energy as it is studied separately) and waste generation (generally water consumption is used in the general life cycle management of Alcan but here it is excluded in the scope of the study). The results show that the new method has a lower impact than the previous method. However the most important result remains that an easy to understand result leads to an easy decision. This tool has demonstrated such a clear advantage in quality management that it was recommended to be used in purchase and design for environmental strategies.

Three LCA studies were critically reviewed in this section. The understanding of the economics, industrial and environmental surrounding situation is important in order to provide good management solutions to environmental problems. It is even more important than having a clear understanding of the technical aspects of environmental science. It provides a good idea of the variability of outputs and the possible actions for the decision makers.

3.3.6 Previous work on boat life cycle.

Fet[74] investigated ship related pollution. She used the definition of sustainability including the social, environmental and economic aspects. She firstly presented the usefulness of effective reporting prior to any assessment of the impact. The author considered the LCA as a tool which can be effectively used for this need of reporting. However LCA tends to focus on the object and so more general operational decisions are not always considered in LCA.

Hedlung-Astrom et al.[6] studied in the framework of an LCA, a 20m aluminium patrol boat and a GRTS sandwich alternative. However the result of the study did not change the design with respect to the material and the author subsequently claimed the GRTS alternative to be non-optimal. The focus was on weight and clearly on the fuel consumption. Five tonnes can be saved with the sandwich structure over the 12 tonnes of aluminium used in the in-production design (the study ignores all the other components) the fuel saving is relatively modest, only around 7% but over 25 years it represents 200,000 litres of fuel. This LCA study remains relatively difficult to interpret. First of all a 25 year ship life is relatively long and no consideration of upgrade or refit is made. In the case of a bulk carrier, the ship can be rebuilt or upgraded once or twice in 25 years[75]. It is expected that a proper upgrade of machinery can lead to a decrease in fuel consumption comparable to the decrease seen in cars in the past few years. The operational aspect of the ship life is not studied and this is a very important aspect.

An opposite approach was taken by Latorre[76]. He studied the impact of marine operation on the environment of fishing boats. The focus was on fuel consumption and NO_x emissions. The author demonstrated that NO_x emissions are directly related to fuel consumption. This can be significantly reduced by decreasing the load on the engines. The proposed solution incorporates hull and propeller blade cleaning and an on-board operation monitoring system. Latorre[76] presented monitoring parameters directly related to the boat activity or fishing operation, for example the fuel consumption per mass of caught fish. It showed that dredging and seining fishing methods are much more effective that bottom trawling (in the particular case of the US fleet studied). The study also revealed the "typical fisherman perspective" of increasing engine power to increase the size of fishing apparatus. This impairs the LCA impact result as it increases the fuel consumption.

Kameyama et al.[77] developed a software package for the life cycle inventory applied to a bulk carrier. This tool allowed very precise data acquisition on ship construction. The high level of detail in the database demonstrated that the energy consumed in lighting the shipyard was similar to the energy required to do the welding of the ship. This demonstrates that clear system boundaries must be defines in the present research and the level of details that is requires by the LCA goal and scope. Chapter 4 defines which energy input goes in the LCA impact inventory and which do not.

In addition with the general literature on LCA, the section on ships shows that all the stakeholders during the life of the boat have an impact on pollution and more generally on the energy consumption. Indirect contribution, such as workshop lighting, can be very high but difficult to assess. The advantage of life cycle assessment is that it deals with technical aspects during the entire life of the boat and so it is capable of dealing with several points of view (customer, manufacturer, society). However, a high level of detail at each stage of the life of the boat requires a high level of expertise and access to operational stakeholder databases.

The literature review on GRTP showed that there is no working boat made of GRTP except a Halmatic RIB prototype and a GRTP troop carrier. It can be expected that very little data is available in workshop data, operational data. Therefore the indirect contribution to the global result is likely to be ignored as not available.

3.3.7 Critical review of LCA and opportunities for research

LCA is a major milestone in the measurement of environmental impact in a fair and reasonable manner, using well documented techniques and well adapted information such as commercial databases. It can be considered as well adapted to engineering problems in the field of environmental engineering. However, this topic is young and lightly studied despite the enormous volume of publications on the subject as each study tends to fill a relatively narrow gap in a very large field of knowledge. In addition the discussion primarily focuses on the application of the model and the creation of new environmental models linking physical flow to environmental impact.

The reader and practitioner of LCA can gain quickly sufficient level of understanding to use LCA. Indeed, LCA has been applied to many systems but have been rarely applied in validation analysis. The large number of assumptions needed can make people uncomfortable about the use of a given LCA. Frischknecht et al. [66] noticed this issue in a 2009 publication. The LCA community of practitioners is reluctant to engage in the discussion and request for simple decision tools, limit the dissemination of LCA studies that have high uncertainties. They demand that LCA maintains a high level of reputation. Finnvedenn [65] also reported critics of LCA. The lack of reproducibility [65], the large gap in results for inflows other than energy and the misuse of some models difficult to apply from an engineering point of view are often criticized [65].

In the present research LCA has a major influence on how the research was conducted. Indeed the progression of the design artefact is based on the LCA result of the previous artefact. However the understanding of the reason for choice is at its core and a database is not sufficient in order to select one material over another. One of the key aspects associated with a successful LCA is the quality of the data used. This was clearly indentified by Zabaniotou et al. [71] in section 3.3.5. For the present research data associated with the four candidate materials, steel, aluminium, GRTS and GRTP need to be collected. One of the the key outputs of this thesis is the gathering of data and the creation of a database which will be used as the core of the LCA analysis. This material database is presented in Appendix A. Within this appendix the details of the sources of the data is provided, the data itself is presented in tabular form and forms part of the LCA design tool used in the present research. Within the assembled database a closer look at steel or aluminium showed that the relatively poor performance of some country in manufacturing steel or aluminium are due to a lack of access to high quality ore. This is the case of the Chinese aluminium which environmental results are impaired by low quality ore. This is also the case of the Indian and South African steel manufacturer which tends to take advantage of their large resources in non coking coal by using alternative process less effective than the regular coking coal route. It seems important to keep in mind that the resources are finite and to be shared fairly and the selection of a given alternative in this appendix is based on the understanding of the reason why an alternative is more polluting than another rather than on pure quantitative performance.

In addition the environmental impact of GRTP manufacturing of large components is not studied at all and the information can only be the information from manufacturer. In this case the energy consumption is the only possibility. Finally, the weighting factors are ignored and energy consumption is chosen for the selection whatever the level of controversy which can be seen on the publication of Frischknecht [69].

The success of the introduction of environmental issues depends on competence, motivation, commitment and enthusiasm. High environmental performance projects have to be carried out as a common project or rather as an innovative project needing cross functional involvement. The LCA approach which will be used further in the research, will take advantage of the learning from the literature but the ultimate goal is to develop a material selection methodology highlighting the working principle of design with material incorporating the Lloyd's Register design rules and environmental impact.

3.4 Boat design and optimisation techniques: an LCA perspective

The following section reviews the literature related to ship design and optimisation. It takes into account the current research aim which is to integrate LCA in a material selection process in ship design. This section discusses the basic principles of ship design, the general theory of genetic algorithms and their application to ship design. Genetic algorithms are a very common technique of optimisation. It has been applied to both the fields of material selection and LCA. Its popularity is due to its robustness. There are many parameters which can influence the selection of one material over another. As seen in section 3.4, Zhou et al. [12] presented a genetic algorithm (GA) for the selection of material for a plastic drink container of various shapes and sizes in which the selection criteria were LCA impact based. However the simplicity of the bottle design model is not relevant to the complex system that is the design of a boat.

3.4.1 Genetic algorithm theory

Ship design is based on the interaction of a large number of parameters and it is a recursive process. In order to assess the best design using all the possible solutions, the use of optimisation or search method may be useful. Genetic algorithms can be used in order to find the best design in the search domain. The general form of a GA is presented in figure 3.4.

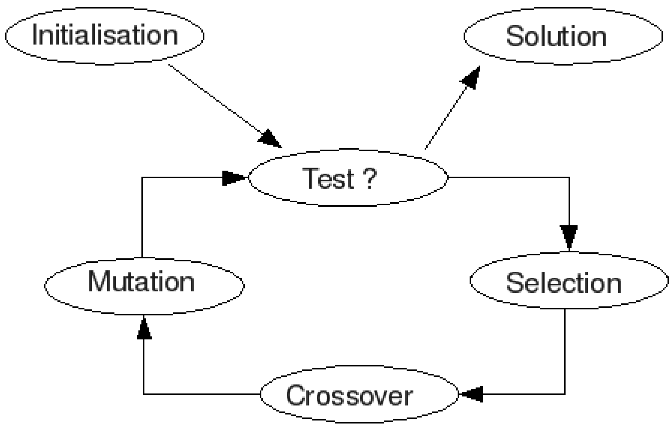


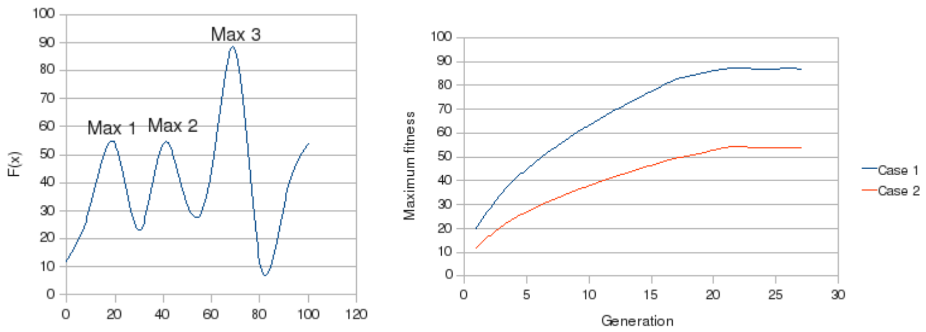
Figure 3.4: Genetic algorithm theory

Genetic algorithms are numerical optimisation algorithms inspired by natural selection and genetics. wrote a comprehensive review of genetic algorithms from which the following description is inspired [78]. The main idea originated in the 1950s and 1960s. John Holland [79] was the most prominent contributor to the theory of GA during that period. A population of solutions was considered in order to solve a complex problem with a large number of parameters. This techniques requires (see figure 3.4):

- A population of possible solutions of the problem represented as binary strings (Initialisation)
- A method for assessing which individuals describe the best solution or the fittest and which individual needs to be kept or withdrawn from the population (Selection)
- A method to mix the best population individuals and create a new generation of population (Crossover)
- A mutation method ensuring the diversity of the population (Mutation)

The relative ease of use and the robustness of the approach enabled the GA to be applied to a large variety of problems such as image processing, spacecraft trajectory, facial recognition, ship design (discussed later), etc.

The advantage of GA over other techniques is to find the global optimum of the possible solutions. The algorithms will converge to a global optimum provided that the diversity of a possible solution population is large enough and maintained for a reasonable number of generations so that the entire domain is thoroughly searched. Figure 3.5 (a) shows a function with two local optima and one global optimum. The properties of natural evolution is to converge to the best solution with the genetic information in the initial population. However if the initial population carries a large number of individuals close to a local optimum i.e. low genetic diversity, the population will converge to this local maximum (such as Max 2 in figure 3.5). The development of an algorithm should take into account that a slow evolution and an appropriate genetic diversity make the algorithm converge toward the best solution e.g. figure 3.5 (b) case 1 [78].



(a) Example of function with local optimum

(b) *case 1*: convergence to the global optimum, *case 2*: convergence to a local optimum

Figure 3.5: Non convergence problem and lack of genetic diversity

There are many ways to implement each stage of a GA. The selection is a key process because a high selection pressure will result in a stagnation of the maximum fitness on a local optimum [78]. The convergence toward a solution result in a loss of diversity and the first generations should ensure that the diversity is high enough. The suitable selection of crossover, mutation and selection techniques can increase the efficiency of GAs and they are necessary for setting up of any GA. Three selection methods are widely used: rank based, roulette wheel and tournament (see table 3.7). Rank based selection is the simplest selection method to implement in a GA. Its drawback is that it makes no distinction between *good* and *very good* solutions. Conversely the probability of an individual to be selected using the roulette wheel selection method depends on its fitness. The roulette wheel selection method takes into account the fitness of individuals and not only their rank as in rank based selections, therefore roulette wheel selection method overcomes the limitations of the rank based selection method. Indeed with the roulette wheel selection method, an individual much fitter than the other individuals would have a much larger chance to be selected but its selection is not guaranteed. The fittest individual may occasionally not be selected. The fact that the fittest individual is not selected each time may have beneficial effects on the GA in ensuring a higher diversity of solutions by not converging to quickly to any highly fit individual. Coley [78] said that ensuring a higher diversity allows the GA to explore more of the search domain. Coley [78] also wrote that balancing the need for the search domain *exploration* with the *exploitation* of the discoveries is a recurrent topic in the area of GA. The more the exploitation, the faster the convergence [78]. Therefore it may beneficial to the speed of convergence of the GA, to select the fittest individual and ensure that no mutation or crossover change it in the following generation. This is called *Elitism* and GA may need to implement it depending on the case study. The drawback of elitism is that it increases to probability of the GA to fail to find the global optimum. Elitism may be implemented with the tournament selection method.

Three crossover methods are generally used: single, two and uniform (see table 3.7). These methods are ranked in order of their ease to be implemented. The limiting factor of a crossover is the ability to create a large variety of new individuals from a given pair of parents. In this case, single point crossover is the method which gives the least number of possible children. The other method reduced this risk of diversity stagnation or inefficient domain exploration [78].

The mutation maintains some diversity by flipping randomly a binary bit in some individuals defining binary string [78]. It has to be mentioned that mutation on its own cannot guaranty a large population diversity, i.e. an efficient domain exploration, if the chosen selection and crossover methods result in a rapid convergence toward a local optimum. It is essential to define an optimal mutation rate in order to efficiently converge on the best solution [78].

Table 3.7: Selection crossover and mutation example (Coley [78])

Process	Example	Comments
Selection	The first X fitter population individuals are kept	Rank based selection
	The probability of a member to be selected is proportional to its fitness	Roulette wheel selection
	The population is divided into subsets. From each of these subsets the fitter element is selected	Tournament selection
Crossover	*0010,0101,0111* and 1101,1010,1010	initial pair of parents
	0010,01/10,1010 and 1101,10/*01,0111*	single point crossover
	00/01,10/*01,0111* and 11/*10,01*/10,1010	two point cross over
	0/101/,*01*/01,0/*111* and 1/*010*/,10/*01,0*/010	uniform crossover
Mutation	1101,1010,1010	Mutation
	1101,1010,**0**010	

The search ends when the maximum fitness and general fitness of the population reach a level defined by the user or when the average fitness stagnates.

As seen in the present section there is a large number of parameters which can be modified in a GA. Chapter 7 will include an application of GA in ship design with an LCA based selection criteria.

3.4.2 Ship design

Ships are a complex system i.e. composed by many subsystems which interact with each other and their respective environment. Mistree et al. [80] pointed out that there is an apparent antithesis between the need to focus on *' the properties of a system as a single entity and the collective properties on the systems and its subsystems in their intrinsic environment'.*

In general boats and ships can be of two types named after their main operating mode at sea:

- Displacement when the hull support is mainly hydrostatic, e.g. cargo ships, ferries, submarines.
- Non displacement when the hull support is mainly hydrodynamic, e.g. planing hull, hydrofoils.

The most important parameter describing the operation mode is the Froude number (given in eq. 6.1 in section 6.3) that links speed and length. The faster the boat the higher the Froude number and the longer the boat the smaller the Froude number. It is widely accepted that Froude numbers over 1 - 1.2 boats operate in non-displacement mode whereas below this level they operate in displacement mode. The limit between the two modes is however not clear. For a given Froude number (or a given speed and length), it is possible to select a boat design that would benefit from the hydrostatic support and adapt its drawbacks. For a Froude number below 1.3, Watson [81] considered that monohulls are generally more effective in terms of construction, power requirement and operation. This is the configuration that is used in most of merchant ship such as tanker, bulk carrier and warship. Other alternative should be considered at higher Froude numbers. Around 2 SWATHs are possible alternatives to monohull, around 2.5 wave piercing catamarans are efficient, above 3, hydrofoils and hovercrafts should be considered. For example, low motion at sea with improved comfort would lead to the selection of SWATHs at high speed (high Froude number). This type of ship remains more expensive to produce and less fuel effective but has a higher speed and improved passenger comfort because the sections of the area of the two hulls at waterline is small and as a result this kind of boat is less sensitive to waves. This area is the main cause of passenger discomfort. The present research focuses on monohulls in non displacement mode because monohulls are cheap to design and produce. The application planing monohull to merchant and passenger ships is limited but planing monohulls are playing a major role in leisure boat, life boats, rigid inflatable boats and patrol boats.

The complexity of design due to the numerous features requires a design method. Classification societies encourage the designer to use *prescriptive* design [80]. A prescriptive design includes:

1. Analysis: Decomposition of the system into subsystems defining their function and relationship to each other
2. Synthesis: Integrating the subsystem into a whole and assessing its properties
3. Evaluation: Assessment of how the requirements are met by the design

The iteration of analysing, synthesising and evaluating makes the design converge toward a solution. The design of a subsystem can be sequential or concurrent, meaning that the task are not completed one after the another but with a time overlap.

It is generally accepted that the design of ship follows an iterative process which is probably best visualised in the spiral representation of Evans' 'general design diagram' [80, 82] (see figure 3.6). This diagram shows a possible sequence of tasks for the conduction and a convergence toward the solution with a number of iterations. Some design inputs may be changed while the design is progressing. The experience of the ship designer is essential in order to start the design with some suitable requirements i.e. main objectives of the boat, such as dimension, speed and kind of operation.

There is an extensive range of literature on the design of ships and boats [83, 84] and although this thesis aims to integrate LCA and ship design and incorporating environmental impact to aid material selection, it does not intend to have a complete and rigorous representation of ship design within the modelling approach. The details of the methodology adopted is a simplified one and is outlined in detail in Appendix B. As the present research aims to develop an LCA framework incorporating design details, future work could involve the further development of the ship design aspects to make them more rigorous. However, it should be noted that within this research the simplified ship design approach is based on the principles of naval architecture.

3.4.3 Genetic algorithms and ship design

GA have been used in ship design in many areas such as composite materials, boat shapes, fluid dynamics, structure and sea keeping.

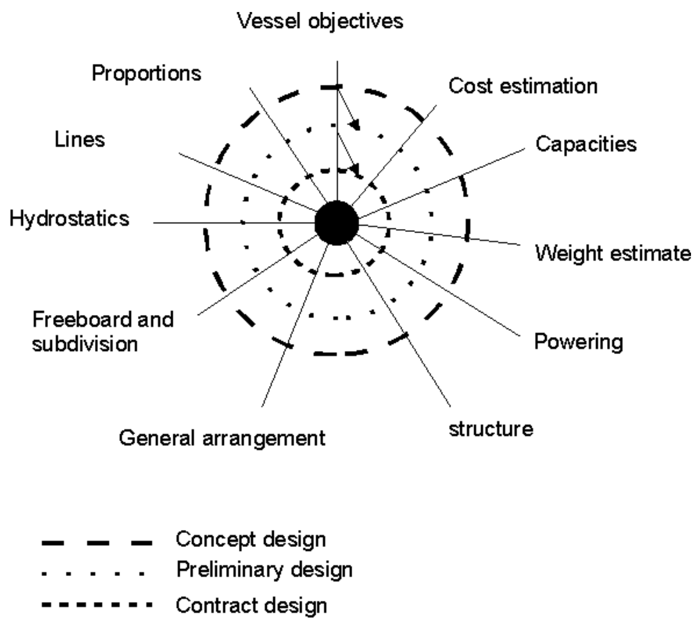


Figure 3.6: Ship design spiral

Zehnder et al. [9] used a GA for selecting the optimum material composition and lay up of a composite in a sailing boat. GA were previously used in the area of composites laminate design [85]. The composite materials were made of patches whose dimension, orientation and material were optimised for stiffness. Cirello et al. used GA to study the sailing yacht hull shape [86] and the keel [87]. Boulougouris et al. [88] used GA for the sea keeping and wave attenuation of LNG float structure. Maneepan et al. [89] optimised a composite marine grillage for lower weight. Boyd et al. [90] used GAs to optimise the structural connection between steel hulls and composite superstructures.

In the domain of fluid dynamics, Poloni et al. [91] used a GA as a general purpose optimiser. GA were selected for their robustness though the computational cost may be high. To the authors' point of view the high robustness of GA and the increasing power of computers will lead GA to be the most prominent optimisation technique. Their research dealt with the combination of a multi-objective GA with a neural network and gradient-based optimisation for increasing the computational cost efficiency. The design was applied to a keel. The designer however pointed out the very high computer demand of such a model.

3.4.4 Conclusion

The present study will extend the body of knowledge by studying the interaction of LCA and material selection in ship design. The GA robustness in finding a global optimum will be used to find the best possible material implementation through the assessment of their environmental friendliness. GA is used in chapter 7 as a tool for finding the design of the most adapted boats to the LCA study and the implication of design in material selection. This will be done on the basis of environmental performance. The above literature review section showed that GAs have been applied to both ship design and LCA but not with the aim of understanding how LCA and ship design interact with each other in a material selection process. This is a novel aspect of the present research.

3.5 Discussion and conclusion.

The through life issues are very important for increasing the effectiveness of a structure. A good understanding of the life cycle can make a product highly optimized for a given application by integrating real load, statistical damage, fire accidents, aging and maintenance and resulting in suitable reliability. With increasing environmental concerns, GRTPs have a good potential for solving problems raised by thermoset composites. In addition, GRTPs have been used in the past in high performance applications with success. It creates a cost effective alternative and the novelty of the work is to focus on environmental effectiveness.

Waste prevention, resource effectiveness (material, water and energy) are a now an important aspect of design. "End-of-pipe" policies begin to be obsolete because it is more and more difficult to find technical solutions and legislation is becoming more strict. The recycling of composites (thermoset and GRTP) material is difficult to implement. There is a large variety of composition, the scrap ultimately create a large amount of ash and recycled materials are not as good as the virgin material resulting in low quality composites, i.e. phone kiosks with ground composite as reinforcement. Therefore what can be done with this new low performance material? Life extension and reuse lead to less negative impact on the environment. These techniques must be accompanied by a high level of innovation, reliability and dismantling possibility to avoid obsolescence. This is important in order to develop a strong understanding of through life issues and the relation with risk, reliability and maintenance. The integration of the customer in that process is also a key aspect which has to be studied.

The literature review highlighted a lack of knowledge in the quantification of the environmental impact assessment of marine structures and the implementation of more environmentally conscious solution improving through life in boat building and marine artefacts. The areas of knowledge where weaknesses encourage further research are:

1. GRTP manufacturing processes for short production of large components such as boats are not widely investigated. It is largely empirical and results are rarely the main subject of scientific literature. The state of the art of large structures in GRTP is presented in the section 3.2.2.

2. The modelling of large structure in composites are not widely studied except for direct context of mechanical modelling and production.

3. The lack of environmental concern in boats. The state of the art of the life cycle of composites is presented in the section 3.3.

4. The disposal of marine structures particularly in composites. The state of the art of the disposal is presented in the section 3.2.4.

A key source of literature in LCA is the International Journal of Life Cycle Assessment and is an influential journal for LCA practitioners. The journal covers complete or partial use of LCA and covers a variety of subject related to LCA. Articles can present LCA case studies, improvement of methods, extension of knowledge for numerous damage in various geographical area and update of the modelling of the relationship of pollutant emissions and damage to the environment. Numerous sectors of industry are dealt with: waste and waste treatment, automotive industry, aluminium, chemicals, agriculture, food and fisheries. A review of the 368 papers available to download, published from January 2005 to July 2008 demonstrated the lack of publications on structures, boats and marine artefacts with only one paper on material selection in the automotive industry [92]. This evidence indicates that very little has been published in the area of LCA applied to structural materials and/or to the marine industry pointing to the need and relevance of research in this field.

Chapter 4

Life cycle assessment of marine structures: methodology

The main objective for the research is to define an LCA framework which can be use for material selection for structural application. Chapter 3 highlighted the need for further research in:

- The development of LCA for material selection based on structural artefacts.
- The application of LCA based on the embodied energy of four materials, i.e. how the LCA behaves when applied to a selection of materials whose implementation in marine structure is of a different level of confidence.
- Influence of the material on life cycle energy consumption.
- Enhancement of the interpretation i.e. how to make use of the LCA results.

The ISO 14040 [5] defines LCA as a technique for assessing the environmental aspect and potential impact of a product by compiling an inventory of the relevant input and output of a system, evaluating the impact and interpreting the results. Figure 3.3 summarises what the LCA ISO standard requires the user to do:

- The study goal and scope definition
- The life cycle inventory of the relevant physical flow i.e. the flows which could lead to an environmental impact
- The evaluation of the environmental impact deriving from the physical flow collated in the life cycle inventory
- The interpretation the result

The present chapter aims at defining the each of these steps in the context of the present research where a new LCA framework is defined to better incorporate structural design and material selection.

4.1 Studied framework

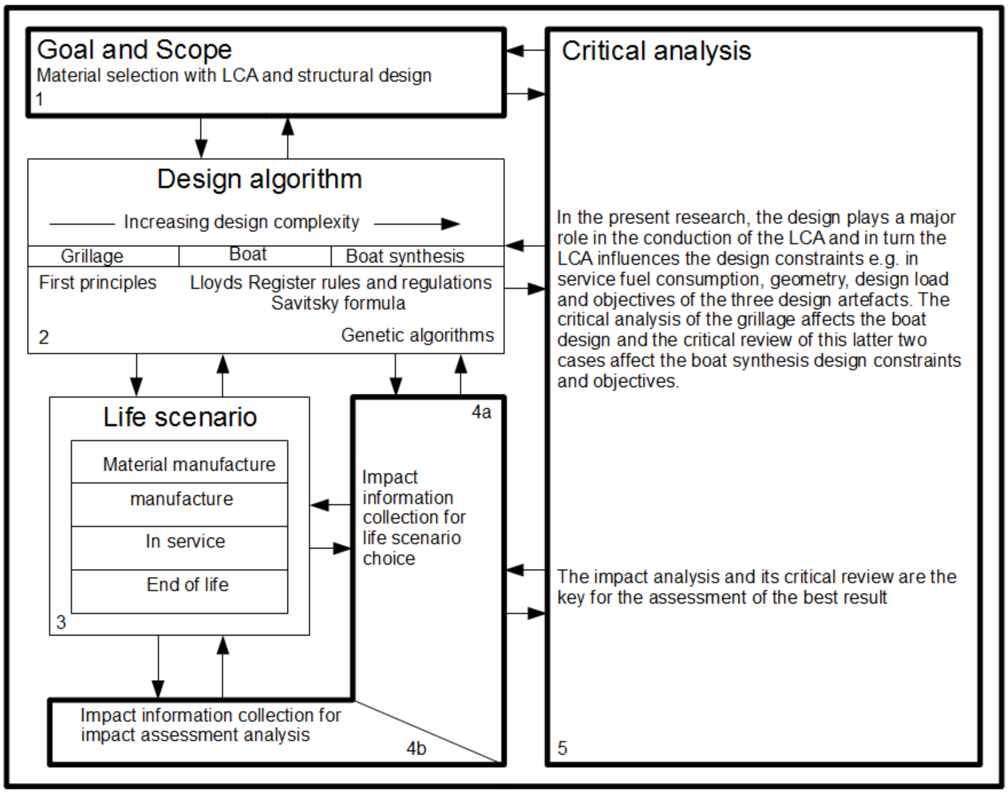


Figure 4.1: Methodology

Figure 4.1 shows the chosen approach for conducting the LCA in the present research. It is an adaptation of the general framework of the ISO 14040 LCA (figure 3.3). This new framework emphasises material selection in the context of marine structures. In the general framework the goal and scope, data inventory, impact assessment and critical review are conducted recursively. The main differences between the original and the new framework are:

- The goal and scope definition respects the LCA standard. In the present study, it focuses more on the framework itself than the impact results for the candidate material because the framework aimed at being reused.

- The design of the three marine structures, i.e. a grillage, boat components and a boat synthesis, is added to the general framework. In the modified framework, including structural design emphasises the fact that design objectives derives directly from the critical analysis of the result.

- The data inventory is changed in the modified framework. It includes three steps, the collation of energy information for a large number of possible processes from different sources (box 4b). In the general framework the processes are selected before conducted the LCA. A life cycle scenario is chosen for each structural artefact on the basis of the critical review (box 5) of the detailed impact information collection (box 4a) for the four studied materials. The final impact, i.e. energy used over the life of each of the three structures, is calculated with compounded energy for the chosen life scenarios of each material (Box 3). Conversely to the present research, LCA is conducted on a system for which every aspect e.g. geometry, manufacturing methods are known.

- In the present research impact assessment is simplified because energy is used as the impact ranking criteria. No normalisation is required.

- The critical review of the impact results influences not only the regular steps of the general LCA framework but it also influences the design objective and complexity, of the modified framework.

4.2 Problem statement

A complete environmental impact analysis would be extremely time consuming and it would require a fully documented product (design and life cycle specifications), but it would be very precise. The use of LCA as described in the ISO and supported by a large practitioner community allows the life cycle impact analysis to be more flexible, less time consuming and more credible. The proposed framework overcomes these limitations and it makes environmental impact available at an early stage for material selection and it can be reused for other applications.

4.2.1 Early impact result availability

The availability of an early impact result at an early stage of design, with little or no information on the final product, is a drawback of the LCA methodology. This is especially true when little information is available due to the lack of design information and published LCA in a given context, e.g. GRTP in marine structures. In the case of material selection in a design process it is essential to have some information to start the selection process.

The modified framework integrates three design specimens requiring few design specifications. It allows the use of the modified framework at an early stage of the design because it minimises time and effort for the impact assessment. The present research uses this modified framework and studies the following:

Design development requirement for easy interpretation of the result (Box 2): Design with several levels of complexity are studied in chapters 5, 6 and 7. They cover a range of complexities from simple structures such as a grillage (representing a small portion of a marine structure topology) to more complex structures like a boat deck and hull and finally a boat synthesis. It also covers a range of constraints from fully fixed to fully free topologies. The topology is fixed for the grillage (chapter 5,) and for the boat components (chapter 6). The length, width and stiffener spacing of the grillage are fixed. For the boat, the general dimensions i.e. length, breath, deadrise angle, draft and freeboard and detailed geometry i.e. stiffener spacing are fixed. No dimensions is fixed in the boat synthesis (Chapter 7), they derives from the design model.

Impact assessment strategy (Box 3 and 4): Energy is the impact ranking criteria. Energy consumption for engineering processes such as welding are readily available and the results using energy as the input are relatively easy to interpret. Its limitations are presented in section 3.3 and studied along with the three design scenarios.

4.2.2 Reusability

The reusability of LCA studies is a known drawback of the technique as each LCA is very case specific. For each new product a new LCA needs to be conducted on a different basis with the little connection with other studies. The outcome of the present research is not a specific product but a framework for a specific type of problem i.e. to select a material for a marine structure. Therefore each new application should derive from the method presented in the present research and not be conducted on a different basis as it is often the case with LCA.

Integrating specimen design and life scenario selection data within the framework allows it to be easily reusable as a design tool for material selection for marine structure design. It includes the basis for the design and the life scenario selection. The critical review process for the energy value allocation is also a reusable feature of the modified framework. The validity and reusability of the impact assessment result and its critical analysis for material selection will be one output of the present research.

The present research targeted audience is worldwide, however the research is conducted with the UK boat/marine industry in mind. The study is relevant to the customer, manufacturer and society and aims to develop a more sustainable material selection approach.

4.3 Outline of the method

The research follows the following sequence based on figure 4.1:

4.3.1 *Box 1*: Goal and scope

The goal of the study is to define a LCA framework for material selection. The present research aims at demonstrating how this framework can be used for material selection. This methodology incorporates the design of structures. As stated before, the framework must be defined so that it can be used at an early stage of the conceptual design of structure and it can be applied to any kind of structures. The chosen application are marine structures for which results are presented. Indeed, it is considered that marine structures have been developed so far with little insight on their potential environmental impact. Their design has excluded ,most of the time, resource management and end of life issues. The increasing use of composite materials due to their high strength-to-weight and stiffness-to-weight characteristics, their low maintenance advantages and aesthetics, have led to a complacent attitude towards disposal at end-of-life. It is difficult to assess whether in service life or end of life has the most adverse effect, particularly when fuel consumption is included in in-service life. However it is certain that boat users have a direct economical benefit from the lower fuel consumption of a GRTS boat compared to a heavier metallic alternative and it has played a great role in the success of GRTS in boat building. The goal of the study is to understand the potential impact of boat structures when materials are best implemented with regards to life cycle environmental impact.

The scope of the LCA is as follow:

Function of the system: The system is required to keep its structural and physical integrity under load in marine conditions. The definition of the structure requirement is different for each artefact.

Functional unit: The functional unit is a measure of the performance of the product. The impact figures derive from the physical input and output to the functional unit. One functional unit is defined for each structural artefact for the comparison of the materials.

- The grillage study functional unit is the grillage itself hence during the information collection and analysis the impact figures are given in energy unit per grillage.
- The boats study functional unit is the boat. The impact results are given for a year of boat use.
- The boat synthesis functional is the boat. This boat is designed in such a manner that the fuel consumption is ignored in the result.

Product system: The current research studies the following structures: a grillage (chapter 5) , a boat (chapters 6 and boat synthesis7)

System boundary: The system relates to the material and energy flows associated with the direct contributions. Direct contributions are strictly the physical flows in or out a studied process. In the case of energy, it is the energy needed for a process. This energy can be converted from a kilogramme of coal to MJ but it would ignore the transport of this coal to the process as it not strictly in the process studied. The impact inventory includes the energy input and output for the processes associated with:

- Primary resources extraction and refining
- Raw material manufacture
- Structure manufacture
- Structure use
- Structure repair and maintenance
- Structure dismantling
- Structure disposal

The study excludes equipment manufacture and off-site indirect contribution to global environmental impact. For reasons of simplification, the study is limited to four materials suitable for use in ship building: steel, aluminium, GRTS and GRTP. The detailed energy information for each material is in Appendix A.

Type of impact assessment: The present research focuses on energy as an environmental impact ranking criteria. Energy information for each material is widely available in scientific and technical literature. Gaps can be easily filled with the use of operational data, physical modelling or data interpolation. The energy availability and easy assessment helps to fulfil the objectives presented in 4.1 bullet 1 to minimise time and effort for conducting the LCA.

Data requirement and quality: The data comes from external sources mainly as scientific literature and supplier documentation. The data is the material and energy flows required through the life of the artefact in order to calculate the embodied energy.

Assumption and limitations: Geometry assumptions needs to taken in order to design each structural artefact. The results are only valid for the geometry presented. Energy is assumed to be representative of the environmental impact intensity. The pollutant emissions are not studied. The present LCA aims at the understanding material / design interaction and compares different candidate materials. The study does not aim at having a very complete emission list since it would be difficult to integrate in the design.

Type of report: The report is part of an academic research which focuses on the quality of the interpretation rather than its adaptation to a specific application or on the application of environmental impact model.

4.3.2 *Box 2*: Design algorithms

A structural design study is conducted for each design, with the assumptions on geometry and simplification presented in the relevant chapters. For the boat structures, the design includes engine selection to meet the installed power requirements. The power derives from the resistance which is influenced by material and topology selection. The output of the design study is to assess the suitable parameters for the conduction of the impact assessment studied, e.g. weight, length of join, surface to be painted, mould manufacture, powering etc.

The present study includes the following three designs in order of increasing complexity:

1. A grillage with a fixed length, width and stiffener spacing (chapter 5). The first principles are used to determinate the plating thickness, height, width and thickness of the stiffener for a given load. Weight, surface and length of joint are derived from these dimensions.

2. A boat hull and deck with a fixed topology (chapter 6). In comparison with the grillage this artefact is a more realistic structural model. However, in the present case, design constraints are high and simplifications are used to decrease the design effort. Lloyd's Register rules and regulations are the basis for the structural design presented in this research. The embodied energy for the material use and the in service fuel consumption are used to measure the

performance of each boats as it is defined by the functional unit. Powering is included in the study in order to get in service life cycle impact due to fuel consumption. It overcomes the grillage limitation for which little in service life is studied.

3. A boat synthesis is the most complex structure studied in the modified LCA framework (chapter 7). This structure is very close to an existing structure. The boat synthesis design is constrained for in service environmental performance. It aims to overcome the lack of interpretation on the boat hull and deck study, reasons explained in section 6.5. The dimensions are free. The in-service fuel consumption, payload, service restriction and speed are fixed. A genetic algorithm optimisation approach is adopted for obtaining the main dimensions of the boat and the structural scantling.

4.3.3 *Box 3*: Life scenario

The life scenario reflects the best possible life cycle practices for each material almost independently from their implementation in the three design artefacts. The life stages are material manufacturing, boat manufacturing, in service and end of life. The life scenario is defined from the critical review of the detailed life cycle information collection (box 4a). The associated database is in Appendix A. For this detailed information collection, the intermediate stages defined in 'system boundaries' (section 4.2.1) such as primary resources extraction and primary resources refining, are included in the LCA. Once the life cycle scenario is defined, it is used in box 4b where the suitable environmental impact figures are allocated.

4.3.4 *Box 4*: Impact information collection

The information collection has two objectives:

The development of life cycle efficient life scenario (box 4a) This requires detailed qualitative and quantitative data on the processes involved in the life of the studied artefacts. The selection is conducted from a UK boat/marine industry perspective. The alternative processes are selected for their low in energy consumption, e.g. UK steel, Twintex, CO_2 welding, most efficiently produced aluminium, composite incineration, etc.

The impact calculation (box 4b) The energy result is the specific energy consumption of the process chosen to be part of the life cycle defined above. The processes and the associated energy were carefully selected and critically analysed to assess the quality of the data collected in each of the presented publications. The quality of the data is therefore close across all the candidate materials and processes. It is assumed to be better than the average of data of different quality requirement. It is therefore more realistic than an average of the information collected.

The energy information used in the present research is collected from several sources which helps to validate the result namely published and peer reviewed scientific papers, environmental reports including LCA published by the government, associations of manufacturers or other agencies. Data from theoretical books that present theoretical energy consumptions and material databases has also helped in filling data gaps. The information derived from the above sources is mostly presented for large scale, i.e. per country or continent. The method of acquisition and interpretation varies from source to source. The main differences are whether the energy calculation includes indirect contribution from manufacturing processes and if it was conducted using physical or economical models. One of the major outcomes of this research is a database of energy data associated with the four candidate materials and the process involved with their manufacture, use and disposal. This data was collected and is presented in tabular form in Appendix A. This database forms the core of data used in the impact assessment in the present research and could be further added to if additional material and processes are developed

On the grillage manufacture, there are a large number of processes that have been investigated. These are, for example, oxygen cutting, plasma welding, bonding, sawing, CO2 welding, resin infusion, GRTP welding, etc. There are two aspects in these selection processes: the applicability and the energy consumption. The information is collected wherever possible from practice manuals e.g. the book *The Modern Welding Technology*[93] which collects working parameters (power input and process speed). These parameters are later converted into primary energy when required. In the case of an electrical device, every electrical joule is converted to three joules of primary energy which is assumed as the conversion rate of electricity plants. The internal conversion of equipment is however difficult to assess and has been estimated. When manuals are not available, commercial manuals are used in the same way. These can be accessed through corporate websites or directly from the companies. Finally some information has been estimated from production parameters used on site given by a member of the consortium supporting the research at an earlier stage.

The major problem of impact assessment and data acquisition is the data inventory. This limitation comes from the boundaries of the system defined at the earliest stage of the life cycle assessment. The effort required for an LCA study may be relatively high, but suitable boundaries aim to create a suitable system for the study and helps to limit the amount of detail to be included in the study and hence affects its cost. Indeed a direct calculation method may be very time consuming as it is derived from the physical or chemical laws on which industrial processes depend. Indirect contributions are not taken into account in this research. These indirect contributions, sometimes called higher order contributions [94] are related to processes that are not directly part of the system e.g. transport of sub-products, lighting of the shipyard, etc. These are maybe the most obvious but very often not the easiest to collect. Although their individual contributions to the final results are low, the sum of all these contributions may be non negligible. It is assumed that these contribustion are equal for each material as each shipyard needs heating, lighting, etc.

4.3.5 *Box 5*: Critical review

The critical review makes the study more flexible and credible by making each box of the modified framework interact with each other. The critical review aims to assess the limitation of the impact result and the material selection. The process is entirely recursive and tends to the best design with the best life scenario and impact calculation for the best final result. The main difference of the present research with a regular LCA is that the critical review influences the complexity gradation from artefact to artefact.

4.4 Summary and discussion

The current chapter presents the problem statement and adopted methodology for the present research. This research is based on a modified LCA framework specifically adapted to the material selection stage of a more global design of a complete marine structure. This represents a new approach and no previous publication has been found in this area e.g. the development of LCA frameworks incorporating the structural design for material assessment. It addresses specifically the question of LCA methodology reusability. The problem investigated within this research is the integration in a time effective manner LCA, design development and life scenario analysis in order to select a material in a marine structure design context. A detailed energy information database has been collated in Appendix A and is used for both life scenario analysis and impact modelling.

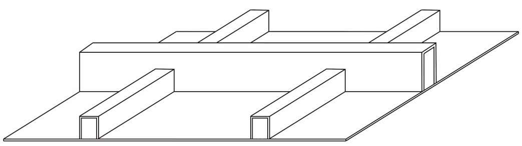
Chapter 5

Modified LCA framework: Structural grillage

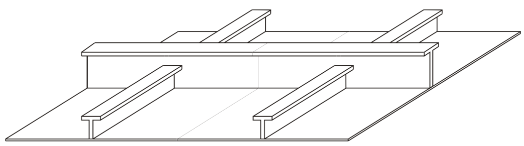
Chapter 4 presented a modified approach of the general LCA framework where the design of three structural specimens, in the order of increasing complexity, are studied. This new LCA methodology aims at measuring the environmental impact of four candidate materials with a view to material selection. The present chapter focuses on the grillage, the least complex structural artefact proposed to be studied in the modified LCA framework. The work sequence follows the flow as shown in figure 4.1.

5.1 Goal and scope

A grillage is a structural element made of a combination of stiffening beams intersecting orthogonally and attached to a plate. Figure 5.1 shows the general configuration of the flat grillage studied here. Figures 5.2 (a) and (b) show grillages implemented in typical marine structures. A grillage study is relevant because it is a key element in almost all thin plated structures used in aircrafts, ships, boats, offshore structures, steel bridges, etc.



(a) Example of grillage topology for composites showing a typical top hat stiffener geometry



(b) Example of grillage grillage topology for metal showing a typical extruded/rolled T profiles

Figure 5.1: *Example of grillage in a boat*

The present research focuses on four materials: steel, aluminium, GRTS and GRTP. The topology of composite material grillages differs from metallic grillages. Figure 5.1 (a) shows a typical top hat

(a) Aluminium boat (b) Grillage of rectangular and T beam

Figure 5.2: Grillage structure of the boat

configuration which uses beams laminated over the plating. Figure 5.1 (b) shows a typical metal configuration which uses rolled or extruded beams. The flexibility of extrusion and / or rolling of metal can result in a large number of metallic profiles and shapes commercially available. Bulbs and Ls are some other example of shapes that can be considered for grillage stiffeners but the present research only considers T-sections.

Figure 5.3 and 5.4 show the main dimensions used in this chapter for the design algorithm (section 5.2). In this figure, f is the plating thickness and b is the thickness of the top of the T beam and the top hat, e is the specific width of an individual stiffener base. The grillage dimension calculation method is derived from first principles and the Vedeler [95] resolution approach.

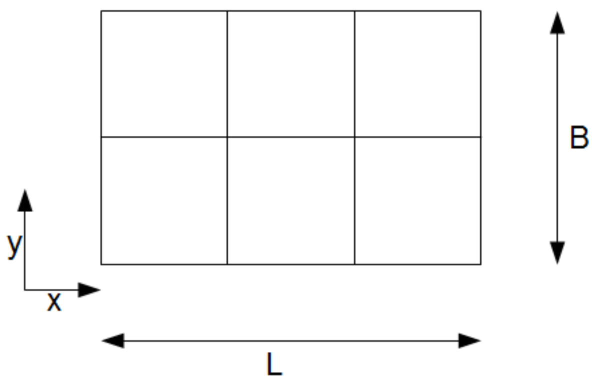


Figure 5.3: Panel dimension: in the present case there is one transverse and two longitudinal stiffeners. L/B = 2

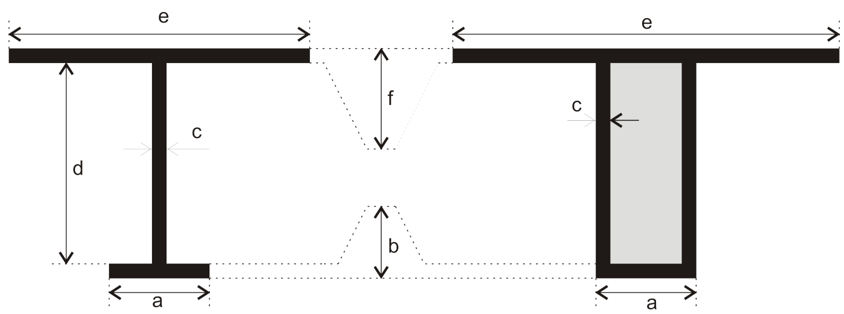


Figure 5.4: Studied section

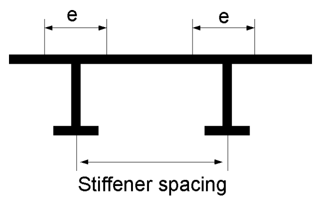


Figure 5.5: Effective breath

5.2 Design algorithm

The comparison between the grillages for each material requires the selection of a modelling method which ensures that each of these grillages responds in an equivalent manner to an externally applied load. The response of the grillage to the load can be investigated numerically or analytically. The analytical approach of the Navier method used by Vedeler is chosen in the present chapter. It is the exact solution of a rectangular grillage of evenly spaced beams simply supported on each edges. It is approximated as a mesh where only the properties of beam are used in the calculation.

The LCA framework presented in chapter 4 stated that the candidate materials must be compared using a grillage with the same geometry in order to be compared fairly. Therefore a common topology is chosen to be 2m long and 1m wide, to have 1 stiffener in the length and 2 stiffeners in the width and to have a spacing between stiffeners equal to B/r+1 for the longitudinal stiffener and L/s+1 for the transverse stiffener.

It is necessary to introduce an effective width of the beam in place of the panel of plating. This is e on the nomenclature figure 5.4. As it is part of the panel of plating, the associated thickness to e_l (longitudinal stiffener) and e_t (transverse stiffener)is f i.e. the thickness of the plating. It is assumed that the spacing is equal to 20% of the spacing between stiffeners. Figure 5.5 illustrates the principle.

The aim of the design algorithm is to search for the lightest panel where the deflection under load is less than 1 % of the width of the grillage, i.e. 1 cm and when the maximum stress is less than 60% of the yield stress of the material from which the grillage is constructed.

The lateral load is 150 kPa. This value is derived from the design load for RNLI life boats where the design load for a side panel is between 100 and 350 kPa depending on the position of the panel on the hull [96]. 150 kPa would be used in the design of a near aft grillage, and is used to provide a realistically arrived external pressure.

The search domain can be described with 7 variables. A first analysis was run in order to define one dimension range in which it is possible to find the best solution for the four candidate materials. Dimensions in percent are given when particular constraints are sought after. For example, it ensures that the height of the transverse stiffener is always smaller than the longitudinal one. For each material the possible dimensions are:

- The thickness f is 5 or 6 mm
- The width of the top of both stiffeners a_l and a_t are equal to 10 - 40% of the effective breath of the beam e_l and e_t, in 10% intervals.
- The thickness b_l and b_t of the top of the stiffeners are equal to each other and range from 3 to 8mm in 1mm intervals.
- The thickness c_l and c_t of the web of the stiffeners are equal to each other and range from 3 to 8mm in 1mm intervals.
- The height of the longitudinal stiffener d_l ranges from 4 to 24 cm in 1 cm intervals.
- The height of the transverse stiffener d_t ranges from 50 to 90% of d_l in 10% intervals.

Equation (5.1) to (5.20) define the governing equations for the determinations of deflections, bending moments and stresses in the grillage structure and is based on the method used by Vedeler [95] and modified for use in the metallic and composite topologies presented here.

The calculation of the lateral deflection of the panel at the point of coordinates x, y (see figure 5.3)is in the form of:

$$\omega = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} a_{mn} \sin\frac{m\pi x}{l} \sin\frac{n\pi y}{b} \tag{5.1}$$

With equation 5.1, the deflection of the qth longitudinal stiffener at x = $\frac{ql}{r+1}$ (Eq. 5.2) and the deflection of the pth transverse stiffener at y = $\frac{pl}{s+1}$ (Eq. 5.3) can be calculated as:

$$\omega_{x=x_q} = \sum_{n=1}^{\infty} b_{qn} \sin\frac{n\pi y}{b} \quad with \quad b_{qn} = \sum_{m=1}^{\infty} a_{mn} \sin\frac{m\pi q}{r+1} \tag{5.2}$$

$$\omega_{y=y_p} = \sum_{m=1}^{\infty} c_{pm} \sin\frac{n\pi x}{l} \quad with \quad b_{qn} = \sum_{n=1}^{\infty} a_{mn} \sin\frac{n\pi p}{s+1} \tag{5.3}$$

The strain energy for all girders is then:

$$V = \int_0^l \frac{E.I_r}{2}\left(\frac{\partial^2\omega}{\partial x^2}\right)^2_{y=y_p} dx + \int_0^b \frac{E.I_s}{2}\left(\frac{\partial^2\omega}{\partial y^2}\right)^2_{x=x_q} dy \tag{5.4}$$

The geometric properties and structural properties of the profiles can be described as below with the dimensions used in figure 5.4. The main information required are the second moment of area and the position of the centroidal axis. As there are two types of profiles the properties for T beam and top hat are different.

For metal, e.g. steel, aluminium:

$$Yc = \frac{ab\frac{b}{2} + cd(b+\frac{b}{2}) + ef(b+d+\frac{f}{2})}{ab+cd+ef} \tag{5.5}$$

$$I = \frac{ab^3}{12} + ab(Y_c - \frac{b}{2})^2 + \frac{cd^3}{12} + cd(d+\frac{d}{2} - Y_c)^2 + \frac{ef^3}{12} + ef(b+d+\frac{f}{2} - Y_c)^2 \tag{5.6}$$

For composites:

$$Yc = \frac{ab\frac{b}{2} + 2[cd(b+\frac{b}{2})] + ef(b+d+\frac{f}{2})}{ab+cd+ef} \tag{5.7}$$

$$I = \frac{ab^3}{12} + ab(Y_c - \frac{b}{2})^2 + 2[\frac{cd^3}{12} + cd(d+\frac{d}{2} - Y_c)^2] + \frac{ef^3}{12} + ef(b+d+\frac{f}{2} - Y_c)^2 \tag{5.8}$$

Then replacement, derivation and integration to obtain the strain energy:

$$V = \int_0^l \frac{E.I_r}{2}\left(\frac{\partial^2}{\partial x^2}\sum_{m=1}^{\infty} c_{pm}\sin\frac{n\pi x}{l}\right)^2_{y=y_p} dx + \int_0^b \frac{E.I_s}{2}\left(\frac{\partial^2}{\partial y^2}\sum_{n=1}^{\infty} b_{qn}\sin\frac{m\pi y}{b}\right)^2_{x=x_q} dy \tag{5.9}$$

$$V = \frac{\pi^4 E.I_r}{2l^4} \int_0^l \left(\sum_{m=1}^{\infty} c_{pm} n^2 \sin \frac{n\pi x}{l} \right)^2_{y=y_p} dx + \frac{\pi^4 E.I_s}{2b^4} \int_0^b \left(\sum_{n=1}^{\infty} b_{qn} m^2 \sin \frac{m\pi y}{b} \right)^2_{x=x_q} dy \quad (5.10)$$

The principle of Navier's method is to take advantage of the orthogonal functions which have the following properties [95] $\int_0^l \sin \frac{m\pi x}{l} \sin \frac{n\pi x}{l} dx$ is 0 when $m \neq n$ and $\frac{l}{2}$ when $m = n$. Then only the b_{mn} and c_{mn} are kept:

$$V_{one} = \frac{\pi^4 E.I_r}{2l^3} \sum_{m=1}^{\infty} n^4 b_{pn}^2 + \frac{\pi^4 E.I_s}{2b^3} \sum_{n=1}^{\infty} m^4 c_{qn}^2 \quad (5.11)$$

If the same principle is applied to all stiffeners then:

$$V_{all} = \frac{\pi^4 E.I_r}{2l^3} \sum_{p=1}^{r} \sum_{m=1}^{\infty} n^4 b_{pn}^2 + \frac{\pi^4 E.I_s}{2b^3} \sum_{q=1}^{s} \sum_{n=1}^{\infty} m^4 c_{qn}^2 \quad (5.12)$$

The work of an uniform pressure p can be expressed as:

$$W = \int_0^l \int_0^b p \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} a_{mn} \sin \frac{m\pi x}{l} \sin \frac{n\pi y}{b} dxdy \quad (5.13)$$

Minimising the potential energy (∂V/∂a$_m n$)and equating it to the work:

$$\frac{\partial V}{\partial a_{mn}} \partial a_{mn} = \partial a_{mn} \int_0^l \int_0^b p \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \sin \frac{m\pi x}{l} \sin \frac{n\pi y}{b} dxdy \quad (5.14)$$

$$\frac{\pi^4 EIs}{2b^3} \sum_{q=1}^{s} b_{qm} \sin \frac{m\pi q}{s+1} + \frac{\pi^4 EIr}{2l^3} \sum_{p=1}^{r} c_{pm} \sin \frac{n\pi p}{r+1} = \frac{4Plb}{\pi^2 mn} \quad with \quad m \quad and \quad n \quad odds \quad (5.15)$$

Then solving and rearranging, a$_{mn}$:

$$a_{mn} = \frac{16pl^4 b/EI_r}{\pi^6 mn[m^4(r+1) + \frac{I_s}{I_r}\frac{l^3}{b^3} n^4(s+1)]} \quad (5.16)$$

With I_s and I_r, the moment of inertia of the longitudinal and the transverse stiffener respectively. These parameters can be calculated with equations (5.5)(5.7) which give the centroid of the area and equation (5.6)(5.8). The dimensions given in figure 5.4.

The deflection of grillage is then equal to:

$$\omega = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{16pl^4 b/EI_r}{\pi^6 mn[m^4(r+1) + \frac{I_s}{I_r}\frac{l^3}{b^3} n^4(s+1)]} \sin \frac{m\pi x}{l} sin \frac{n\pi p}{b} \quad (5.17)$$

From the moment calculation it is then possible to get moment values for the p^{th} longitudinal stiffener:

$$M = -EI_r \frac{\partial^2 \omega}{\partial x^2} = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{16pl^2b}{\pi^4 \frac{n}{m}[m^4(r+1) + \frac{I_s}{I_r}\frac{l^3}{b^3}n^4(s+1)]} \sin\frac{m\pi x}{l} sin\frac{n\pi p}{r+1} \quad (5.18)$$

For the q^{th} transversal stiffener:

$$M = -EI_s \frac{\partial^2 \omega}{\partial y^2} = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{16plb^2}{\pi^4 \frac{m}{n}[n^4(s+1) + \frac{I_r}{I_s}\frac{b^3}{l^3}m^4(r+1)]} \sin\frac{m\pi q}{s+1} sin\frac{n\pi y}{b} \quad (5.19)$$

The calculation of the deflection and moment depends on a large number of geometric properties. The solution can be obtained through trial and error. This is very time consuming and authors have used genetic algorithms[89] in order to get an optimum design for weight. The present study aims to compare materials in a structural application and design under the same mathematical model. For all these reasons, geometry simplifications have been chosen in order to reduce calculation time. It has to be noted that the current method applies only to the bending of beams and not to the panel directly.

The maximum stress on the longitudinal stiffener, using the beam bending equation the stress can be obtained:

$$\sigma_{max} = \frac{M_{max}y}{I} \quad (5.20)$$

Where y is the distance from the neutral axis to the point where the maximum stress occurs I is the second moment of area, and M_{max} the maximum bending moment obtain from equation(5.18)(5.19).

The equations for the grillage analysis and the seven geometric variables defined earlier were used in an exhaustive search to provide the deflection, maximum stress and a weight calculation, based on calculated volume and the density of the material as presented in Table 5.1. The material properties for steel and aluminium are from LR-SSC rules. The GRTS is an epoxy / E-glass (woven fabric) composite chosen from the CES material selector database [97]. It is a prepreg with a weight fibre fraction of 50% and suitable for vacuum bagging. Using this method, these GRTS mechanical properties are high. LR-SSC[98] rules would estimate the ultimate tensile strength at 125 MPa (200 G_c + 25 Mpa with G_c the fibre content in weight) and tensile modulus of 9.5 GPa (15 G_c + 2 GPa). The values used for the research are optimistic. The GRTP is made of Twintex [99]. Twintex is commingled yarn of PP and E-glass fibre with a 60% weight fibre. This material is suitable for vacuum bagging. In Chapter 6 and 7, the material properties are calculated using LR-SSC as requires by the rules. It is assumed that both composite are anisotropic in the model.

Table 5.1 also summarises the material mechanical properties, the geometric parameters, the deflection and stress under load and the weight of the lightest grillage for each material, respecting the limits on stress and deflection presented earlier. The topology of the grillage with one larger beam in the x direction was chosen so that the maximum deflection and stress happens in the middle of the longitudinal stiffener in the centre of the grillage. The deflection derives from equation 5.17 in which the second moment of area for metal alternatives i.e. T-section derives from equation 5.5 and 5.6 and the second moment of area of the composites alternatives i.e. top hat derives from equation 5.7 and 5.8. The maximum stress is used for the calculation with equation 5.20. The moment is calculated in the middle of the longitudinal stiffener using equation 5.18 and the same equation for the second moment of area than for the calculation of the deflection. y is obtained by subtracting the height of the centre of mass to the overall height of the stiffener ($a_l + b_l + f$). All possible combinations of variables were tested and the lightest grillage for each material is presented graphically in figure 5.6 and in detail in table 5.1. Table 5.1 shows that the grillage deflection is the most significant contraint for the present design objective to lower the weight. For the four materials any further weight decrease from the presented solution would lead to an unacceptable deflection while the stress would remain far from the maximum allowed limit.

Table 5.1: Calculation result

Parameter	Steel	Alu	GRTS [97]	GRTP [100]
E (GPa)	200	69	26.4	13.4
σ_{max}(MPa)	235	240	375	276
Density (kg/m^2)	7800	2700	2000	1485
f (mm)	5	5	5	5
a_l (mm)	10	10	10	10
b_l (mm)	4	3	3	3
c_l (mm)	3	3	3	3
d_l (mm)	80	120	140	170
e_l (mm)	100	100	100	100
a_t (mm)	13	13	13	13
b_t (mm)	4	3	3	3
c_t (mm)	3	3	3	3
d_t (mm)	40	60	70	85
e_t (mm)	133	133	133	133
Deflection (mm)	9.4	9.5	8.7	9.8
Stress (MPa)	11	3	6	5
Weight (kg)	86	31	23	18

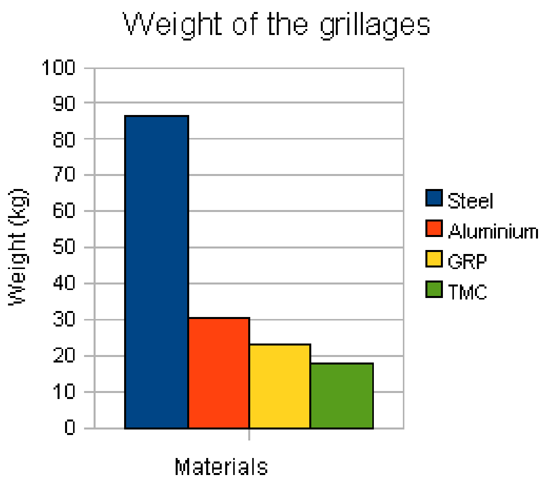


Figure 5.6: Weight of the structure

The influence of the number of stiffeners on the weight was investigated and the results for aluminium are presented in figure 5.7. The calculation is conducted under the same conditions presented previously, only the number of stiffener changes. By increasing the number of stiffeners, the stiffener spacing was reduced therefore for a given load the moment of inertia for each stiffener can be reduced to get the same panel stiffness. The increase in weight due to an increased number of stiffeners is therefore compensated by reduced geometry of each stiffener. The results therefore shows that by increasing the number of stiffeners does not dramatically influence weight (3% in standard deviation).

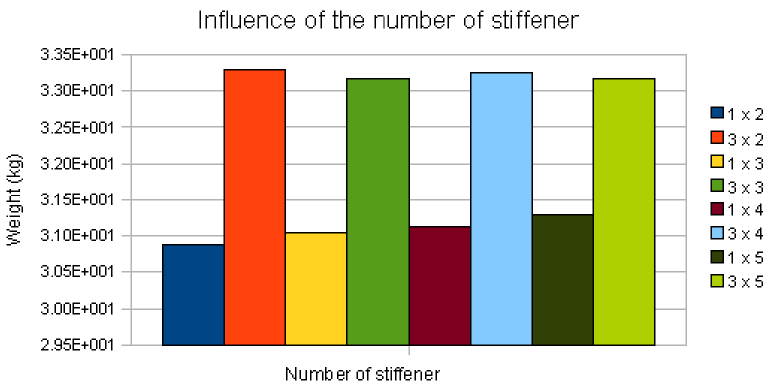


Figure 5.7: Influence of the number of stiffener on the weight of the grillage

The influence of the effective breath on the weight of the grillage is presented in figure 5.8 and demonstrates that the weight of the panel is not affected much by this parameter. The greatest weight is only 4% heavier than the lightest. It is noticed that the greater the effective breath, the greater the weight, and the contrary would have been expected because the second moment of area increases with e. The stress on the top of the stiffener must increase with the centre of gravity moving (see equation 5.20) closer to the panel plate when e increases.

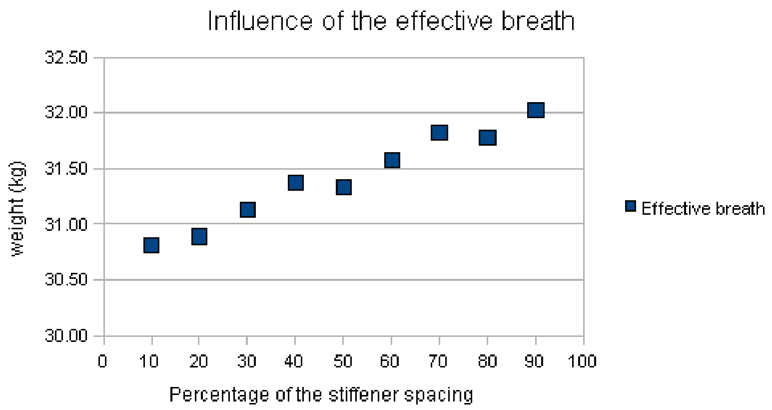


Figure 5.8: Influence of effective breath on the weight of the grillage

Figure 5.9 shows the relationship between the applied load and the weight of the grillage. Ideally as the load tends to zero the weight would also tends to zero. However due to the dimensional constraints, the design space is constrained providing a limited minimum weight. This minimum weight is not far away from the weight of the panel design for 150 kPa. The lighter case with no load is the lightest case of the search domain as expected. The little change in weight shows that the minimum dimensions of the search domain are sufficient to result in a structure which can resist some load. Table 5.1 shows that the thickness of plate, webs and top of the beam and the ratio of the longitudinal beam to the transverse beam height are the smallest possible values of the search domain. These values can probably be made thinner but it may appear unrealistic to decrease them as they would be unrepresentative of a real marine structure.

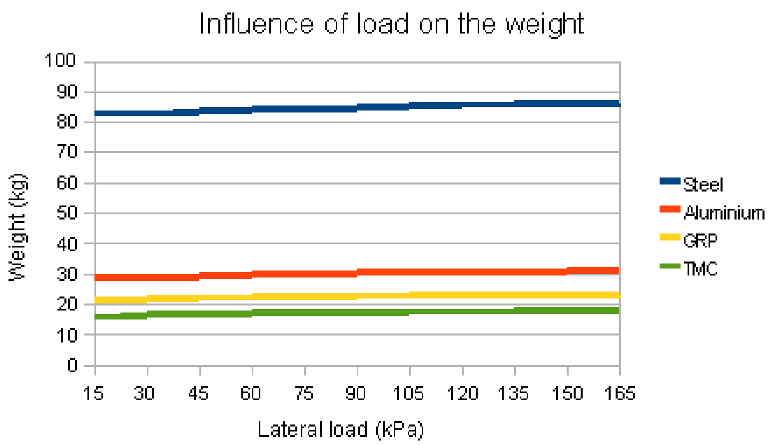


Figure 5.9: Influence of the lateral load on the weight of the grillage

This section has presented the structural design algorithm for a representative part of a marine structure, i.e. a grillage. The results of the exhaustive search of the domain show that realistic results are obtained from the algorithm and the topologies differ significantly from material to material. The next phase is to examine the grillage design with a life scenario incorporating impact assessment. The combination of traditional engineering functions of stiffness, strength and weight will be supplemented with an assessment of environmental impact providing a societal contribution to decision making in material selection.

5.3 Life scenario and impact assessment inventory

This section details the collation of life scenario data for the manufacture of each grillage structure output from the design stage in order to create an impact value for each. The information used to provide this environmental assessment has been collected from a wide range of sources as discussed in chapter 4. The database can be found in Appendix A.

Each of the materials are dealt with individually, outlining the relevant data from the database to complete the impact assessment.

5.3.1 Steel

Table 5.2 and 5.3 show respectively the the energy consumption of the primary steel and recycled steel grillage over their complete lives. For each grillage, the result of the LCA is presented in a table where the first column presents the most effective processes from a selection of processes (presented in appendix A) for the life described in section 4.3, i.e. system boundaries. The second column is the specific energy consumption (SEC) of the processes. The values used can be referred to in appendix A and the condition of use of these SEC figures is described in the comments associated with each table in part D of appendix A. The third column is the variable associated with the grillage and converts the specific energy consumption into an energy per functional unit and as discussed earlier the functional unit for this analysis is a single grillage assembly. The variable can be weight, length of the beams, surface area, etc. The energy per functional unit is equal to the variable parameter times the SEC. This same logic is applied to the other three candidate materials.

Table 5.2: Life cycle scenario and impact calculation of the steel grillage

Process name	SEC	Variable	Energy impact	Comment
		Material acquisition		
Uk primary steel	22 MJ/kg	86 kg	1900 MJ	
		Grillage manufacturing		
Oxycutting	0.25 MJ/m	1m x 5mm	0.25 MJ	Cut in the middle of the panel of plating
CO_2 welding	1.9 MJ/m	1m x 5mm	1.9 MJ	Weld in the middle of the panel of plating
	0.7 MJ/m	7m x 3mm	4.9 MJ	Stiffener weld
		In service		
10% of material renewval	22 MJ/kg	8.6 kg	190 MJ	The material is assumed to be recycled
Paint underwater	38 MJ/m^2	1 m^2	38 MJ	Half of one side of the panel is supposed to be above the water
Paint above water	25 MJ/m^2	1 m^2	25 MJ	Half of one site of the panel is supposed to be below the water
Paint subject to wear	5 MJ/m^2	2 m^2	10 MJ	one full side of the panel is supposed to be subject to wear
		End of life		
Oxycutting	0.25 MJ/m	8 m	2 MJ	
			2100 MJ	Virgin material

Table 5.3: Life cycle scenario and impact calculation of the recycled steel grillage

Process name	SEC	Variable	Energy impact	Comment
		Material acquisition		
Uk primary steel	8.6 MJ/kg	86 kg	740 MJ	
		Grillage manufacturing		
Oxycutting	0.25 MJ/m	1m x 5mm	0.25 MJ	Cut in the middle of the panel of plating
CO_2 welding	1.9 MJ/m	1m x 5mm	1.9 MJ	Weld in the middle of the panel of plating
	0.7 MJ/m	7m x 3mm	4.9 MJ	Stiffener weld
		In service		
10% of material renewval	8.6 MJ/kg	8.6 kg	74 MJ	The material is assumed to be recycled
Paint underwater	38 MJ/m^2	1 m^2	38 MJ	Half of one side of the panel is supposed to be above the water
Paint above water	25 MJ/m^2	1 m^2	25 MJ	Half of one site of the panel is supposed to be below the water
Paint subject to wear	5 MJ/m^2	2 m^2	10 MJ	one full side of the panel is supposed to be subject to wear
		End of life		
Oxycutting	0.25 MJ/m	8 m	2 MJ	
			960 MJ	Recycled grillage

In the steel grillage life, the largest energy consuming processes are the manufacture of the primary steel, recycling at the manufacture stage and in service damaged area renewal. The next most energy consuming process is painting. The paint thickness is about half a millimetre, i.e. 10% of the grillage plating thickness. Even if in terms of weight it is much lower than 10% of the grillage, the high energy consumption of the paint main component, the epoxy resin (see table A.6) makes the energy consumption contribution of paint higher than the grillage manufacture stage. Energy consumption associated with grillage manufacture is low thanks to a very low steel oxy cutting SEC. In the model used in the current research, the grillage requires to be cut and welded. A one metre cut is made in the middle of the 5 mm thick panel of plating. The amount of welding energy depends on the length of the beam to be welded and the length of plating to be welded and their respective thickness. In the current case one metre of the 5 mm thick panel of plating (f in the table 5.1) and 7m of the 3mm thick beam (c_l and c_t in the table 5.1) need to be welded.

In comparison with all the other processes, material manufacture is by far the most significant process for the calculation of the energy and energy must be allocated coherently so as to aim for credible results. By default the material used for the manufacture of the grillage is manufactured from primary resources which consume a lot of energy. However if the grillage is recycled at life end an offset of 13 MJ per kilogramme of steel recycled is subtracted from the overall energy consumed over the life of the grillage. If the steel is fully recycled, it leads to energy per grillage of 800 MJ instead of 1900 MJ when the steel is not recycled. This demonstrates that if the correct means of dismantling and recycling of the steel are in place, the embodied energy of the manufacture of the original grillage can be offset by using recycled steel.

5.3.2 Aluminium

Table 5.4 and 5.5 show respectively the energy consumption of a primary aluminium and recycled aluminium grillage over their lives. The topology of the table follows the same principle as table 5.2 for steel. The calculation of energy follows the same methodology. The data used in table 5.4 is obtained from Appendix A.

Table 5.4: Life cycle scenario and impact calculation of the aluminium grillage

Process name	SEC	Variable	Energy impact	Comment
		Material acquisition		
UK primary aluminium	220 MJ/kg	31 kg	6800 MJ	
		Grillage manufacturing		
Waterjet	27 kJ/m	1 m	0.027 MJ	Cut in the middle of the panel of plating
Friction stir welding	0.15 MJ/m	8 m	1.2 MJ	Weld in the middle of the panel and stiffeners
		In service		
10% of material renewal	220 MJ/kg	3.1 kg	680 MJ	
Paint underwater	28 MJ/m^2	1 m^2	28 MJ	Half of one side of the panel is supposed to be above the water
Paint above water	15 MJ/m^2	1 m^2	15 MJ	Half of one side of the panel is supposed to be below the water
Paint subject to wear	10 MJ/m^2	2 m^2	20 MJ	one full side of the panel is supposed to be subject to wear
		End of life		
Plasma cutting	0.42 MJ/m	1m x 5mm	0.42 MJ	
	0.42 MJ/m	7m x 3mm	1.5 MJ	
			6900 MJ	Virgin material

Table 5.5: Life cycle scenario and impact calculation of the recycled aluminium grillage

Process name	SEC	Variable	Energy impact	Comment
		Material acquisition		
UK primary aluminium	20 MJ/kg	31 kg	620 MJ	
		Grillage manufacturing		
Waterjet	27 kJ/m	1 m	0.027 MJ	Cut in the middle of the panel of plating
Friction stir welding	0.15 MJ/m	8 m	1.2 MJ	Weld in the middle of the panel and stiffeners
		In service		
10% of material renewal	20 MJ/kg	3.1 kg	62 MJ	
Paint underwater	28 MJ/m^2	1 m^2	28 MJ	Half of one side of the panel is supposed to be above the water
Paint above water	15 MJ/m^2	1 m^2	15 MJ	Half of one side of the panel is supposed to be below the water
Paint subject to wear	10 MJ/m^2	2 m^2	20 MJ	one full side of the panel is supposed to be subject to wear
		End of life		
Plasma cutting	0.42 MJ/m	1m x 5mm	0.42 MJ	
	0.42 MJ/m	7m x 3mm	1.5 MJ	
			700 MJ	Recycled grillage

As with the steel grillage, the largest energy consuming process of aluminium is also the material manufacture and recycling followed by the in service painting and damaged area renewal. The end of life grillage dismantling is the third most energy consuming process due to the large energy consumption of the plasma cutting. Finally the grillage manufacturing processes have the lowest energy consumption. In general it can be said that mechanically driven manufacturing processes use less energy consuming than electrically / thermally driven processes. This can be illustrated by waterjet and friction stir welding (FSW) that use little energy in comparison with plasma cutting for instance.

The method for the allocation of energy for the material manufacture follows the same principle as for steel. However the energy involved in the manufacture of aluminium is much larger than for production of steel and the energy requirement for the manufacture of aluminium from recycled material is smaller than for the recycling of steel. Aluminium shows a very large range of possible energy consumptions for material acquisition and a very low energy requirement for the manufacture of the grillage. It is essential to collect and recycle aluminium to decrease the embodied energy in the grillage. The sorting of aluminium per grade (in the present case marine grade), cleaning and paint removal in order to limit the possible contamination needs to be conducted in order to achieve an efficient recycling of this sensitive material. In comparison steel is less sensitive to contamination.

5.3.3 GRTS

Table 5.6 shows the energy consumption of the epoxy / glass grillage over its life. The topology of the table follows the same principle used for steel, depicted in table 5.2. The calculation of energy follows the same methodology. The information collected in table 5.6 can be referred to in appendix A and the condition of use of these SEC figure is described in the comments associated with each table in the GRTS section part D of appendix A.

In the case of GRTS, the material acquisition and grillage manufacture requires a lot of material for the vacuum bag, the mould and the backing structure of the mould. As seen before in the case of steel and aluminium material production requires a lot of energy. The reuse of the mould, however, can decrease the relative energy impact for each grillage. In addition to material requirements the oven curing adds more energy to the final result. Despite its low density, the energy requirement for the GRTS grillage is higher than either the steel grillage and the recycled aluminium grillage. The only way to decrease slightly the energy is to offset some energy by incinerating the composites at

Table 5.6: Life cycle scenario and impact calculation of the GRTS grillage

Process name	SEC	Variable	Energy impact	Comment
		Material acquisition		
GRTS raw material manufacture	70 MJ/kg	23 kg	1600 MJ	
		Grillage manufacturing		
Mould	51 MJ/m^2	2 m^2	100 MJ	Mould curing is assumed to be without any energy input. The mould is 5 mm thick and reuse 10 times
Steel backing structure	10 MJ/m^2	2 m^2	20 MJ	Assumed to be in recycled steel
Vacuum bag	7 MJ/m^2	2 m^2	14 MJ	Not reusable
Curing	430 MJ/m^2	2 m^2	860 MJ	
		In service		
10% of material renewal	70 MJ/kg	2.3 kg	160 MJ	
Paint underwater	28 MJ/m^2	1 m^2	28 MJ	Half of one side of the panel is supposed to be above the water
Paint above water	15 MJ/m^2	1 m^2	15 MJ	Half of one site of the panel is supposed to be below the water
Paint subject to wear	10 MJ/m^2	2 m^2	20 MJ	one full side of the panel is supposed to be subject to wear
		End of life		
Shredding	0.92 MJ/kg	23 kg	21 MJ	
Incineration	- 30 MJ/kg	11.5 MJ	- 350 MJ	Energy released per kg of resin incinerated
Incinerated composites			2500 MJ	
non incinerated composites			2800 MJ	

the end of their usable life. However this has the disadvantage of creating a large amount of ash due to the glass content.

5.3.4 GRTP

Table 5.7 show the energy consumption of the GRTP grillage over its life. The topology of the table follows the same principle used for steel and depicted in table 5.2. The calculation of energy follows the same methodology. The information collected in table 5.6 can be referred to in appendix A and the condition of use of these SEC figure is described in the comments associated with each table in the GRTP section part D of appendix A.

Table 5.7: Life cycle scenario and impact calculation of the GRTP grillage

Process name	SEC	Variable	Energy impact	Comment
		Material acquisition		
GRTP raw material manufacture	60 MJ/kg	18 kg	1100 MJ	
		Grillage manufacturing		
Mould	51 MJ/m^2	2 m^2	100 MJ	Mould curing is assumed to be without any energy input. The mould is 5 mm thick and reuse 10 times
Steel backing structure	10 MJ/m^2	2 m^2	20 MJ	Assumed to be in recycled steel
Vacuum bag	7 MJ/m^2	2 m^2	14 MJ	Not reusable
Curing	430 MJ/m^2	2 m^2	860 MJ	
Welding	0.125 MJ/m^2	14 m	1.8 MJ	Top hats are welded on both side of their base.
		In service		
10% of material renewal	60 MJ/kg	1.8 kg	110 MJ	
10% of material renewal curing	430 MJ/m^2	0.2 m^2	86 MJ	
Paint underwater	28 MJ/m^2	1 m^2	28 MJ	Half of one side of the panel is supposed to be above the water
Paint above water	15 MJ/m^2	1 m^2	15 MJ	Half of one site of the panel is supposed to be below the water
Paint subject to wear	10 MJ/m^2	2 m^2	20 MJ	one full side of the panel is supposed to be subject to wear
		End of life		
Shredding	0.92 MJ/kg	18 kg	17 MJ	
Incineration	- 30 MJ/kg	7.2 MJ	- 220 MJ	Energy released per kg of resin incinerated
reprocessing	59 MJ/kg	18 kg	1100 MJ	
Incinerated composites			2100 MJ	Once shredded GRTP can be landfilled or reprocessed
non incinerated composites			2300 MJ	
Reprocessed and incinerated composites			3200 MJ	Once reprocessed the raw material can be sold and used as a raw material

The material contribution to the energy result is very high for the same reason as for the GRTS grillages. The energy consumption for the mould and the consumables is also high. However the lower density of GRTP in comparison with GRTS allows the impact result to be lower than GRTS but higher than recycled aluminium and primary and recycled steel. The curing is surface dependent hence the energy is equal for GRTS and GRTP. The renewal of material requires curing hence adding up more energy for the in service life of the GRTP than for the GRTS. At life end the incineration allows for a small decrease of the overall energy. The shredding of GRTP can create a new ready to use raw material but the GRTP fibre content used in demanding marine structure is high. It is most likely that the resulting shredding recyclate would require an addition of resin in order to ease the manufacturing of non structural applications in which the amount of resin is low. The curing and the addition of the resin can increase the energy for recycling. As a case study, an end of life scenario where GRTP is recycled under the responsibility of the marine structure manufacturer in order to create a high value reprocessed GRTP recyclate is presented in table 5.7. In this scenario, the marine GRTP structure is shredded and reprocessed with addition of resin into a marketable product, e.g. a consolidated panel or pellet. The LCA resulting energy is very high, the second highest after the non recycled aluminium structure, but the value of the new recyclate and the waste saving can be considered as not negligible for a material such as composites where end of life solutions are most of the time limited to incineration. It is observed that energy based LCA does not show any particular advantage to this end of life scenario however good it might be in terms of waste management and recyclate monetary value.

5.4 Critical analysis

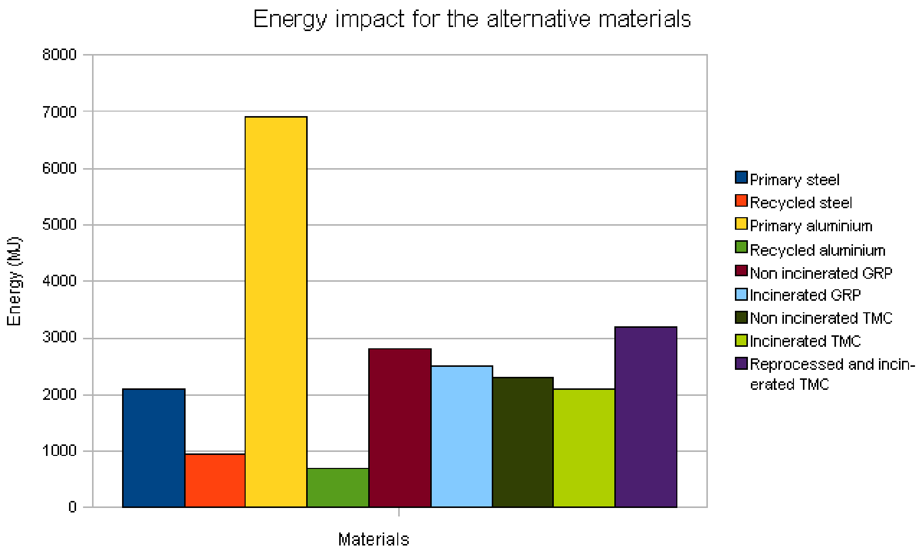


Figure 5.10: Panel Results

Figure 5.10 provides the results of the energy analysis of the 4 candidate materials. Primary aluminium is the least energy effective material and recycled aluminium is the most effective. Two groups can be isolated: the low energy use of recycled metal and the relatively constant but high energy consumption of composites. Primary steel demonstrates a level of energy consumption close to composites. The energy result for the grillage does not take into account any time scale. It shows the large influence of the recycling of material to the end result especially on aluminium. The reprocessing of GRTP in order to manufacture a secondary raw material such as pellets for injection moulding or a preconsolidated panel requires a lot of energy however it is assumed to be valuable on the market and reduces waste. The quantification of market value and waste management are outside the scope of the study but if it were to be quantified and included these GRTP secondary products may be very attractive.

Xu et al. [21] (paper reviewed in section 3.1.3) used LCA to measure the performance of PP composites materials. The authors reviewed several functional units: constant volume, constant mass, or the material service density. For each candidate material at constant volume or when the material service density is calculated and used, composites performed better than plain polypropylene. They focused on material service density (volume and weight of material required to fulfil a function) as a functional unit. This is the approach taken in the present research but the result are not as conclusive. They demonstrated that for their candidate materials an increase in fibre content would lead to a decrease in material service density. This decrease led to a lower impact. In the present study it is not possible to draw a conclusion on the material service density because the lighter structure i.e. GRTP is not the most environmentally friendly, it is recycled aluminium. However it is clear that for any given material the structure requiring the least amount of material is the most environmentally friendly. Therefore it is correct to seek the lighter structure configuration for each candidate material. Xu et al. [21] reviewed only on type of composites for a simple sheet structure. The larger variety of candidate materials in the present research and the structure complexity make it particularly difficult to conclude on which material is the best for all application. The current results are only valid for the grillage. A new functional unit with a new design model is studied in the next chapter as the grillage does not give as clear answer on what material to chose as Xun et al. [21] and Song et al. [22] shows different result than the one presented in the previous section.

The values of the impact used in the present research are in a similar range of order as those present in the literature. Song et al [22] studied the life cycle energy analysis of glass fibre reinforced composite compared to recycled steel and recycled aluminium. For the manufacture of material the authors presented a range of value for steel of 30 - 60 MJ/kg, for aluminium of 196 - 257 MJ/kg, for epoxy of 76 - 80 MJ/kg, for PP of 53 - 80 MJ/kg and for glass fibre 13 - 32 MJ/kg. The recycling credit for steel is 21.9 MJ/kg and 172 MJ/kg for aluminium. The values are close to the value used in the present chapter. It is representative of the value collected and presented in appendix A. As for the present research, the authors presented an energy analysis for a structural artefact in three different materials. It shows that the manufacturing it with composite structure had a lower energy demand than with steel or with aluminium. Conversely in the present research, the steel and aluminium structures require less energy to be manufacture. It shows clearly that for the same input values, energy result energy result can change dramatically. The design of marine structure should be studied in greater detail to be more specific to marine application and give a clearer answer on which material is best. This will be done in the next two chapters.

Finnverden [65] discussed three point of LCA application i.e. the impact evaluation, the comparison of similar products of function (e.g. maturity of alternative, investment requirement) and the reproducibility [65, 101]. The present study is theoretical and access to pollutant emissions is limited. Physical flows other than energy flow inventories are subject to gaps and the selected parameter may differ from one study to another whereas energy is always used in LCA with minor uncertainties [65]. With the energy approach, values are more easily accessible and energy encapsulates a large amount of information and is responsible for a large part of the environmental impact. The energy is however considered on a large definition basis: coke in steel manufacturing processes, oil as basis of and processing energy associated with polymer resins. In the later case it should be noted that this definition of the energy may lead to paradox due to the oil being considered twice, once as a polymer basis and once as a combustible if the polymer is incinerated.

The comparison of similar products is complex. Physical flow can be close from one given process to another but the impact associated may differ greatly. Finnvedenn [65] stated that it is very important to study the exact same function. Hence in their comparison of incineration with energy recovery and landfilling of paper, the author presented the *function broadening concept* where the study compares 'incineration with energy recovery' and 'landfilling + energy production with alternative energy source'. This alternative energy production uses a very large assumption about what it is replacing that may lead to uncertainties and the material origin from recyclate may not be as efficient as current virgin production. The subfunction of the grillage system has the same properties. Incineration with energy recovery, landfilling and recycling are three ways to dispose of the grillage. However they would not have the same function as defined by the LCA standard and Finnvedenn [65]. Indeed some processes are net energy producers whereas others are net energy importers. In the present research on the grillage this is ignored and only material flow and energy are taken into account.

The result of the LCA can be applied in future designs of complete structures such as boats or aircrafts. It will be useful in order to assess the effect of specific design rules such as those used in the marine industry which are not using first principles for designing the structure as in the present grillage study. In addition the in service life of these complete structures will need to be considered as well as the main function. The functional unit will be different as energy would not be given per grillage unit but per function, i.e. energy per tonne of freight carried or per passenger. The present grillage study will be the basis of the material selection. It is clear that no material shows a greater benefit and that recycling will play a major role.

The present chapter investigated a structural artefact design in a fixed topology and presented a scenario with the lowest embodied energy for each material. Chapter 6 will aim to assess how other design methods (Lloyd's Register Rules and Regulations) and a more detailed in service scenario will affect the embodied energy result.

Chapter 6

Modified LCA framework: planing boat components

Chapter 5 showed the behaviour of a relatively simple grillage assembly to be studied in the modified LCA framework depicted in figure 4.1. The present chapter is an extension to the design of a boat hull and deck for a fixed topology.

6.1 Goal and scope

The present research deals with material selection and how it influences the environmental life cycle performance of a boat. Size, speed, cargo types and operational route can result in very different ship designs. Moreover, the study is part of an LCA and the results depend on the physical properties of the boat. The scantlings and the power requirements have a major impact on the weight, fuel consumption, and quantity of material used. The quantity of material plays a major role on the environmental impact measurement. The following sections highlight design decisions and material implications in a general ship design process. It addresses the basic scantling of a boat according to the Lloyd's Register special service craft (LR-SSC) rules and regulations. The design method takes is based on details obtained from the literature review on ship design (section 3.4.2).

As described in chapter 4 section 4.3, the environmental impact measurement parameter is the embodied energy of the boats per functional unit. In the present case the functional unit is a year of use. The embodied energy is the sum of the energy required for the manufacture of the material, the manufacture of the boat and its disposal and the fuel consumption in service. The calculation of the embodied energy per functional unit is conducted following the sequence:

1. Section 6.2 deals with the scantling of the boat. The result of this section is the amount of

material required and the amount of assembly, manufacturing or curing. The structure weight calculated is used in section 6.3.

2. Section 6.3 deals with the calculation of the power requirement for the boat for each candidate material. Each of these boats has the same geometry but a different total weight. The total weight is the payload, constant for each material, and the structure weight which is calculated in section 6.2.

3. Section 6.4 combines the result of section 6.2 and 6.3 by calculating the SEC for each aspect of the life of the boats (material manufacture, boat manufacturing, fuel consumption, etc.) and by normalising it for a year of use.

Sections 6.2 and 6.3 aim to define the scantling of the hull and deck and the installed power for each candidate material. It should be noted that the design algorithms used are not considered to be perfect. A large number of approaches could be adopted to obtain the principal characteristics of the boat. The novelty of the research is the use of the output from the design algorithm in an LCA environment to assess the impact of the design.

6.2 Structural definition

The LR-SSC rules and regulations can be applied to high speed boats. The two basic components covered in the regulations and used in the present section are platings and stiffeners. It must be mentioned that there are two concepts that can be assessed on the basis of structural design: The ship girder and the local structural definition. Ship girder studies assume that boats behave like beams under bending moment loads. Large vessels are modelled as long beams for which stresses can be large due to larger bending moments. However, it is assumed that small boats behave like short beams, for which stresses are small enough not to reach the maximum strength of the materials, therefore it is assumed that the ship local design fulfils strength requirements. In the present research the ship is assumed to be small enough that only local definition is required.

The material mechanical properties are defined directly in the LR-SSC rules. There is no material information input for the four materials apart from the material type i.e. steel, aluminium or for both the composites, the fibre weight content and the reinforcement configuration. The fibre content is 50% and the configuration is a woven fabric for both the GRTS and 60% for the GRTP. The composites are manufactured using a vacuum bagging technique.

The main dimensions of the ship are presented in table 6.1. These dimension are assumed to be representative of a fast patrol boat. the results are therefore only valid for these dimensions. The stiffener spacing, height and width of the top hat are set as constant and are equal to those set for the grillage study (see chapter 5).

Table 6.1: Dimension of the boat

Regulation length	20 m
Breadth	5 m
Draft	1 m
Freeboard	2 m
Speed of the boat	30 kn
Displacement of the boat	20 tonnes
Cb	0.4
Fn	2.11
Deadrise angle	28 deg
Side panel deadrise angle	75 deg
Panel length	0.66 m
Panel width	0.5 m

The details of the calculation of the scantling is defined in appendix B. The design algorithms of the current section deal with 6 design variables, 4 for the metal alternatives and 2 for the composites alternatives. For the metal alternative the calculation deals with the following parameters:

- The thickness of plating for hull and deck
- The section modulus of the stiffeners
- The stiffener second moment of area
- The web area

Once all these variables are calculated, standard commercially available sections are chosen to meet these requirements and the weight, length of stiffener, thickness to weld are calculated and used in the life scenario impact assessment.

In the case of composite materials, the design algorithm deals with:

- The thickness of plating for hull and deck

- The thickness of the stiffener skin

The weight and other parameters can be deduced straight from the calculated dimensions as no standard section are available as in the case of steel or aluminium.

The scantling is derived from design load and pressures on the hull. These pressures are related to several phenomena (static load, dynamic load, impact, etc.) and the scantling is conducted using the largest of these pressures. Appendix B, section B.2 describes how the pressures can be calculated. As it can be seen in the appendix, the pressure depends on the area where it is calculated. It is chosen to calculate the pressure at mid length of the boat. Calculating the pressure at only one place reduces considerably the calculation time but reduce the accuracy. Conversely, pressure are calculated along the full length of the boat in chapter 7. It is assumed that calculating the scantling of a boat using this pressure results in a boat of average weight. The calculated pressures are presented in table 6.2. The largest pressure is the bottom impact and this is used for the scantling. The design pressure used in the present chapter is much lower that the design pressure used in the grillage study (150 kPa [96]).

Table 6.2: Design pressure result

The shell envelope pressure (P_s)	25 kPa
The bottom impact pressure (P_{dL})	63 kPa
The forebody impact pressure (P_f)	8 kPa
The pressure on weather deck (P_{wL})	21 kPa
The cargo deck design pressure (P_{cd})	8 kPa

A scantling study was conducted using the method presented in appendix B, section B.3. The result of the scantling is presented in the tables 6.3 and 6.4. The calculation of dimensions for the metal alternative is straightforward because in the LR-SSC rules, the dimensions are derived directly from equations (B.3.14) to (B.3.17). In the case of composite materials a proposed plating and beam lay-up sequence is studied. The thickness of these sequences is at least the thickness calculated in equation (B.3.18) for the plating and (B.3.19) for the stiffener. The stress is calculated in each layer in order to assess whether it is below 60 % of the yield stress. The calculation process uses equation (B.3.20) to (B.3.28) in order to populate a table such as the example given in table B.2 from which the maximum stress can be calculated following the process presented in table B.3. The steel profile selection is taken from Corus and Dent steel stockholders. Aluminium profiles are not so readily available since aluminium's ease of extrusion gives more freedom in the choice for sections.

The selection is based on a calculation for a T profile where the web height is equal to 1.5 times the top width and where the thickness of the web and the top is equal to 0.1 times the top width. For the steel deck, the calculated inertia is very low and standard T beams cannot be purchased for such dimensions and standard bulb sections were selected in the place of standard T because their second moment of area are smaller.

Table 6.3: Dimensions for metallic structures

Material	Steel		Aluminium	
Bottom plating thickness	9 mm		9 mm	
Deck plating thickness	3 mm		3 mm	
Position	Longitudinal	Transverse	Longitudinal	Transverse
Bottom inertia (cm^4)	257	338	733	968
Bottom web area (cm^2)	11.2	14.7	10.9	14.4
Bottom section selection	102x127x14	152x127x13	99x149x10	106x159x10
Deck inertia (cm^4)	47	62	134	177
Deck web area (cm^2)	2.1	4.3	2.1	4.2
Deck section selection	100x6x15.5	100x6x15.5	65x98x7	70x105x7

Table 6.4: Dimensions for Composites structures

Material	Epoxy/glass		PP/glass	
Bottom plating minimum thickness	13 mm		12 mm	
Bottom plating stress verification	51%		45%	
Deck plating minimum thickness	8 mm		7 mm	
Deck plating stress verification	21%		23%	
Bottom stiff. dimension	70x70	70x70	70x70	70x70
Bottom minimum thickness	2 mm	2 mm	2 mm	2 mm
Stress verification	17%	12%	14%	2%
Deck stiff dimension	70x70	70x70	70x70	70x70
Deck minimum thickness	2 mm	2 mm	2 mm	2 mm
Stress verification	3%	12%	3%	10%

The main plating area, stiffener lengths, specific weight of sections are presented in the table 6.5. The weight units are metric tonnes.

6.3 Power requirement

The study focuses on the "steady behaviour of a planing vessel on a straight course" as described in Faltinsen [102]. This behaviour depends on the trim moment, vertical force and horizontal force. The boat studied is a planing vessel i.e. monohull in non displacement mode. This type of vessel is used for variety of applications, e.g. patrol boat, sport fishing, service craft, and recreational craft.

Table 6.5: Weight summary (tonnes)

	Dimension	Steel	Aluminium	Epoxy/Glass	PP/Glass
Bottom plating	125 m^2	17	5.95	6.37	4.38
Bottom long.	245 m	3.09	1.64	0.723	0.538
Bottom trans.	189 m	2.34	1.49	0.558	0.415
Deck plating	88 m^2	2.03	0.713	1.41	0.917
Deck long	175 m	1.01	0.539	0.516	0.384
Deck trans	132.5 m	0.759	0.436	0.389	0.290
Total		26.2	10.8	9.95	6.92

A vessel is considered as planing when the hydrodynamic load (lifting force) is greater than the buoyancy. Trim angle is also modified during the lift process. Mathematically, this would mean that the length froude number (equation 6.1) is greater than 1.2 (from Faltinsen [102]) In equation 6.1, U is the speed in knots, L is the submerged length in feet and g is the acceleration of gravity.

$$F_n = U/\sqrt{L.g} \tag{6.1}$$

Figure 6.1 details graphically the geometric parameter of a prismatic planing hull.

Faltinsen introduced [102] Savitsky's extensive experimental work which results in the calculation of the lift coefficients given is equation 6.2, 6.3 and 6.4 (β is the deadrise angle):

$$C_{L\beta} = C_{L0} - 0.0065\beta C_{L0}^{0.60} \tag{6.2}$$

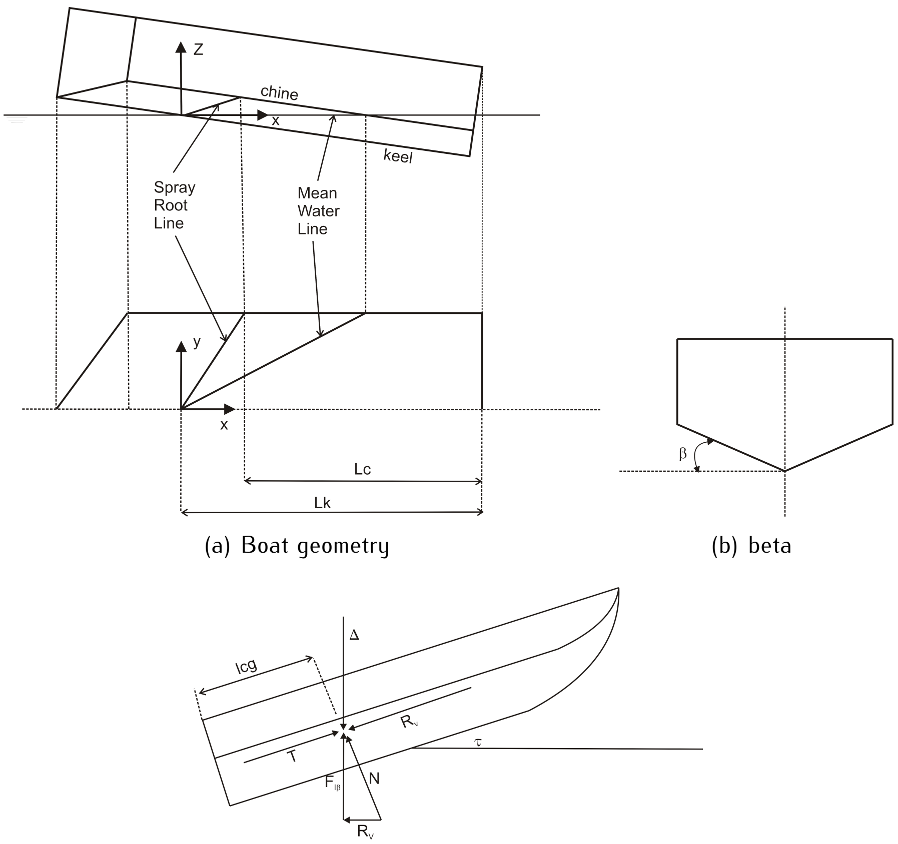
Where β is the angle of deadrise of planing surface in degrees, C_{L0} is the lift coefficient for zero deadrise angle ($\beta = 0$) and $C_{L\beta}$ is the lift coefficient.

$$C_{L\beta} = \frac{F_{L\beta}}{0.5\rho U^2 B^2} \tag{6.3}$$

Where B is the beam of planing surface, $F_{L\beta}$ is the lift force, ρ is the density of salted water (1026 kg/m^3) and $Fn_B = U/(gB)^{0.5}$ is the beam Foude number.

$$C_{L0} = \frac{F_{L0}}{0.5\rho U^2 B^2} = \tau_{deg}^{1.1}\left(0.012\lambda_W^{0.5} + 0.0055\lambda_W^{2.5}/Fn_B^2\right) \tag{6.4}$$

F_{L0} is the lift force for zero deadrise angle ($\beta = 0$), λ_W is the mean wetted length to beam ratio (valid when $\lambda_W \leq 4$) and τ_{deg} is trim angle of planing area in degrees (valid for $2 \leq \tau \leq 15$). The mean wetted length-to-beam ratio λ_W is equal to:



(a) Boat geometry (b) beta

(c) boatforce

Figure 6.1: Boat detail

$$\lambda_W = 0.5(L_K + L_C)/B \tag{6.5}$$

Where L_K is the keel wetted length and L_C is the chine wetted length. The resistance component R_P is then:

$$R_P = F_{L\beta}\tau \tag{6.6}$$

When τ is in radians. The centre of pressure respects the following equation.

$$\frac{l_p}{\lambda_W B} = 0.75 - \frac{1}{5.21 Fn_B^2/\lambda_W^2 + 2.39} \tag{6.7}$$

There are two cases for the determination of the resistance and then the power requirement calculation. The first case is the particular case when the force acts through the centre of gravity. The second case is the general case when there no assumptions on where the force acts. When the forces act through the centre of gravity, Faltinsen [102] detailed the calculation in 4 steps based on

Savitsky's formula.

1. The calculation of the average wetted length-to-beam ratio (λ)
2. The calculation of the trim angle
3. The calculation of the wetted length
4. The calculation of the effective horsepower

The calculation of the average wetted length-to-beam ratio (λ)

The centre of pressure is assumed to be at the position of the centre of gravity ($l_c = lcg$) as described above. The present study focuses on the structure of the boat and how the material affects the impact on the environment. In this case the position of the centre of gravity may change from one boat to another. The centre of pressure is chosen and it is assumed that there are enough features such as the engine and tanks whose position may vary to be able to make this assumption realistic.

$$\frac{lcg}{\lambda_W B} = 0.75 - \frac{1}{5.21 Fn_B^2/\lambda_W^2 + 2.39} \tag{6.8}$$

The numerical solution of λ can be found.

The calculation of the trim angle

Considering that the lifting force is balancing the weight of the boat, $C_{L\beta}$ can be obtained from equation 6.3.

$$C_{L\beta} = \frac{Mg}{0.5\rho U^2 B^2} \tag{6.9}$$

C_{L0} can be obtained by solving the equation 6.10

$$C_{L\beta} - \left(C_{L0} - 0.0065\beta C_{L0}^{0.6}\right) = 0 \tag{6.10}$$

And then the trim angle τ_{deg} can be obtained from equation 6.4

$$\tau_{deg} = \sqrt[1.1]{\frac{C_{L0}}{0.012\lambda_W^{0.5} + 0.005\lambda_W^{2.5}/Fn_B^2}} \tag{6.11}$$

The calculation of the wetted length

Lets define x_s as $L_C - L_K$. The figure 6.1 gives

$$x_s = \frac{2B\tan\beta}{2\tau\pi} \tag{6.12}$$

$$\lambda_W = 0.5(L_K + L_C)/B = 0.5(x_s + 2L_C)/B \tag{6.13}$$

Equation 6.12 provides L_C L_K and then the draft D of the keel at transom is:

$$D = L_K sin\tau \tag{6.14}$$

The calculation of the effective horse power

The figure 6.1 provides the details of the force on the boat. T is the thrust, N is the force due to hydrodynamic pressure on the hull, δ is the vessel weight and R_V is the viscous friction force on the hull. The viscous friction is given as:

$$R_V = 0.5\rho C_F S U^2 \tag{6.15}$$

With Reynolds number being equal to $R_n = UL_K/\nu$, ν being the kinematic viscosity coefficient and the S being the wetted surface C_F, the coefficient of friction. C_F for a smooth hull surface is

$$C_F = \frac{0.075}{(\lg R_n - 2)^2} \tag{6.16}$$

The surface S can be divided in the wetted area from x up to where the chine is wetted (S_1 in equation 6.18) and the rest toward the transom where the entire width of the boat is wetted (S_2 in equation 6.17). The latter surface is:

$$S_2 = \frac{B}{\cos\beta} L_C \tag{6.17}$$

At the front portion of the submerged surface (x $\geq$ 0 see fig. 6.1)the flow does not separate from the chine, hence creating a wetted zone due to the spray of water that is in addition to the submerged area. Faltinsen [102] introduced the dimensionless slamming parameter z_{max}/Vt where V is a vertical speed and t is the time (fig. 6.2). In the present case Vt is equal to $x\tau$, Faltinsen [102] cited that Zhao and Faltinsen who published on these parameters.

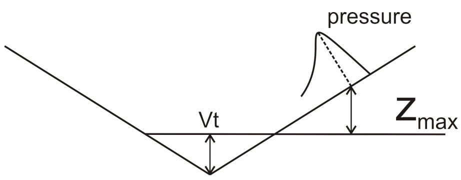


Figure 6.2: Slamming parameter

The vertical distance $d(x)$ from the top of the wetted area to the bottom of the keel is $Vt + z_{max} = (1 + \frac{z_{max}}{Vt})Vt$ is defined as a function of the slamming parameter. Vt at any x can be defined as $x\tau$, then S_1 can be defined as:

$$S_1 = 2\int_0^{x_s} \frac{d(x)}{\sin\beta}dx = \frac{1}{\sin\beta}\int_0^{x_s}(1 + \frac{z_{max}}{Vt})x\tau dx = \frac{\tau}{\sin\beta}(1 + \frac{z_{max}}{Vt})x_s^2 \tag{6.18}$$

At $x = x_s$ the entire width of the boat is wetted and following the same demonstration as before, x_s can be define as:

$$\frac{B}{2\tan\beta} = (1 + \frac{z_{max}}{Vt})x_s\tau \tag{6.19}$$

Then S_1:

$$S_1 = \frac{\tan^2\beta}{\sin\beta}\left(\frac{B^2}{4(1 + z_{max}/Vt)\tau}\right) \tag{6.20}$$

The effective power is then the product of $R_T = R_V + R_P$ the longitudinal drag with U being the boat speed. The longitudinal drag is the sum of frictional force (R_V) given by equation 6.15 and the lift induced force (R_P) given by equation 6.6. The efficiency of the engine can be defined by comparing the currently available boats to the specimen studied here.

In the present study, the boat is assumed to be 20 metres long and 5 metres wide with a deadrise angle of 25 °. The speed is 30 Knots. The mass of the boat is different for the four studied materials. The centre of gravity does not change from one boat to another. The engine is different for each material. Payload and crew requirements are assumed to be constant.

The effective power requirement and the engine selection is presented in the table 6.6. The engines selected are the lightest possible for a corrected displacement of the boat. The calculation is conducted according to Faltinsen [102] with a boat displacement of 20 tonnes. However table 6.5 showed that the weight for each candidate material is different. As discussed, the payload for each candidate material is constant at 10 tonnes. This will be formed from the weight of tanks, engines, cargo and passengers. This provides totals displacement for the four candidate materials as the sum of the structural weight from table 6.5 and the payload. The aluminium and epoxy/glass boats displace 20 tonnes, PP/glass 17 tonnes and steel 36 tonnes.

The effective power (P_E) is the power necessary to tow the ship hull but the power at the shaft end of the engines (P_S) must be higher than the effective power to overcome the loss e.g. in the transmission mechanism, at the propeller, etc. As seen in equation 6.21 , the ratio between the effective power and the shaft power is the propulsive efficiency (η_D) [103].

$$\eta_D = \frac{P_E}{P_S} \tag{6.21}$$

η_D can be defined by eq 6.22 as a product of hull efficiency (η_H), propeller efficiency (η_O) and relative rotative efficiency (η_R) and the shaft transmission efficiency (η_S) [83, 103].

$$\eta_D = \eta_H.\eta_O.\eta_R.\eta_S \tag{6.22}$$

Faltinsen [102] gives some efficiency values for the high speed boat i.e. η_R is generally between 1 and 1.2, η_H is generally between 1 and 1.1 and η_O is inferior to 0.8. Neuman considered that maximum propeller efficiency (η_O) are between 0.6 and 0.8 [104]. However in the example taken by Faltinsen [102] and used for the validation of the model presented in section 7.2.2 η_O is 0.699. η_S should be taken as to 0.98 for machinery aft as this is the position taken for the present boat specimens. [83]. In the present section η_R, η_H and η_O are respectively taken as equal to 1.05, 1.1 and 0.7 therefore η_D equals 0.8.

Table 6.6: Power

Material	Eff. power	shaft. power	Engine	Power	Consumption
Steel	735 HP	918 HP	Yanmar	2 x 480 HP	2 x 95L/hr
Aluminium	560 HP	700 HP	Yanmar	2 x 380 HP	2 x 70 L/hr
Epoxy/glass	560 HP	700 HP	Yanmar	2 x 380 HP	2 x 70 L/hr
PP/glass	539 HP	673 HP	Yanmar	2 x 380 HP	2 x 70 L/hr

6.4 Life scenario and impact assessment inventory

As for chapter 5 on the life cycle of a structural grillages, this section details the collation of the life scenario data for the manufacture of a boat with the design output from the structural definition section and for each candidate materials. The information used to provide this environmental assessment has been collected from a wide range of sources as discussed in chapter 4. The database can be found in appendix A. Each of the material are dealt with individually outlining the relevant data from the database to complete the impact assessment.

6.4.1 Steel

Table 6.7 and 6.8 show respectively the energy consumption of a primary steel boat and a recycled steel boat over their complete lives. For each material, the result of the LCA is presented in a table where the first column presents the most effective processes from a selection of processes (presented in appendix A) for the life described in section 4.3, i.e. system boundaries. The second column is the SEC of the processes. The values used, were obtained from the database in appendix A and the condition of use of these SEC figures is described in the comments associated with each table in part D of appendix A. The third column is the variable associated with the process e.g. length of weld, area of painted surface, etc. The fourth column i.e. the energy impact, is the result of variable times SEC divided by the number of years of use (assumed life of the boat is 20 years). The energy is given per functional unit which is a year of use. In other words, the third column is the yearly energy contribution of each process. It has to be noted that the paint system for steel lasts only 5 years while other systems last 1 year. The overall logic presented above is the same for the tables of results for each of the other candidate materials.

Table 6.7: Life cycle scenario and impact calculation of the steel boat components

Process name	SEC	Variable	Energy impact / year	Comment
	Material acquisition			
Material manufacture	22 MJ/m	26000 kg	29 GJ	Primary steel
	Grillage manufacturing			
Oxy cutting (plates)	0.25 MJ/m	105 m	13 MJ	
CO_2 welding (hull trans. stiff.)	4.7 MJ/m	189 m x 13 mm	44 MJ	
CO_2 welding (hull long. stiff.)	5.5 MJ/m	245 m x 14 mm	67 MJ	
CO_2 welding (deck trans. stiff.)	6.0 MJ/m	132.5 m x 15.5 mm	40 MJ	
CO_2 welding (deck trans. stiff.)	6.0 MJ/m	175 m x 15.5 mm	53 MJ	
CO_2 welding (hull plating)	3.3 MJ/m	62 m x 9 mm	10 MJ	
CO_2 welding (deck plating)	0.7 MJ/m	43 m x 3 mm	1.5 MJ	
	In service			
10% material renewal	22 MJ/kg	2600 kg	2.9 GJ	The material is assumed to be recycled
Paint underwater	38 $MJ/m^2/5yr$	125/2 m^2	480 MJ	Half the hull is under water
Paint above water	25 $MJ/m^2/5yr$	125/2 m^2	310 MJ	Half the hull is above water
Paint subject to wear	10 $MJ/m^2/5yr$	88 * 2 + 125 m^2	150 MJ	The inside of the hull and both side of the deck are painted
Fuel consumption	40 MJ/l	500h/yr, 190l/h	3800 GJ	
	End of life			
Dismantling	0.25 MJ/m	846 m	11 MJ	Oxycutting of the weld joint
Recycling	-13 MJ/kg	26000 kg	17 GJ	
Primary steel			3.8 TJ	with fuel
Primary steel			33 GJ	without fuel

Table 6.8: Life cycle scenario and impact calculation of the recycled steel boat components

Process name	SEC	Variable	Energy impact / year	Comment
	Material acquisition			
Material manufacture	8.6 MJ/kg	26000 kg	11 GJ	Primary steel
	Grillage manufacturing			
Oxy cutting (plates)	0.25 MJ/m	105 m	13 MJ	
CO_2 welding (hull trans. stiff.)	4.7 MJ/m	189 m x 13 mm	44 MJ	
CO_2 welding (hull long. stiff.)	5.5 MJ/m	245 m x 14 mm	67 MJ	
CO_2 welding (deck trans. stiff.)	6.0 MJ/m	132.5 m x 15.5 mm	40 MJ	
CO_2 welding (deck trans. stiff.)	6.0 MJ/m	175 m x 15.5 mm	53 MJ	
CO_2 welding (hull plating)	3.3 MJ/m	62 m x 9 mm	10 MJ	
CO_2 welding (deck plating)	0.7 MJ/m	43 m x 3 mm	1.5 MJ	
	In service			
10% material renewal	8.6 MJ/kg	2600 kg	1.1 GJ	The material is assumed to be recycled
Paint underwater	38 $MJ/m^2/5yr$	125/2 m^2	480 MJ	Half the hull is under water
Paint above water	25 $MJ/m^2/5yr$	125/2 m^2	310 MJ	Half the hull is above water
Paint subject to wear	10 $MJ/m^2/5yr$	88 * 2 + 125 m^2	150 MJ	The inside of the hull and both side of the deck are painted
Fuel consumption	40 MJ/l	500h/yr, 190l/h	3800 GJ	
	End of life			
Dismantling	0.25 MJ/m	846 m	11 MJ	Oxycutting of the weld joint
Recycled steel			3.8 TJ	with fuel
Recycled steel			14 GJ	without fuel

The largest energy consuming process is the in service fuel consumption. It is so high that any other process energy consumption is negligible in comparison. The second largest energy consuming process is the material manufacture, this value is high but much lower than the fuel consumption and the accuracy of the collected data and the limitation of the result to two significant figures makes the material manufacture invisible in the final result if fuel is included. The other processes energy consumption is 2 to 3 orders of magnitude lower than the material manufacture. Similar to the steel grillage study, a large amount of energy can be saved with the use of recycled the material. The previous chapter introduces that good practices in waste management such as recycling does not necessarily appear in the figures of energy based LCA. It is especially true when energy savings are low. For instance, the recycling of GRTP demonstrates this problem because it is good practice but has a large energy consumption. In chapter 5 it was concluded that the functions of end of life process lack equivalence, e.g. landfilling, recycling, incineration plus energy recovery, show that some figures are difficult to compare because they focus on different actions. In the present case the waste management aspects of the recycling or incineration does not appear significant due to the level of fuel consumption and the fact that little energy is involved in the end of life treatment for a specific function, the associated energy is invisible to the LCA reader.

The result of the LCA on the boat is extremely difficult to interpret and use. It is reasonable to consider that energy is one of the most important parameters in an environmental assessment study. The environmental impact is proportional to the energy consumption. However, some environmental impact, such as those solely due to chemical exposure are not included in the energy parameter. The comparison between SEC and ecoindicator (a compounded impact parameter from a commercially available database) shows that the two impact figures of material are in the same range keeping in mind the uncertainties on energy which has been raised in the appendix A. Table 6.9 shows the comparison between material manufacture SEC and ecoindicators, which is made by non dimensionalising the ecoindicator and SEC data using the values obtained from primary steel.

Table 6.9: Ecoindicator 99 impact value

Material	Ecoindicator (in millipoint)	Non dimensional Ecoindicator	Energy value (Gj)	Non dimensional energy
Primary steel	94	1	22	1
Recycled steel	24	3.9	210	2.5
Primary aluminium	780	0.12	0.12	0.1
Recycled aluminium	60	23	1.56	0.95
Glass	58	-	-	-
Platic (average value)	390-630	-	-	-
interpolation to GRTS	225-345	0.41-0.31	70	0.31

From the results from the steel structure it is apparent that in order to draw comparison between the energies for all the materials fuel consumption must be neglected. Here, recycled and primary steel have the same fuel consumption. The fuel consumption does not influence the selection of a material as it is the same for both candidates, the fuel consumption can be ignored for this partial comparison. The LCA therefore suggests that recycled steel has a lower embodied energy, as one would expect.

The grillage study (chapter 5) showed that the design pressure has little impact on the weight of the structure because of the minimum thickness requirements (see figure 5.9). A small weight decrease may however decrease the fuel consumption but any fuel consumption is more likely to be influenced by operational decisions rather than design change in the way steel is implemented (see figure 5.7). A decrease in operation time of one percent per year shows a bigger impact decrease than recycling the material or not. Society traditionally deals with the end of life of a product, landfilling, incineration and recycling and still faces the problem of disposal of the boat scrap. Therefore society is probably more interested in having a more environmentally friendly and energy efficient method of disposing of the boat. There is a divergence in concern between customer, society and the boat builder and the LCA based energy does not show much sensitivity with regards to these stakeholders.

6.4.2 Aluminium

Table 6.10 and 6.11 show respectively the energy consumption of a primary aluminium boat and a recycled aluminum boat over their complete lives. The topology of the table follows the same principle as table 6.7. The calculation of energy follows the same methodology. The data used to create the results in table 6.10 is obtained from appendix A.

Table 6.10: Life cycle scenario and impact calculation of the aluminium boat components

Process name	SEC	Variable	Energy impact /year	Comment
	Material acquisition			
Material manufacture	220 MJ/kg	10000 kg	110 GJ	
	Grillage manufacturing			
Waterjet hull cutting	62 m x 9 mm	66 kJ/m	4 MJ	
Waterjet deck cutting	43 m x 3 mm	15 KJ/m	650 kJ	
FSW (hull and deck)	105 m	1.2 MJ/m	6.3 MJ	
FSW (hull long stiffener)	245 m x 10 mm	1.2 MJ/m	15 MJ	
FSW (hull trans stiffener)	189 m x 10 mm	1.2 MJ/m	11 MJ	
FSW (deck long stiffener)	175 m x 7 mm	1.2 MJ/m	11 MJ	
FSW (deck trans stiffener)	132 m x 7 mm	1.2 MJ/m	7.9 MJ	
	In service			
10% material renewal	220 MJ/kg	1000 kg	1.1 GJ	The material is assumed to be recycled
Paint underwater	28 $MJ/m^2/yr$	125/2 m^2	1.8 GJ	Half the hull is under water
Paint above water	15 $MJ/m^2/yr$	125/2 m^2	940 MJ	Half the hull is above water
Paint subject to wear	10 $MJ/m^2/yr$	88 * 2 + 125 m^2	3 GJ	The inside of the hull and both side of the deck are painted
Fuel consumption	40 MJ/l	500h/yr, 140l/h	2800 GJ	
	End of life			
Dismantling (plasma cutting)	860 kJ/m	803 m x 7-9 mm	690 MJ	Plasma cutting of the weld joint
Dismantling (plasma cutting)	200 kJ/m	43 m x 3 mm	8.6 MJ	Plasma cutting of the weld joint
Primary al.			2.8 TJ	with fuel
Primary al.			130 GJ	without fuel

Table 6.11: Life cycle scenario and impact calculation of the recycycled aluminium boat components

Process name	SEC	Variable	Energy impact /year	Comment
	Material acquisition			
Material manufacture	20 MJ/kg	10000 kg	10 GJ	
	Grillage manufacturing			
Waterjet hull cutting	62 m x 9 mm	66 kJ/m	4 MJ	
Waterjet deck cutting	43 m x 3 mm	15 KJ/m	650 kJ	
FSW (hull and deck)	105 m	1.2 MJ/m	6.3 MJ	
FSW (hull long stiffener)	245 m x 10 mm	1.2 MJ/m	15 MJ	
FSW (hull trans stiffener)	189 m x 10 mm	1.2 MJ/m	11 MJ	
FSW (deck long stiffener)	175 m x 7 mm	1.2 MJ/m	11 MJ	
FSW (deck trans stiffener)	132 m x 7 mm	1.2 MJ/m	7.9 MJ	
	In service			
10% material renewal	20 MJ/kg	1000 kg	1000 MJ	The material is assumed to be recycled
Paint underwater	28 MJ/m^2/yr	125/2 m^2	1.8 GJ	Half the hull is under water
Paint above water	15 MJ/m^2/yr	125/2 m^2	940 MJ	Half the hull is above water
Paint subject to wear	10 MJ/m^2/yr	88 * 2 + 125 m^2	3 GJ	The inside of the hull and both side of the deck are painted
Fuel consumption	40 MJ/l	500h/yr, 140l/h	2800 GJ	
	End of life			
Dismantling (plasma cutting)	860 kJ/m	803 m x 7-9 mm	690 MJ	Plasma cutting of the weld joint
Dismantling (plasma cutting)	200 kJ/m	43 m x 3 mm	8.6 MJ	Plasma cutting of the weld joint
Recycled al.			2.8 TJ	with fuel
Recycled al.			18 GJ	without fuel

From the design point of view the implementation of LR rules and regulations results in an increase in the weight of aluminium structure. The aluminium grillage weight is 36% of the steel grillage (chapter 5) whereas the aluminium boat component weight is 42% of the steel boat weight. The main difference between the steel and aluminium LCA conduction is the selection of commercially available profile in the boat study. However the impact of this selection is supposed to be negligible as commercial profiles would be chosen to be as close as possible to the calculated dimension. The difference is due to the difference in the design methods.

Similar to the recycled steel structure, which shows a lower energy consumption, the recycled aluminium structure shows a much lower energy consumption than its primary alternative when fuel consumption is excluded. Again with fuel consumption being included the impact of the material is completely masked by the impact of the fuel. The aluminium structure's low weight is beneficial to the fuel consumption which is much lower than for the steel boat. The fuel consumption is however so high that the energy requirement for the manufacture of primary aluminium is negligible i.e. the recycling of aluminium does not show any significant energy gain. No extra investment can be expected for the manufacturer to use recycled aluminium, if aluminium is chosen over steel, because the energy saved by this decision is about 1.4 TJ per year, much more than the energy required to recycle steel or aluminium.

Similar to the grillage, manufacturing processes for the structure consume relatively little energy whereas the plasma cutting during the dismantling shows a significantly higher energy intensity. The thickness of the paint is thinner than for steel and it has to be renewed on a yearly basis. The relative contribution of paint to the overall boat is however lower than for the grillage because for the same thickness of paint the thickness of the boat plating is much larger.

The aluminium structure study shows that the design method influences the relative energy consumption of one material from another. LR-SSC boat design (chapter 6) and the first principles based grillage design (chapter 5) give two different relative weights and therefore different embodied energies. The difference in design requirements and associated results demonstrate that design with a material cannot be based only on specific stiffness, specific strength, stiffness to SEC and strength to SEC ratios. The design method should be included in the material decision making process, and the present research aims to assess how design influences the LCA results. This comparison between steel and aluminium and the 4 grillages start to validate the assumption of the modified LCA framework (figure 4.1) that several designs should be used in order to evaluate the potential environmental impact and select the best material candidate. However the SEC of fuel, the material manufacture, boat manufacture and paint cover three order of magnitude in SEC, i.e. the manufacture SEC is a thousand times less than of the fuel SEC. The LCA result is insensitive to design variation as fuel makes it comparatively negligible.

6.4.3 GRTS

Table 6.12 shows the energy consumption of a GRTS boat over its life. The topology of the table follows the same principle as table 6.7. The calculation of energy follows the same methodology. The data used to create the results is obtained from appendix A.

Table 6.12: Life cycle scenario et impact calculation of the GRTS boat components

Process name	SEC	Variable	Energy impact / year	Comment
		Material acquisition		
GRTS raw material manufacture	70 MJ/kg	10000 kg	35 GJ	
		Grillage manufacturing		
Mould	51 MJ/m^2	213 m^2	540 MJ	5 mm thick mould ??
Steel backing structure	10 MJ/m^2	213 m^2	110 MJ	
Vacuum bag	7 MJ/m^2	213 m^2	75 MJ	
Curing	430 MJ/m^2	213 m^2	4.6 GJ	
		In service		
10% material renewal	70 MJ/kg	1000 kg	3.5 GJ	The material is assumed to be recycled
Paint underwater	28 MJ/m^2/yr	125/2 m^2	1.8 GJ	Half the hull is under water
Paint above water	15 MJ/m^2/yr	125/2 m^2	940 MJ	Half the hull is above water
Paint subject to wear	10 MJ/m^2/yr	88 * 2 + 125 m^2	3 GJ	The inside of the hull and both side of the deck are painted
Fuel consumption	40 MJ/l	500h/yr, 140l/h	2800 GJ	
		End of life		
Shredding	0.92 MJ/m	10000 m	11 MJ	
Incineration	-30 MJ/kg of resin	5000 kg	- 7.5 GJ	
Incinerated GRTS			2.8 TJ	with fuel
Incinerated GRTS			44 GJ	without fuel
Non inc. GRTS			2.8 TJ	with fuel
Non inc. GRTS			51 GJ	without fuel

As with steel and aluminium the life cycle energy including fuel consumption is extremely high in comparison with material manufacture. The main difference between the boat studied in this chapter and the grillage from chapter 6 is that the aluminium boat weight and the GRTS boat weight are similar. As a result the fuel consumption of GRTS and aluminium boats are equal because the engine selection is the same, the calculated effective power is the same. The GRTP alternative have the same installed power than aluminium and GRTS. However the calculated effective power is smaller and therefore the fuel consumption should be smaller. Considering the large difference in range of order between fuel consumption and material SEC figures it is expected that the small decrease in fuel consumption of GRTP would result in a dramatic decrease in environmental impact making it difficult to compare GRTP with aluminum and GRTS. The GRTS and aluminium both perform better than steel from an energy consumption perspective and should be preferentially selected to lower the impact of a boat. The fuel consumption is not significant for both comparison between the GRTS and aluminium because it is same.

GRTS takes advantage of its low density and its medium material manufacture SEC to be more energy efficient than primary aluminium. However the relatively small decrease in energy when GRTS is incinerated, makes the recycled aluminium more energy efficient than any GRTS structure.

For a large boat such as that considered in the present research, a production volume of 10 boats may be viewed as large, but it is the assumption taken for the grillage in chapter 6 and the same assumption is kept in for the boat. The mould thickness remains 5 mm such as proposed by Vetrotex for the vacuum bagging of TWINTEX [99] even if it may appear too thin to a industrial application. The amount of steel for the backing structure is the same as that of the grillage. The energy contribution of the mould stiffening is ignored because it is low. The top hat stiffeners of the boat are very small and the mould structure is not loaded during the curing apart from the weight of the composite system. The shredding of the boat and the hull contributes to about 1% of the total energy when the fuel consumption is ignored.

6.4.4 GRTP

Table 6.13 shows the energy consumption of a GRTP boat over its life. The topology of the table follows the same principle as table 6.7. The calculation of energy follows the same methodology. The data used to create the results is obtained from appendix A.

Table 6.13: Life cycle scenario et impact calculation of the GRTP boat components

Process name	SEC	Variable	Energy impact / year	Comment
		Material acquisition		
GRTP raw material manufacture	60 MJ/kg	6900 kg	21 GJ	
		Grillage manufacturing		
Mould	51 MJ/m^2	213 m^2	540 MJ	5 mm thick mould ??
Steel backing structure	10 MJ/m^2	213 m^2	110 MJ	
Vacuum bag	7 MJ/m^2	213 m^2	75 MJ	
Curing	430 MJ/m^2	213 m^2	4.6 GJ	
Welding	1500 m	0.125 MJ/m	9 MJ	Ignoring mesh material
		In service		
10% material renewal	60 MJ/kg	690 kg	2 GJ	The material is assumed to be recycled
Paint underwater	28 MJ/m^2/yr	125/2 m^2	1.8 GJ	Half the hull is under water
Paint above water	15 MJ/m^2/yr	125/2 m^2	940 MJ	Half the hull is above water
Paint subject to wear	10 MJ/m^2/yr	88 * 2 + 125 m^2	3 GJ	The inside of the hull and both side of the deck are painted
Fuel consumption	40 MJ/l	500h/yr, 140l/h	2800 GJ	
		End of life		
Shredding	0.92 MJ/m	6900 kg	320 MJ	
Reprocessed	59 MJ/kg	6900 kg	20 GJ	
Incineration	-30 MJ/kg of resin	2800 kg	-4.2 GJ	
Inc. GRTP			2.8 TJ	with fuel
Non inc. GRTP			2.8 TJ	with fuel
Reproc. GRTP			2.8 TJ	with fuel
Inc. GRTP			30 GJ	without fuel
Non inc. GRTP			34 GJ	without fuel
Reproc. GRTP			50 GJ	without fuel

The in service fuel consumption for the GRTP structure is also very high, in the same order of magnitude as the three other candidate materials. GRTP is expected to have the lowest life cycle energy of the four candidate materials when fuel consumption is included because the calculated effective power is smaller than for the other materials and therefore the figure presented in table 6.13 are overestimated. Therefore GRTP could be considered as the best material alternative. However the structural definition of the hull and the deck is based on LR-SSC where the material properties of the material depend only on the fibre content in weight. The fibre content parameter is very high in the case of PP/glass structural grade composites because the PP has a very low density in comparison with the unsaturated polyester and epoxy. LR-SSC rules are based on the latter two resins. The weight of the structure as seen in this section, may appear extremely optimistic. Indeed, the aluminium and epoxy/glass boats have a similar weight but chapter 5 showed the GRTP grillage weight is also lighter than both the aluminium and GRTS grillages.

The comments on the manufacture of GRTS apply to GRTP. Indeed these energy impacts are related to surface parameters and not to weight. The mould, vacuum bag and curing of GRTP are a function of the surface unit and not laminate weight, as in the case of steel and aluminium (see appendix A). The only difference is that it is possible to weld the stiffener to the deck and the hull in the GRTP boat. The GRTP welding energy is low. The incineration recovered energy of GRTP is lower than for GRTS due to the lower weight of the structure and higher fibre weight content. The possible treatment of the boat into a valuable recyclate requires a lot of energy as seen in the grillage study. In chapter 5, the energy requirement to process GRTP grillage scraps into a finished product is the responsibility of the manufacturer and requires a lot of energy. In the case of boat structures, the life cycle energy is negligible in comparison with the energy saved through fuel saving from a possible migration from GRTS or aluminium to PP/glass.

6.5 Critical analysis

The fuel consumption is by far the largest contribution to the impact. It is directly influence by the weight of the boats and therefore it would be expected that GRTP would be the best material. The result can be compared to Xun et al. [21] and Song et al. [22] researches. Their paper already gave a reference to compare manufacturing figure in the previous chapter. In the present chapter their publications can give a reference for the in service figure. Indeed both publications include in service aspects. Xu et al. [21] claims that lighter structures are beneficial to the impact during use. However the authors mostly focus on comparing weight and mechanical properties. Song et al. [22] highlight more clearly that composite material creates large amount of energy saving in use compared to steel for transportation application. The authors compared two structures, a truck application with a 190,000 km life time and a bus application with a 3,200,000 km life time. The bus application shows the largest difference between composites and steel or aluminium because energy saving occurs over a longer life time. The longer is the distance, the larger is the savings. Comparatively the energy decrease for manufacturing is the same for the bus and the truck because it is independent from life use choice.

For the bus application, manufacturing the studied structure with composite requires 15.3GJ less than with steel. In service the saving of composites needs 461GJ less energy, 30 times higher than for manufacturing. In the present research, the difference in yearly fuel consumption is 1000GJ. Recycled steel requires 16GJ less than composites. The energy saving in service of composites in service is therefore 60 times higher than the energy saving from manufacturing with steel. This figure is larger than the figure presented by Song et al. [22] . It is however the same range of order. It makes the figure of the present research acceptable. It should be kept in mind that the weight decrease for the bus application is 400kg on the overall weight of the bus (probably less than 10%) whereas composites save between 16 to 20 tonnes on the structures (45 to 55%).

Aluminium and epoxy/glass structures, calculated with the LR-SSC rules have a very similar structural weight and hence the same fuel consumption. The two material can be compared ignoring the fuel cosumption contribution because it is equal for the two material. Recycled aluminium can have significantly lower environmental impact (low energy consumption). In addition the recycling of a large and thick aluminium structure is very attractive because thick structures show relatively low oxide contamination (only a thin film on the surface) and create less waste. Recycled aluminium embodied energy is lower than composite embodied energy but it is not the case for primary aluminium. It could be expected that as the recycling industry for composite materials matures, the efficiency of the process will increase reducing the energy required. The results show clearly the importance of recycling and dismantling of the boat structure in order to reduce the embodied energy of the boat with respect to embodied energy. The involvement of the manufacturer in recycling and dismantling plays a great role in having low life cycle energy results because it decides how to dispose the boat with respect to embodied energy.

With direct calculation, the epoxy/glass structure would be lighter than aluminium (chapter 5) and require less energy to be manufactured and less energy to be propelled. However, the LR-SSC rules use large safety factors for the design of composite structures. This safety precaution is most evident in the difference between the composite grillage thickness studied in chapter 5 and the laminate thickness of the boat studied in chapter 5. Encouraging Lloyd's Register to accept laminate thickness based on direct calculation derived from first principles would benefit Epoxy/glass. This structure would have a lower weight that would benefit by decreasing its fuel consumption and material manufacture energy consumption. The high mechanical properties of PP/glass based on the LR-SSC rules using fibre weight fraction would disappear and the weight of this structure would increase. Its fuel consumption will increase as well as its material requirements.

The comparison between materials on the basis of their impact on the environment was difficult because the embodied energy of fuel consumption hides the contribution of the material to the final result. However in the particular case of aluminium and epoxy/glass boats, it was possible to have a discussion on only the material's environmental benefit, the reason being that the fuel consumption was constant. Chapter 6 focused on a design method where the main dimensions (beam, length, etc.) of the boat were fixed design inputs. In the present research the LCA focused on the material with an environmental insight. However the main impact was fuel consumption, and the material variable influenced the LCA result not because of any environmental properties gathered in appendix A but due to the weight to stiffness ratio of the four candidate materials. Any variation of the embodied energy due to material induced process is associated with an even greater variation of the fuel consumption, masking the former. The variation of the fuel consumption must be avoided by constraining fuel consumption in the design. In this case it is not possible to fix the main dimensions and the power requirements because the weight of the structure changes due to the material stiffness to weight ratio. Design and decisions within design must be a compromise. One way of assessing the influence of material choice and eliminating the contribution of the fuel consumption on embodied energy is to supply a single installed power and required speed. The design would compromise on space variability as length and breadth would become variable.

This chapter is a clear addition to the incremental development of the modified LCA framework. It introduces two new design approaches, one for boat design and one for calculating boat power requirement. The present chapter demonstrated that the modified LCA framework is robust enough to give results even with more complex design approaches. The grillage study showed that each material can give an answer to a simple problem in a reasonable range of order in term of weight, structural capability and environmental performance. The change in design from Chapter 5 to 6 shows that the comparative material requirement for each material varied. The detailed geometry is different and the thicknesses are larger than for the grillage study. The grillage study could have been misleading in the case of material selection for boat structure. In the case of aluminium and GRTS, recycled aluminium is more energy efficient in the grillage study but the two materials are equal for the boat study. Real boat designs are indeed more likely to tend towards the LR-SSC rules than the grillage approach. The approach is clearly incremental because the efforts shift from a LCA intensive work which focused on energy information inventory (Chapter 5) towards a work focusing more on the design activities (Chapter 6). The results are more convincing because there are closer to a possible application. In chapter7, the impact inventory and system boundaries were changed and in service environmental impacts are added. The incremental approach can be further developed in the next chapter. The output used for the next chapter is that that both scantling and power requirement depends on the geometry. The knowledge on impact is completed and the efforts are on the design optimisation with new geometry considerations.

Chapter 7

Modified LCA framework: LCA boat design synthesis

Chapter 7 details the development stage and critical analysis of the design algorithm of a boat synthesis. It is the last and most extensive design algorithm proposed to be studied within the methodology of the present research (see figure 4.1). It extends the goal and scope of chapter 5 i.e. grillage study and chapter 6 i.e. fixed topology boat study. Chapter 5 demonstrated the relevance of life cycle study for material selection but lacked in service information such as fuel consumption. Chapter 6 continued the demonstration by adding the influence of fuel consumption. It highlighted the overshadowing effect of fuel consumption over material induced impact. The present chapter aims to articulate the modelling approach around a fuel consumption constraint i.e where fuel consumption is constant across all boat designs. It shows a general structural / LCA interaction for a part of a design domain.

7.1 Motivation

The material selection result of the grillage and the boat with fixed topology highlighted contradictory results. The main difference between the two previous studies is the change in the structural principles used for the grillage and the boat. The concept of work principles is explained in section 3.1.2.

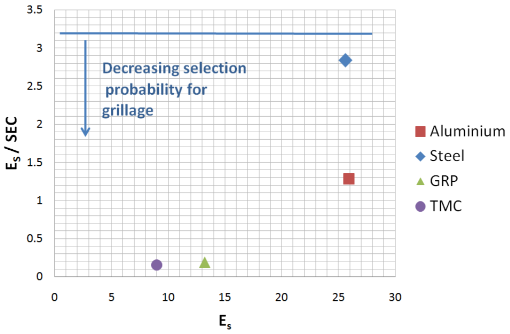
Table 7.1 shows the properties of the four candidate materials. The first part of the table mentions their general properties and the second part describes the same properties normalised to density and specific energy consumption for manufacturing. These two set of properties are thought to be of major importance in differentiating the working principle of the two previous algorithms. This is discussed in this section. The normalised properties are represented on graph 7.1 and 7.3. These two graphs are an attempt to adapt the Ashby material selection [58] to the present context.

	Steel	Aluminium	GRTS	GRTP[100]
E(GPa)	200	70	26.4	13.4
σ (MPa)	235	240	375	276
η (kg/m^3)	7800	2700	2000	1485
SEC (MJ/kg)	9	20	70	60
E_s (MNm/kg)	25.6	25.9	13.2	9
σ_s (kNm/kg)	30.1	89	187	186
E_s/SEC (MNm/MJ)	2.84	1.28	0.189	0.15
σ_s/SEC (kNm/MJ)	3.34	4.45	2.67	3.1

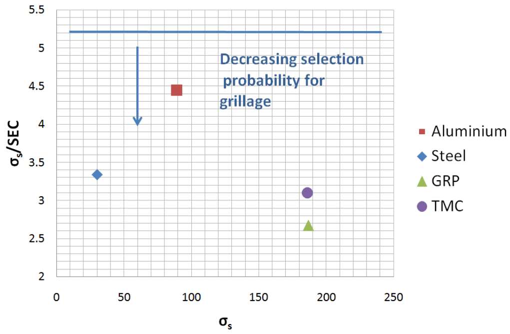
Table 7.1: Material properties

On the one hand, the grillage study demonstrated that recycled aluminium followed by recycled steel are the materials most likely to be selected when focusing on the environmental impact of the grillage. On the other hand, the boat studied with a fixed topology showed that GRTP is the material most likely to be selected. In the grillage study design context, the selecting parameter would be the ratio of specific mechanical properties to specific environmental impact. Figure 7.1 shows clearly that recycled aluminium, the material most likely to be selected, is at the top of the graph of σ_s vs σ_s/SEC, and the composite materials at the bottom. The material with the best specific strength to SEC ratio has the smallest life cycle energy consumption which increases with descending σ_s/SEC. It must be mentioned that the graph comparing E_s with E_s/SEC shows the metal alternative most likely to be selected and composites the least likely to be selected, but the ranking between materials is different than for the graph E_s / E_s/SEC. It would have been expected that this stiffness graph would be more useful to select a material since the limiting design factor of the grillage is the maximum deflection. It is therefore surprising to find that the strength parameters are more influential for material selection.

The environmental impact would be measured as the specific energy consumption as defined in the LCA framework in figure 4.1. The steel has a very low SEC but its specific properties are impaired by its high density. Recycled aluminium shows good performance on both specific stiffness, specific strength and SEC. Composite materials have a high specific strength but a very high SEC therefore a low σ_S/SEC.



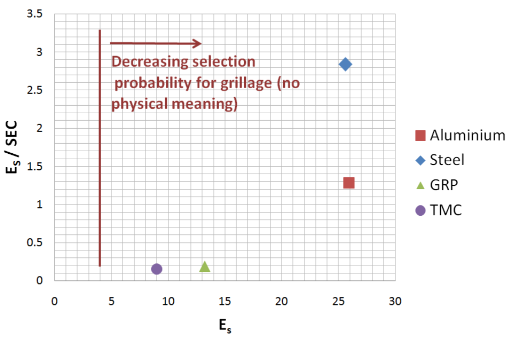
(a) E_s vs E_s / SEC



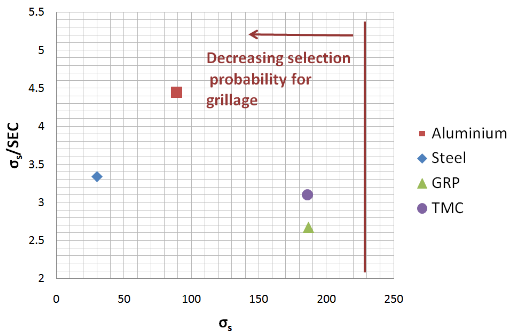
(b) σ_s vs σ_s / SEC

Figure 7.1: Material selection criteria for the grillage

Chapter 6 shows that GRTP is the best alternative for the presented application. Figure 7.3 (b) shows that specific strength is the most decisive criteria. Figure 7.3 (a) cannot be used as a criteria because it lacks physical meaning. There is no reason why a decrease young modulus would be beneficial to impact. Conversely, it is common sense that higher specific strength materials would result in lighter structure. The chapters 6 showed that lighter structures have smaller impacts because of smaller in-service energy consumption. The SECs is not decisive because they relates to manufacturing only. The contribution of manufacturing is two range of order smaller than the in-service contribution i.e. fuel consumption.



(a) E_s vs E_s / SEC



(b) σ_s vs σ_s / SEC

Figure 7.2: Material selection criteria for the boat with fixed topology

It is clear therefore that the design approach influences the mechanism of material selection and that the two designs have two different working principles.

The specific research question for this chapter is therefore to develop a *design context* in which the selection is based on a compromise between SEC and specific mechanical properties for a given fuel consumption.

The research questions are :

- What is the design domain in which the approach is valid?
- What is the material selection paradigm?
- What is the contribution of the design approach to life cycle?

The approach is based on the following assumptions :

- It is possible to define the geometry from Faltinsen's model starting from the fuel consumption or installed power.
- It is assumed that the fuel consumption difference, required to reach the same speed, for boat of different weight, is ignored. The in-service energy consumption is defined as the fuel consumption of a boat at full speed in straight line.
- The boat is designed with the same payload, speed, installed power and service restrictions are compared for the purpose of material assessment.
- The manufactufacturing processes assumed for chapter 5 and 6 are used in the boat synthesis.
- Only the material manufacture figures are used in the present chapter as it has been demonstrated that boat manufacture processes are negligeable. Fuel consumption is ignored as it is equal for each candidate material.

Finally, it is expected that the selection process will be based on a compromise between the strict specific properties and environmental properties. Figure 7.3 shows an example of a possible solution strategy. The line represents an objective function which takes into account SEC and specific mechanical properties. It follows the same principle displayed in figure 3.1 (d) where the objective function taking into account take into account weight and cost. All materials, whose properties fall along the line, are equally desirable. In this case not only a variation of one parameter such as σ_s and σ_s/SEC give equivalent solution but a variation of both specific mechanical properties and the ratio of specific mechanical properties to strength.

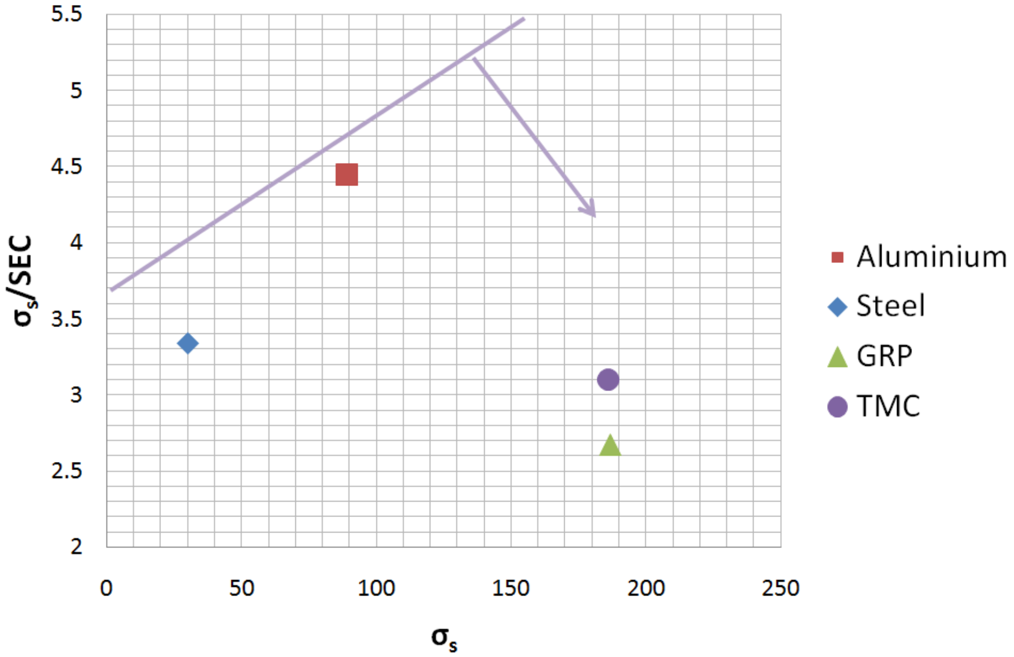


Figure 7.3: Example of possible selection strategy with a boat synthesis design context

7.2 Methodology

7.2.1 Outline

A model for the analysis of a systematic boat design was developed in order to assess the influence of material on the life cycle environmental impact of boats. The **objective** of the design model is to minimize the environmental impact of the boat structure for each material at different points of a relevant design domain. The domain is defined at different stages of the analysis. The main design **constraint** is the fuel consumption limitation. In terms of design input it means that the installed power is fixed. In section 6.3, Faltinsen's model [102] took geometry information as an input and returned this power. In the present chapter, the model is adapted to power as an input parameter and returns the geometry of the boat as an output. An application was developped in C# .NET and compiled on a PC using Microsoft Visual Studio 2008 (professional edition). The advantage of this language is that it is object oriented. Each of the following work packages is encapsulated in different sets of classes (or objects) which allow the code to be easy to maintain. Indeed each modification only affects one class and not the rest of the program. Each point was therefore developed independently. The advanced debugging capability of Visual Studio was of great help in analysis the intermediate calculation step. At last the .NET library includes classes allowing the application to export the results into Microsoft excel documents.

Figure 7.4 shows the design algorithm for the present study. The model is divided into module in which the design tasks are grouped coherently in order to make sure that each module can be studied and validated before proceeding to the next module. The modules are:

Power module: this module is articulated around the power calculation model of Faltinsen [102] but used in an alternative way. The aim of this module is to define a large and dense design area in which it is possible to conduct a systematic boat design study.

Geometry module: this module aims at creating a realistic and detailed geometry from which it is possible to assess the draft of the boat and also plating surface and stiffener length.

Design pressure calculation and scantling module: This module focuses on the use of LR-SSC rules. It defines the design pressure and scantling along the full surface of the boat for the hull and the deck.

Other feature module: this module aims at defining the position of the engine and bulkheads as well as the scantlings of the bulkheads, flooring and superstructures. The specification of the bulkheads, the flooring and the superstructure are derived from the surrounding structure by ensuring continuity from previously designed hull and deck structure.

Specification module: this module aims at calculating the weight of the boat and the surface plating. The selection of commercially available beam sections is conducted in this module. The selection is based on the geometric properties of the stiffener which are calculated in the design pressure and scantling module. The boat is divided into four sections for which the thickness of plating is equal.

Information inventory: This module aims at defining the interaction between permanent data such as commercial profile dimension and scantling.

Loop module: This module ensures that the estimated weight input in the model and the calculated weight returned at the end of the specification module are equal.

Energy module: This module returns the embodied energy of the structure.

GA module: This module deals with the minimization of the embodied energy of the entire boat structure. A sensitivity analysis is presented in appendix C

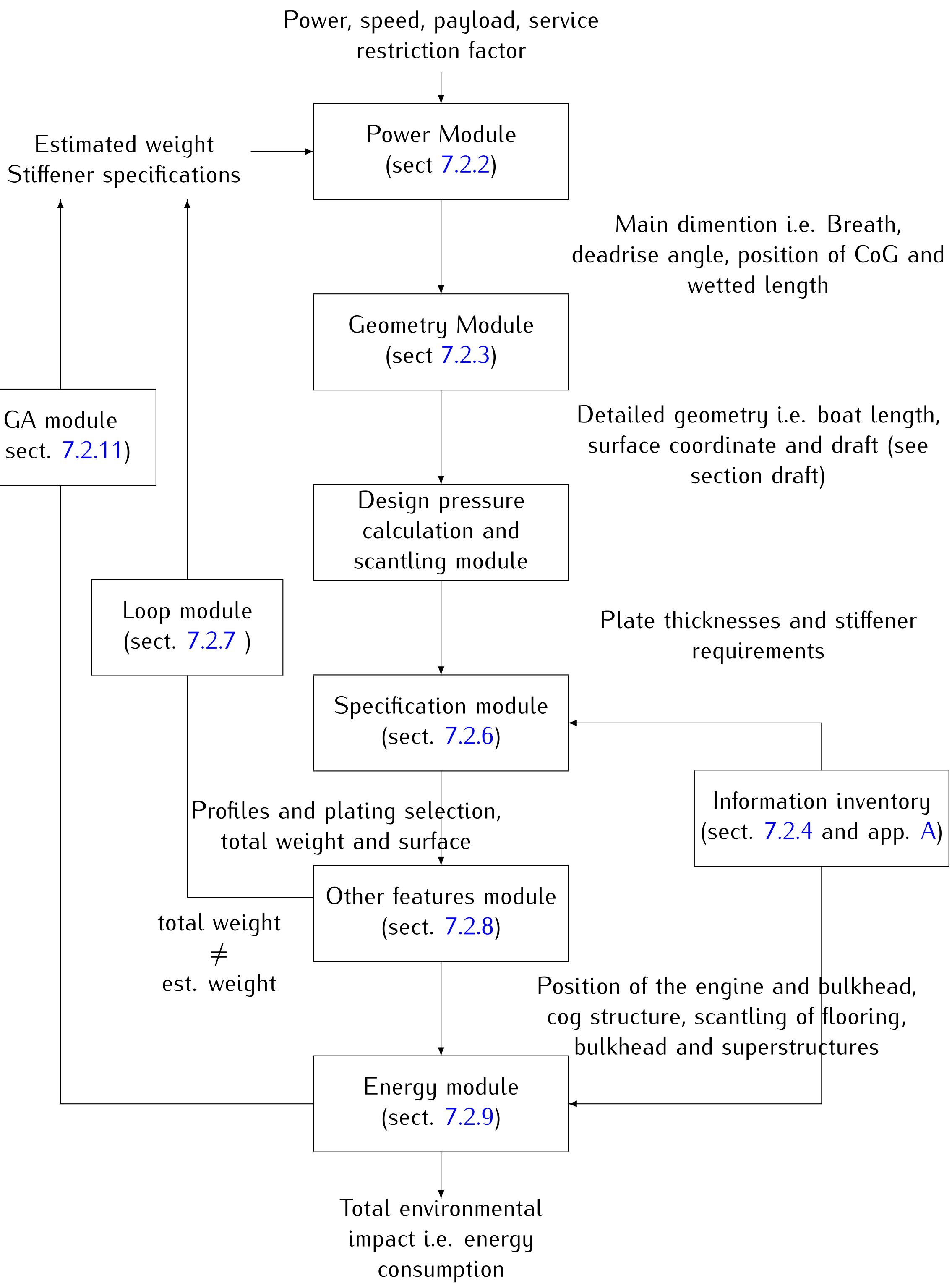


Figure 7.4: Boat synthesis analysis methodology

7.2.2 Module *Power*: Main dimension

The *power module* is based on the equations of chapter 6. It follows the same four step resolution from Faltinsen [102]. The model aims to define the beam, position of the centre of gravity and the deadrise angle from the input power, speed and displacement of the boat design requirement.

The best {beam (B), centre of gravity position (CoG), desadrise angle (β) } parameter set was searched in the entire domain defined in table 7.2. Chapter 6 showed an approach where the 5 inputs {B, CoG, β, speed (U), displacement (M) } resulted in a power (P). In the present case only three parameters are input { M, U, P } in order to get as output set {B, CoG, β } therefore a selection criteria must be used to find the optimum set and this is the minimum bottom impact pressure. The calculation method is given by Lloyds Register (see equation B.2.8).

Table 7.2: Powering module search domain

Parameter	Min	Max	Step	Comments
		OUTPUT PARAMETERS		
B (m)	3.5	6	0.5	
β (^{o})	5	40	1	
CoG	a = 1.5	a = 4	0.1	CoG = a * B
		VALIDATION PARAMETERS		
P(kW)	800	5600	200	
U (kn)	20	40	5	
M (t)	30	100	1	

The approach was validated in 2 ways:

- The program ability to provide result over the full search domain (domain described in table 7.2).
- The reproducibility of Faltinsen's case study within the present research model. Figure 7.5 shows how the two models are used.

The first validation made use of the case study of Faltinsen. The module calculates the power for a full set of parameter {B, CoG, β, U, M } such as the approach explained in chapter 6 and the selection of the best alternatives output set {B, CoG, β } for given input set { M, U, P }. There are three tests for the selection:

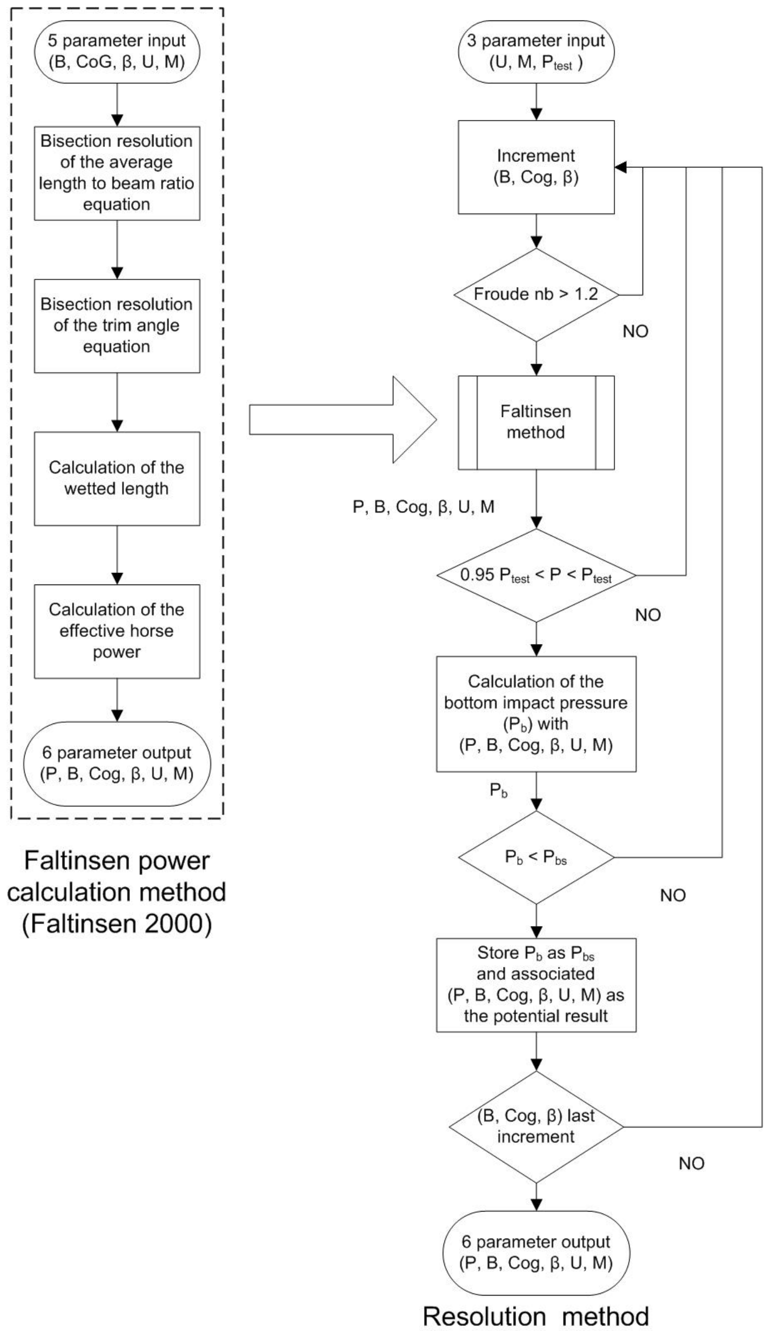


Figure 7.5: Comparison between Faltinsen method and the current method

- A Froude number larger than 1.2 ($Fn = U/\sqrt{g * L_k}$ with L_k the wetted length). It must be mentioned that in this equation the speed is in knots and length in feet.
- A power between 0.95 and 1 times the power of the input set.
- A minimum bottom impact pressure.

The program main methods or functions are:

- The calculation of the wetted length to beam ratio. It solves numerically equation (6.5) using a bisection search algorithm. The function was graphically assessed in order to check its continuity and monotony. Figure 7.6 shows the result. The specific case study of Faltinsen [102] is on the curves.

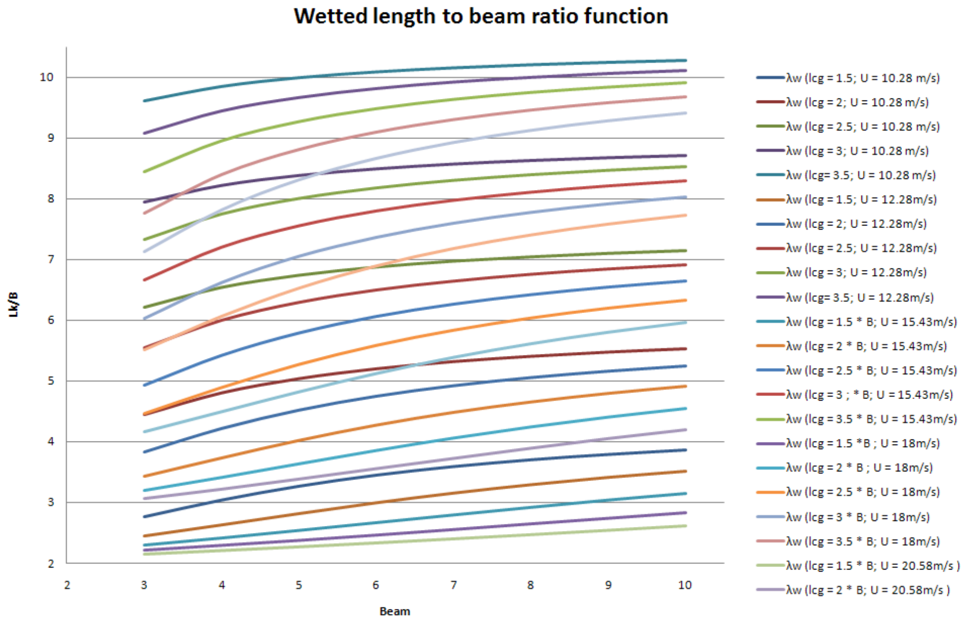


Figure 7.6: Wetted length to beam ratio function study

- The calculation of the trim angle. It solves numerically equation 6.6 and 6.7 using a bisection search algorithm. A graphical validation was conducted in order to assess if a solution can be found for each case over the search domain. Figure 7.7 shows the result. It must be mentioned that there has been a slight difference between the book trim angle result and the calculated trim angle result.

- The power calculation method gives the same output power as the case study of Faltinsen [102].

- The selection of a particular set of parameters {B, CoG, β} is validated by looking at the full search domain using the three tests described above. Table 7.3 shows the output of the validation process. The boat sample from Faltinsen [102], which can reasonably be thought as a realistic design, is close to the result of the current model. The difference between the two results is due to the algorithm used in this calculation (Figure 7.5), that uses the minimum bottom impact pressure as a selection method. Chapter 6 showed that the bottom impact pressure was the maximum design pressure which played a major role in the calculation of the

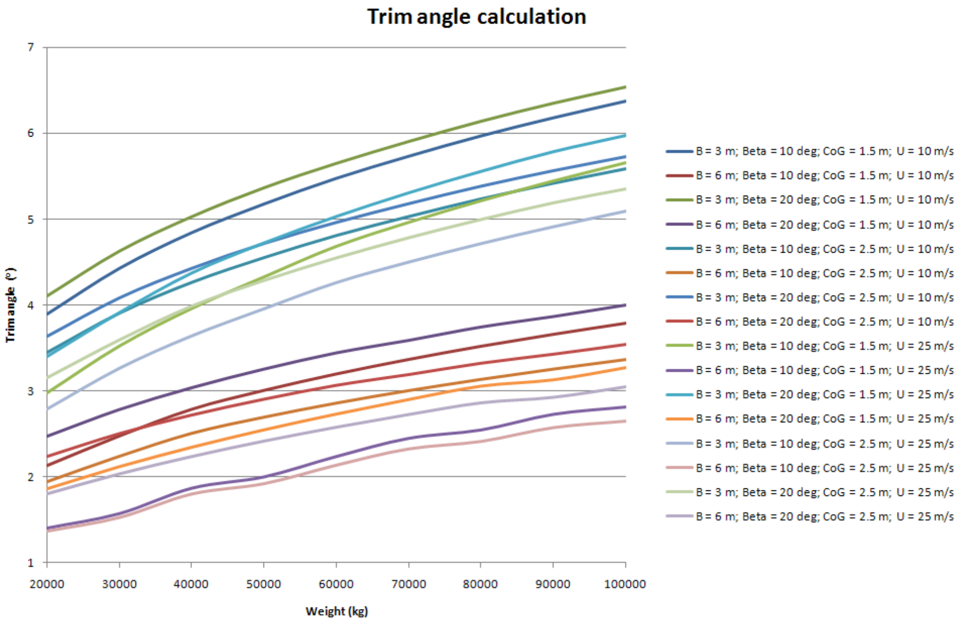


Figure 7.7: Trim angle study

scantling. Lowering this value results in a lighter structure requiring less raw material. It is assumed that the case study is representative of a real boat where limiting the weight of the structure is important. The result is encouraging and demonstrates the validity of the method and the result with the miminum bottom impact pressure criteria provides a realistic set of values.

Table 7.3: Comparison between model and developed model

	Faltinsen result	Present model
U (knots)	40	40
M (t)	27	27
B (m)	4.3	*4*
CoG (m)	8.9	*11.2*
$/beta$ (o)	10	*8*
P (kW)	840	840

The calculation gives an output only for a part of the search domain. Figure 7.8 indicates the solution for the power / speed domain. The figure represents the ratio between the number of weights for which a [beam, deadrise angle, position of the centre of gravity] set can be found. The graphed output is 1 when a solution exists for the full weight domain and 0 when there is none. The graph shows that there is no solution for the smaller speed and power on the left hand side of the graph (blue). The right hand side shows that there the model provide a solution for all hull weights. At the centre of the graph a band shows a transition where solutions are possible only for part of the domain. It is noted that while the power increases more speed is required to have solution over the full domain.

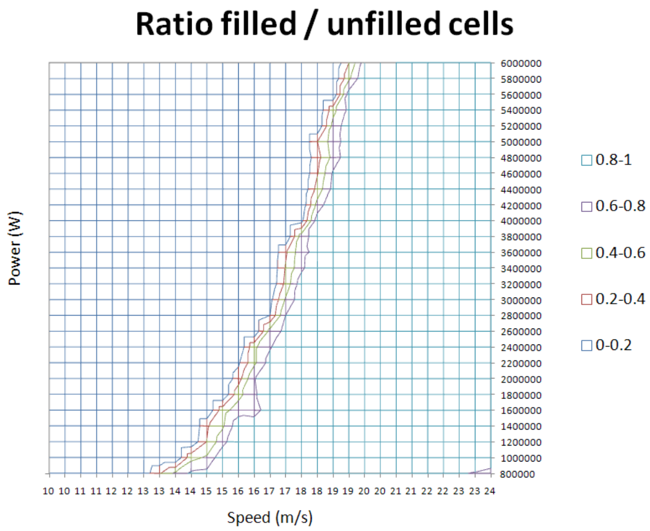


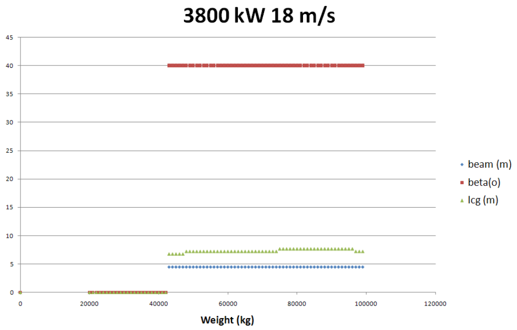
Figure 7.8: Study of the solution existence

Detailed graphs were automatically produced for each set of [P, W, U] giving non zero answers. Figure 7.9 highlights the three types of behaviours found in the validation process. The study of these graphs show three types of behaviours whose understanding is used in the following sections to highlight the most relevant domain for the study of the modified LCA. The three behaviours are:

- Large variation on the full domain such as for 2000 kW and 23 m/s conditions. It appears as normal with regard to the extreme weight variation

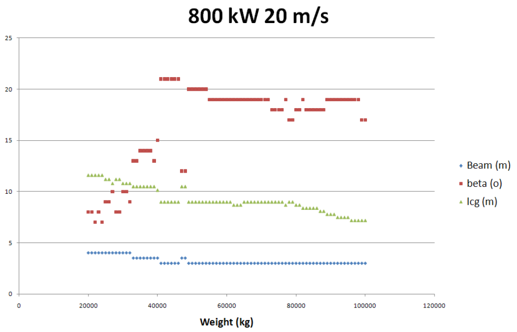
- Little variation such as for the 5000 kW and 22 m/s conditions. In this case this behaviour appears less natural with regard to the weight. In addition the 3800 kW and 18 m/s conditions return solutions only for part of the domain (highest weight). It can be seen that this set of parameters is on the transition band described in Figure 7.8 whereas all the other graphs would be on the right hand side of the graph.

- A intermediary case for the 800 kW and 20 m/s

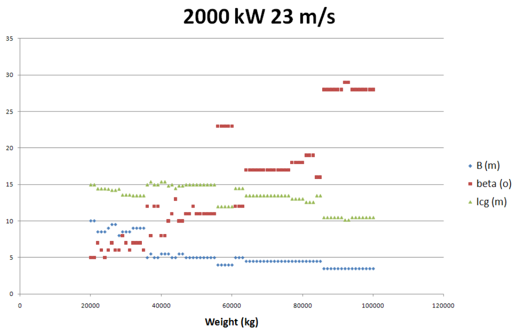


(a) Transition area

(b) Little variability



(c) Partial variability

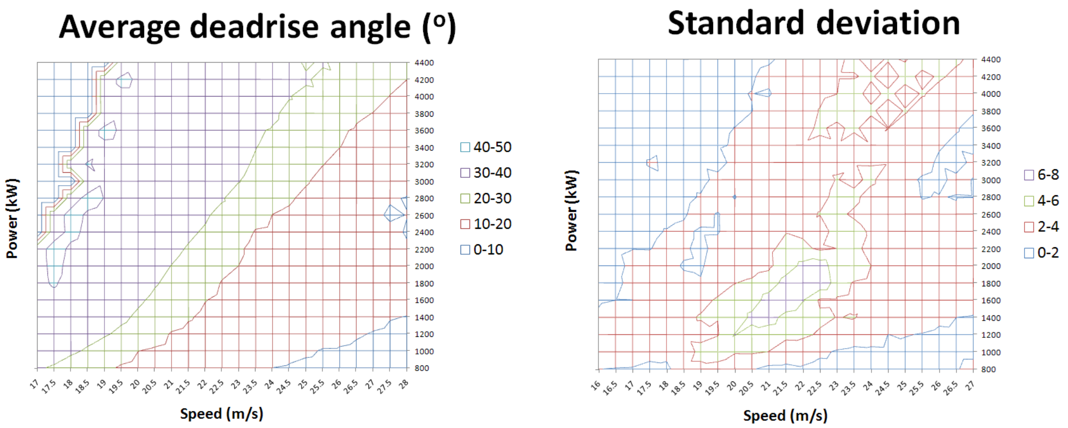


(d) Large variability

Figure 7.9: Beam, deadrise angle and centre of gravity position with several behaviours

In Figure 7.10 (a) and (b) shows a study of the deadrise angle mean and variation as a function of power, speed and boat weight. This study aims to characterize the domain for which the present module is valid. In figure 7.10 (a) the surface graph indicates the average deadrise angle for the entire weight domain as a function of speed and power. It has been shown in figure 7.8 that when the deadrise angle reaches 40^o, the variation of $\{B, CoG, \beta\}$ is very small for any large variation of the speed, the power and the weight of the boat. The planning behaviour of the boat can be questioned even though the Froude number is higher than 1.2 as fixed in the selection test. The bottom right corner of figure 7.10 (a) shows β values small to medium which means that the module can be applied. Figure 7.8 showed that for this space domain a solution can be found for any weight. The behaviour expected in this area is depicted in figure 7.9 (d) as it shows a medium β average. However for low power and high speed, the β average is very small for the full weight domain. These high speed and low power solutions appear as unrealistic as the solutions of high power and low speed, but for these latter case the average deadrise angle test discriminates them. Therefore a new approach is needed to discriminate the solution for low power and high speed.

A second approach is presented figure 7.10 (b). It shows the standard deviation of the deadrise angle. This test is selected because figure 7.9(c) and (d) showed that smaller deadrise angle shows large variations whereas larger weight shows smaller variation with increasing weight. High standard deviation solutions are in green and purple in the graph and conversely average deadrise angle, solutions at lower power and high speed are excluded.



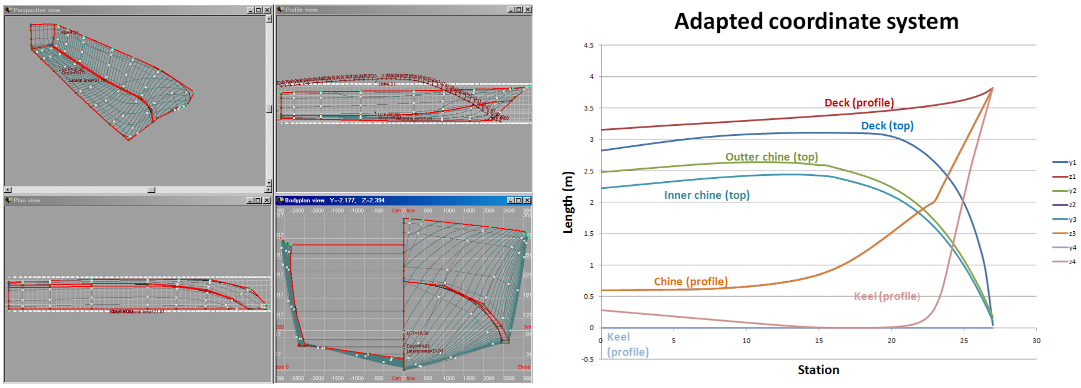
(a) Average deadrise angle (b) Standard deviation

Figure 7.10: Example of grillage in a boat

In the approach taken by Faltinsen [102], his demonstration fourth step indicates that the power derives directly from the wetted surface. The drag increases with the wetted surface and for a given beam and wetted length, the wetted surface increases with the deadrise angle. The direct perception of these assertions seem to be in contradiction with figure 7.9 where higher speeds show extreme deadrise angles without any apparent continuous relationship. The explanation lies in the fact that the dynamic lift cannot be created at such speeds and the geometry adapts itself to a low lift geometry with a high deadrise angle geometry, thereby increasing the drag of the boat. It must be added that the wetted area is even larger at zero speed than in motion and the chines, which aim to detach the water flow from the hull in the normal planning mode, may not be suitable. In consequence, the study of high angles may appear irrelevant because it may reveal a speed not reachable for a low lift geometry especially because a lower speed / high lift geometry shows the best results.

7.2.3 Module *Geometry*: Main dimension and geometry

The objective of the geometry is to describe a full design using the three parameters {B, CoG, β} selected from the first module. This step is necessary to obtain additional parameters for the scantling of the boat. These parameters are the length at the waterline, and the draft.



(a) Freeship geometry (b) Adapted geometry

Figure 7.11: Ship coordinate for the 'Freeship' software (a) and adapted model (b)

Figure 7.11 shows the starting point of the geometry on (a) and the model adapted (b) to the need of the present research. (a) shows a geometry example from the editor corporate website of the 'Freeship' software. It can be downloaded as a freeware with limited features in comparison with the fully licensed version. The community of users upload examples of geometries on the website and the editor states it can be used as a base for new design. The boat studied in this chapter is a 27m patrol boat whose detailed geometry is taken from the Freeship website. Figure 7.11 (b) is the modified version where the chines go up to the very end of the keel instead of reaching the keel midway between the waterline and the top of the keel. It allows one to keep the same profile type along the entire boat whereas the front of the original boat can only be described as a triangle. Table 7.4 shows the transformation used to adapt the geometry of the boat sample to the beam and deadrise angle constraints from the power module. The result is a new boat with a suitable beam and deadrise angle to be powered by the installed power from the powering module.

The coordinates of the boat are modified in order to be proportional with the beam and deadrise angle figure, calculated in the power module. The simple indices are for the new boat and the indices with 's' are for the boat sample. Figure 7.4 gives two examples of the new boat coordinates and the change is most noticeable in the rise of the chine (Z_3).

Table 7.4: Transformation equations

	Transformation equation	comment
$Y_{1,i}$	$Y_{s1,i} * \frac{B/2}{Y_{s3,15}}$	The beams of the beam are taken as directly proportional to the calculated beam B. The sample max inner chine beam is at station 15 of 54 and taken equal to the calculated beam. The coordinate is half the beam
$Z_{1,i}$	$\frac{Z_{s1,i}}{Y_{s3,i}} * Y_{3,i}$	The ratio Z1 / Y3 is assumed constant from the sample to the new boat.
$Y_{2,i}$	$Y_{s2,i} * \frac{B/2}{Y_{s3,15}}$	See $Y_{1,i}$.
$Z_{2,i}$	$Z_{3,i}$	The chines are at the same height. See $Z_{3,i}$.
$Y_{3,i}$	$Y_{s2,i} * \frac{B/2}{Y_{s3,15}}$	See $Y_{1,i}$.
$Z_{3,i}$	$\beta_{26-,i} = \left(\frac{1}{2} + \frac{i}{52}\right) * \beta_{s,i}$ $\beta_{s,54} = \frac{\beta_{s,i}+\beta_{26+,i}}{\beta_{s,54}-\beta_{s,26}} * \beta_{s,54}$ $Z_{4,i} + Y_{3,i} * tan\beta_{26\pm,i}$	The 26 station β equals to the calculated β. Toward aft β linearly decrease to the half. Toward bow β it rises from the calculated β to the sample 54^{th} station angle proportionally to the raise of the sample.
$Y_{4,i}$	0	On the longitudinal symmetry axis.
$Z_{4,i}$	$\frac{Z_{s4,i}}{Z_{s1,i}} * Z_{1,i}$	The ratio Z_4/Z_1 is assumed constant from the sample to the new boat.

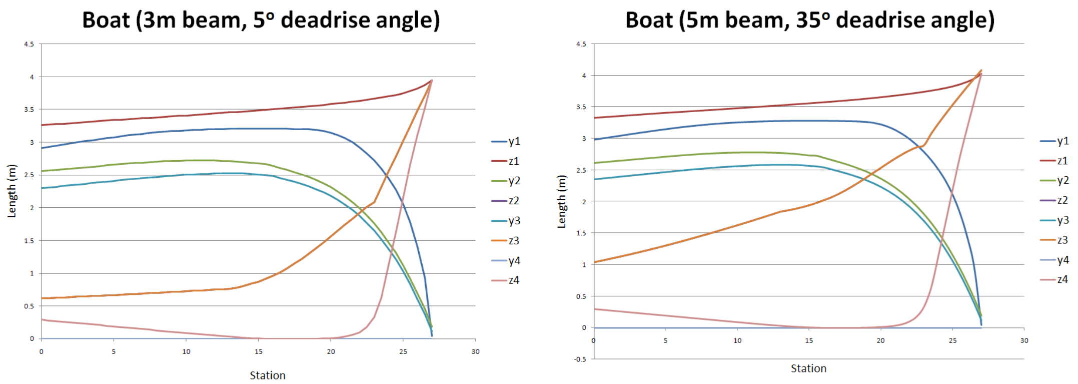


Figure 7.12: Examples from the geometry module

The calculation of the draft is an essential step for the definition of the boat. However several approaches were tested to get a suitable method.

7.2.3.1 *Method 1*

As seen in chapter 6, the waterline length (LWL) is required for the scantling of the boat. The waterline length depends on the cross section of the boat at each section, the displacement of the boat and at which station the keel line reaches surface. In the example taken from the 'Freeship' software, the first 23.5 meters are below water which is the 47^{th} station in the present model. In other words the keel line (Z_4 in figure 7.11) reaches the surface at the 47^{th} station or the z coordinate of station 47 is the draft of the boat. It ensures that the same relative amount of surface area is below the water. The volume below waterline can be calculated as a function of LWL which equals to the displacement. The calculation indicated that an LWL value can be found for the domain where the power module returns medium β values. Figure 7.12 shows the results for boats with 3m and 5m beam.

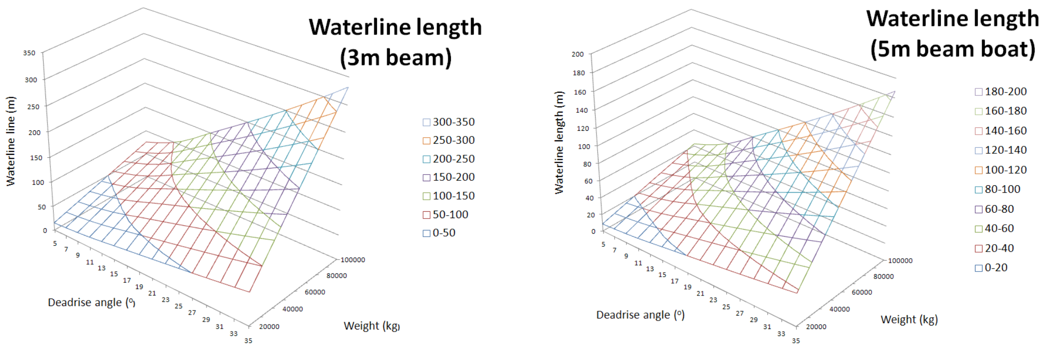


Figure 7.13: Waterline length study

Figure 7.13 shows a large number of extreme values either much too short or much too long to be reasonably accepted. In order to sort the acceptable value from the unacceptable, the calculated waterline length is compared with the wetted length of the powering module. Table 7.5 and table 7.6 show the result for a 40 tonne and 70 tonne hull displacement. In table 7.5, the grey cells have the calculated length in a range close to the wetted length.

Table 7.5: Ratio waterline length to wetted length for a 40 t boat

	1000 kW	1500 kW	2000 kW	2500 kW	3000 kW	3500 kW	4000 kW	4500 kW	5000 kW
13.0 m/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14.0 m/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15.0 m/s	37.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16.0 m/s	17.7	32.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17.0 m/s	11.2	20.2	31.1	0.0	0.0	0.0	0.0	0.0	0.0
18.0 m/s	7.0	11.8	13.0	17.0	35.9	0.0	0.0	0.0	0.0
19.0 m/s	2.7	10.0	13.4	14.0	14.0	23.1	56.6	0.0	0.0
20.0 m/s	3.4	2.2	12.2	15.7	9.7	9.6	12.9	16.1	29.3
21.0 m/s	1.2	2.4	12.5	14.2	8.0	9.4	8.1	9.1	10.3
22.0 m/s	2.2	1.2	1.7	14.5	15.6	8.9	12.7	5.9	6.6

Table 7.6: Ratio waterline length to wetted length for a 70 t boat

	1000 kW	1500 kW	2000 kW	2500 kW	3000 kW	3500 kW	4000 kW	4500 kW	5000 kW
13.0 m/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14.0 m/s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15.0 m/s	0.0	84.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16.0 m/s	37.1	36.5	87.2	0.0	0.0	0.0	0.0	0.0	0.0
17.0 m/s	21.1	27.3	33.2	55.2	0.0	0.0	0.0	0.0	0.0
18.0 m/s	12.4	21.0	17.1	25.4	30.0	46.7	0.0	0.0	0.0
19.0 m/s	14.9	10.8	23.5	16.6	21.6	19.9	28.4	36.6	206.9
20.0 m/s	12.9	5.7	7.5	23.9	13.5	17.0	16.4	15.7	22.1
21.0 m/s	10.9	8.7	6.0	24.6	26.4	14.9	16.5	11.9	13.3
22.0 m/s	8.9	3.5	6.0	4.4	25.0	13.5	15.7	17.3	10.4

Figure 7.13 and tables 7.5 and 7.6 show that it is not practical to use a constant index station to calculate the draft of the boats. This is because of the very large variety of boat designs which result from the approach taken to calculate the power. Boat designs, that are unrealistic, are taken into account in the present study because the material selection is the focus of the research. The behaviour of the model for each tested material is of prime interest, in comparison with the boat. Very often these boats have a small beam and a relatively shallow draft resulting in the length to increase. In addition to having a length at zero speed much larger than the wetted length at cruise speed, the centre of gravity position would be impossible to maintain at the level calculated with the sole addition of tanks, engine and other features. It is necessary for these extreme designs to be feasable that there is an increase in the draft of the boat.

7.2.3.2 *Method 2*

The second approach considers that the draft is equal to either the z coordinate of the keel at station 47, 48 or half way between these two stations. It is decided to choose the station with the highest keel coordinate. As a result the draft tends to increase over the full search domain and the length of the boat decreases for the same wetted length. It should be noted that the wetted length does not depend on the geometry but only on the power calculation. The criteria for the selection of the station number takes into account the centre of gravity position. The model requires that LWL is at least twice the distance from the stern to the centre of gravity. Tables 7.7 and 7.8 show the ratio of waterline length/wetted length. The positive effect of this approach is that it corrects the excessive distortion between the waterline length and wetted length illustrated in figure 7.5 and 7.6 by an increase of gray cells in comparison with figures 7.5 and 7.6. These two parameters are in the same range. However, abnormal situations where the wetted length (cruise speed length) is longer than the waterline length (zero speed length) are in red in figures 7.7 and 7.8. It is due to a very small LCG value.

Table 7.7: Ratio waterline length to wetted length for a 40 t boat (LCG constrained)

	1000 kW	1500 kW	2000 kW	2500 kW	3000 kW	3500 kW	4000 kW	4500 kW	5000 kW
13.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15.0 m/s	2.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16.0 m/s	1.92	2.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17.0 m/s	0.96	1.28	1.35	1.29	0.00	0.00	0.00	0.00	0.00
18.0 m/s	0.91	1.79	1.88	1.45	1.18	0.99	0.00	0.00	0.00
19.0 m/s	0.78	0.86	1.56	0.94	1.28	1.03	0.86	0.82	0.00
20.0 m/s	1.25	0.81	0.87	1.57	1.65	1.25	0.96	0.85	0.72
21.0 m/s	1.17	1.05	1.00	1.19	1.10	1.54	1.27	0.77	0.79
22.0 m/s	1.13	0.79	0.66	0.80	1.64	1.46	1.56	1.29	0.71

Table 7.8: Ratio waterline length to wetted length for a 70 t boat (lcg constrained)

	1000 kW	1500 kW	2000 kW	2500 kW	3000 kW	3500 kW	4000 kW	4500 kW	5000 kW
13.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16.0 m/s	2.80	3.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00
17.0 m/s	3.18	0.00	3.18	2.22	0.00	0.00	0.00	0.00	0.00
18.0 m/s	2.81	1.88	2.75	2.40	2.31	1.56	0.00	0.00	0.00
19.0 m/s	2.83	1.95	1.24	2.77	2.25	1.66	1.70	1.38	1.26
20.0 m/s	2.18	2.25	1.31	0.96	1.60	2.29	1.60	1.50	1.41
21.0 m/s	2.68	2.47	1.25	0.99	0.76	2.22	2.34	2.04	1.27
22.0 m/s	2.54	0.99	1.49	0.81	0.77	0.94	2.64	2.37	2.07

7.2.3.3 *Method 3*

The waterline length is constrained further in order to ensuredthat the LWL / Lk is greater than one, whenever it is possible. It follows the same principle as in method 2 but if LWL /Lk < 1 then the draft is reduced and LWL increases. Table 7.9 and 7.11 show relatively few values below one. By default the value of the draft is below the height of the keel at station 47 regardless of any constraints on the position of the centre of gravity or the ratio LWL / Lk.

Table 7.9: Ratio waterline length to wetted length for a 40 t boat (LCG and LWL/Lk constrained)

	1000 kW	1500 kW	2000 kW	2500 kW	3000 kW	3500 kW	4000 kW	4500 kW	5000 kW
13.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15.0 m/s	2.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16.0 m/s	1.92	2.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17.0 m/s	1.45	1.28	1.35	1.29	0.00	0.00	0.00	0.00	0.00
18.0 m/s	1.46	1.79	1.88	1.45	1.18	1.44	0.00	0.00	0.00
19.0 m/s	0.78	1.18	1.56	1.40	1.28	1.03	1.26	1.19	0.00
20.0 m/s	1.25	1.15	0.87	1.57	1.65	1.25	1.39	1.23	1.04
21.0 m/s	1.17	1.05	1.00	1.19	1.10	1.54	1.27	1.12	1.15
22.0 m/s	1.13	0.79	0.66	0.80	1.64	1.46	1.56	1.29	1.04

Table 7.10: Ratio waterline length to wetted length for a 70 t boat (LCG and LWL/Lk constrained)

	1000 kW	1500 kW	2000 kW	2500 kW	3000 kW	3500 kW	4000 kW	4500 kW	5000 kW
13.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15.0 m/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16.0 m/s	2.80	3.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00
17.0 m/s	3.18	0.00	3.18	2.22	0.00	0.00	0.00	0.00	0.00
18.0 m/s	2.81	1.88	2.75	2.40	2.31	1.56	0.00	0.00	0.00
19.0 m/s	2.83	1.95	1.24	2.77	2.25	1.66	1.70	1.38	1.26
20.0 m/s	2.18	2.25	1.31	1.41	1.60	2.29	1.60	1.50	1.41
21.0 m/s	2.68	2.47	1.25	1.49	1.14	2.22	2.34	2.04	1.27
22.0 m/s	2.54	1.85	1.49	1.30	1.17	1.26	2.64	2.37	2.07

7.2.3.4 *Method 4*

This method comes in correction to an adverse effect of method 3 and it is shown in section 7.2.7. It was demonstrated in section 7.2.7 that the design weight loop was an extremely unstable process since there was a big difference between very close designs, the draft would jump from the height of the keel at station 47 to station 48 or the virtual station 47.5. The need for a more continuous draft calculation in order to loop the design on itself for a smooth convergence to a weight output was clear. In this case any draft, providing it is between station 46 and 48, could be accepted. The possible draft was extended to station 46 because it allows more boat solutions to be accepted in the model than the more restrictive draft interval. The constraint system must be different because the selection of the draft is not being done between 3 possible drafts but infinity. The new constant constrain is that LWL is equal to 1.05 Lk. In this case the focus is to decrease the difference between planning and non planning wetted surface. It is mentioned that the LCG constrains is irrelevant in this case because there is no more distortion between LWL and LCG as LWL is now close to Lk. Lk and LCG are calculated in the same module and follow the same model. Therefore the two values are better related. Table 7.11 shows the new result for the 40 tonne boat where the ratio of LWL to Lk is constant as it is fixed in the current draft calculation method. For simplification reasons, LWL is calculated as station 47 as the keel reaches the surface between station 46 and 48. It is assumed acceptable because the volume contribution between sections near the intersection of the keel line and the surface is much smaller and therefore negligible in comparison with the volume contribution at the centre of the boat where beam and draft are maximum.

Table 7.11: Ratio waterline length to wetted length for a 70 t boat (LCG constrained)

	1000 kW	1500 kW	2000 kW	2500 kW	3000 kW	3500 kW	4000 kW	4500 kW	5000 kW
13.0 m/s	0	0	0	0	0	0	0	0	0
14.0 m/s	1.05	0	0	0	0	0	0	0	0
15.0 m/s	1.05	1.05	0	0	0	0	0	0	0
16.0 m/s	1.05	1.05	1.05	0	0	0	0	0	0
17.0 m/s	1.05	1.05	1.05	1.05	1.05	0	0	0	0
18.0 m/s	1.05	1.05	1.05	1.05	1.05	1.05	1.05	0	0
19.0 m/s	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
20.0 m/s	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
21.0 m/s	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
22.0 m/s	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05

7.2.4 Module *Text file*: Design input, material and engines files

The control data of the model are stored in text files, this allows one to store information in separate files in a permanent way and to modify them in a text editor or even in Microsoft Excel as comma separated values. These files are used in order to instantiate class i.e. material and engine. It make the use of the I/O (input / output) class and more precisely the C# standard *streamreader* method [105]. In addition it is possible to write information to additional files or to modify files in a much easier way. The use of Microsoft Excel files is interesting for the validation of module such as looping but the source of this script is long and technical to implement and are more suitable when a very large amount of data needs to be processed in a workbook. Ultimately the sensitivity analysis and the genetic algorithm which are presented in appendix C use text files extensively .

The Figure 7.14 shows the structure of an example of a comma separated text file. The table 7.12

defines each vairable in figure 7.14 with the rows and columns in figure 7.14 corresponding to the rows and colums in table 7.12. It must be mentioned that the 0 in the aluminium and steel line are set to 0 for technical reason but are not used in the instantiation of any class of the model. Indeed the last figures of the GRTS and GRTP line define the top hat stiffeners whereas the dimension of steel and aluminium stiffeners are taken from commercially available database.

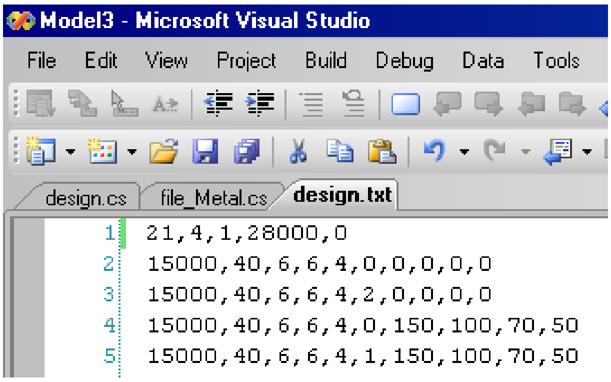


Figure 7.14: Example of a design control text file

Table 7.12: Details of the design control text file

speed (m/s)	Service restriction area	Payload (kg)	Ply thickness (mm)	Engine index						
estim. struct. weight steel	Nb. trans. stiff. steel	Nb. long. stiff. bottom steel	Nb. long. stiff. side steel	Nb. long. stiff. half deck steel	metal index steel	0	0	0	0	
id. alu.	id. alu.	id. alu.	id. alu.	id. alu.	id. alu.	0	0	0	0	
id. GRTS	id. GRTS	id. GRTS	id. GRTS	id. GRTS	id. GRTS	Composite index	Height trans. stiff.	Width trans. stiff.	Height long. stiff.	Width long. stiff.
id. GRTP	id. GRTP	id. GRTP	id. GRTP	id. GRTP	id. GRTP	id. GRTP	id. GRTP	id. GRTP	id. GRTP	id. GRTP

Table 7.12 is the index for materials and engines. These are the indexes of the elements in the following tables. The metals are selected in table 7.13 and composites in table 7.14. The engines are selected in table 7.17.

There are two steels (regular marine grade and high strength), one aluminium, one GRTP and one GRTS (50%). The high strength steel has not been investigated but it shows how the model can implement other materials.

As seen in table 7.14, the table for the definition of the composites collect very few values. SEC and density derive from the energy collected for both fibres (table 7.15)and resins (table 7.16) and are instantiated with specific method in the composites class. It must also be noted that the mechanical properties of the composites do not really derive from the respective properties of the fibre and resin

Table 7.13: Metal selection

Name	E (GPa)	σ (MPa)	Density (kg/m^3)	SEC (MJ/kg)	Paint under water (MJ/m^2)	Paint above water (MJ/m^2)	Paint subject to wear (MJ/m^2)	Recycling (MJ/kg)
Steel	200	235	7800	22	38	10	10	13
Steel HS	200	255	7800	22	38	10	10	13
Aluminium	70	235	2700	220	28	10	10	200

Table 7.14: Composite selection

Name	Gc	Fibre index	Resin index	Paint under water (MJ/m^2)	Paint above water (MJ/m^2)	Paint subject to wear (MJ/m^2)	Recycling (MJ/kg)
Epoxy/E-glass	0.5	0	0	28	10	10	30
PP / E-glass	0.6	0	1	28	10	10	30

but depends only on the fibre content on the LR point of view. The density and SEC are calculated from the value of fibre, resin and glass weight content (g_c). Although these rules give a good approximation for GRTS mechanical properties, it gives a relatively poor one for GRTP properties. Therefore the actual properties of GRTP are used in the model instead of the LR-SSC approximation.

Table 7.15: Fibre selection

Name	Type	E (MPa)	SEC (MJ/kg)	Density (kg/m^3)
epoxy	TD	3500	80	1380
PP	TP	800	60	900

Table 7.16: Resin selection

Name	E (GPa)	SEC (MJ/kg)	Density (kg/m^3)
E-glass	69	50	2560
aramid	124	50	1450

A selection of engines which are commercially available or purely virtual are collected in a text file. Table 7.17 shows the information in the text file. It presents the name of the engine starting by its brand followed by it specification.

Table 7.17: Engine selection

Name	Length (mm)	Width (mm)	Height (mm)	Weight (kg)	Fuel consumption (l/h)	Power (kW)
Specimen						
test1	2000	1000	1000	1500	140	450
test2	2000	1000	1000	1500	140	475
...	...	...	...	...	...	...
test16	2000	1000	1000	1500	140	825
test17	2000	1000	1000	1500	140	850
Commercially availlable boats						
Volvo D12 650	1950	1027	1067	1400	122	478
Yanmar SY 530	1910	870	1038	1280	140	530
Yanmar SY 662	1860	1000*	1000*	1906	180	662

* = estimation

7.2.5 Module *scantling*: Design pressures, scantling

Lloyd's Register provides all the necessary rules for the scantling of steel, aluminium and GRTS boats. Minor changes are required for the calculation of the strength and stiffness of GRTP as the use of the glass fibre weight content for the calculation of mechanical properties tends to distort the properties of GRTP. A linear correction factor was used in order to have a better correlation between GRTP fibre content and mechanical properties.

The basic object manipulated by the program used for the simulation of the model is the area between two transverse stiffeners and two longitudinal stiffeners. The design pressure is calculated at the centre of the plate and this pressure is used for the calculation of the two stiffeners attached, one transverse stiffener at the fore side of the panel and one longitudinal at the bottom side of the panel. Figure 7.15 shows each panel with indices i and j, i being the number of the fore tranverse stiffener attached to the panel and j being the number of the bottom longitudinal stiffener attached to the panel.

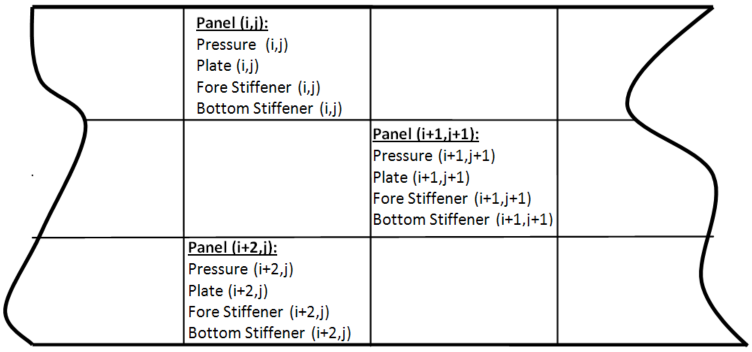


Figure 7.15: Structural component panel division for part of a structural artefact

These basic elements are grouped in several tables, one for each main component:

- Side panel
- Bottom panel
- Deck
- the watertight bulkhead
- Inner deck floor
- superstructure

The design pressure calculation is presented in the chapter 6. In this chapter the approach to scantling was to define one pressure and to apply it to the entire boat. As a result, the thickness of the plating and the stiffener were the same over the entire length of the boat and the scantling in the aft area of the boat was overestimated. Graph 7.16 is an example of the pressure pattern for a steel boat bottom plating. It has been decided in this example to use 7 longitudinal stiffeners therefore 7 'lines' of plate calculation elements. It shows clearly the increase in load toward fore end. It is noticed that between transverse stiffener 15 to 40 for the panel close to the keel and stiffener 15 to 35 for the panel close the chine, the pressure is relatively linear, identical in the transverse direction of the component and peaks around station 30. The very end of the curve is very irregular because the fore end of the boat is out of the water and the shape of the panel may be very distorted (long and narrow panel, see Figure 7.16 at the front of the boat where keel, chine and deck line intersect). In the present chapter the scantling is detailed in order to optimise the weight of the boat.

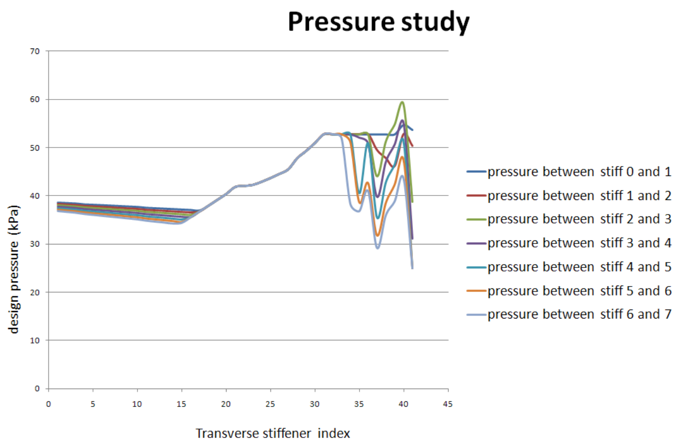


Figure 7.16: Design pressure study

The output of this module is a list of all the dimensions for each panels made by the intersection of a transverse and a longitudinal stiffener. This list is used in the *specification* module in order to define the thickness of the plating and the geometry of the stiffeners for four sections of the boats.

Table 7.18 shows an example of a stress verification result for a bottom panel. This panel is a bottom panel, the most aft and the closest to keel. It would be the [0,0] panel using the system of coordinate of table 7.15. The design variables are 1100 kW, 21 m/s, 45 t of payload, 40 transverses stiffeners, 6 longitudinal stiffeners on the bottom hull. The calculation method follows the sequence presented in table B.2 and table B.3 in appendix B. In the scantling process used to create the following table, the first estimation of the laminate thickness was to use only one ply of 1 mm. The stress verification showed that it was not satisfactory and the stress reached an acceptable level with 9 plies. Table 7.18 shows the results for each ply. Table 7.19 summarises the stress and moment results. It shows that the maximum stress is at the centre of the panel and that the stress is inferior to one quarter of the ultimate stress (safety factor) of the composite laminate (147 MPa).

Table 7.18: Loading criteria

Ply n°	Description	G_c	t (mm)	Lever (mm)	E (N/mm^2)	E * t	E * t * x	I	E * I
1	WR	0.5	1	8.5	14500	14500	123250	723	10488300
2	WR	0.5	1	7.5	14500	14500	108750	563	8168300
3	WR	0.5	1	6.5	14500	14500	94250	423	6138300
4	WR	0.5	1	5.5	14500	14500	79750	303	4398300
5	WR	0.5	1	4.5	14500	14500	65250	203	2948300
6	WR	0.5	1	3.5	14500	14500	50750	123	1788300
7	WR	0.5	1	2.5	14500	14500	36250	63.3	918300
8	WR	0.5	1	1.5	14500	14500	21750	23.3	338300
9	WR	0.5	1	0.5	14500	14500	7250	3.33	48300
SUM				9		130500	587000		35 10^6

Table 7.19: Loading criteria

Step	description	Value	Comments
1	Moment (plate centre)	11.2 Nm	B.3.22
	Moment (at the stiff.)	17.1 Nm	B.3.23
2	Position of the neutral axis	4.5 mm	B.3.24
3	Tensile Modulus of the section	14500 N/mm^2	
4	Stiffness about neutral axis	881 Ncm^4/mm^2	B.3.26
5	Tensile stress (center, dry side)	31 N/mm^2	B.3.27
	Compression stress (center, wet side)	32 N/mm^2	B.3.28
	Tensile stress (stiff., wet side)	21 N/mm^2	B.3.27
	Compression stress (stiff., dry side)	20 N/mm^2	B.3.28

7.2.6 Module *specification*: Weight and linear dimension

The specification module of the present model aims to select commercially available sections for the metal stiffeners, select areas where the dimensions are constant for composites and metals. There are three structural artefacts going from the aft to fore end of the boat. These are:

- Deck
- Side plating
- Bottom plating

For these three structural artefacts it is decided to divide the length in four equal areas for which the plate thickness is constant, each longitudinal stiffener has a constant section geometry (though the section geometry may change while the distance of the stiffener to the keel increases). Each transverse stiffener along the length of the boat has a different value. These stiffeners are only constant along the bottom hull, the side hull and the deck.

For the metal boats, the chosen stiffener types are bulb sections taken from the online catalogue of Dent Steel [106]. Standard bulb sections cover a more relevant set of structural specifications for boats studied in the present research than standard T bars. T bars have a much higher second moment of inertia and are more adapted to a ship with stiffener spacing in the order of metres. In the present boat the distance between stiffeners is in the range of a metre to half a metre. The section for aluminium is much less standardised and more custom made because of the flexibility of aluminium extrusion. It is one advantage of aluminium to provide better stiffness to section area ratio than steel standard sections. In the present research, the ease for extrusion of aluminium is ignored and the same section specifications are used for steel and aluminium. The section has the density of aluminium.

For the composite structure the geometry of the stiffener is an input to the model. There is no need to select any commercially available component and the weight of the boat derives from the surface and thickness of the hull plating and stiffeners.

The specification module returns the weight of the structure, the position of its centre of gravity and the collection of stiffener section dimensions.

7.2.7 Module *Design looping*

Ship design is an iterative process as can be seen in figure 3.6. Any boat design, in the present approach or in the traditional approach, requires a weight estimation of the boat to define power, full geometry, scantling and specifications. The scantling definition results in a set of parameters such as the plating thickness and stiffener section geometry from which a new weight can be calculated. The tested design is accepted only if estimated weight and calculated weight are equal. In the present research the design is accepted if the calculated weight is between 0.975 and 1.025 times the estimated one. If these two weights are not within this range, the newly calculated weight becomes the estimated weight of the following design model run. This operation is to be repeated until the convergence of the two weights. It must be mentioned that the design process may not converge to an acceptable weight or not converge at all. In the case of a non or bad convergence, the traditional approach of ship design would be to impose a change in power but little or no constrains on the geometry.

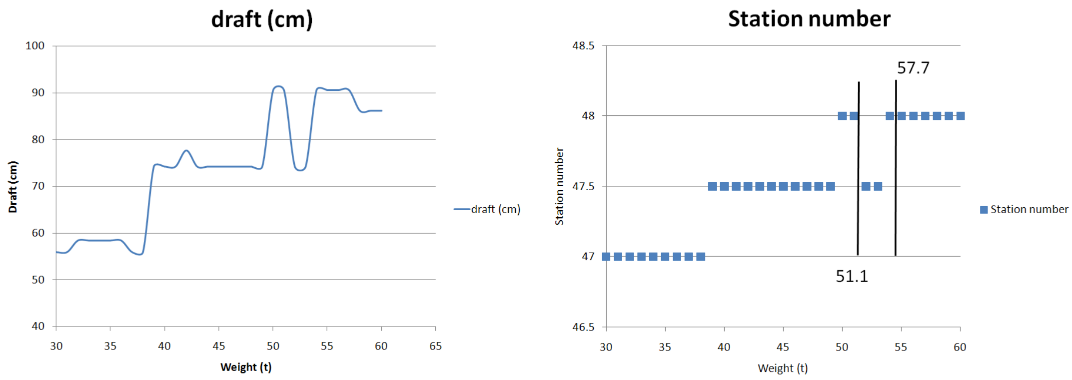
A change in power for a constant geometry is the opposite of the approach taken in the present research. Here, the power is constant and the geometry varies. In the traditional design approach, experience gained on a given design geometry can be used to define beforehand the range of weight converging without design geometry modification. In the present design model, each run of the model uses a different geometry on which little is known on its convergance potential with regards to the design model. The work conducted for this section highlights the reason why a change in geometry has a big influence on the convergence of the model. The section focuses with a particular emphasis on the evolution of the model development. It shows how the geometry module was improved by using the draft calculation method 4 instead of the 3 and why the power module was improved in order to ease the convergence of the model.

7.2.7.1 Improvement of the geometry module

The model was run for many {estimated weight, speed, power} set ({M, U, P}) and in some cases the model neither converged nor diverged completely. Using the step by step debugging capability of MS Visual Studio, it appeared that the only values consistently balancing from run to run were the draft and more precisely the station at which the draft was calculated. The third draft calculation method was used at this stage of the model development. In this draft calculation method (section 7.2.3.3) only three values of the draft for a given geometry can be used. These are the height of the keel at station 47, 48 and virtual station 47.5. This calculation method had a major adverse effect on the convergence of the model for many {M, U, P} set and an aluminium boat with 1050 kW installed power running at an operation speed of 21 knots is considered. Only the deck and the hull are designed for the purpose of the demonstration ignoring any other components of the boat. This boat does not converge toward any weight and run after run the calculated weight switched constantly between 51.1 and 57.7 tonnes. The structural weight was 16.1 and 22.8 tonnes and the payload was 35 tonnes. The initial weight estimation for the first loop was 15 tonnes. Only a few digits changed in each loop, beyond the 100 kilos digit, without any sign of convergence even after a large number of runs. Most converging cases returned a value within 10 runs.

Observations on the present model showed that boat displacements are much more sensitive to draft and waterline length than beam and deadrise angles. In other words, two different tested weights are more likely to show large waterline length and draft variation rather than beam or deadrise angle. For the rest of the demonstration the weight is assumed to depend only on waterline length (Lwl) and draft (Tx) in order to simplify the concept. At constant draft, the longer the boat the more material is needed and the boat gets heavier. At constant LWL, heavier boats have a larger draft.

Figure 7.17 shows the draft variation in cm (a) and the station number at which the draft is calculated (b) for a weight range from 30 to 60 tonnes, for an aluminium boat with 1050 kW installed and cruising speed of 21 m/s. At constant station number the draft in cm shows little variations due to geometric parameter variations, in comparison a change in station number shows a large variation in cm. The figures shown in figure 7.17 are calculated using only the power and geometry module. These figures do not depend on scantling module and no loop control module is implemented. When the loop control module is implemented, observations on the present design model behaviour showed that model convergence occurred more easily when estimated and calculated weight are situated, run after run, in a weight interval where the draft is calculated at a fixed station number. This is the case between 40 and 50 tonnes in figure 7.17 (b).



(a) Draft (b) Station Number where the draft is calculated

Figure 7.17: Draft study

However between 50 and 60 tonnes, the convergence is more difficult to reach. The draft is calculated as station 47.5 and 48 and convergence issues appear. Table 7.20 shows a non converging scenario, detailed in the following points. The boat tested is an aluminium boat with 35 t payload, 1050 kW installed power and running at 21 m/s. The weight collected in the table is the weight of the structure only. This is the result at the end of the specification module. In order to use graph 7.17, the payload must be add to the structural weight.

Table 7.20: Non converging example (aluminium boat 1050 kW, 21 m/s, 35 t payload)

Run number	estimated weight (kg)	Calculated Weight (kg)	Draft (cm)	Station	Lwl (m)	Beam (m)	Deadrise angle (^{o})
1	15000	22327	74.1	47.5	33.4	4.3	11
2	22327	15800	86.1	48	30.6	3.9	17
3	15800	22800	74.1	47.5	34	4.3	11
4	22800	16100	86.1	48	30.8	3.9	17
5	16100	22800	74.1	47.5	34.1	4.3	11
6	22800	16100	86.1	48	30.8	3.9	17
7	16100	22800	...	...	...	...	...
8	22800	...					

1. In run 1, the initial estimated structural weight input in the present model is 15 t. It returns a calculated weight of 22.3 t.
2. In run 2, the estimated weight is 22.3 t and the calculated weight is 15.8.
3. In run 3, the estimated weight is 15.8 and the calculated weight is 22.8 t.
4. In run 4, the estimated weight is 22.8, therefore the total weight is 57.8 t. Graph 7.17 associates 57.8 to a draft calculated at station 48, which is the largest possible draft. The calculated weight is 16.1 t for a total weight of 51.1 t. Graph 7.17 associates 51.1 to a draft calculated at station 47.5. The looping problem starts at this point
5. In run 5, the estimated weight is 16.1 and the returned weight is 22.8. The drafts are identical to the draft of the previous run. The relatively little difference in weight between estimation and calculation results but the large draft difference has a major impact on the result. Graph 7.17 shows that 51.1 and 57.8 are on both sides of a step. The following runs will always follow the same pattern, the larger weight (22.8 t) is associated with a large draft which requires a small LWL and small LWL return a small weight (16.1 t) but as this weight is associated with a smaller draft, LWL increases and weight result increase and the following run is conducted with a larger weight and smaller draft.

In comparison table 7.21 shows a very quick convergence of a similar set of input where only the payload is changed to 26 t. In this case most of the calculation is conducted at constant draft number, because the total weight of the boat is between 40 and 48 tonnes and figure 7.17 shows that the draft is calculated at station 47.5 for these weight. In the run 3 and 4, draft and draft station number does not change and only LWL changes. Estimated and calculated weights are in the 5%

range decided as acceptable in the present model.

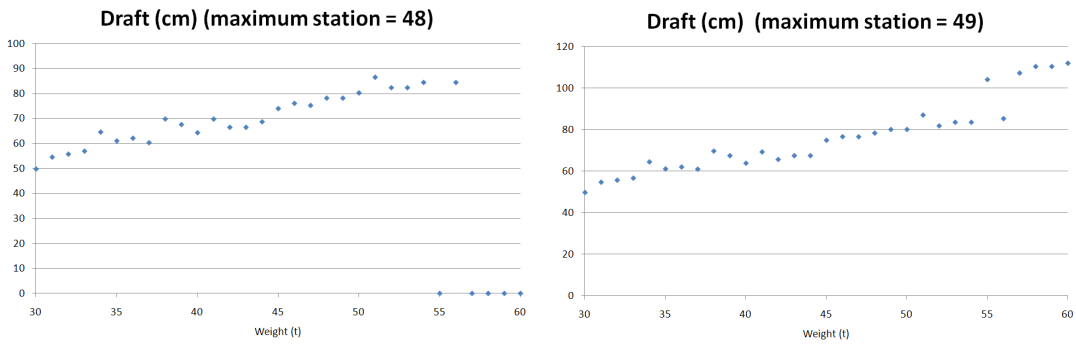
Table 7.21: Converging example (aluminium boat 1050 kW, 21 m/s, 26 t payload)

Run number	estimated weight (kg)	Calculated Weight (kg)	Draft (cm)	Station	Lwl (m)	Beam (m)	Deadrise angle (^{o})
1	15000	15900	77.6	47.5	25	4.5	11
2	15900	24300	55.8	47	33.3	4.5	9
3	24300	22400	74.1	47.5	33.6	4.3	11
4	22400	21700	74.1	47.5	32.4	4.3	11

Method 4 was developed in order to have a smooth increase of the draft instead of the large step seen in figure 7.17. The method is explained in details in table 7.2.3. Table 7.22 shows the that the new draft calculation allows a convergence for results which would not converge otherwise. Figure 7.18 illustrates that the draft is more linear than the draft on Figure 7.17. The other parameters i.e. beam, deadrise angle and the centre of gravity are more influential and the draft is directly proportional to these parameter and the displacement.

Table 7.22: Converging example (aluminium boat 1050 kW, 21 m/s, 35 t payload)

Run number	estimated weight (kg)	Calculated Weight (kg)	Draft (cm)	Station	Lwl (m)	Beam (m)	Deadrise angle (^{o})
1	15000	15410	80	47	23.8	4.3	11
2	15410	15410	80	47	23.8	4.3	11



(a) Draft (between station 46 and 48) (b) Draft (between station 46 and 49)

Figure 7.18: Draft study (method 4)

This new draft method was tested to a larger search domain for masses from 30 to 60 tonnes, speed from 21 to 26 knots and power from 900 to 1400 kW. It showed that a large number of sets of parameters were not converging and a closer look at some example convergence steps showed that the estimated and calculated mass were flipping between two values in the same manner described earlier in this section. The problem was very different as values of beam, deadrise angle and position of the centre of gravity were picked in a large search domain whereas the draft was calculated. The table of results showed that only few values of parameter were found in the acceptable solution. The details of the results are all grouped in the next section

To conclude, the present subsection highlights two results:

- In order to decrease the irregularities due to the draft calculation, the method described in section 7.2.3.4 was developed and used in the present model.
- The extreme sensitivity to the refinement and smoothness of the search area needs to be assessed in order to have as many weights as possible converge and to be used ultimately, for the purpose of the study in assessing the life cycle performance of materials. Indeed the coarse treatment of the draft using method 3 (Section 7.2.3.3) lead to dramatic convergence problems. It must be noticed that the same convergence pattern was found using the method 4 of the draft calculation. The draft problem being solved, the origin of these new issues was examined for the accuracy needed for the calculation of beam, LCG and deadrise angle in the powering module.

7.2.7.2 Improvement of the power module

The previous section showed that it was necessary to address the question of poor convergence with a change of approach for the calculation of the draft. In the present section, the non convergence problem is considered over a large part of the search domain in order to ensure that a large part of this domain will provide solutions in the further development of the model. The domain is however limited to the lower right corner of figure 7.9. It is known that the deadrise angle and deadrise angle standard deviation (the solution fitness criteria for this section) are in a moderate range synonym of viable solutions. In comparison, larger deadrise angles with small standard deviations are questionable in their feasibility (see last paragraph of section 7.2.2). In this particular case a study was carried for the four studied materials. The results are shown in table 7.23.

Table 7.23 shows a study of the convergence of the weight of the boat in the model. The total is the sum of the structural weight and a payload constant for each material case study. The first and sixth column shows the installed power in kW. At this particular stage of the development only the plating of the deck, side and bottom plating and transverse stiffener are taken into account. The zeros are set for non converging solutions. For each material, these solutions tend to show three areas:

- at low power there are a large number of missing solutions, e.g. between 900 and 1000 kW for steel and GRTP. This is due to the fact that in the model, lightly powered craft tend to

Table 7.23: Converging example for each material

Power (kW)	Steel (kg)	Alu (kg)	GRTS (kg)	GRTP (kg)	Power (kW)	Steel (kg)	Alu (kg)	GRTS (kg)	GRTP (kg)
900	0	0	0	0	1160	0	0	0	0
910	0	12462	0	0	1170	27552	0	13822	0
920	19010	0	0	9012	1180	0	17806	0	12909
930	0	0	0	0	1190	0	17207	0	0
940	19014	13377	11054	0	1200	27975	0	0	0
950	0	13377	11047	0	1210	0	19581	0	11769
960	19796	12755	11568	0	1220	0	0	14490	0
970	20024	0	11858	9107	1230	0	0	14490	0
980	0	14481	11203	9107	1240	0	18306	14490	13954
990	0	14481	11203	10130	1250	0	0	0	0
1000	0	14481	12420	9835	1260	0	0	0	14436
1010	22247	15034	12261	0	1270	0	0	0	14436
1020	22247	15736	12261	0	1280	0	22906	0	14860
1030	22980	15736	0	10787	1290	0	22906	0	15064
1040	22980	15736	0	10787	1300	0	0	0	0
1050	0	15736	12943	10787	1310	0	0	0	0
1060	0	16685	12943	10792	1320	0	0	0	15204
1070	23088	16685	12943	0	1330	0	0	0	15204
1080	23083	16685	11975	10946	1340	0	0	0	15031
1090	24451	0	13318	10946	1350	0	0	0	15539
1100	24554	17468	13318	10946	1360	0	0	0	0
1110	24476	17468	13318	10946	1370	0	0	0	0
1120	24476	17468	13301	11437	1380	0	0	0	16165
1130	24535	15456	0	0	1390	0	0	0	0
1140	0	15456	0	0	1400	0	0	0	16773
1150	27569	15456	0	0					

be shorter. The displacement of boat is relatively constant therefore these shorter boats need larger draft. It has been seen in section 7.2.3.4 that the draft is bounded and outside these limits no solutions are accepted.

- an area where very few solutions are missing, e.g. for steel the power between 1000 and 1150 kW or for aluminium between 950 kW and 1150 kW.
- at higher speeds, the number of missing solutions increased to a level where no solutions are found. One reason may be that the weight is constantly increasing for reasons difficult to assess, as neither the weight nor the payload increase (these two parameters are of prime importance to calculate the design load, see appendix B). The larger amount of energy to dissipate requires a larger wetted surface. However section 7.2.4 showed that the number of stiffeners are given regardless of the length therefore the spacing increases with higher power. This problem will be addressed in the sensitivity analysis and the genetic algorithm, where a better weight will be part of the fitness / selection criteria therefore an extension of the second domain is expected because a reduction of the weight over the full search domain will be the objective.

The aim of the refinement is to lower the number of missing solution and to show clearly the boundary between solution and non solution domains.

The first attempt was to increase the number of runs of the model (loop), where estimated weight is set to equal to the calculated weight of the previous run, after which the search is stopped. By default this number is set to ten and the previous section showed that solutions converge quickly, e.g. as seen in table 7.21 and 7.22. The computational time increased dramatically with no impact on the number of zeroes whatever the number of loops.

The refinement of the search domain was conducted by increasing the number of intervals between solutions. For the table 7.23, the interval for each parameter were divided in 10 steps and in each loop 1000 solutions were tested to get the optimum bottom impact. It must be noted that higher deadrise angles ($>25^o$) were supposed to be filtered from the solution because the search domain selection. The search domain described in table 7.2 apply in the present study but the deadrise angle are searched between 5 and 25 ^{o}. The flipping phenomenon seen on the draft and solved in the previous section was seen in for the beam, deadrise and CoG parameter for which only a very limited number of values were found in the detailed result. The refinement for the search solution was increased ten times. As a result 1,000,000 parameter sets were search to get the best solution. The number of zeros decreased dramatically with computing time hugely increasing. Figure 7.5 highlights that the algorithm made the use of computationally ineffective *FOR* loop for each parameter. The *FOR* loops are symbolised by the arrows starting from the diamond shaped test box going up to a start box of the Faltinsen algorithm. The results were good but the method was not acceptable.

It was decided to refine the study around a selected number of points giving the best results according to the initial power method. Little is known on the points surrounding any given point and even if a point is a global minimum for the bottom impact pressure a surrounding point may be the real global optimum. Six points were chosen as it increased little the computational time. The qualitative impact on the result was not studied. For each of the six selected points, a refined study around the point of 1 interval unit of the previous run is conducted. This can be repeated the same way several times. The set giving the lowest value is selected and used in the next module. The studied power were extended from 900 - 1400 kW to 900 - 2500 kW.

Table 7.24 and 7.25 grey area shows the relevance of selecting several points for the refinement study. While the values for these two tables are relatively close up to 1100 - 1200 kW, for higher powers another set of parameter seems to give better results with one refinement run showing that the optimum parameter set for the grey area of table 7.25 is only a local optimum.

Table 7.26 shows that the refinement does not only have a beneficial impact on the reduction of the zeroes. The red figure shows that there is a decrease of the number of zeroes but the green

Table 7.24: Converging example for each material (24m/s, 1 power refinement loop)

Power (kW)	Steel (kg)	Alu (kg)	GRTS (kg)	GRTP (kg)	Power (kW)	Steel (kg)	Alu (kg)	GRTS (kg)	GRTP (kg)
900	10958	0	0	0	1750	30138	22124	16477	13382
950	0	0	0	0	1800	0	23151	16836	13333
1000	0	0	0	0	1850	32361	22965	17259	14138
1050	0	0	0	0	1900	33422	22694	17243	14391
1100	14550	8734	8304	6727	1950	35076	24449	17257	0
1150	14423	0	9478	7628	2000	37090	26499	17431	14197
1200	0	11585	9623	8047	2050	36895	24791	16636	13917
1250	17463	12710	10438	8625	2100	0	26276	16284	13283
1300	18283	12870	10775	8692	2150	42164	23266	16337	13403
1350	20164	13288	10862	9176	2200	39261	24306	16452	13858
1400	20255	14414	11639	9729	2250	37915	24382	14617	12817
1450	22848	15202	11805	9788	2300	43334	24193	0	0
1500	23321	15687	12711	10923	2350	34627	24793	0	14212
1550	25503	17030	13835	11799	2400	34603	0	0	14815
1600	24939	18214	14302	11348	2450	39176	20217	16740	14532
1650	25882	0	14385	0	2500	36467	22150	17507	15042
1700	27218	19177	14927	12616					

Table 7.25: Converging example for each material (24m/s, 0 power refinement loop)

Power (kW)	Steel (kg)	Alu (kg)	GRTS (kg)	GRTP (kg)	Power (kW)	Steel (kg)	Alu (kg)	GRTS (kg)	GRTP (kg)
900	0	0	0	0	1750	0	0	0	0
950	0	0	0	0	1800	33132	0	17700	14727
1000	0	0	0	0	1850	36928	0	0	0
1050	0	0	0	0	1900	36963	24772	0	14554
1100	0	0	0	0	1950	0	0	0	0
1150	0	0	0	0	2000	41144	0	0	0
1200	0	0	0	0	2050	42975	0	0	0
1250	0	0	0	0	2100	44064	0	0	0
1300	0	0	0	0	2150	44064	25554	0	0
1350	22119	0	11610	0	2200	45711	27910	0	0
1400	0	16568	12456	10102	2250	45731	28887	0	0
1450	24004	16691	13116	0	2300	45731	29396	0	0
1500	24760	0	0	0	2350	43262	29396	0	0
1550	25040	18144	0	0	2400	46189	24713	0	0
1600	25995	17188	0	12517	2450	45624	24713	0	0
1650	29485	0	15806	12800	2500	47711	26067	0	15194
1700	0	0	0	13259					

Table 7.26: Convergence comparison several power refinement loop numbers

Power (kW)	Nb loop	Speed (kn)	Steel (kg)	Alu (kg)	GRTS (kg)	GRTP (kg)
1900	1	21	28593	21142	0	0
1950	1	21	0	20982	0	14853
1900	2	21	38977	20860	18055	0
1950	2	21	30220	20372	18542	14402
1900	3	21	27830	20816	18046	0
1950	3	21	29763	20385	18537	14389
1900	1	24	33422	22693	17242	14391
1950	1	24	35076	24449	17257	0
1900	2	24	33756	22620	17315	13680
1950	2	24	33323	23665	18057	0
1900	3	24	0	22569	17312	13624
1950	3	24	0	23626	18034	0
1950	1	26	26916	19071	14278	11987
2000	1	26	27386	0	14791	12387
2050	1	26	27779	21955	15070	12296
1950	2	26	26840	18520	14203	11772
2000	2	26	26998	20467	14738	12228
2000	2	26	0	20787	14875	12258
1950	3	26	26731	18488	14175	11640
2000	3	26	26925	20378	14720	12206
2050	3	26	0	20709	14845	12165

value shows otherwise. Indeed, the green figures show that the number of missing values remains the same, but, the position of this missing values changes. In addition three values of power are given for this example, 1950, 2000 and 2050 kW. It shows that the results are not linear and it would be difficult to interpolate missing values as centre of the interval. It must be accepted that some missing values will remain in areas where it might be expected that values should converge. The results are sensitive to stiffener parameters and estimated weight, given in the text file and some variation of the these values in the sensitivity analysis and genetic algorithm will reduce the problem. It must be mentioned that one value (grey) background is unexpected.

The refinement of the search domain shows a beneficial impact in increasing the number of converging solutions. However some values are still missing in areas for no evident reasons. These missing values are expected to be found with a better model information input, e.g. the estimated weight, the payload or minimum beam, and this question will be addressed in the sensitivity analysis / genetic algorithm section.

7.2.8 Module *Secondary component geometry*

This section presents the design algorithm for the definition of the bulkhead, transom plating and superstructures, the calculation of which is conditioned on the successful search of the position of the engine. The engine is considered as the main equipment which ensures that the position of the centre of gravity calculated at the power module stage coincides with the position of the centre of gravity from the specification module.

7.2.8.1 Machinery position

The power studied so far is representative of typical fast boat such as a patrol boat. The engine specifications are presented in the text file module (section 7.2.4). It highlights the difference between the weight of the structure, which is between 12 and 25 tonnes depending on the material, and the weight of two engines, which is between 2 and 3 tonnes. It shows the difficulties to move the position of the gravity of the group { structure weight + machinery }. The engine is assumed in the present research not to be further aft than the first 10 % of the boat length from transom. The position of the engine test is very selective and it is difficult to assess its influence as easily as the looping problem. The influence will be studied in the sensitivity analysis.

7.2.8.2 Bulkhead and transom

The bulkheads and transom can be calculated for the boats for which an engine position is acceptable. Although the position of the bulkhead must be as evenly spaced as possible, it is difficult to ensure it. Their influence on the position of the centre of gravity is however limited because the weight of these features are small (about 10% of the weight of the hull and deck) and their positions are either side of the position of the centre of gravity. The bulkheads are situated in following sequence

- Two bulkheads, one metre far from each end of the engine e.g. for most engines these two bulkhead are about 3.5 to 4 metres apart. Their influence on the centre of gravity are small.

- One bulkhead at the fore end of the waterline length which counteracts the effect of transom on the centre of gravity. The power calculation module shows that the centre of gravity is around the middle of the wetted length. The draft calculation (section 7.2.3.4) show that the waterline length is 1.05 times the wetted length therefore transom and bulkhead at waterline length are evenly spaced around the centre of gravity. It must be mentioned that the bulkhead is thicker than the transom part but the bulkhead surface is smaller as it is at the converging end of the hull.

In addition, boats larger than 24 metres required to be fitted with a fourth bulkhead. This bulkhead is supposed to be fitted in the larger space created between the transom and engine room or LWL and engine room.

The bulkhead scantling must be at least equal to the one of the shells attached. In other words no calculation is needed. The bulkheads are divided in two areas:

- The bottom part of the bulkheads, which is attached to the bottom plating from keel to chine

  Plating: The plating thicknesses of the bottom part of the bulkheads are equal to the attached bottom plating thickness.

  Vertical stiffeners: The geometry of these stiffeners is equal to the closest transverse stiffener attached to the bottom plating. It is the same spacing as the transverse stiffener spacing along the boat.

  Horizontal stiffeners: These stiffeners are aligned to the longitudinal stiffeners of the bottom hull. The spacing is smaller than the spacing of the longitudinal because for the same number of stiffeners the length in which they are fitted is smaller by a factor equal to the tangent of the deadrise angle. The bulkheads are much stiffer than the attached plating because the bottom plating deadrise angle is small.

- The upper part of the bulkheads, which is attached to the side plating from chine to deck

  Plating: The plating thicknesses of the upper part of the bulkheads are equal to the attached side plating thickness.

Vertical stiffener: The geometry of these stiffeners is equal to the vertical stiffener of the bottom part of the bulkhead or transom plating.

Horizontal stiffener: It follows the same principle as the bottom part but the stiffener is less affected because the deadrise angle is much higher.

The weight of the bulkhead is integrated in the loop module. In the *design control text file* (see figure 7.12), the payload weight is decreased and the structure weight estimation is increased. The behaviour of the convergence remains stable. However fewer boats converged because the model was unabled to find a machinery position.

7.2.8.3 Other features

These features include the deckhouse, the covered deck and the inner floor.

The experience gained in the scantling module was used in the present chapter in order to speed up the scantling process. The scantling module allowed the understanding of the behaviour of pressure and thickness along the boat. It required an extensive calculation of design pressure and scantling between each stiffener. It also required an extensive ranking and selection module i.e. the specification module to deal with this large number of results. It showed that the design load increased with the distance from the transom.

It was decided not to calculate the scantling at the centre of each panel as it has been done in the scantling module and only one panel of flooring was checked for each boat quarter. This is the most forward panel of each quarter. The result for this panel was multiplied by the floor area of each the boat quarter.

The panel of the deckhouse was designed with properties equal to the surrounding deck.

7.2.9 Module *Energy calculation*

Chapter 5 and 6 showed that the most significant energy consuming processes are manufacture of the materials. The specific energy consumption of each material are described in tables 5.2 to 5.7 and from table 6.7 to 6.13 and in appendix A. Table 7.1 summarises the material manufacturing results. The fuel consumption is excluded because it is equal for each candidate material (i.e. equal installed power). The energy calculation takes into account the paint and the materials manufacture for the four materials. It excludes all the manufacturing process as the previous study on the grillage and the boat with fixed topology showed that the contribution of manufacturing processes is very small. It also ignores the curing process of the composites even though it is not so small. The energy information on curing is uncertain and not backed up with any elements from literature. They rely only on industrial measurements for which the methodology is unknown. The model focuses, therefore, with a particular emphasis on the material manufacture influence on the life cycle energy consumption. These energy consumptions are larger and validated by a large volume of literature as it can be seen in appendix A.

7.2.10 Module *Sensitivity analysis*

A sensitivity analysis was conducted on the model. It showed that all the parameters have an influence on the energy result. The details on the analysis are presented in appendix C, where each parameter is studied for each of the four candidate materials.

The present boat synthesis design model depends on six input parameters:

Installed power, speed and payload : They are assumed that they influence the results as seen in section 7.2.2. Indeed, any power, speed or payload modification changed the geometry and therefore the energy used during the life of the boat.

Service restriction : The results are presented in graph C.1 and shows that it influences the energy used during the life of the boat.

Number of stiffeners : The results are presented in graphs C.4, C.5 and C.6.

size of the stiffeners : The results are presented in graphs C.7 and C.8.

Estimated weight : The results are presented in graph C.2.

The first four parameters are design input and they are required to define a boat in the present design approach. They are referred as the *specification parameters* hereafter. The following two parameters define the stiffener properties as a design input. These parameters are referred as the *stiffener parameters* hereafter.

The most noticeable result is that the stiffener parameters and service restriction influence the results significantly showing that they need to be included in the calculation process. Each of these parameters has a major influence in the calculation of the design pressure and the plating thickness. The detail of these calculations is given in appendix B.

The estimated weight has a minor influence on the energy result. The slight variations are due to the numerous convergence level which are all at about 5 %, and therefore draft and loop convergence criteria may lead to slightly different results each time. In addition there is only a limited number of possible geometry e.g. beam, deadrise angle, but also a limited number of possible thickness e.g. metal thickness have 0.5 mm steps as required from Lloyd's Register and the composite layer thickness is limited to 1 mm, 1 mm being the thickness of a Twintex layer. It is decided to exclude the estimated weight from the study and to use the minimum estimated weight tested in the sensitivity analysis study (25 tonnes) as it allowed a greater number of solution to converge. This can be explained by the fact that when the weight is too high it is not possible to calculate the draft and therefore the looping process stops. It is necessary to avoid an early loop stop of a heavy boat. Indeed if a draft can be calculated, it is possible to conduct a second run of the program in which a more suitable estimated weight is used.

The time for calculation of non null points (a point which returns an energy value) is in general between 30 seconds and 1 minute. The calculation length depends on how quickly the draft is calculated (the draft calculation is described in section 7.2.3) and how fast the weight convergence takes place (described in section 7.2.7). This time is relatively large considering that genetic algorithms assess each member of each population, at each generation, for each candidate material.

7.2.11 Module *Genetic algorithm*

As shown in the previous section the design parameters are of two types, (1) parameters deriving directly from the customer specifications for a given service e.g. power, payload (2) and the internal parameters required for the conduction of the design model e.g. the stiffener properties. These stiffener parameters influence the boat life cycle energy consumption and should be optimized for the best material used. In addition, the four materials have different properties and therefore their implementation should differ. In the present section the best set of stiffeners properties is studied in order to adapt the design to specific mechanical properties of each material within the design model of Lloyd's Register. The adaptation of the stiffener size and number are an improvement of the design algorithm implemented in chapter 6 where the stiffener topology was fixed, therefore not taking advantage of the difference in properties of each material. It must be mentioned that in the present boat design model, the differences in implementation for the four materials are strictly based on the mechanical properties and not on cost or manufacturability.

As shown in the methodology, a genetic algorithm (GA) was implemented. Section 3.4.1 gave the theoretical background for GA. The present GA uses a tournament selection with subsets of two individuals. The probability of passing two parents to the next generation without crossover is 0.6. The mutation is probability is 0.01. The GA made use of a double point crossover. The fitness criterion is the inverse of energy consumption. The fitness of non converging boats is set to zero.

The time necessary for a complete boat optimization is relatively large. It was decided to focus on the GA's speed of execution instead of the accuracy of the results. As a consequence, the search domain was limited to a minimal size which resulted in short strings for the coding of chromosomes. The population size for the metal alternatives is 16 individuals and the model converges after 18 generations. For the composite materials the population size is 20 and the number of generations used is 18. It provides a relatively good approximation while limiting the calculation time to a minimum, generally between 2 to 4 hours. A comparison between the four materials for one set of parameters took more than 10 hours of calculation when the 4 materials were converging. When a boat is not converging it takes about 20 to 30 minutes to calculate each individual of the first generation population and to pass to another set of specification parameters.

Table 7.27 shows the search domain and the coding of each individual for the metal and composite candidate materials for the number of stiffener.

Table 7.27: Coding of the number of stiffeners

Parameter	Minimum	Maximum	Step	Number of digit used to code the parameter
Number of transverse stiffener	29	45	1	Coded on the first four digits of the individual
Number of longitudinal stiffener on the bottom plating	2	9	1	Coded on the three following digits
Number of longitudinal stiffener on the side plating	2	9	1	Coded on the three following digits
Number of longitudinal stiffener on half deck plating	2	9	1	Coded on the two following digits

Table 7.28 shows the search domain and coding of each individual for the composites alternatives for the stiffener size.

Table 7.28: Coding of the size of the stiffeners

Parameter	Minimum	Maximum	Step	Number of digit used to code the parameter
Height of transverse stiffener	120	200	10	Coded on the first three digits
Width of transverse stiffener	50	90	5	Coded on the following three digits
Height of longitudinal stiffener	0.5	0.9	0.05	Calculated as a percentage of the traverse stiffener height. Coded on the following three digits
Width of longitudinal stiffener	0.5	0.9	0.05	Calculated as a percentage of the traverse stiffener height. Coded on the following three digits

Table 7.27 and Table 7.28 shows that each metal individual is coded over 12 digits and each composite individual over 24 digits.

The most noticeable effect of the use of a genetic algorithm is the dramatic decrease of non converging boats. Indeed, it was noticed that a slight change in payload could make a boat design converge to a solution. In the present case the change in number of stiffeners may change the thickness of the plating and consequently the weight. In the initial population the number of boat designs converging to a solution may be small but the results were more continuous with less disruption on the power, speed, payload, service restriction space.

As it has been seen there are three reasons of non convergence:

1. A boat that is too heavy makes the 'geometry module' fails to return a draft (described in section 7.2.10). The number of stiffeners and their dimensions are not taken into account for the calculation of the draft in the first iteration of the boat design because the draft is calculated using the estimated weight. It is used thereafter for the calculation of total weight in the scantling and specification module.
2. A boat that is too light makes the 'other features module' fails to return an engine position (described in section 7.2.10).
3. For some input data the boat is not converging due to the search domain refinement problem. This phenomenon is described in section 7.2.7.

The first two non converging problems are not improved by the GA. The draft calculation very rarely fails on the first run of the loop because the estimated weight chosen is as relatively low. The effect of the estimated weight is shown in appendix C and the weight was chosen to be 25,000

Table 7.29: Design domain investigated in the model

Parameter	Min	Max	Step
Installed power (kW)	1110	1230	30
Speed (kn)	21	23	2
Payload (t)	10	20	5
Service restriction	2	6	2

kg, which is a very low weight. The position of engine can be calculated for a large design domain because it is likely that at least one set of stiffener parameters would result in an artificially high weight. For this parameter set, the model would converge by avoiding the problem of convergence of light boats. In case (3), when the model is stuck between two values but still returning a value, a small change in weight can make a large difference to the model convergence as seen in section 7.2.7. Indeed, table 7.20 and table 7.21 show how a change in weight (payload in this case) can make the model converge.

7.2.12 Running and storage of the result

The model was run on a PC equipped with dual core processor for about a month. It provided results for 90 different sets of specification parameters. In total 360 boats were optimized. Table 7.29 summarises the design parameter for which the model was run. As the model was very time consuming to run, only a small design domain was calculated.

The results for each boat were continuously stored in text files in order to avoid any accidental loss of information. The raw data was analysed using the *streamreader* object of the .NET framework which is associated with the C# language. The data was grouped automatically with a C# macro in an .xlsx document (Excel 2007) and was analysed using a pivot table. The results for the domain investigated are presented in table 7.30.

7.3 Critical analysis of the result

Table 7.1 shows the results of specific energy consumption per kilogramme of material for steel, aluminium, GRTS and GRTP .

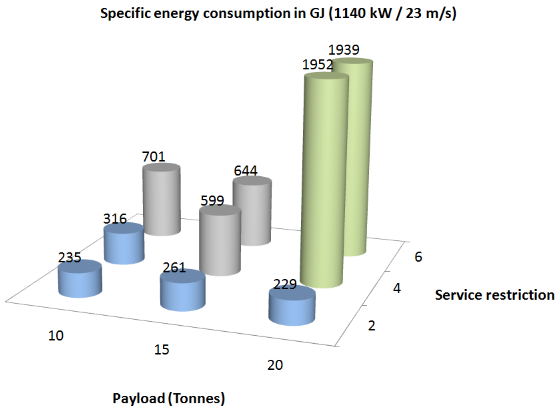
Table 7.30 summarises the result for a search domain presented in table 7.29. The figure presented is the life cycle energy consumption, in MJ, for each material. It shows that, when a recycled

Table 7.30: Model results

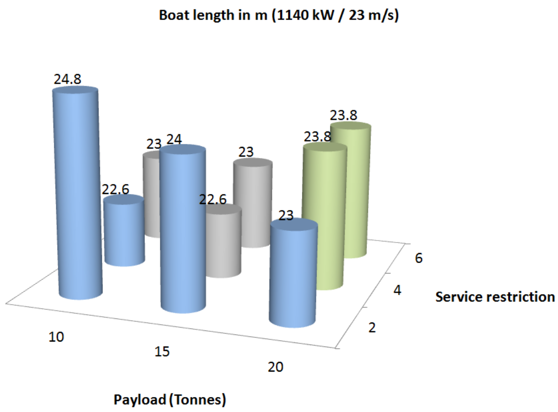
Power (kW)	Speed (m/s)	Payload (t)	Serv Rest	Aluminium	GRTS	Steel	GRTP
1110	21	10000	2	0	0	0	1172477
			4	0	0	0	1181554
			6	0	0	0	0
		15000	2	606916	1404074	380235	1065997
			4	789962	1654463	0	1221683
			6	0	1928909	0	1287586
		20000	2	485774	1462387	292198	1007164
			4	900991	1684450	0	1179880
			6	788026	1594231	0	1318411
	23	10000	2	477676	1205655	236792	778411
			4	732229	1498084	351063	988508
			6	674621	1454428	0	1002731
		15000	2	497894	1062721	255771	762544
			4	612555	1469526	296363	962941
			6	630103	1394626	0	958815
		20000	2	467974	1074327	230161	726736
			4	0	1366257	0	1011921
			6	0	2928155	0	1914661
1140	21	10000	2	0	0	0	0
			4	0	0	0	0
			6	0	0	0	0
		15000	2	557077	1438288	328351	1059355
			4	836045	1752941	0	1131805
			6	828347	1729262	0	1156645
		20000	2	535100	1477053	279250	922370
			4	794704	1650251	0	1188044
			6	796113	1898467	0	1261846
	23	10000	2	507311	2368662	235660	1614454
			4	736907	3096800	316489	2105840
			6	701383	2997855	0	1974325
		15000	2	474035	2291475	261337	1559787
			4	599822	2982219	0	1999080
			6	644222	3213515	0	2022052
		20000	2	494481	2156584	229301	1664876
			4	0	2845446	0	1952155
			6	0	2993469	0	1939443
1170	21	10000	2	0	0	0	0
			4	0	0	0	0
			6	0	0	0	0
		15000	2	576515	1387373	0	1083751
			4	0	1633043	0	1216492
			6	0	1587051	0	1216257
		20000	2	573504	1408034	0	936247
			4	0	1702593	422321	1105086
			6	950258	1703141	0	1099611
	23	10000	2	520847	1180416	243064	853562
			4	701026	1503395	0	1119653
			6	807264	1527912	0	1074490
		15000	2	498682	1196147	247890	861020
			4	749167	1404408	385485	1017931
			6	782324	1481506	0	1021041
		20000	2	488913	1138554	242628	804319
			4	630419	1437651	0	1006419
			6	0	1505684	0	1044755
1200	21	10000	2	0	0	0	1298284
			4	0	0	0	0
			6	0	0	0	0
		15000	2	596805	1608165	0	1162200
			4	0	1736468	0	1280777
			6	0	0	0	1366916
		20000	2	577489	1453437	243130	1121576
			4	739484	1782916	0	1196928
			6	774623	1659476	0	1182936
	23	10000	2	558732	1237345	275368	915434
			4	749114	1571507	0	1089983
			6	841548	1617921	0	1095313
		15000	2	510178	1314429	267776	844998
			4	758097	1476773	0	1070091
			6	808194	1566633	408768	1067423
		20000	2	511282	1243535	270563	899673
			4	772650	1638746	0	1027169
			6	788027	1569840	0	1051818
1230	21	10000	2	0	0	0	0
			4	0	0	0	0
			6	0	0	0	0
		15000	2	0	0	0	1222809
			4	0	0	0	1404358
			6	0	0	0	1306872
		20000	2	579053	1353829	0	1133952
			4	0	1701660	0	1416254
			6	0	1713745	0	1329365
	23	10000	2	573916	1377817	0	958315
			4	817231	1614437	0	1137273
			6	0	1662460	0	1106553
		15000	2	555435	1353666	273212	870107
			4	745177	1605099	0	1112046
			6	727836	1640987	0	1172046
		20000	2	528814	1256897	240851	873198
			4	641443	1548048	0	1114574
			6	0	1746061	0	1154960

steel solution can be found, it is always the best results. However the steel is impaired by its weight and it gives a solution for fewer cases than the other materials. When no recycled steel solution can be found, but an aluminium solution is available, it is the best solution. GRTP conversely has a generally higher life cycle energy than aluminium and steel but has a solution for the largest number of design parameter sets, almost all. It is the best material alternative when the boat synthesis design model failed to return a solution for steel and aluminium.

The results are analysed in details for two sets of parameters: figure 7.19 for 1140 kW and 23 m/s and figure 7.20 for 1230 kW and 23 m/s. The values are taken from table 7.30.



(a) Energy

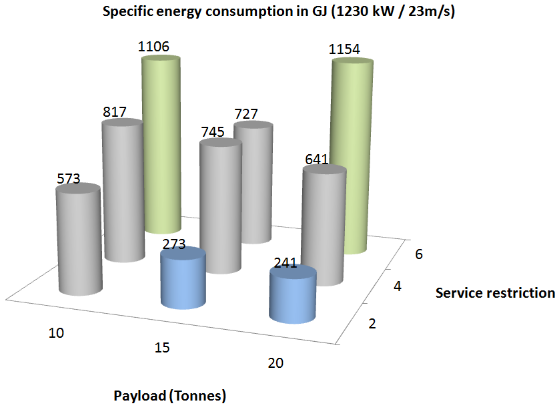


(b) Boat length

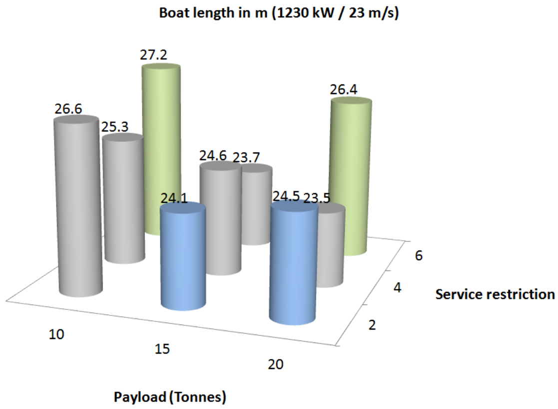
Figure 7.19: Energy value and boat length for 1140 kW and 23 m/s

Figure 7.19 shows in color the best material for a given set of payload and service restriction. In this figure, blue is steel, grey is aluminium and green is GRTP. It shows that steel is the best suited material for the least demanding conditions e.g. most restricted area of operation and low payload. Conversely GRTP are better suited for the least restricted area of operation and large payload. In these cases there is no solution for steel and aluminium as it can be seen in table 7.30. The boat design model also converged to a GRTS solution but with a higher energy level than GRTP.

Figure 7.19 also shows the quantitative figure for life cycle energy (a) and boat length (b). The energy result shows that for the least demanding conditions i.e. low payload and small service restriction parameter G2, the life cycle energy requirements are relatively low because of the steel environmental performance. The boat life cycle energy increases dramatically for the most demanding condition, high payload and unlimited restriction area, for the GRTP boat design solutions because of the larger structural requirements and the higher specific energy consumption of GRTP. It can be seen that the length of the boat tends to decrease with an increase in payload and/or service restriction parameter (G2 to G6). This can be seen for the steel boats. Indeed, the length decreases from 24.8 m to 24 m and to 23 m for increasing payload at a service restriction constant and equal to 2. For a constant payload of 10 tonnes, the steel boat length decreases from 24.8 m to 22.6 m. When the material selected changes from one material to another e.g. from steel to aluminium or aluminium to GRTP, the length of the boats tend to increase and this is followed by a decrease of length until a new material change. Overall the length of boat is relatively constant over the design domain considering the very large changes in payload and service restrictions.



(a) Energy



(b) Boat length

Figure 7.20: Energy value and boat length for 1230 kW and 23 m/s

Figure 7.20 shows the result for another set of parameters: 1230 kW and 23 m/s. It shows the same kind of pattern which is representative of the present model, for the least demanding conditions steel has the lowest energy level and therefore is selected, for the more demanding condition GRTP has the best results, and aluminium is suited for the more intermediate conditions.

Figure 7.20 presents the results in terms of life cycle energy and boat length. In figure 7.20 (a) energy level are within a much closer interval than in figure 7.19. It shows that from power/speed set to set, the overall energy requirement can vary considerably (in the first figure GRTP SEC is equal to 1900 GJ and in the second to 1100 GJ). In this case the result on the boat length shows the same pattern as in figure 7.19 demonstrating the reproducibility of the approach.

7.4 Conclusion

The key aspects of material selection are to be able to judge which solution is the best. However it has been seen in the critical review of previous research that many solution can be considered as equivalent (solution with on the same value function line as described by Ashby [58, 10]). The interaction between design and mechanical properties, shape possibility and manufacturability are very important in order to assess the best material.

It has been seen in the present chapter that not only is it possible to find equivalent solutions with regards to fuel consumption but it showed that using the LCA standard allows one to broaden the design paradigm to better assess material and take advantage of their specific life cycle energy consumption and specific mechanical properties.

In this case the materials are not selected strictly on their intrinsic performance but on their ability to provide a solution within the boat design model. This is the case of steel. Indeed, it requires little energy to be manufactured and should be a natural choice when it comes to build a boat. However, if the design starts with a fixed geometry, materials with a higher specific strength are better suited to limit the life cycle impact as it is the fuel consumption that is the most discriminating factor (see chapter 6). In the least demanding conditions, boats in steel can be designed with a length similar to other materials for the same power and speed. This goes against common practice to build small boat in light weight composites. However, with the introduction of energy impact as part of the design criteria this percieved opinion is reversed with small boats in steel and larger in composites.

The boat synthesis is the last design implemented in the incremental approach defined in the modified LCA framework. The following summarises the work conducted and highlights the contribution of the boat synthesis to the modified LCA framework.

1. The grillage demonstrated that incorporating design in LCA allowed the definition of the relevant functional unit in order to measure the performance of each candidate material. Each grillage was designed according to the material property. The relevance of integrating design was supported by Xu et al [21] and Song et al. [22]. The impact inventory and figure validation is conducted during the grillage study that is the least complex design. It showed that the impact results were close and that it was possible to further investigate the influence of design

on the environmental impact.

2. The boat with fixed topology showed that a change in design would result in different resut. The boat study showed that fuel consumption was by far the biggest impact and that the material with the highest specific mechanical properties are the best. However, it shows it ignores the specific environmental properties of material and any material with a high specific

3. The boat synthesis is not a suitable design candidate for the first study in the modified LCA framework because it was to extensive. Indeed, the energy value collection is time consuming and the amount litterature reviewed to gather all the relevant information can be seen in appendix A. Conducting both design optimisation and impact inventory activities at the same time would be uncertain. Moreover, it is not possible to defined the design constrains i.e. constant fuel consumption and weight minimisation without the boat study. The boat synthesis position in the modified LCA framwork iTherefore, the modified framework allows to integrate very complex design requirement in LCA.

The modified LCA framwork gives a structured method to investigate material selection for complex structures. The work conducted in the present research demonstrates that integrating design in an LCA study provide results. These results can be the basis of highly optimised structure with regards to environmental impact.

Chapter 8

Conclusions

8.1 Discussion

The goal of the research was to study the environmental performance of materials for structural applications. The LCA methodology was chosen to provide a solid and well documented framework upon which to build the research. The literature on LCA is rich and the approach chosen for the present research could be compared with work from other authors. Early in the research however, the extreme complexity of the environmental impact model, the lack of transparency of the database to the non specialist, and the data missing for GRTP life cycle and manufacturing process lead to the development of an energy database for the purpose of the present work. The energy database shows the complexity for the selection of alternative material production routes but adds to the present model a transparent information database and the justification for the selection of specific material related values. The research had four main steps:

Definition of the LCA framework: The objective was to develop a reusable framework for material selection using LCA. A modified LCA framework incorporating structure design was studied. In this framework four materials were evaluated. Three designs were chosen to be investigated using the same impact assessment method and same environmental impact figures: a grillage, a boat with fixed topology and a boat synthesis. These three artefacts were chosen so that the complexity of their design increased in an incremental manner. It followed the increase in knowledge about each candidate materials, design itself and LCA. The critical analysis played an important role in order to organise the change in design constraints. The boat with fixed topology took into account the result of the grillage and the boat synthesis took into account the result of the two first studies in order to overcome their limitations while providing a more precise and better optimised design. The functional unit definition was a key aspect of the framework. The quantity of material required to fulfil the design requirements was used as the functional unit. The flow of material, energy and fuel for the life of the functional unit of each structure was investigated. The definition of the functional unit varied slightly for each design. For the boat 6, the quantity of material and fuel consumption was given per annum and for the other structures only the quantity of material was taken into account. The following are the detailed result of the three structural artefacts.

The grillage study: this study gave the first insight on the interaction between specific mechanical properties, specific environmental properties and a design algorithm in the context of a material selection. The collation of life cycle energy values highlighted that there is a large difference of SEC values between the candidate materials. This difference demonstrated that there was potential for a selection based on environmental impact criteria.

The study showed that the specific stiffness and specific environmental impact would be key for the selection of a material but the structural model was not relevant enough to material selection in boat building as it ignored completely in service life aspects for example fuel consumption. The result of the modelling showed that recycled metal alternatives demonstrate a lower impact than the intensively used composites.

The study of a boat with a fixed topology: the introduction of a new design model for the four materials overcame the drawbacks of the grillage model. However this boat design model neither took into account the specific properties of each material in terms of their mechanical properties nor their environmental properties at the design stage. It shows that the specific strength was the most significant parameter. Indeed, the higher the specific strength, the lower the weight of the boat and therefore fuel consumption. The critical review of the grillages and boat study showed clearly the influence of the design model on the life cycle performance and selection criteria.

In the context of the modified LCA framework presented in chapter 4 the results were interpreted, as required in the original LCA framework as seen in figure 3.3, in order to select a design model better adapted to the present research on material selection. This new approach to LCA critical review gave a new scope to the application of LCA in boat design and in engineering in general by focusing on the adaption of a design model to an LCA study.

The study of a boat synthesis: the design approach for this study required the fuel consumption to be fixed. The development of a new model approach showed that it was possible to design a large number of boats for all the candidate materials using a new design paradigm. The result confirmed that the careful selection of the design modelling for the LCA study can better highlight the candidate material's specific environmental properties in a contextual design. It showed that recycled steel was the most environmentally friendly solution but was suitable only for a limited design domain whereas GRTP would be very suitable for design where neither steel nor aluminium could be used.

This result showed that material can not only be chosen for a specific application leading to preconceived material choice e.g. the quasi automatic selection of composites for boats, but that their specific environmental properties can be the base for a design provided that this design respects some life cycle criteria.

8.2 Specific contributions to the subject

The work conducted contributes uniquely in the field of the LCA applied to material selection for marine applications. Though LCAs have been applied to ships and shipping, its implementation for the selection of materials and processes at an early stage of design is new. It must be mentioned the LCA framework used in the present research can be applied to any engineering artefact because many aspect of design covered in the present research are not unique to marine structures but common to any design. The novelty of the work includes the four following areas where no significant publications have been published:

A The main output was the creation of an LCA framework incorporating design aproaches for material selection. In this framework LCA and boat design are interacting in giving a functional unit value used to measure the performance of each candidate material. The framework reusability was demonstrated by the study of three designs in the order of increasing complexity were conducted during the research showing that each of them was useful in assessing the four materials. The design took into account the requirements for material selection in boat design when environmental impact is the main focus. It includes in the design all the major materials used in boat building as well as GRTP and the design specification evolved with the conduction of the LCA.

B The collation of information for use within the LCA framework was conducted and the data presented in tabular form in Appendix A. The life cycle impact collection highlighted the difficulty in the use of commercial databases. It was suitable for the design aims and the objective of the present research and life cycle scenario could be derived from the collection of information. This information, readily available, allows the framework to be extended to other applications.

C The framework presented was successfully applied to a material selection problem. The model shows the advantage GRTP over other material as it is a more flexible material than its metal alternative in the context of LR-SSC rules as it provides a solution in a much larger design domain than steel and aluminium even though its environmental impact is higher that these two metals. The life cycle model showed that materials are mainly selected based on the specific energy consumption and specific mechanical properties. Steel can be selected for part of the design area as its adaptation to a design to life cycle took into account its good environmental performance.

D The critical review of the outcome of the first two application of the new LCA framework created an opportunity to study boat structure with a novel approach. The design of the boat is adapted to design working principles derived from traditional approaches to marine structure showed that geometry and power calculations can be adapted to new design objectives for a significant amount of the design space. This new approach is therefore possible and design to a better life cycle should be investigated because it is not limited to a small design domain, but to range where it can be possible to take advantage of material environmental characteristics.

Chapter 9

Further work

Further work could be conducted on the four following aspects:

The addition of new impact model and the influence of a weighting process : Indeed the material selection could gain in having a more precise approach. In addition, the introduction of new environmental impact factors leads to the need for a weighting approach. This is probably a very important aspect as the design to life cycle can without any doubt be part of the material.

A better life scenario in which life uncertainties are better taken into account : The paper of Latorre [76] highlighted that the life of boat may be more complex and a reliability study may be required if any boat requirement changes. Indeed if the speed increases ever so slightly, the GRTP boat may be more attractive because they are always lighter.

The implementation in term of cost : In the present research the cost were assumed to be similar for each material. It is expected that the cost of manufacturing with steel and aluminium would be higher and more labour intensive. However the cost in service can be considered as relative similar because it is possible to make the fuel consumption constant for each candidate materials. In addition the real cost of dismantling a boat is not really well known but at least the cost in service due to the fuel consumption is constant for the four alternatives

The analysis of uncertainties in the design : The model presented in chapter 7 is relatively simple. It is possible that some more work could be considered on assessing the seaworthiness of each boat. In this case it is possible that more steel, aluminium, GRTS or GRTP could have been accepted or rejected. In addition the boat geometry and interior change for each candidate material and some design may not be accepted by the customer.

Appendix A

Detailed energy information inventory

The present appendix presents the information collected in the context of the modified LCA framework (figure 4.1) for the life scenario selection and the energy impact allocation (box 4a and 4b of figure 4.1). It covers the life cycle stage of the four studied materials for the life cycle stage described in figure 4.1 box 3. The specific energy consumptions (SEC) are given per unit of length or weight independently of any structural implementation.

A.1 Information inventory methodology

For each material and each life cycle stage, SEC information was collected and presented in tabular forms (see tables A.1 to A.8). These tables cover a large selection of processes, each of them are possible process alternatives during the life cycle of a marine structures. When processes are related or very similar, the table for several life stage or for several materials were merged e.g. the steel manufacturing and steel recycling are merge in a single table and so are GRTS and GRTP manufacturing. The analysis of these information follows the sequence:

A **Process description**: The life cycle and the relationship between processes and subprocesses are described in general terms

B **Possible life stage scenario statement**: From the collected set of information, some data can be grouped or opposed in order to described coherent possible life stage sets of process alternatives. It defines also which figures can be used in the LCA.

C **Best life stage alternative selection**: The aim of the present research is to find the material with the most efficient life cycle impact when implemented in a marine structure. It requires to select for each life cycle stage the best set of processes that have the lowest energy impact. The list of the best life cycle stage set of processes is the life scenario (figure 4.1 box 3)

D **SEC figure implementation**: Within the top to bottom approach of the modified LCA framework, collected information are first used in parallel with the life cycle scenario definition (figure 4.1 box 4a) and after the value for the process is calculated for the functional unit (figure 4.1 box 4b). This section deals on the figure implementation guidance.

E **Critical review**: The limitation of the collected values and their implementations in the energy impact are discussed in order to ensure the credibility of the LCA.

A.2 Steel manufacture and recycling

Information inventory part A: Process description

Steel marine structures generally require large amount of mild steel (low alloy steel). The table A.1 shows the SEC for the manufacture and recycling of mild steel. This kind of steel can be produced either from primary resources or recycled from scrap.

- Primary steel can be manufactured in two ways: *conventional Blast Furnace (BF) and Basic Oxygen Furnace (BOF)* and requires prepared ore and coke and from *Direct Reduced Iron (DRI)* using iron ore and steam coal or natural gas. DRI are converted into steel in Electric Arc Furnace (EAF). The finish always follows the sequence: casting, hot rolling and cold rolling (if thinner products are required)

- Recycled scrap can be processed in BOF up to a furnace content of 30% taking advantage of the energy release during the conversion of liquid iron with the injection of liquid oxygen or in EAF where scrap are melted and refined. The finish follows the same sequence than for primary steel

Information inventory part B: Possible life stage scenario statement

Steel is by far the world most produced metal [107]. It requires extremely heavy equipments and it is responsible for a large amount of pollution of any kind. Hence it is widely monitored and resulted in a large amount of scientific and public literature. It is mostly published per country. It is difficult to generate a realistic SEC by adding subprocess figure from different sources because of calculation assumption. Lenzen et al. demonstrated [94] the variability of such a calculation. The selection of the best process is to be done within the global steel value given per country (line 28 to 40 of table A.1)

Information inventory part C: Best life stage alternative selection

Figures from each country converge to the conclusion that recycled steel is the most energy efficient steel available on market. The SEC of recycled steel is difficult to assess because the energy recovered in BOF for the recycling of steel is considered as zero. It is assumed that the SEC of recycled steel is the SEC for steel in EAF. UK steel figure from Michaelis [108] is chosen as UK is one of the most efficient and is locally produced.

Information inventory part D: SEC figure implementation

As for most products of heavy industries, steel can be only purchase from stockholders. It is not possible to purchase a material manufactured from a given technology. This is the involvement in the collection of scrap that decides the allocation of the SEC value. 100% of scrap collected the value for UK recycled steel[108] is taken. Conversely, if no effort on collection is done the UK value for primary steel [108] is used.

Information inventory part E: Critical review

The SEC figure from Michaelis [108] is derived from exergy analysis which is different from the actual energy by 5% at most. This is regarded as accurate enough considering the large uncertainties on the SEC calculation.

A.3 Manufacturing with steel

Information inventory part A: Process description

Raw steel semi products such as plates and sections are usually marked, cut and welded into marine structures in the manufacturer facilities. Marking SEC is assumed to be negligible. Table A.2 shows the SEC for the cutting and welding of steel. It presents a selection of the most current processes. Sawing, oxy-cutting, laser, plasma cutting and waterjet are the selected cutting methods.

Metal Active Gas (MAG), Metal Inert Gas (MIG), Tungsten Inert Gas (TIG), plasma welding, shielded electrodes welding, carbon arc welding and oxyacetylene are the selected welding methods.

Information inventory part B: Possible life stage scenario statement

The selected processes are benchmarked for a 5mm thick 1 metre cut or weld. For each process the calculation of the SEC derived from the process specification from Cary's Modern Welding Technology [93] or commercial literature from Thermal Dynamics, Flow Corp. or Trumph. The resulting electrical power is multiplied by 3 in order to take into account the loss in conversion from primary resources such as natural gas to electricity.

Information inventory part C: Best life stage alternative selection

Oxycutting is the most efficient cutting process and as it is portable it can be used for manufacturing but also repair and dismantling. CO_2 MAG is chosen because it is one of the most efficient and fastest process. It is portable then it can be used for manufacturing and repair. Oxyacetylene is ignored because it is a slow and very manual. Fine wire MAG welding is ignored because with increase in material thickness it requires a lot more passes to do the weld than CO_2 and ultimately it requires more energy. For the 5mm thickness however the two methods are similar.

Information inventory part D: SEC figure implementation

Oxy-cutting requires very little energy in comparison with CO_2 welding. It is ignored in the LCA impact assessment. Chart A.1 shows the SEC for one metre of weld in two welding configuration as a function of the thickness for CO_2 welding.

Information inventory part E: Critical review

The input used for all these processes have all the same industrial quality (gas, electrodes, power supplies, etc.) on the contrary of steel manufacture where the ore quality may differ from a country to another and requires technology adaptation. For this reason it is assumed the value calculated from a limited batch of sources remains accurate enough for the purpose of the present research.

A.4 In service

Information inventory part A: Process description

Although steel, and aluminium and composites do not used the same paint system, the reasoning for the two set of material is similar. Table A.3 shows the energy consumption for the in service input of steel and Table A.3 shows the energy consumption for the 3 other materials. Only paint is presented as it is just a function of the surface. Repair is also an in service issues. It is assumed that over the life of the structure 10% of the material is replaced. The fuel consumption in the case of boat does not appear in the present table because it needs in depth calculation of the propulsion resistance and does not depend on design parameter such as weight, length of weld surface, but require technical choice such as engine selection.

Information inventory part B: Possible life stage scenario statement

The value derived from the commercial literature from International Paint. It defined the paint system required in the case of a boat. The system for this company is comparable in thickness and configuration with other companies such as: Sigma, Sikkens, Marclear, Seajet.

Information inventory part C: Best life stage alternative selection

The paint SEC calculation is conducted considering the paint as epoxy only ignoring additive such as aluminium.

Information inventory part D: SEC figure implementation

The SEC is implemented from the table A.3.

Information inventory part E: Critical review

The approximation about the paint composition is acceptable because the alternative paint systems for the other materials are about the same thickness and composition. This approximation does not bring any advantage to any material toward another then the LCA consistency is kept.

A.5 Aluminium manufacturing

Information inventory part A: Process description

Aluminium is the second most produced metal in the world [107] far behind steel. Aluminium is mostly used alloyed and the studied marine structures require marine grade alloys. The table A.5 shows the SEC for aluminium regardless any alloying. Aluminium can be produced from natural resources or recycled from scrap:

- Primary aluminium is produced from bauxite (alumina ore) which is incorporate into slurry, refined and concentrated in pure alumina through Bayer process for higher grade of ore or a combination of Bayer and sinter process for lower grade of ore. The alumina is converted in melted aluminium through a smelting process using prebaked carbon electrodes. The material is then continuously cast into slabs and then rolled or extruded.
- Recycled aluminium is produced from sorted scrap in furnace with the addition of fluxing salts which agglomerate impurities and oxides in slags. The outcome is cast, rolled and extruded.

Information inventory part B: Possible life stage scenario statement

Aluminium is a large consumer of electricity and a fast adapting process. The selection can be done on smelting technology value but the variability is relatively small and each manufacturer of aluminium tends to upgrade the tools quickly. The main variation takes place in the refining or alumina process because of the unequal quality of ore but the selection of an aluminium cannot be done on ore basis. Liu [109] et al. review showed that European countries produced aluminium from higher grade of ore resulting in a lower energy consumption. The selection is done on a country basis from global values.

Information inventory part C: Best life stage alternative selection

There is very little published on SEC of recycling aluminium. However recycled aluminium consumes a lot less energy than primary. The UK value from Hammond [110] is taken for the study. This result is in the same range of order than figures from other sources. There is no evidence that marine grade aluminiums are produced in the UK.

Information inventory part D: SEC figure implementation

The same reasoning than steel applies for the allocation of energy values. Both recycling and primary aluminium SEC figures are chosen from [110].

Information inventory part E: Critical review

Aluminium is always alloyed and it is present in a large variety of application in various grades. The representativeness of general purpose aluminium is an uncertainty because it means most of the time packaging aluminium. Little is published on specific aspects of marine grade aluminium and indirect SEC contribution of processes during the manufacture of those alloys.

A.6 Manufacturing with aluminium

The method adopted in the information inventory of manufacturing with aluminium is similar to the method for manufacturing with steel.

Information inventory part A: Process description

As with steel, semi products such as plates and sections are usually marked, cut and welded into marine structures in the manufacturer facilities. Marking SEC is assumed to be negligible. Table A.5 shows the SEC for the cutting and welding of aluminium. It presents a selection of the most current processes. Sawing, laser, plasma cutting and waterjet are the selected cutting methods while Metal Inert Gas (MIG), Tungsten Inert Gas (TIG), plasma welding, laser beam welding and Friction Stir Welding FSW the selected welding methods. The welding of aluminium remains more technical and heat sensitive than the welding of steel.

Information inventory part B: Possible life stage scenario statement

The selected processes are benchmarked for a 5mm thick 1 metre cut or weld. For each process the calculation of the SEC derived from the process specification from Cary's Modern Welding Technology [93], commercial literature from Thermal Dynamics, Flow Corp. or Trumph and scientific literature for laser beam welding and FSW. The resulting electrical power is multiplied by 3 in order to take into account the loss in conversion from primary resources such as natural gas to electricity.

Information inventory part C: Best life stage alternative selection

The best cutting process is waterjet. It is not portable then when it is required, e.g. repair, plasma cutting is used. FSW is the most efficient welding alternatives. The portable alternative is the plasma arc welding.

Information inventory part D: SEC figure implementation

Chart A.2 shows the SEC for 1 metre of cut in two welding configuration as a function of the thickness for waterjet and A.3 show the SEC for the energy for plasma cutting.

Information inventory part E: Critical review

The same comment than for the manufacturing with steel apply. However the FSW SEC is difficult to assess as very little has been published. It is more and more used especially in marine structure but it is more customised than for other welding equipments. The energy derived from the laser beam calculation considering that it is 40 times less energy intensive. This approximation does not impair the result because the energy requirement is low in comparison to the cutting requirement for the manufacturing and dismantling.

A.7 Composite material manufacture

Information inventory part A: Process description

Table A.6 shows the value of energy consumption for the two composite material studied in the present research. Epoxy is thermoset resin product through the chemical reaction of sub product of cracked oil and brine. Epoxy stands as a raw material as two separate liquids, epichlorohydrin and bisphenol-A. When mixed these two materials polymerises into a hard polymer. PP is a thermoplastic which is the result of the polymerisation of propene. It is processed in its liquid form which is obtained at about 200 ° C. Glass fibre is the result of the spinning of melted silica and other minerals.

Information inventory part B: Possible life stage scenario statement

The collected SEC for both PP and epoxy shows a lack of consistence in comparison with aluminium and steel. The two main reason for the differences between the number are:

- The lack of boundary between raw material and finished product for polymer. Ideally energy figures needed for the present research should be the energy consumed up to the door of the marine structure factory. However this kind of figure is not of any use for plastic manufacturer associations or for the society in general in order to communicate about their environmental performance. The boundary between raw material manufacturer compounder and industrial product manufacture is unclear then polymers are mostly studied in their final form instead of pellet or liquid thermoset. The polymer product range is huge and for epoxy can be used in paints, adhesives, composites in which reinforcement and filler content may change from an application to another and which curing can take place in an oven or not. The same range of application applies to PP. It demonstrated that it is difficult to describe the SEC of a product outside its application and manufacturing process and it interferes with the need of the present research.
- Some SEC figures do not include the feedstock energy. This is the case of the 29 GJ/t for epoxy where only the actual material manufacture strictly speaking is taken into account leaving aside the contribution of the oil that create the polymer chain. This oil does not create any pollution when not burnt out. However, in the present research, it is assumed that when a marine structure reached its end of life and is incinerated, the resulting energy is subtracted from the overall LCA energy result. If the oil in the chain is not included SEC after incineration, the consumption over the life of the product would be close to zero (feedstock contribution are about 40 GJ/t) . If the structure is not incinerated then the potential energy stored in the polymer chain is wasted. The polymer SEC figures should be those that include the feedstock SEC and that are generally above 70 GJ/t.

The mean value of all the collected value is excluded because the difference in number reflect a wide range of reason. The mean of Ashby's figure [97] are chosen for the calculation of the SEC of composites because they are supplied with a material selection aim, the steel and aluminium values in this database are very close to the value chosen in the present research and they are in the range of order of the figure from other sources.

The mean value of 44 GJ/t of glass is chosen because of the lack of information about how the values are calculated and for which processes they are calculated.

Information inventory part C: Best life stage alternative selection

There is no alternative.

Information inventory part D: SEC figure implementation

The figure is implemented directly from the table A.6.

Information inventory part E: Critical review

Composite materials do not exist in a raw material form but only in its processed form e.g. a boat hull. For this reason the energy the boundary between material and final is unclear and affect the information collected in the literature. The SEC figure is calculated from a very sparse knowledge. The uncertainties on the manufacture of composites are high but the value are generally in the same range of order. The comparison between the two composites however should be relatively accurate as the SEC figures are collected with the same method.

A.8 Composite materials end of life

Information inventory part A: Process description

The processes involved in the end of life of composites are defined in table A.8. They are described in section 2.3.1.

Information inventory part B: Possible life stage scenario statement

Recycled material cannot be used for such a structurally demanding marine structures. The recycling consists to create product that are valuable to other industries. The recycling processes SEC is then added to the impact result of the LCA. Marine structures are first shredded and processed.

Information inventory part C: Best life stage alternative selection

Incineration is the most energy efficient method to reduce the impact energy over the life of marine structures.

Information inventory part D: SEC figure implementation

- Each structure is shredded with a SEC defined in table A.8
- Each kg of polymer incinerated releases 30 MJ [49]. This figure can be subtracted from the LCA energy impact.
- The mechanical recycling of GRTP creates 1.5 kg of new material for a SEC of 59 GJ/t that is added to the LCA energy impact.
- All other processes aiming to recover fibre are considered to have neutral SEC and as for incineration the energy released just maintain the process running. They have a beneficial impact in terms of waste management.

Information inventory part E: Critical review

The end of life treatment of composites is very beneficial in terms of waste management but it does not appear in any way the LCA results. It shows the limitation of LCA based only energy which ignored some environmental benefit of solution. The requirement for virgin material creates ultimately waste that at most can be reused in other shapes but a closing loop, such as the one of metal, is far to be reached with the recycling of composites.

Table A.1: Steel resource treatment, material manufacture and recycling

Nb	Process	Input	Ouput	associated proc	SEC	Collection	Ref	Comment
					Raw material extraction			
1	Iron ore extraction	Rock	Usable ore	Mining	0.2 GJ/t	1998, UK Exergy analysis	[108]	The iron extraction depends of the quality of the deposits.
2	Coal extraction	Rock	Coking coal	Mining	0.1 GJ/t	998, UK Exergy analysis	[108]	The conventional coal (steaming coal) can be used in DRI
					Raw material preparation			
3	Iron ore refining	Ore	Sinter	Sintering	0.56 GJ/t	1994, USA from country overall energy consumption	[111]	Agglomeration of the ore
4				Sintering	2.3 GJ/t	1994, Japan statistic estimation	[112]	
5				Sintering	1.6 GJ/t	1998, UK Exergy analysis	[108]	
6				Pelletising	2.1 GJ/t	1994, Japan statistic estimation	[112]	
7	Coal preparation	Coal	Coke	Cokering	1.4 GJ/t	1994, USA	[111]	
					Pig iron / Sponge iron manufacture			
8	Blast furnace	Iron ore + coke	Pig iron		12 GJ/t	1994, USA	[111]	
9					13 - 19 GJ/t	2001 (paper year), Global average	[113]	Average value found over the world
10					14 GJ/t	1994, Japan statistic estimation	[112]	
11					4.1 GJ/t	1998, UK Exergy analysis	[108]	
12	Direct reduced iron	Iron + conventional fuel	Sponge iron		11 -17 GJ/t	2001 (paper year), Global average	[113]	Sponge iron is often called artificial scrap and is refined in EAF
					Steel manufacture			
13	Open earth furnace							Obsolete
14	Basic oxygen furnace	Pig iron and 0 to 30% Scrap			0.7 - 1 GJ/t	2001 (paper year), Global average	[113]	
15					0.4 GJ/t	1994, Japan statistic estimation	[112]	
16					1.5 GJ/t	1998, UK Exergy analysis	[108]	
17	Electric arc furnace	Scrap or sponge iron	melted steel		4 - 6.7 GJ/t	2001 (paper year), Global average	[113]	
18					5.5 GJ/t	1994, Japan statistic estimation	[112]	
19					2.3 GJ/t	1998, UK Exergy analysis	[108]	
					Finishing			
20	Continuous casting	Melted steel	crude steel		GJ/t			
21					0.8-1.2 GJ/t	1998, UK Exergy analysis	[108]	The value depend whether the steel originated from BF-BOF or EAF. In the case of EAF the author noticed that the slab is thinner and require less energy to be finished
22	Thin slab casting	Melted steel	finished steel		0.6 - 0.9 GJ/t	2001 (paper year), Global average	[113]	It avoids the needs for finishing however there is no information about to suitabillity to ship building
23	Ingot casting	Melted steel	crude steel		1.2 - 3.2 GJ/t	2001 (paper year), Global average	[113]	Tends to be obsolete due to high energy consumption
24	Hot rolling	Crude steel	Finished product		2.3 - 5.4 GJ/t	2001 (paper year), Global average	[113]	Hot rolled steel are suitable for marine structure
25					4.2 GJ/t	1994, Japan statistic estimation	[112]	
26					4.2 GJ/t	1994, Japan statistic estimation	[112]	
27	Cold rolling				1.6 - 2.8 GJ/t	2001 (paper year), Global average	[113]	Larger decrease in thickness than hot rolling
					Global			
28	100% primary and cold rolled steel				21 GJ/t	2002, The Netherland, Collection initiated by the Dutch government	[114]	Most efficient primarry steel producer
29	Primary steel				26 GJ/t	1994, USA	[111]	Detailed review aiming to energy reduction
30	Recycled steel				12 GJ/t			
31	Average market steel				21 GJ/t			
32	Average market steel				32 GJ/t	1991, Brazil	[115]	The higher value are due to both a lack in structure efficiency (percentage of EAF and BOF) and efficiency in energy consumption
33	Average market steel				42 GJ/t	1991, China		
34	Average market steel				24 GJ/t	1991, France		
35	Average market steel				18 GJ/t	1991, Germany		
36	Average market steel				21 GJ/t	1991, Japan		
37	Average market steel				28 GJ/t	1991, Poland		
38	Average market steel				27 GJ/t	1991, USA		
39	Average market steel				24 GJ/t	1994, Japan statistic estimation	[112]	
40	Primary steel				22 GJ/t	1998, UK Exergy analysis	[108]	
41	Recycled steel				8.6 GJ/t	1998, UK Exergy analysis	[108]	
40	Primary steel				23 GJ/t	2006, Australia	[107]	

Table A.2: Steel manufacture

Nb	Process	Input	SEC	Collection	Ref	Comment
			5 mm steel plate cutting			
1	Oxygen cutting	Oxygene + heating gas (acetylene,propane, etc)	250 kJ/m	Energy for the production of oxygen	[116]	This is the lowest energy consumer. The process is highly portable and can be use in manufacturing, repair and dismantling. The energy form the heating gas is ignored
2	Plasma	electricity + pulsed air	88 MJ/m	Commercial literature	[117]	It is assumed that energy consumption varies little from a manufacturer to another
3	Laser	Electricity + pulsed nitrogen	42 MJ/m	Commercial literature	[118]	The process is efficient but not portable
4	Waterjet	water + abrasive + electricity	2.5 MJ/m	Commercial literature	[119]	Very efficient alternative, but not portable and creating waste.
			Steel profile cutting			
5	Oxygen cutting		negligible		[116]	
6	Sawing	circular saw or band saw	negligible		[120]	Extremely efficient. The example of machine is given in Corus website (Kaltenbach ltd saw).
			5 mm steel plate and profile welding			
7	CO_2	CO_2 + Electricity	2.4 MJ/m		[93]	Fast and energy efficient but can only be used of flat joints
8	Spray	Argon +5% O2 , electricity	3.8 MJ/m		[93]	Flat and horizontal joint
9	Shielded metal	Covered electrode (E6011 for the use on site for repair fillet and E6012 for the plate) + electricity	18 MJ/m^2		[93]	This process is highly portable and can be used on site repair
10	TIG	electricity + inert gas	130 MJ/m		[93]	Low deposition rate
11	Plasma arc	electricity + inert gas	65 MJ/m		[93]	Very similar to TIG, high weld quality and higher deposition rate
12	Carbon arc	Electricity and electrode	- MJ/m		[93]	Obsolete and replaced by TIG or MIG/MAG
12	Fine wire	electricity + pulsed air	9.7 - 19 MJ/m		[93]	All position possible
12	Oxy acetylene	oxygen +acetylene	630 kJ/h		[93]	Very low energy consumption, highly portable but requires very skilled worker

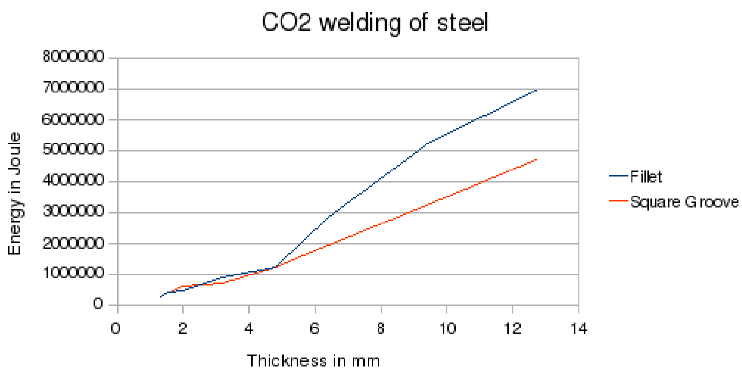


Figure A.1: Steel CO_2 welding energy consumption

Table A.3: Steel in service

Nb	Alternatives	Input	associated proc	SEC	Collection	Ref	Comment
1	Corrosion			0.4mm/year 63 MJ / m^2	Literature		Maximum corrosion rate
2	Surface preparation		Sand Blasting slurry Blasting Water blasting				No value of energy. Energy is considered however as negligible
				Painting			
3	Panel underwater	Intershield (250μm) 300		25 MJ/m^2	International paint data	[121]	Primer anticorrosive and abrasive control with aluminium. The aluminium is ignore for the calculation and only the epoxy part is considered as with an input as described in table A.6
4		Intersleek (125μm) 425		13 MJ/m^2	International paint data	[121]	Antifouling. The composition of antifouling is not know. It is considered as epoxy for the calculation. It has to be renewed every 5 years
5	Panel above water	Intershield (250μm) 300		25 MJ/m^2	International paint data	[121]	See above
6	Panel subject to wear	Intershield (250μm) 300		25 MJ/m^2	International paint data	[121]	See above
7		Intergard 740 (50μm)		5 MJ/m^2	International paint data	[121]	Hard wearing cosmetic coating

Table A.4: Aluminium resource treatment, material manufacture and recycling

Nb	Process	Input	Output	associated proc	SEC	Collection	Ref	Comment
					Raw material extraction			
1	Mining	Rock	Bauxite ore		0.3 GJ/t	2001	[122]	The quality and type of bauxite may differ from one deposit to another
2					0.4 GJ/t	2005, Worldwide	[63]	
					Raw material refining			
3	Alumina production	Any type of bauxite	Alumina	Bayer	18 - 30 GJ/t	2006, China and Europe	[109]	There is 3 type of bauxite whose alumina concentration differ from one site to another and chemical composition requires different treatment. It lead to significant difference from one process to another
4				Sinter	81 GJ/t	2006, China	[109]	
5				Combined	64 - 104 GJ/t	2006, China and Europe	[109]	
6					7 - 17 GJ/t	2001	[122]	Extremely optimistic value that reach lower value of [109]
					Aluminium smelting			
7	Anode production	Petrol coke + pitch + thermal energy	prebaked anode	baking	19 GJ/t	2005, Worldwide	[63]	The prebaked anodes are a consumable of the smelting process
8	Aluminium smelting (Electrolysis)	Alumina	Melted aluminium	Soderberg	180 GJ/t	1995, Worldwide	[122]	little difference between method. The quality of input (alumina) from one site to another is supposed to be constant (PB =Prebaked carbon anode)
9				CWPB	170 GJ/t			
10				SWPB	160 GJ/t			
11				PFPB	160 GJ/t			
12				PB	140 - 160 GJ/t	Oceania		Rio Tinto corporate information
					Aluminium recycling			
13	Pyrolysis	Contaminated scrap	Aluminium only contaminated with a film of oxyde		0	Germany	[123]	The organic contamination of the scrap is removed by pyrolysis. The energy produced is used to sutained the reaction.
14	Laser pain stripping	Painted aluminium	aluminium (The oxide film remains)		3.3 MJ/m^2	Laboratory scale work	[124]	Easy treatment of waste
14	Waterjet	Painted aluminium	aluminium (The oxide film remains)	with or without abrasive				difficult treatment of waste
15	furnace	Sorted, oxide film aluminium + salt slag		Rotary kiln				The amount of lost due to contamination and the waste to treat decrease with scrap cleanliness increase
					Finishing			
16	Casting	Melted aluminium	Aluminium slab	Ingot casting	2.4 GJ/t	2005, Worldwide	[63]	
17				Continuous cast.	2.4 GJ/t	Estimation from above		
18				Continuous chill				
19	Extrusion	aluminium slab	extruded profile		16 GJ/t	2002, Experimental work	[125]	The extrusion ease of aluminium allows a large shape flexibility with higher stiffness to linear length ratio
20	Temper	Aluminium	Tempered aluminium					The suitable temper are H111, H116, H32, H=strain hardening. The three hardening are cold worked treatment [126]
					Global			
21	Primary aluminium				165 GJ/t	2001, Germany	[123]	
22	Recycled aluminium				23 - 26 GJ/t	2001, Germany	[123]	
23	Primary aluminium				210 GJ/t	2007, Australia	[107]	
24	primary aluminium				220 GJ/t	2006, UK	[97]	
25	Recycled aluminium				17 GJ/t	2006, UK	[97]	
26	Average aluminium				150 GJ/t	2006, UK	[97]	
27	Recycled cast aluminium ingot				12 GJ/t	1997, Finland	[127]	

Table A.5: Manufacturing with aluminium

Nb	Process	Input	SEC	Collection	Ref	Comment
5 mm aluminium plate and profile cutting						
1	Laser	Electricity + nitrogen	28 MJ/m^2	Commercial literature	[118]	energy efficient but not portable
2	Plasma	Electricity + pulsed air	420 kJ/m^2	Commercial literature	[117]	Portable can be use on site
3	Sawing	Saw(circular or band) + electricity	≤10kj/m^2	Commercial literature	[120]	In shipyard use only
4	Waterjet	Water + abrasive + electricity	26 kJ/m^2	Commercial literature	[119]	highly efficient but not portable
5 mm aluminium plate and profile welding						
5	TIG	Electricity + inert gas	2.5 - 3.9 MJ/m^2		[93]	Low deposition rate
6	MIG	Electricity + inert gas	1.5 MJ/m^2		[93]	
7	Plasma arc	Electricity + inert gas	1.3 - 1.9 MJ/m^2		[93]	Deposition rate twice higher than TIG for the same input current
8	Laser beam	Electricity + inert gas	6.1 MJ/m^2		[128]	High energy consumption
9	Friction Stir Welding	Tool + electricity	0.15 MJ/m^2	Laboratory data	[129]	A rotating tool weld the two side of the joint in the solid state. Very high energy efficiency, clean and reliable production. Data from in-laboratory test. The FSW is claimed to use 2.5% of the energy required for the laser beam. The numerical value is based on the laser result.

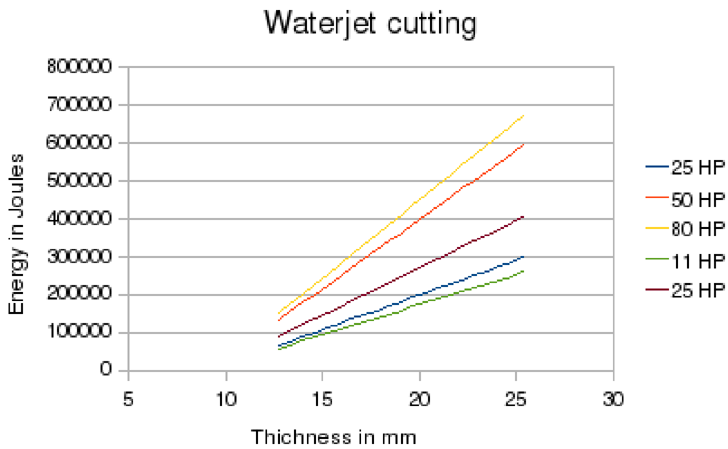


Figure A.2: Aluminium waterjet energy consumption

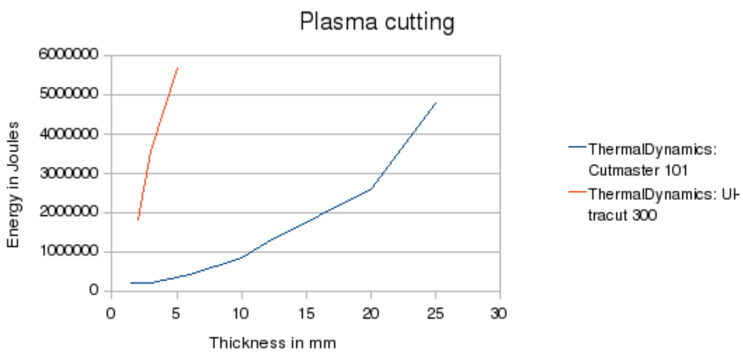


Figure A.3: Aluminium Plasma cutting energy consumption

Table A.6: Composites manufacture

Nb	Process	Input	Output	associated proc	SEC	Collection	Ref	Comment
					Raw material			
1	PP	Cracked oil	PP		101 GJ/t	2001	[64]	Propene is the monomere for the polymerisation
2					120 GJ/t	2005	[130]	Injection moulding
3					77 GJ/t	2004	[131]	
3					99 -120 GJ/t	2006	[110]	For misc. product. Higher value for injection
4					81 - 89 GJ/t	2006, Database	[97]	
5	Epoxy	cracked oil + brine	epychlorohydrine + bisphenol A		30 GJ/t	2001, Literature	[132]	By ignoring the feedstock contribution the SEC is very small. However in case of incineration it is more difficult to deal with the energy input
6					141 GJ/t	2004	[131]	Very large value showing the large difference between author
7					90 - 99 GJ/t	2006, Database	[97]	
8	E glass	Silica + additives	Glass fibre	Melting + spinning + preparation	48 GJ/t	2001	[64]	
9					28 GJ/t	2006	[110]	
10					55 GJ/t	2004	[131]	A very large number with an extremely large contribution for the mat fabrication
11	White glass				13 GJ/t	2005	[130]	In comparison packaging glass uses twice less energy
					Selection of material			
12	TWINTEX			60 % G.W.F.	60 GJ/t			For the marine structure
13	Epoxy / E Glass			41 % G.W.F.	74 GJ/t			For the mould manufacture according to TWINTEX [99]
14				50 % G.W.F.	70 GJ/t			For the marine structure
					Manufacture with composites			
15	Mould manufacture	5 mm thick mould			510 MJ/m^2			TWINTEX requirement
16	Mould manufacture	10 mm thick mould			1000 MJ/m^2			Industry requirement
17	Backing structure	Steel box section beam			98 MJ/m^2			Steel box 100x100, 3 mm thick steel box spaced of 800 mm.
18	Consumable	Cracked oil + other	Nylon	Vacuum bag	7 MJ/m^2			The thickness of the bag is
					Manufacture with composites			
19	GRTP and GRTS curing	Unconsolidated composites bagged up			430 MJ/m^2	Interpolation from exiting production item.	[133]	It is assumed that the limiting factor is not weight but surface to cure because it limit the amount of material to be processed in the oven. Moreover the comparison between weight of mould and structure is small compared to the
					Manufacture with composites			
20	Resistance welding	Metal mesh + electricity			126 kJ/m		??	700 W/m for 120 secondes at 50% charge. Suitable only for GRTP.

Table A.7: Aluminium and composite in service

Nb	Alternatives	Input	Output	associated proc	SEC	Collection	Ref	Comment
1	Panel underwater	Interprotect (200μm)			20 MJ/m^2	International paint data	[121]	Primer, energy calculated as epoxy layer only
2		Trilux(80μm)			8.1 MJ/m^2	International paint data	[121]	Antifouling. The composition of antifouling is not known. It is considered as epoxy for the calculation. It has to be renewed every year
3	Out of the water	Prekote (70μm)			7 MJ/m^2	International paint data	[121]	
4		Toplac (76μm)			7.7 MJ/m^2	International paint data	[121]	Interior finish coating
5	Deck	Interdeck (100μm			10 MJ/m^2	International paint data	[121]	Antiwear coating

Table A.8: Composites end of life

Nb	Alternatives	Input	Output	associated proc	SEC	Collection	Ref	Comment
					Dismantling			
1	Mechanical cutting		Processable scrap		-			mechanical cutting is usually a very low energy consumer. Suitable for both GRTS and GRTP.
2	Shredding	Tool + energy	Chips		920 MJ/t	1996, Japan	[55]	The chips are suitable for transport, reinforcement charges and incineration. The process studied is inspired from the process presented by Hedlung Astrom. Suitable for both GRTS and GRTP.
					Recovery			
3	Incineration	Shredded scrap	Energy and ashes	Regular combustion	30 GJ/t of resin		[50, 49]	The amount of ash is high. The incineration can be used for local heating, electricity, and cement production. The pollution released by this incineration is however higher than normal city waste. There is relatively little difference in energy release between plastic. Fire retardants do not impair the energy release.
4	Pyrolysis	Shredded scrap	Energy and ashes	Incineration is absence of oxygen	-			Recovery of the fibre. Heat tends to degrade the mechanical properties of glass fibre. Elementary can be theoretically recovered but the separation of this elements are difficult. The vapour can be used as a fuel and it is expected that the energy release just maintain the reaction as in the pyrolysis of aluminium (see table A.4)
5	Fluidised bed	Schredded scrap	Fibre	combustion under flux of medium temperature air	-		[50, 49, 48]	The controlled incineration allows a recovery of the fibre without large loss of properties because of the low temperature of the polymer removal. The control incineration allow a controlled incineration is not so much a problem for polypropylene. However it keeps the advantage of removing the ashes from the resin.
6	Solvent treatment	Solvent and scrap	monomer and fibre	-				Fibre and polymer are separated. In the case of epoxy is difficult to sort the resulting monemer. The recovery of the monomer is theoretically easier for GRTP as there is only propene
7	Mechanical recycling of GRTS	Shredded scrap + resin + reinforcement or charge	New composites	depends on the amount of virgin resin required	-		[49]	The amount of charge is limited to 20% in weight and requires a lot of virgin material. The shredded material goes through a hammer mill to reduce the size of the charge through a cleaning/ screening process. The mechanical properties of the resulting material are low.
8	Mechanical recycling of GRTP	Shredded scrap + resin	New composites	Compressive moulding or pelletising and injection	59 GJ/t		[64]	Scrap can be processed directly as raw material for compression moulding. The resin is optional but the very fibre content of the studied GRTP would require an addition of resin for better processing (40 % of fibre content is more common value for GMT like composites). It is noted that recycling of 1 kg of Twintex requires 500 g of PP then resulting in 1.5 kg of recycled material in which 1 kg is recycled

Appendix B

Lloyd's Register design algorithms

The present section describes how Lloyd's Register (LR) Rules and Regulations For Special Service Crafts were used to calculate the scantling from which the weight of the boat derive. The rules used were taken of the rulefinder software version 9.4 released in July 2005.

B.1 Nomenclature

L_R = rule length of the craft (m)
B = moulded breath of the craft (m)
Z = section modulus of the stiffener (cm3)
I = second moment of area of the stiffener (cm3)
A_W = shear area of stiffener web (cm2)
l= stiffener overall length (m)
l_e = effective span length (m)
P = design pressure (kN/m^2)
s = stiffener spacing (mm)
t_p = plating thickness (mm)
β = panel aspect ratio correction factor
γ = convex curvature correction factor
k_s = high tensile steel factor = $235/\sigma_s$
σ_s = guaranteed minimum yield strength of the material (N/mm^2)
$t_s = \frac{\sigma_s}{\sqrt{3}}$
E = modulus of elasticity (N/mm^2)
Φ_Z = section modulus coefficient
f_σ = limiting bending stress coefficient for stiffening member σ_s
f_δ = limiting factor coefficient
Φ_I = inertia coefficient
Φ_A = web area coefficient
f_t = limiting shear stress coefficient for stiffener member
d_w = unsupported web depth
f_w = fibre content by weight of the web laminate

B.2 Design load calculation

The calculation of the thickness of the boat plating and stiffener geometric properties is conducted with the load defined by LR. This load is the product of:

- The maximum pressure: this pressure selected from a range of phenomena derived pressure such as the impact related pressure, hydrostatic or hydrodynamic pressure, etc. (all these pressure are defined in section B.2.3)
- A product of safety factors: these factors depend on the operation type the boat is design for i.e. the operation water type or the boat type (fishing, patrol, or passenger boat)

B.2.1 Introduction

The calculation of the design load according to LR requires the use of numerous equations, variables and comparisons between results. The current research used only part of the very extensive LR's rules and the present section aims at explaining how the rules were interpreted and used. The articulation of these equations with each other is presented in a series of diagram. The presentation follows a 'top to bottom' approach. It reflects both LR's design algorithm hierarchy and the programmatical aspect of LR's rules implementation. Indeed the identification of this hierarchy of function was very useful in order to code the algorithm in a structure way.

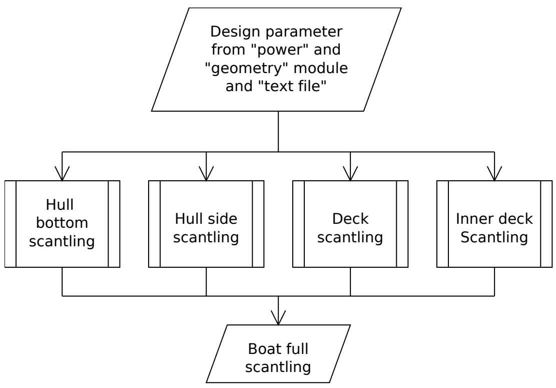


Figure B.1: Designed elements

Figure B.1 is the first level of the design algorithm which will be detailed in several succesive step. It highlights the input requires for the calculation of the boat scantling in chapter 7 for the boat synthesis. In Chapter ??, the boat with fixed topology follows the same rule. In the present case the full geometry is needed to do *the calculation of the design load*.

Figure B.2 shows how each component described in the figure B.1 is calculated e.g. hull side, hull bottom, etc. The figure shows the difference in approach between composite and metal structure.

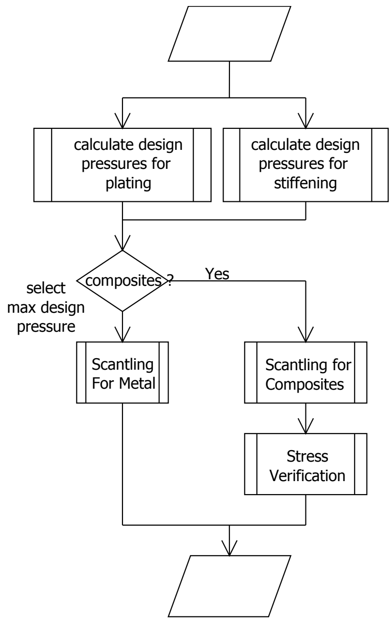


Figure B.2: Load calculation details

Figure B.2 shows that three types of load are needed to be calculated in the present research: the load at the bottom and side shell of the boat, and at the wet deck. The load at the coachroof deck, the interior deck, the deckhouses, the bulwarks and superstructure and the watertight and deep tank bulkheads are ignored. Only some boat element will be calculated in the present research: the load at the bottom and side shell of the boat, and at the wet deck. The load at the coachroof deck, the interior deck, the deckhouses, the bulwarks and superstructure and the watertight and deep tank bulkheads are ignored.

B.2.2 Detailled calculation of design pressure

The design load is defined in the present research as the maximum design pressure multiplied by the serie of parameters depending on the operation requirement. The design load are dealt with in the three sections of the following chapter of LR:

`Rules and Regulations for the Classification of Special Service Craft /`

`Chapter 3 Local Design Criteria for Craft Operating in Non-Displacement Mode /`

B.2.3 detailed equation

Table B.1 shows how the loading criteria are calculated by multiplying the calculated pressure by factor provided by LR.

Table B.1: Loading criteria

Criteria	Should be the greater of
Bottom shell plating	$H_f S_f P_s$ or $H_f S_f P_{dL}$ or $H_f S_f C_f G_f P_f$
Weather deck plating	$H_f S_f C_f G_f P_{wL}$ or P_{cd}
Stiffener bottom shell plating	$\delta_f H_f S_f P_s$ or $\delta_f H_f S_f P_{dL}$ or $\delta_f H_f S_f C_f G_f P_f$
Stiffener weather deck plating	$\delta_f H_f S_f C_f G_f P_{wL}$ or P_{cd}

Bottom shell and side shell are calculated in the same way but the result is different because of the position of the hull and the deadrise angle. The hull notation factor (H_f),the service type factor (S_f), the craft type notation factor (C_f) and the service areas restriction factor (G_f) are provided within the rules and regulations. The four pressures to be calculated are:

- The shell envelope pressure (P_s)
- The bottom impact pressure (P_{dL})
- The forebody impact pressure (P_f)
- The pressure on weather deck (P_{wL})
- The cargo deck design pressure (P_{cd})

The shell envelope pressure

For the calculation of P_s the shell envelope pressure, the hull needs to be divided in 3 separate area. The area under the waterline where the pressure is equal to the sum of hydrostatic (P_h) and hydrodynamic pressure P_w. The area above the waterline and up to the nominal wave limit where the pressure is equal to the P_d the weather deck pressure. The area from above the nominal wave limit up to the limit where the pressure is equal to half of the weather deck pressure.

$$P_h = 10\left(T_x - (z - z_k)\right) \tag{B.2.1}$$

Where T_x is draft and z the distance from the keel. P_w is taken as the greater value given by equation B.2.2 the left hand side describing the hydrodynamic pressure while the right hand side describing the pitching motion phenomena.

$$P_w = 10 f_z H_{rm} \quad or \quad P_w = 10 H_{pm} \tag{B.2.2}$$

Where f_z is the vertical motion factor, H_{rm} is the relative vertical motion.

$$f_z = e^{\left(\frac{2\pi T_x}{L_{WL}}\right)} + \left(1 - e^{\left(\frac{2\pi T_x}{L_{WL}}\right)}\right)\left(\frac{z}{T_x}\right) \tag{B.2.3}$$

$$H_{rm} = \frac{C_w}{K_m}\left(1 + \frac{k_r}{C_b + 0.2}\left(\frac{x_{WL}}{L_{WL}} - x_m\right)\right) \tag{B.2.4}$$

With

$$K_m = 1 + \frac{k_x(0.5 - x_m)^2}{C_b + 0.2} \quad ; \quad x_m = 0.45 - 0.6F_n \quad ; \quad F_n = \frac{0.515 V_m}{\sqrt{g L_{WL}}} \tag{B.2.5}$$

However x_m needs to be at least 2. The Froude number F_n uses $V_m = 2/3V$ with V (m/s) the speed. C_b is the block coefficient, L_{WL} is the waterline length and X_{WL} is the distance from the aft end of the boat. The wave head in metres is:

$$C_w = 0.0771 L_{WL}(C_b + 0.2)^{0.3} e^{-0.0044 L_{WL}} \tag{B.2.6}$$

For the pitching pressure, H_{pm} needs to be calculated:

$$H_{pm} = 1.1\left(\frac{x_{WL}}{L_{WL}} - 1\right)\sqrt{L_p} \tag{B.2.7}$$

However, H_{pm} should not be taken less than $0.6\sqrt{L_p}$. It should be noted that the nominal height limit H_w is equal to twice the relative vertical motion H_{rm}

The bottom impact pressure

The bottom impact pressure P_{dLb} due to slamming is equal to:

$$P_{dL} = \frac{f_d \delta \phi (1 + a_v)}{L_{WL} G_0} \tag{B.2.8}$$

f_d is the hull form pressure factor which is given in the regulations, G_0 distance between chines. If the boat is divided in 4 equal section, ϕ value would be 0.5 at L_{WL} from aft end, 1 at 75% of L_{WL} and 50% of L_{WL} and 0.5 at aft end.

The weather deck pressure

The pressure acting on the weather deck is equal P_{wL}. It should be noted that the P_d is equal to P_{wL} just above the under water area.

$$P_{wL} = f_l\,(5 + 0.01L_{WL})\,(1 + 0.5a_v) + \frac{0.7 + 0.08L_{WL}}{D - T} \tag{B.2.9}$$

f_L is a location factor equals 1 from aft to 0.88 L_R, 1.25 from 0.88 L_R to 0.925 L_R and 1.50 from 0.925 L_R to forward end.

$$a_v = 1.5\theta \frac{L_{WL}B^3}{B_W\Delta}\left(\frac{H_{1/3}}{B_W + 0.084}\right)(5 - 0.1\theta_D)\left(\frac{V}{\sqrt{L_{WL}}}\right)^2 \tag{B.2.10}$$

The ratio L_{WL}/B_W is to be larger than 3. B_W is the breadth of the hull between the chine tangential point. Δ is the displacement, Θ_D deadrise angle at LCG ($\Theta_D < 30°$), $H_{1/3}$ is the design significant wave height.

The forebody impact pressure

P_f is the greater of P_{dLs} (equation B.2.11) the side impact pressure and $f_p L_{WL}(0.8 + 0.15\frac{V}{\sqrt{L_{WL}}})2$ at FP. P_f equals P_{dLs} at L_{WL} from aft end of LWL, P_{dLs} at 0,75 L_{WL} from aft end of LWL, Pw at $\leq<$ 0,5 L_{WL} from aft end of LWL and 0 between aft end of L_{WL} and 0,75 L_{WL} from aft end of L_{WL}

$$P_{dLs} = P_{dL}\frac{\tan(40 - \theta_B)}{\tan(\theta_S - 40)} \tag{B.2.11}$$

With θ_B the mean deadrise angle of bottom plating and θ_S the mean deadrise of side plating. The rules gives f_f, the forebody impact pressure.

The cargo deck pressure

P_{cd} is the cargo deck design and can be defined as:

$$P_{cd} = W_{CDP}\left(1 + 0.5a_v\left[0.86 - 0.32\frac{x_a}{L_{WL}} + 1.76\left(\frac{x_a}{L_{WL}}\right)^2 + \epsilon_a\right]\right) \tag{B.2.12}$$

$$\epsilon_a = 0.14 + 0.32\frac{X_{LCG}}{L_{WL}} - 1.76\left(\frac{X_{LCG}}{L_{WL}}\right)^2 \tag{B.2.13}$$

W_{CDP} is the pressure of the cargo on deck and it is specified by the designer.

Each of the above figures needs to be calculated in order to calculate each line of the table B.1. Once all the lines are calculated the loading design is the greater value for each area. The loading is then used in equation B.2.1 to B.2.12 instead of P where dimensions such as hull thickness can be found. The larger value of pressure is then used in order to calculate the hull dimensions.

B.3 Scantling

B.3.1 Scantling for metal

The scantling of metal boats is fully defined when the following four design variables are calculated. By definition the scantling also depends on the spacing of the stiffener which is fixed as a design variable.

The thickness of plating for metal hull and deck derives from equation B.3.14.

$$t_p = s\gamma\beta\sqrt{\frac{P}{f_\sigma \sigma_s}} \tag{B.3.14}$$

The metal stiffeners section modulus derives from equation B.3.15.

$$Z = \Phi_Z \frac{P s l_e^2}{f_\sigma \sigma_s} \tag{B.3.15}$$

The metal stiffener second moment of area derives from B.3.16.

$$I = \Phi_I f_\delta \frac{P s l_e^3}{E} * 100 \tag{B.3.16}$$

The metal stiffener web area derives from B.3.17.

$$A_W = \Phi_A \frac{P s l_e^3}{100 f_t \sigma_s} \tag{B.3.17}$$

Equations B.3.14 to B.3.17 were used in chapter 6 and 7, then the results of these equation is used to select commercially available beams.

B.3.2 Scantling for composite materials

The scantling of the composite boats is fully defined when the thickness of both the hull and the stiffener is calculated. The thickness of theses members depend on their geometry. The geometry of the stiffener is not given through any calculation rules but it is fixed as a design variable.

The thickness of plating for composites hull and deck derives from equation B.3.18.

$$t_p = s\gamma\beta\sqrt{\frac{P}{f_\sigma \sigma_s}} \tag{B.3.18}$$

The composites stiffener thickness derives from equation B.3.19.

$$t_w = \frac{0.025 d_w + 1.1}{1.3 f_w + 0.61} \tag{B.3.19}$$

In the case of composite materials the result must be validated. The stress in each ply must be calculated with a strategy defined in LR rules and reported in the section B.3.3. The strategy is illustrated by an example taken from LR rules *Guidance information* which act as a closing chapter of the rules and illustrates a couple of concepts i.e. the composite laminates stress verification strategy.

B.3.3 Stress verification for composites material

The aim of the stress verification is to calculate the stress in every ply. The maximum stress can be around the bottom of the stiffener or in the middle on the panel at both the internal (i.e. dry) or external (i.e. wet) ply. The stress verification follows the sequence of figure B.3 flow diagram.

The geometry parameter, ratio of base width of stiffener to panel breadth (γ) and bending moment influence coefficient (k) derive respectively from equation B.3.20 and B.3.21. b_w is the width of the stiffener measured at its base and b is the distance between the stiffener sides.

$$\gamma = \frac{b_w}{b} \tag{B.3.20}$$

$$k = \frac{\gamma^3 + 1}{\gamma + 1} \tag{B.3.21}$$

The bending moment, in Nm, at the center of the panel and at the stiffener derives respectively from equation B.3.22 and B.3.23.

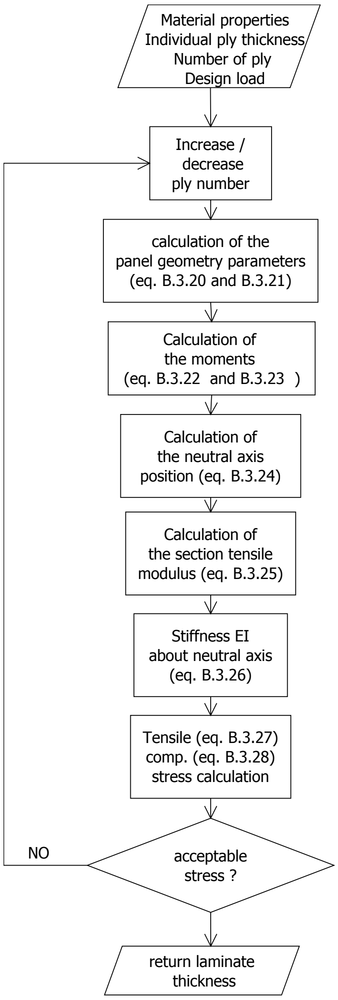


Figure B.3: Designed elements

$$M_b = \frac{kpb^2}{12} 10^{-5} \tag{B.3.22}$$

$$M_c = \frac{(1.5 - k)pb^2}{12} 10^{-5} \tag{B.3.23}$$

The position of the neutral axis derives from equation B.3.24. The calculation requires the tensile or compressive modulus (E), the thickness (t) and the position about the wet side (x) of each ply i.

$$x_s = \frac{\sum E_i t_i x_i}{\sum E_{ti} t_i} \tag{B.3.24}$$

The section tensile modulus, in N/mm^2 derives from equation B.3.25.

$$E_t = \frac{\sum E_i t_i}{\sum t_i} \tag{B.3.25}$$

The stiffness about neutral axis derives from equation B.3.26.

$$\sum EI = \sum EI_{base} - (\sum Et) * 10 * x_s^2 \tag{B.3.26}$$

The compressive and tensile stress, in n/mm^2 derive respectively from equation B.3.27 and B.3.28.

$$\sigma_{ti} = \frac{0.1 E_{ti} y_i M}{\sum E_i I_i} \tag{B.3.27}$$

$$\sigma_{ci} = \frac{0.1 E_{ci} y_i M}{\sum E_i I_i} \tag{B.3.28}$$

It must noted that the maximum compression stresses are located in the centre of the panel wet skin and at the dry skin intersection of the stiffener with the plating. Conversely, the maximum tensile stresses occur at the panel centre dry skin and at the wet skin intersection of the stiffener with the plating.

Table B.2: Loading criteria

Ply n^o	Description	G$_c$	Weight	t (g/m^2)	Lever (mm)	E (mm)	E * t (N/mm^2)	E * t * x	I	E * I
1	CSM	0.33	600	1.250	10.149	7200	9000	91341	1289.2	9281917
2	CSM	0.33	600	1.250	8.899	7200	9000	80091	991.5	7139017
3	CSM	0.33	600	1.250	7.649	7200	9000	68841	733.0	5277367
4	CSM	0.33	600	1.250	6.399	7200	9000	57591	513.5	3696967
5	WR	0.5	600	0.734	5.407	14000	10276	55562	214.9	3008869
6	CSM	0.33	600	1.250	4.415	6950	8688	38355	245.3	1704699
7	CSM	0.33	600	1.250	3.165	6950	8688	27496	126.8	881558
8	WR	0.5	600	0.734	2.173	14500	10643	23127	35.0	507333
9	CSM	0.33	600	1.250	1.181	6950	8688	10260	19.1	132482
10	CSM	0.268	225	0.556	0.278	6290	3497	972	0.6	3604
SUM				10.8			86400	453000		316 10^6

A laminate plate of 2000 mm by 500 mm is taken as example in LR's rules in order to illustrate the stress validation process. This panel is under a 33 kN/m^2 load. It is composed by 10 plies. Table B.2 shows the figures for this example. The columns of the table are:

- The ply number. The first ply is on the dry side whereas the last ply is on the wet side.
- The description of the ply. CSM and WR stand respectively for chopped strand mat and for woven roving.
- The fibre content in weight.
- The weight per unit of area.

- The ply thickness.
- The distance from the centre of the ply to wet side of the laminate.
- The stiffness of the ply.
- The product of the stiffness by the ply thickness
- The product of the previous column time the distance to the wet ply.
- The second moment of area of the ply taken from the wet ply.
- The product of the stiffness by the second moment of area.

The complete result is presented in table B.3 as in the LR guide.

Table B.3: Loading criteria summary

Step	Description	Numerical result	Equation
1	Moment (plate centre)	5.43 Nm	B.3.22
2	Position of the neutral axis	5.25 mm	B.3.24
3	Tensile modulus of section	8030 N/mm^2	B.3.25
4	Stiffness about neutral axis	783 Ncm^4/mm^2	B.3.26
5	Tensile stress (centre, dry side)	22.9 N	B.3.27

The following table is an example of the output from the model developed in the chapter

B.4 Final remarks

The LR rules and regulations were adapted to the current context in order to provide a model of a boat. The rules were simplified in order to ease the process of modelling. No minimum thicknesses were used in the model. Although it is in contradiction with the need of an accurate model for the conduction of the LCA driven material selection, it highlights in a better way the intrinsic properties of material and decrease the impact what can be perceived as a lack of confidence in composites materials. In addition the GRTP are not treated in the rules and the result of the modelling is based solely on the direct scantling rules.

Appendix C

Sensitivity analysis

The present section aims at describing the behaviour of the model used in chapter 7. The sensitivity analysis is used to define the design space where the genetic algorithm can be implemented for the search of the most energy efficient design. Any model has a limited domain of validity and the sensitivity study aims to isolate this domain by assessing which parameters influence the model output, i.e. the life cycle energy. The limitations of the model are of two types:

- Limitations due the design model itself.
- Limitations due to assumption during the programming.

The parameters can be hierarchised. The parameter of speed, power and payload are design parameter necessary to define the boat design. The number of stiffeners and their sizes are parameter set by the use for the conclusion of the scantling. The material properties are presented in the Chapter 7 table 7.1.

the parametre studied are:

- The service restriction factor in section C.1
- The payload and estimated weight C.2
- The number of stiffeners C.3
- The dimension of the stiffeners C.4

It must be mentioned that during the calculation process:

- The ply thickness will be kept at one millimetre.
- The material index are unchanged and represent the material at the time of the study (marine grade steel and aluminium, epoxy/glass(50%) and PP/glass(60%)

- The same estimated weight is used for the four materials.

In each section, all the parameters are given in a table summary.

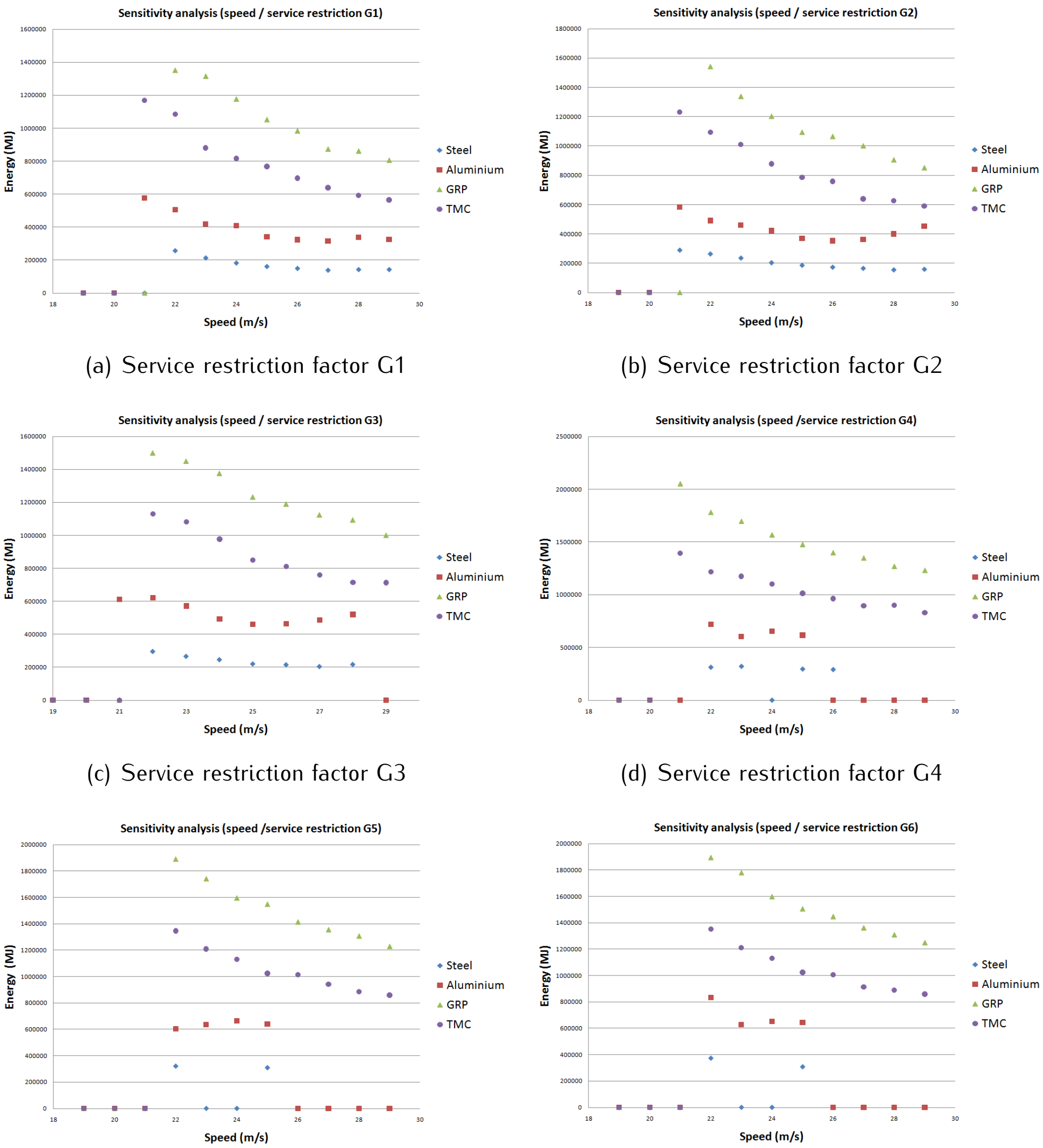
C.1 Service restriction factor influence

The influence of the service restriction factor is studied in the present section. It is a multiplication constant used for the calculation of the design pressure. The same constant is applied to each boat. The constant are named in Lloyds rules G1 to G6 for the value 0.6, 0.75, 0.85, 1, 1.2, and 1.25. The service restriction use is shown in Appendix B, table B.1. Figures C.1 shows the design parameters used in the service restriction study. As it can be seen in the table, x stands for the variable.

Table C.1: Details of the design control text file

			Speed (m/s)	Service restriction area	Payload (kg)	Ply thickness (mm)	Engine index		
			x	4	1	10000	11		
Material	estim. struct. weight (kg)	Nb. trans. stiff.	Nb. long. stiff. bottom	Nb. long. stiff. side	Nb. long. stiff. half deck	Height trans. stiff.	Width trans. stiff.	Height long. stiff.	Width long. stiff.
Steel	25000	40	6	6	4	na	na	na	na
Aluminium	25000	40	6	6	4	na	na	na	na
GRTS	25000	40	6	6	4	150	100	70	50
GRTP	25000	40	6	6	4	150	100	70	50

Figure C.1 shows the result for the 6 possible values of the restriction factor and for several value of the speed from 19 to 29 m/s. With the increase in speed the energy intensity of the structure tend to be lower even if it would seems more logical to have an increase in plating thickness to counteract the effect due to an increase in load because of the higher speed. The amount of energy decreases for every material because the length of the boat decreases in order to limit the wetted surface and the power requirement. The results are given for a small power (table see C.1 engine with index is 11 which correspond to an installed power of twice 505 kW). The variation of the factor is rather large, the variation in terms of energy is not of the same magnitude and the model shows a relatively small increase in energy level. The main impact of the service restriction area is on the missing solutions. For the heaviest boat i.e. steel and aluminium, the model fail to converge for speed greater than 26 m/s and service restriction G4 to G6 (see figures C.1 (d) to (f)). In addition there the model does not converge for the smaller speed because for these speed, the power model returns a short wetted length, therefore a short overall length for which no draft can be calculated. It is the result of an assumption of the model which does not allow the keel to reach the surface at a station further aft than station 49 (see Chapter 7 7.2.3 and 7.2.7). The service restriction factor should be included in the sensitivity analysis as this factor influences the life cycle energy.



(a) Service restriction factor G1

(b) Service restriction factor G2

(c) Service restriction factor G3

(d) Service restriction factor G4

(e) Service restriction factor G5

(f) Service restriction factor G6

Figure C.1: Influence of the service restriction factor

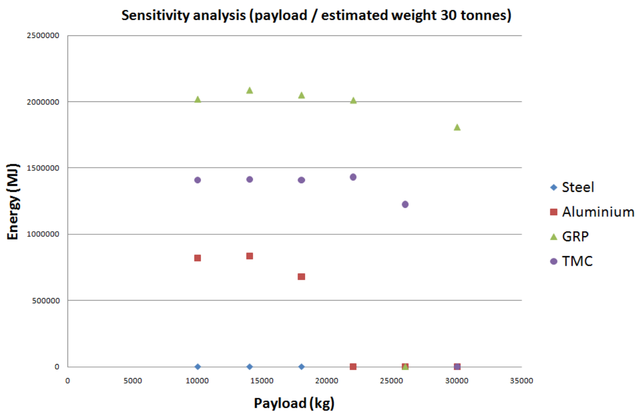
C.2 Payload and estimated weight influence

The present section highlights the influence of payloads and estimated weights on the energy consumption of the structure. Figure C.2 shows the default value of the constant.

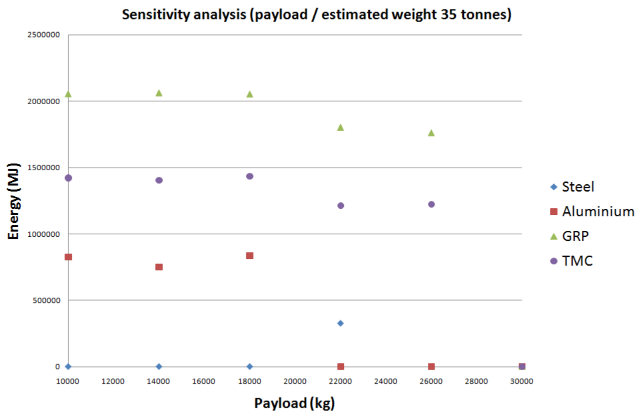
Table C.2: Details of the design control text file

			Speed (m/s)	Service restriction area	Payload (kg)	Ply thickness (mm)	Engine index		
			22	4	1	x	20		
Material	estim. struct. weight (kg)	Nb. trans. stiff.	Nb. long. stiff. bottom	Nb. long. stiff. side	Nb. long. stiff. half deck	Height trans. stiff.	Width trans. stiff.	Height long. stiff.	Width long. stiff.
Steel	x	40	6	6	4	na	na	na	na
Aluminium	x	40	6	6	4	na	na	na	na
GRTS	x	40	6	6	4	150	100	70	50
GRTP	x	40	6	6	4	150	100	70	50

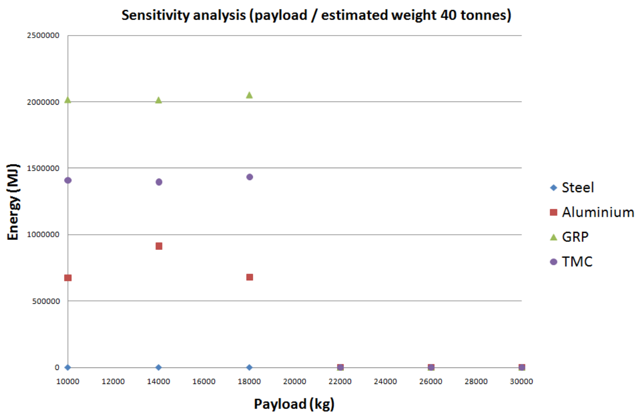
Figure C.2 shows the variation of the energy for the structure as a function of the payload for several values of the estimated weight. The estimated weight was defined in section 7.2.7 as total weight of the boat used in the first design loop of the calculation of the power parameter (see 7.2.2). The payload influences the results but to level lesser than expected. Indeed even if the increase in load is large the variation in energy is small and random. It must be mentioned that an increase in payload come generally with a decrease in boat length and beam as it can be seen on figure C.3 for GRTS and GRTP with an estimated load of 30 tonnes. The energy result is also influenced by the estimated weight. Firstly, high estimated weights decrease the number of possible solutions for each material. Figure C.2 (a) to (c)) show a decrease in the number of non zero dots. The result changes for a same payload and different estimated weight. For example for a constant payload of 14 tonnes GRTS energy results are 2010 GJ, 2060 GJ and 2080 GJ for respectively an estimated weight of 30, 35 and 40 tonnes. This is due to the model and the fact that the condition of convergence is to be within 5% of the target, in the case of the weight or the draft iteration. As the starting point is different for the 3 GRTS boats with 3 estimated weights, the convergence path for each boat is different. The difference in result is acceptable and it is assumed that with a more severe convergence criteria, the 3 boats would converge to the same figure.



(a) Estimated weight 30,000 kg

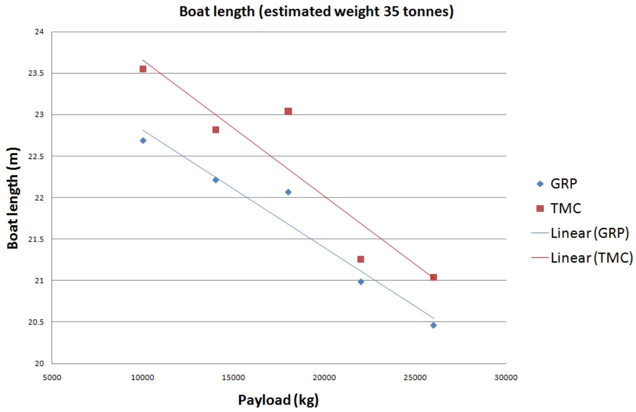


(b) Estimated weight 35,000 kg

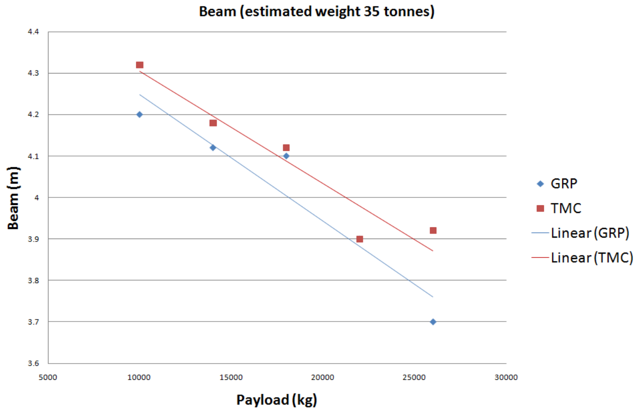


(c) Estimated weight 40,000 kg

Figure C.2: Influence of payload and estimated weight



(a) Boat length



(b) Beam

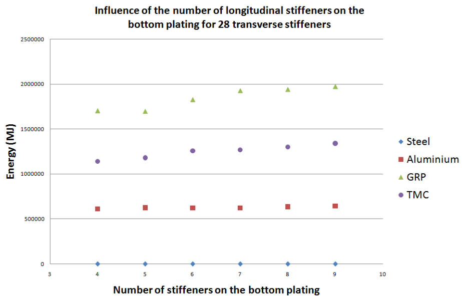
Figure C.3: Influence of the payload on the beam and the boat length for GRTS and GRTP with an estimated weight of 30 tonnes

C.3 Number of stiffener influence

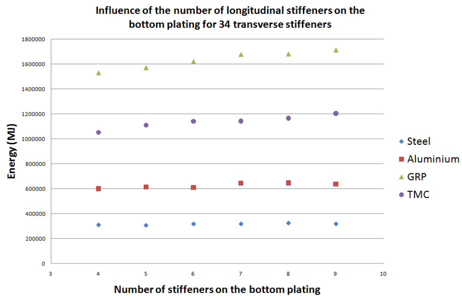
The present section aims at studying the influence of the number of transverse stiffeners along the boat and the the influence of the longitudinal stiffeners on the bottom, side plating and the deck. For simplification reason only half the boat has been studied because it is assumed to be symmetric and the result were multiplied by two in the model. For this reason the number of stiffener on the deck can only be changed on half the deck. Figure C.3 shows the default value of the constants. The number of transverse stiffener was studied for value from 26 to 46 but only the figure for 28, 34, 40 and 46 stiffeners are presented in the present section. The influence of longitudinal stiffener is presented in each section for several value of the number of transverse stiffeners. The results for the transverse stiffener derives from the figure for each type of longitudinal stiffeners.

Table C.3: Details of the design control text file

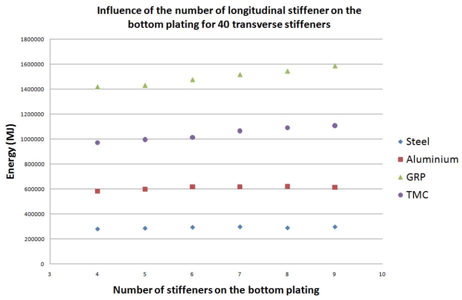
			Speed (m/s)	Service restriction area	Payload (kg)	Ply thickness (mm)	Engine index		
			21	4	1	10000	11		
Material	estim. struct. weight (kg)	Nb. trans. stiff.	Nb. long. stiff. bottom	Nb. long. stiff. side	Nb. long. stiff. half deck	Height trans. stiff.	Width trans. stiff.	Height long. stiff.	Width long. stiff.
Steel	25000	x	x	x	x	na	na	na	na
Aluminium	25000	x	x	x	x	na	na	na	na
GRTS	25000	x	x	x	x	150	100	70	50
GRTP	25000	x	x	x	x	150	100	70	50



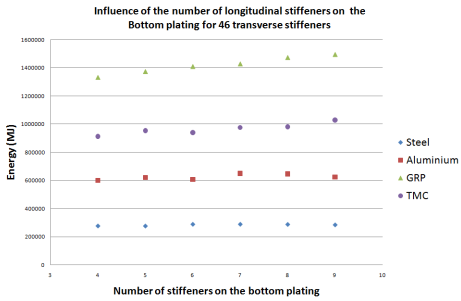
(a) 28 transverse stiffener



(b) 34 transverse stiffener

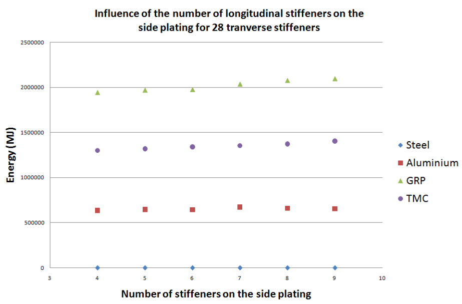


(c) 40 transverse stiffener

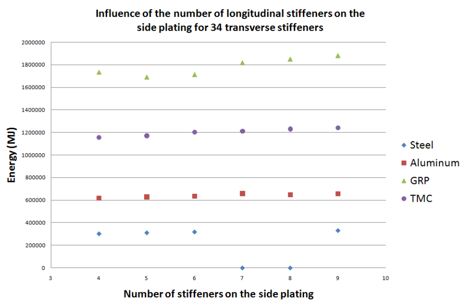


(d) 46 transverse stiffener

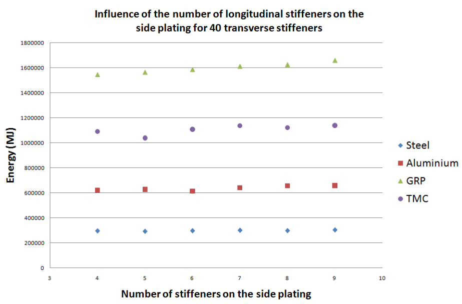
Figure C.4: Influence of the number of stiffeners on the bottom plating



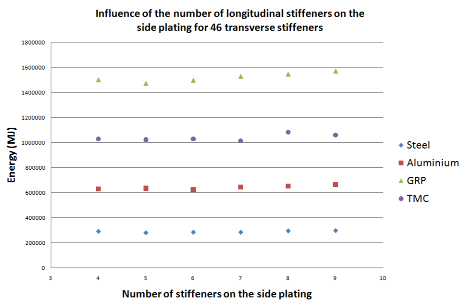
(a) 28 transverse stiffener



(b) 34 transverse stiffener

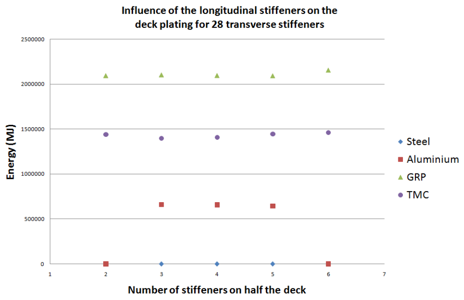


(c) 40 transverse stiffener

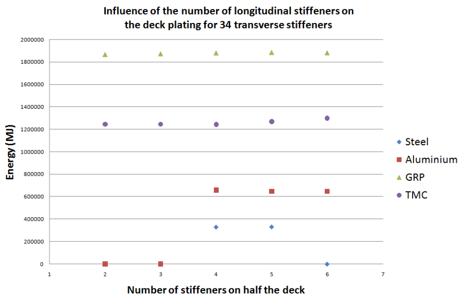


(d) 46 transverse stiffener

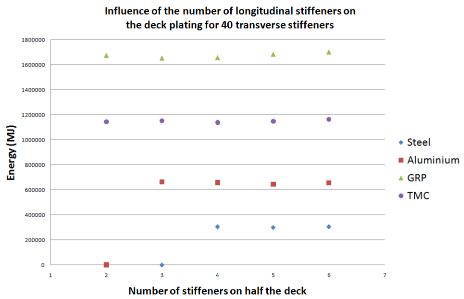
Figure C.5: Influence of the number of stiffeners on the side plating



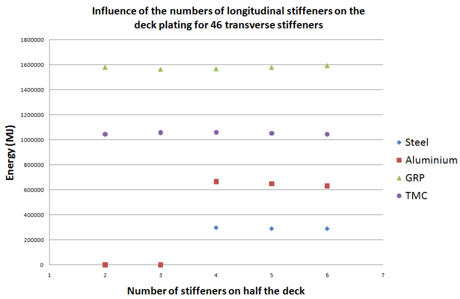
(a) 28 transverse stiffener



(b) 34 transverse stiffener



(c) 40 transverse stiffener



(d) 46 transverse stiffener

Figure C.6: Influence of the number of stiffeners on the deck plating

Figure C.4 reveals that the number of stiffeners on the bottom plating should be included in the model optimisation as the energy is not constant over the domain of search of the sensitivity analysis. Figure C.5 and figure C.6 show respectively the influence of the number of stiffeners on the side plating and on the deck. These two parameters affect the energy result and therefore should be included in the optimisation. In addition, figures C.4, C.5 and C.6 make clear that the number of stiffener modify the energy result and it should be included in the optimisation strategy for a number of transverse stiffener between 26 and 46.

C.4 Dimension of the stiffener influence

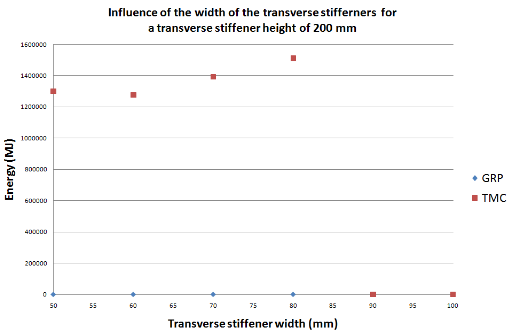
The present section highlights the influence of the dimension of the composite stiffeners on the energy consumption of the structure. This applies only to composite materials as the metal alternatives stiffeners are chosen in a list of stiffeners. In the case of composites, the dimensions are given as an input to the model and the model adapts the stiffener to the load by calculating the suitable number of laminated layers. Table C.4 shows the default value of the constants.

Figure C.7 and figure C.8 shows respectively the variation of the energy for the structure as

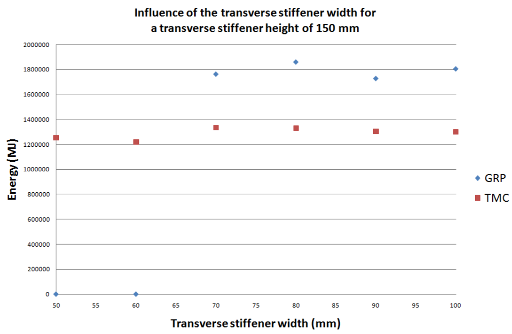
Table C.4: Details of the design control text file

			Speed (m/s)	Service restriction area	Payload (kg)	Ply thickness (mm)	Engine index		
			22	4	1	x	20		
Material	estim. struct. weight (kg)	Nb. trans. stiff.	Nb. long. stiff. bottom	Nb. long. stiff. side	Nb. long. stiff. half deck	Height trans. stiff.	Width trans. stiff.	Height long. stiff.	Width long. stiff.
Steel	na	na	na	na	na	na	na	na	na
Aluminium	na	na0	na	na	na	na	na	na	na
GRTS	25000	40	6	6	4	150	100	70	50
GRTP	25000	40	6	6	4	150	100	70	50

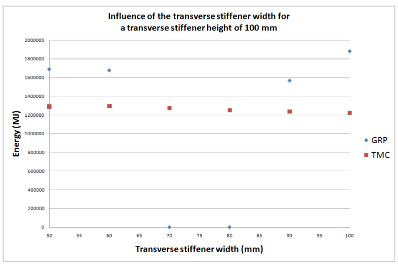
a function of the height and width of the transverse stiffeners and the longitudinal stiffeners. The transverse stiffener studied values are 100, 150 and 200 mm high and 50, 75 and 100 mm wide. The longitudinal studied values are 100, 125 and 150 mm high and 50, 70 and 90 mm wide. The result shows that the size of the stiffeners influences the energy result and therefore should be included in the optimization module.



(a) Transverse stiffener height 200 mm

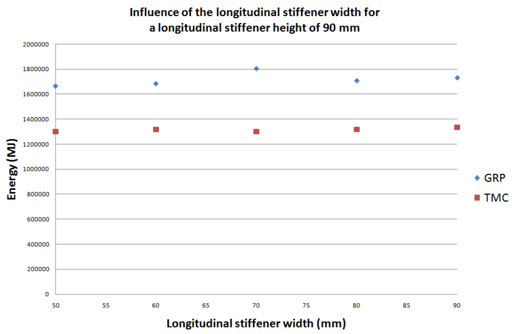


(b) Transverse stiffener height 150 mm

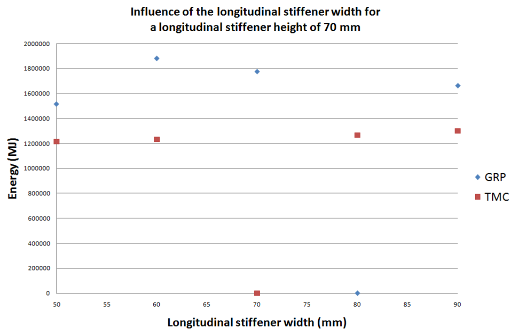


(c) Transverse stiffener height 100 mm

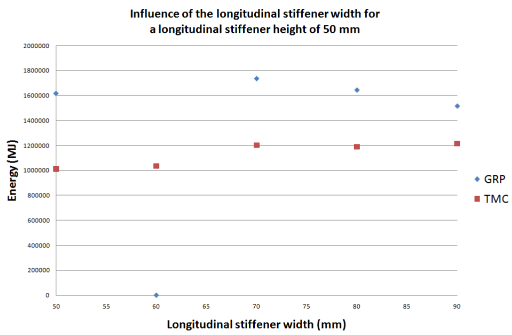
Figure C.7: Influence of the transverse stiffener dimensions



(a) Transverse stiffener height 90 mm



(b) Transverse stiffener height 70 mm



(c) Transverse stiffener height 50 mm

Figure C.8: Influence of the longitudinal stiffener dimensions

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