Aalto University
School of Engineering

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Department of Applied Mechanics

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Modularisation of passenger ship hotel areas

Master's Thesis

Espoo, 2014

Supervisor: Professor Jani Romanoff (Aalto University)

Instructors: Heikki Remes, D.Sc. (Aalto University)
Kristjan Tabri, D.Sc. (Tallinn University of Technology)

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Abstract of the Master's Thesis

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For the last few decades, the manufacturing method of the passenger ship cabin area has remained unchanged. While the current manufacturing technique, based on a single cabin modulus, was novel in the 80s, it is inefficient for the high standards of the current competitive shipbuilding market. This has motivated shipbuilding companies to develop new methods of cabin area manufacturing. It is proposed that the hotel area would be assembled from functionally complete and self-supporting macro-modules. A macro-module includes several cabins, which would be prefabricated in factory conditions and installed on a ship in the final phase of the building process. This thesis focuses on the feasibility of macro-module based manufacturing.

In order to assess feasibility, three macro-module based concepts are compared with the current concept used in Europe. The concept properties are assessed for weight, cost, and the manufacturing time. A synthesis model is developed in order to evaluate the technical and economic feasibility of the concepts.

The results indicate that a macro-module based concept has significant advantages when compared to the current concept. Increasing the level of the prefabrication, the extensive use of sandwich panels, and the vertical outfitting solution have contributed to significant weight and space savings. The deckhouse built utilising the new concept has more cabins while maintaining a similar price and weight level.

Despite achieving satisfactory results, the new concept should be tested in practice. It is essential to note that the new concept involves a great amount of innovations that may be excessive for the conservative shipbuilding industry. Moreover, a significant initial investment is required to update shipyard facilities in order to enable the new approach to be implemented.

Keywords: cruise ship, passenger ship, modularity, and cabin area.

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Reisilaevade kajutite ala ehitusmeetod on viimaste aastakümnete jooksul püsinud suuremate muutusteta. Hetkel kasutusel olev metoodika oli innovaatiline kaheksakümnendatel, kuid on ebaefektiivne tänapäeva konkurentsitiheda laevaehituse kontekstis. Antud probleem on ajendanud laevaehituse ettevõtteid otsima uusi lahendusi. Ühe võimaliku lahendusena on pakutud välja ehitada kajutite ala funktsionaalselt valmis olevatest makromoodulitest. Mitut kajutit hõlmavad makromoodulid valmistataks eraldiseisvas tehases sisetingimustes ning paigaldataks laevale ehituse hilises faasis. Magistritöö eesmärk on selgitada uue meetodi tasuvus.

Tasuvus selgitatakse võrreldes kolme makromoodulitel põhinevat kontsepti hetkel kasutuses oleva metoodikaga. Kontseptide kaalu, maksumuse ja tootmisele kuluva aja hindamiseks töötatakse välja laiapõhjaline arvutusmudel.

Tulemustest järeldub, et uuel kontseptsioonil on hetkel kasutuses oleva metoodikaga võrreldes tugevad eelised. Eeltootmise osakaalu suurendamine, laialdane *sandwich* paneelide kasutus ja vertikaalne läbiviikude süsteemi juurutamise tulemusel saavutatakse märkimisväärne kaalu ja ruumi kokkuhoid.

Vaatamata rahuldavatele tulemustele on vajalik edasine arendustöö. Uus kontseptsioon kätkeb endas mitut olulist uuendust, mis võivad olla liialt uuenduslikud konservatiivse laevaehituse sektori jaoks. Samuti on oluline märkida, et uue lahenduse juurutamine nõuab laevaehitustehaselt märgatavaid investeeringuid.

Märksõnad: kruiisilaev, parvlaev, modulaarsus.

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Martin Jõgeva

Espoo, May 12, 2014

Table of Contents

List of Figures

1 Introduction

1.1 Background

In the current international competitive shipbuilding market, success is based on offering both competitive prices as well as short delivery times (Bertram, 2005). This has led to a focus on reducing costs in terms of steel structure, machinery, and the optimisation of the manufacturing process. However, with diminishing scope for further improving both the steel structure manufacture as well as assembly techniques, the shipbuilding industry has explored other options to reduce lead time and costs. Recently, modularisation has become an increasingly popular approach to decrease manufacturing costs (Erikstad, 2009).

Modularity is an approach which subdivides a system into smaller parts (modules) that can be independently created and assembled to form the final product. Modular manufacturing is widely used in the automotive, aircraft, and other industries, repeatedly proving to save time and money (Eskildsen, 2011). Characteristic features of modular manufacturing, such as the use of assembly lines, the high level of prefabrication, and outsourcing, allow major improvements in quality while reducing costs and manufacturing lead time.

The cabin area is one of the most important areas in a passenger ship. Passenger cabins account for approximately half of the passenger facility space, thus contributing significantly to a ship's weight. Furthermore, the relatively high location of the cabin area greatly affects the position of the vertical centre of gravity. From the economic point of view, the number of passenger cabins is directly proportional to the number of passengers that the ship is able to accommodate as well as the revenue.

The passenger ship cabin area would be an ideal target for implementing a modular manufacturing approach due to its complex, repetitive nature. Another reason for introducing modularity in the manufacture of this area is that passenger cabins have many complicated systems, including heating, ventilation, air conditioning, and electrical cabling. The installation of these systems requires high precision, easy accessibility, and accurate testing, which is difficult to fulfil under on-site conditions, though easy to fulfil when prefabricated at the factory.

Thus far, the shipbuilding industry has given moderate attention to implementing modularity in the manufacturing process despite the many opportunities to do so, especially in the cabin area of a passenger ship. Traditionally, cabins have been built one-by-one on-board. The first breakthrough in the modularisation of a cabin area was done in the 1960s when Blohm+Voss developed a 'design for production' ship called the 'Pioneer'. This ship included a prefabricated accommodation system M1000, which involved a steel framework for cabin structure as well as standardised parts and furniture (Bertram, 2005; Gallin, 1977). Since the late 1970s, the modular cabin approach gained more popularity until it became common practice in the 1990s and has not considerably changed since that time. Small unit size, double structures, and long installation time are properties characteristic to the contemporary method, limiting continuous workflow and using excessive valuable space on-board, and resulting in longer lead time and higher cost.

Several studies have focused on solving problems associated with the current cabin area manufacturing method. Increasing module size and the level of prefabrication have been considered as potential directions for development. The expansion of modules provides an opportunity to prefabricate interfaces between the cabins and outfitting in factory conditions. Installation of functionally complete macro-modules is not only faster but can also be postponed to a latter phase of ship manufacturing. Recent efforts to increase the effectiveness of passenger ship cabin area manufacturing include the joint project of Finnish maritime companies that aims to develop a ship concept that would increase the level of modularity in the cabin area fabrication process. The outcome of the project was the Cell Cabin (CC) concept. The construction method is based on steel sandwich panels that are assembled to form macro-modules that consist of up to twelve functionally complete accommodation cabins (see Figure 1). This method allows the passenger ship hull and hotel area to be built separately. Macro-modules are finished under factory conditions, well protected from weather and other undesired interference. Complete modules are towed to the building site where they are hoisted on board the hull under construction (Laiterä, 2010). When stacked into an accommodation tower, macro-modules are self-supporting and do not participate in the global strength of the vessel (ibid.).

Figure 1. A module of eight cabins (Finnfacts, 2011)

This thesis aims to further improve and elaborate the CC concept by developing a synthesis model. The purpose of the synthesis model is to provide a tool for the evaluation of the technical and economic properties of the concepts with a macro-module based superstructure design. The model is used to combine initial data with the authors' contributions and evaluate the CC concept as well as two additional proposed modifications. The technical and economic feasibility of the proposed concepts are then evaluated against the conventional design.

The thesis is divided into four chapters. Chapter 2 presents the methods used in this study. The chapter is divided into two parts, the first introducing the passenger ship design process methodology and the second outlining assessment criteria. Chapter 3 presents and discusses the results of the analysis. Finally, Chapter 4 presents the conclusions that can be drawn from this study and suggests topics for future research.

1.2 State of the art

This section presents current state of the art methods for passenger ship superstructure manufacturing and introduces a new macro-module based approach.

1.2.1 Conventional approach to building passenger ship superstructures

Conventional passenger ship superstructures vary in size, cross-section, and general arrangement. Nevertheless, it is possible to outline common features in terms of structural design and manufacturing methods.

The structural design of a passenger ship cabin area aims to fit the maximum amount of cabins into a given space, while keeping the weight low and strength criteria fulfilled. The arrangement of cabins is typically repetitive and simple, as shown in Figure 2. The dimensions and framing characteristics are chosen based on cabin size and strength criteria. Cabin deck plating and side shell are usually longitudinally stiffened with a spacing of 600–800 mm and supported by transverse deck girders with a spacing of 2.0–3.2 m. Vertical force is carried by pillars that are placed at every second web frame. In addition, the structural design is governed by the International Convention for the Safety of Life at Sea (SOLAS), which determines numerous measurements to prevent fire spreading on board passenger ships (IMO, 2002). From the structural point of view, the most important requirement of SOLAS is the need to place transverse fire safety bulkheads, which extend from the bottom to the sundeck with a maximum step of 48 meters, provided that the total area of the main vertical zone is not greater than 1,600 m^2 (Safety of Life at Sea, 2004).

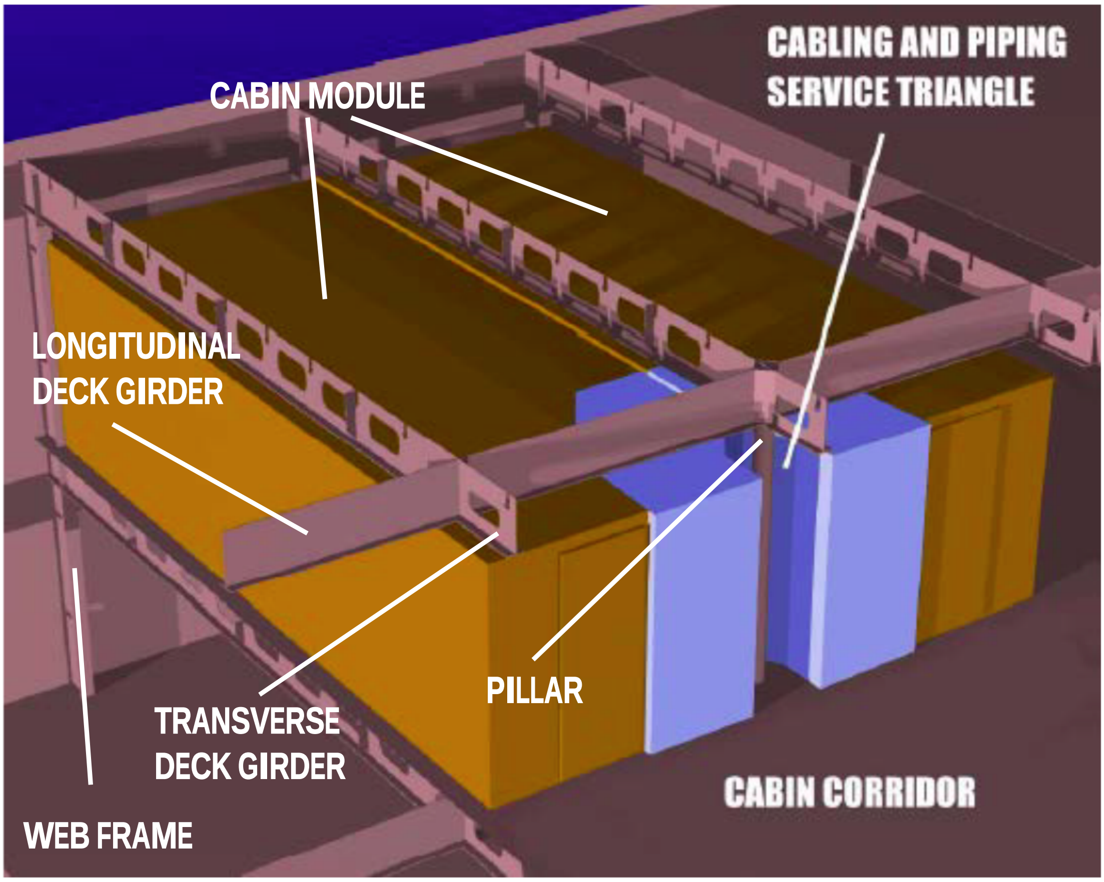

Figure 2. Allocation of cabin modules (Kawser, 2012)

Currently, the construction of large ships includes a number of stages assembling increasingly larger elements of the ship. This approach was introduced in World War II and, because of the numerous benefits, has been adopted by all modern shipyards (Eyres, 2012). According to Eyres, typical assemblies are:

- **Minor assembly**. Basic structural elements, including stiffeners, plates, and brackets, are welded into simple elements, such as part of the deck.
- **Sub-assembly**. Two-dimensional structure with a size up to 12×12 meters. Several minor assemblies are connected and large stiffening elements (web frames, girders, etc.) are generally added at this stage.
- **Unit assembly**. Two-dimensional sub-assemblies are built into three-dimensional unit assemblies with a weight of up to 60 tonnes.

- **Block**. Units are combined into large blocks that are lifted into the building dock for the erection of the final structure of the ship.

Units and blocks are typically partly outfitted and painted in the workshop prior to installation on-board. Outfitting is preferably done in the workshop since accessibility and working conditions are significantly better than those on board. The workshop environment also provides easier access to central services and cranes enable turning units over to allow easier downhand welding.

The outfitting of the cabin area is primarily done in the building dock using cabin modules (see Figure 3). The cabin module consists of a lightweight frame with cabin walls and ceiling, equipped with most of the wall-mounted furnishings and a ready-to-operate bathroom module (Kauppi, 2012). Modules are typically manufactured in a separate factory and transported to the building site prior to installation. More information about the assembly of modern ships can be found in Eyres (2012) and SNAME (2003).

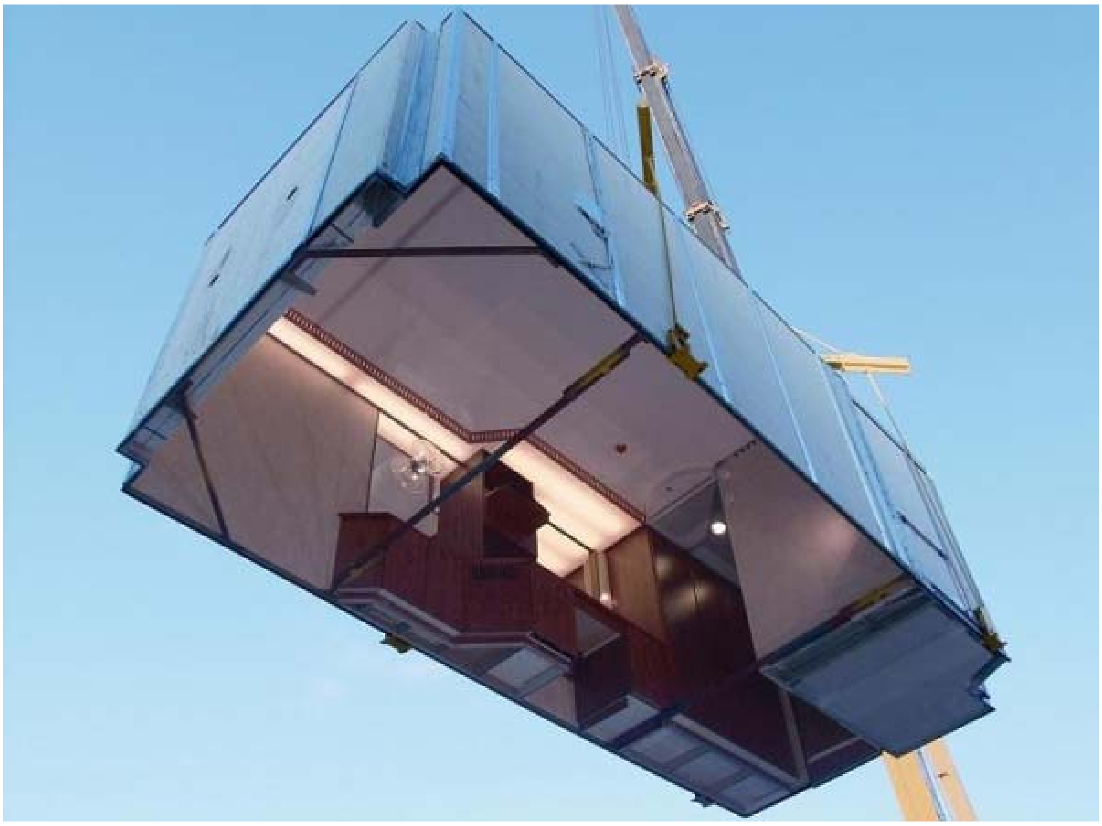

Figure 3. Prefabricated passenger ship cabin (STX Finland Oy)

Limitations of conventional approach

The introduction of conventional prefabricated modular cabins reduced on-board outfitting time and consequently shortened the lead time; however, despite the major improvement compared to the previous approach, the manoeuvring and installation of cabin modules is still too time consuming for modern shipbuilding standards. First of all, large temporary openings need to be cut into the side shell to insert cabin modules onto a deck. Thereafter, every module has to be individually lifted on board, moved into place by using special wheeled frames, and installed by welding the cabin frame on to the steel deck. Repeating this process with every cabin takes a significant amount of time. In addition, the cabin module does not include a window or a floor, which prevents the finalisation of the entire interior in the factory conditions and thus, creates a considerable amount of work that still needs to be done on-board. Moreover, each cabin has to be connected to the HVAC (Heating, Ventilation and Air Conditioning) system and electrical mains one-by-one, as well as tested correspondingly. Since the intensive outfitting work tends to go on beyond the cabin installation, the tasks of many workers continue to overlap for an extensive period of time causing unnecessary hassle and cost (Laiterä, 2010).

1.2.2 Macro-module based passenger ship superstructures

The drawbacks of the conventional approach to cabin area manufacturing have been a driver for the development of new methods. Increasing the size of the cabin modules and the level of pre-outfitting has been seen as a potential direction for development. Therefore, cabin macro-modules were introduced. In this thesis, the cabin macro-module is defined as a prefabricated and functionally complete construction unit that consist of 2–12 cabins. The macro-module includes all required outfitting and can be installed quickly without any additional modifications made to the existing structure. Subsequently, two proposed cabin macro-module concepts are presented.

m^2cell concept

The m^2cell is a cruise ship concept that places emphasise on a modular design; see Figure 4 and Figure 5. The concept was first introduced by Kauppi (2012) and further developed by other Aalto University Master's degree students Ylirisku (2012) and Parmasto (2012). The idea of the concept is that the hotel space of the ship consists of interchangeable self-supporting macro-modules, thus making it possible to refit and reconfigure cabin areas as a continuous process while the vessel is in normal operation (Kauppi, 2012). Although Kauppi's work established a preliminary foundation for the m^2cell design concept, the thesis did not include calculations to demonstrate the advantages of the design method over those currently used. Subsequent work by Ylirisku (2012) further developed the m^2cell concept by simulating how the concept would work in the current cruise industry. According to Ylirisku, factors needed for the m^2cell concept to operate are the shipyard that builds the ship and the macro-modules, the shipping company that operates the ship, and the module company that maintains stores and rents out the macro-modules as well as port with special cranes to execute the change procedure. The cruise experience would not change for the passengers but cruise companies would be able to adjust faster to upcoming trends and better answer their customers' preferences.

Parmasto (2012) investigated the narrow deckhouse structure that is required to realise the m^2cell concept. In his work, Parmasto determined the hull-deckhouse interaction and performance of the proposed structure under vertical bending and compared these parameters to those in a conventional cruise ship structure which has internal longitudinal bulkheads for carrying the shear forces in the superstructure. Results indicated that removing decks from the conventional cruise ship structure had no effect on the nature of the hull-deckhouse interaction. Analysis showed that the proposed structure can achieve the same stiffness under vertical bending as the conventional cruise ship structure while achieving a lesser weight and height for the vertical centre of gravity in the steel structure.

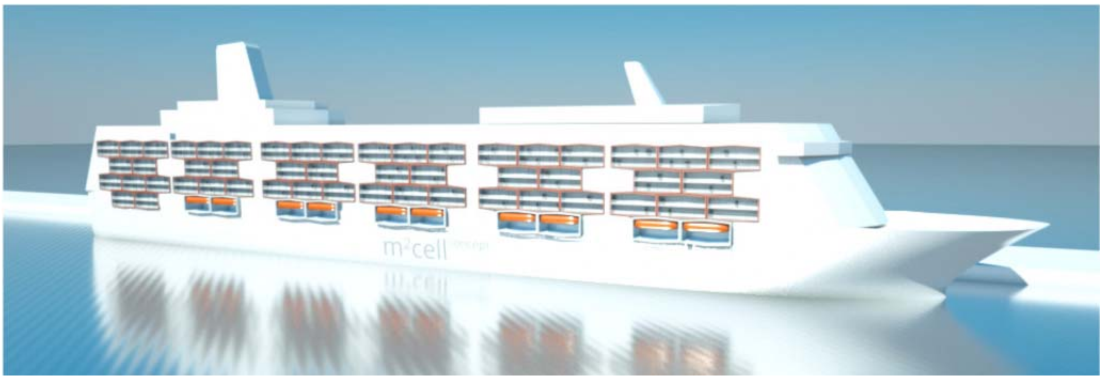

Figure 4. m^2cell concept ship (Kauppi, 2012)

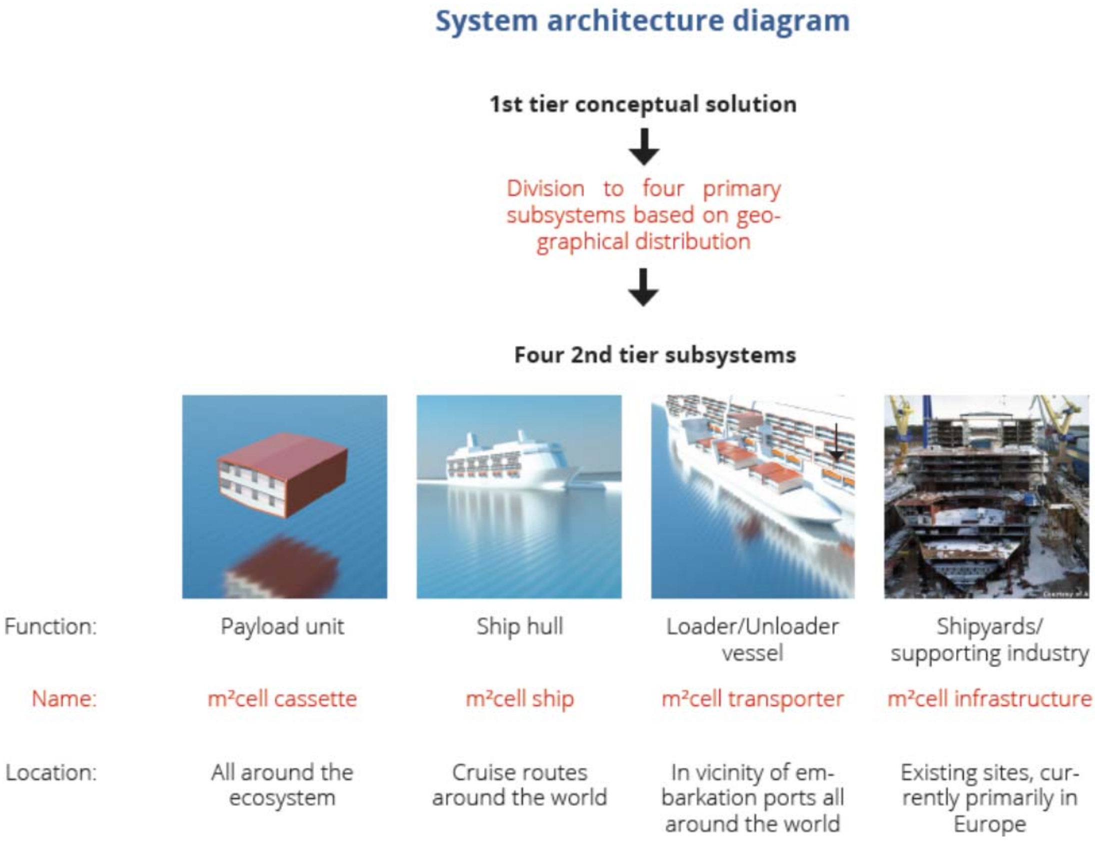

Figure 5. System architecture diagram of the m^2cell concept (Kauppi, 2012)

Cell Cabin concept

The Cell Cabin (CC) concept was developed by Oy Shippax Ltd and STX Finland Oy. This concept aims to develop the next generation building technique of passenger ship cabin areas. In the CC concept, the cabin area is constructed using prefabricated and functionally complete macro-modules, as shown in Figure 6. Cabin macro-modules are used as construction units to increase production efficiency and take advantage of new construction technologies. Fixcel sandwich panel based macro-modules are self-supporting and do not participate in the global strength of the vessel; they are installed on both sides of the ship in the final phase of the ship's construction.

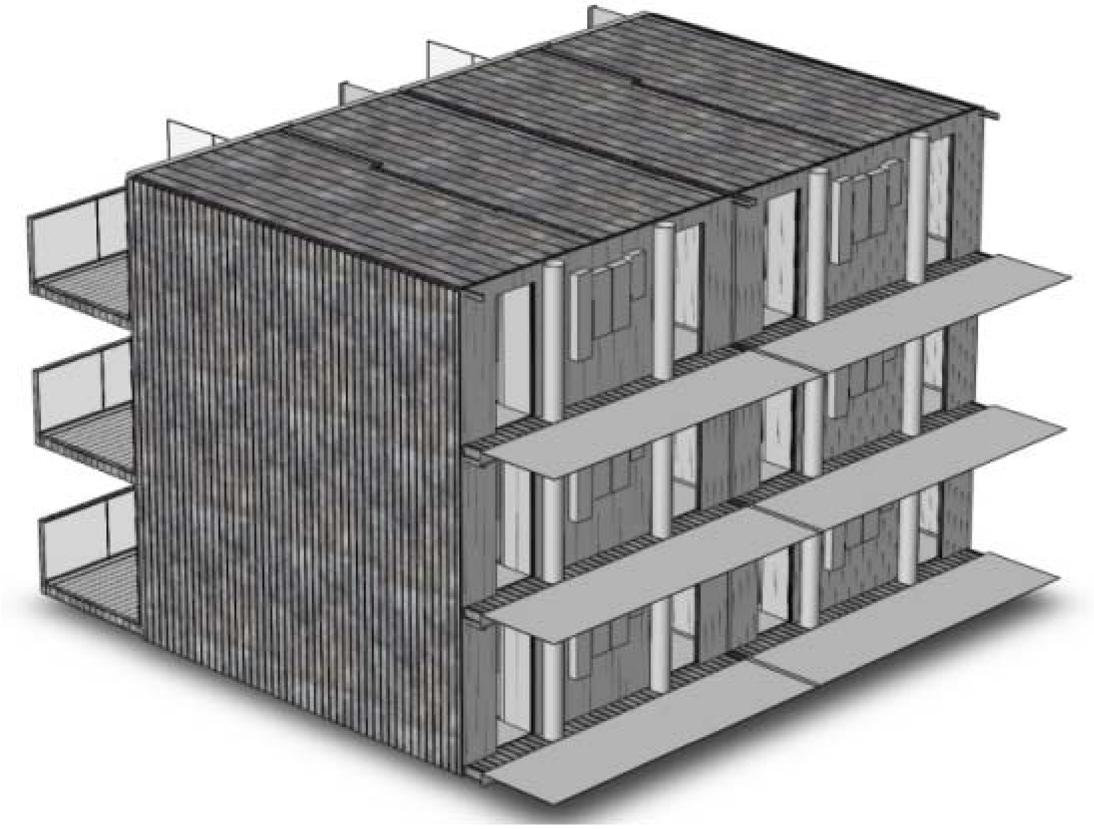

Figure 6. Module design (STX Finland Oy)

The CC concept and m^2cell concept have several similarities. Both principles are based on the utilisation of modular approach benefits and are concentrating on the cabin area of the ship. The main difference is that in the case of the m^2cell concept, macro-modules are interchangeable while the CC concept has stationary macro-modules. The interchangeability of macro-modules has many benefits; however, the technical solution is complicated and excessive novelty makes it unacceptable for the conservative ship building industry. The CC concept represents a more modest approach for the evaluation of the cabin area construction method that is fully based on technologies that are currently available.

The proposed manufacturing technique has numerous benefits as well as few challenges. Sandwich panels and the utilisation of the serial production advantages decrease weight and shorten the lead time. Similarly, the lack of deck stiffeners and double structures allows for the lowering of the deck height from 2750 to 2400 mm, which then allows for additional deck space without increasing the height of the ship's superstructure. However, decreasing the deck height also eliminates the space previously used for outfitting routing, which yields to the demand for the new solution. This mentioned issue, as well as a number of other technical challenges, are discussed in the next sub-section.

1.2.3 Cell Cabin concept

Fixcel panels

Fixcel panels are Oy Shippax Ltd. patented steel sandwich panels (see Figure 7) which are the main construction material of the Cell Cabin concept. The panels were specially developed for use in modular construction projects (NEAPO Corporation, 2013). If most of the other commercial steel sandwich panel production is based on applying welding techniques then Fixcel panels are made of thin, hot galvanized steel plates by means of triple seam rolling technology. The production process that employs purpose built semi-automatic machinery is currently capable of delivering about 500 m^2 of panels in a day with thicknesses varying from 68 to 300 mm (Laiterä, 2010).

To ensure that construction complies with all standards, fire resistance tests have been performed in cooperation with the Technical Research Centre of Finland, and sound measurements and bending tests have been conducted at the Tampere University of Technology (NEAPO Corporation, 2013; Fimecc, 2011). The results of all the tests satisfied or exceeded the requirements.

According to Laiterä (2010), Fixcel panels offer several benefits:

- Good stiffness to weight ratio
- Considerable reductions of insulation, levelling, and surface material weight as well as in related work and cost due to the flat surface of the panels
- Good heat insulation, noise attenuation, and fire resistance properties, especially when top layers or filling materials are used
- High accuracy in manufacturing with minimal distortions
- Cost savings due to series effect and automated manufacturing
- Possibility of large, unsupported, and even spans

Difficulties have been experienced in joining techniques, integration into the surrounding structure, and design optimisation (Laiterä, 2010).

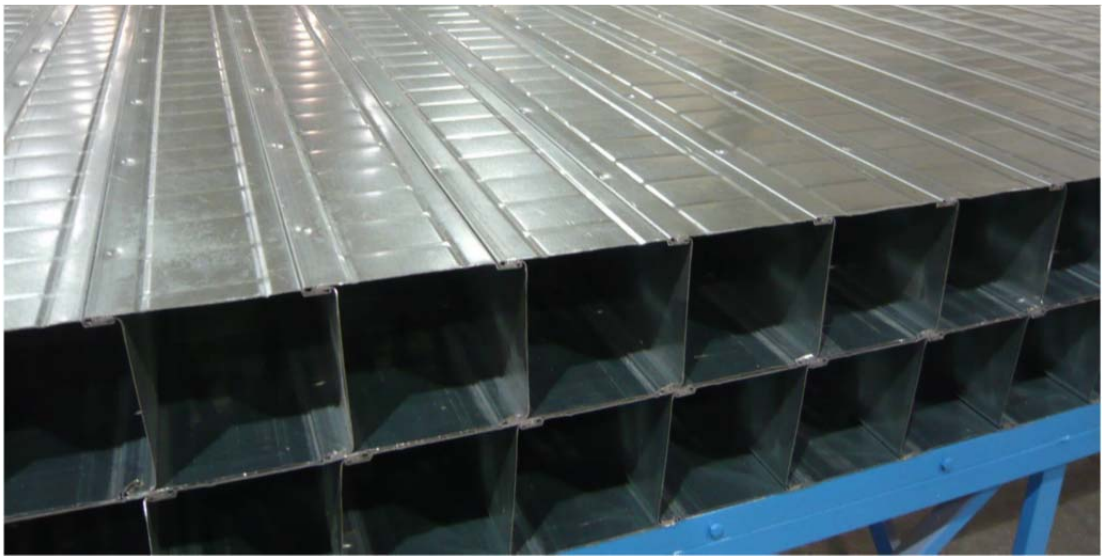

Figure 7. Fixcel panel (Laiterä, 2010)

Cabin macro-module

A cabin macro-module is a sandwich panel based on a construction unit (see Figure 6) that contains up to twelve fully functioning accommodation cabins. The design of the macro-module and the level of outfitting can vary depending on the specific requirements. A typical macro-module includes a balcony, all the interior, and outfitting. Cabin corridors can be a part of the macro-module; however, this would make the installation process more complicated and thus is not considered in this thesis.

Fixcel panels are assembled to form accommodation modules (see Figure 8) by means of tack welding. An adhesive bond is another option but even though gluing offers greater effectiveness from the production point of view and sufficient shear strength, currently welding is the prevailing method. The reason preventing the use of the adhesive bond is that its fire endurance and immunity to aging in the dynamic marine environment require further study (Laiterä, 2010).

The installation of all complicated outfitting systems requires high precision, great accessibility, and accurate testing. To minimise quality fluctuations, costs, and material losses, everything from the insulation and piping to the last details of cabin furnishing is entirely prefabricated and installed on the factory premises. Factory conditions protect manufacturing from the climatic influences, supporting the use of assembly lines which speed up the process, respectively reducing costs and achieving consistently higher and more uniform levels of finish.

Figure 8. The illustration of the macro-module built balcony cabins (Oy Shippax Ltd.)

Steel structure

The feasibility of the steel structure – a prerequisite for the implementation of the concept – was a prevailing concern from the beginning of the project. Placing modules on both sides of the ship requires the significant decrease of the load-carrying part of the cabin area steel structure. Several designs were considered but a structure that imitates the I-beam in the large scale was selected (see Figure 9). In this design, the hull act as a lower flange and the upper steel deck acts as an upper flange; the middle narrow part (the so-called backbone) acts as a web. The homogeneous backbone structure alternates with the wider staircase sections and transverse fire safety bulkheads (see Figure 10 and Figure 11). Spaces in the backbone are used for the air conditioning equipment and inside the cabins.

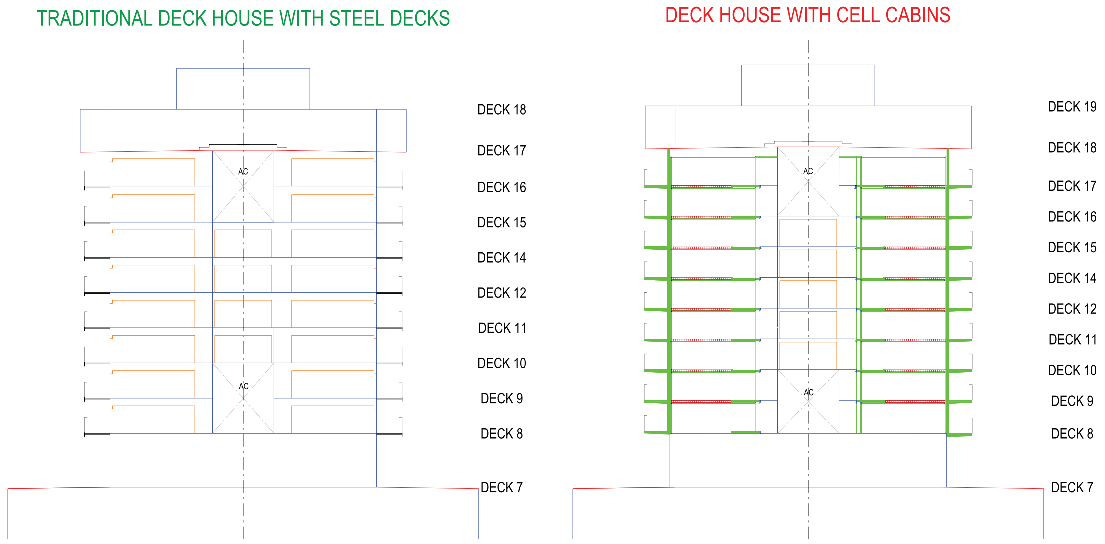

Figure 9. Comparison of deckhouse structure

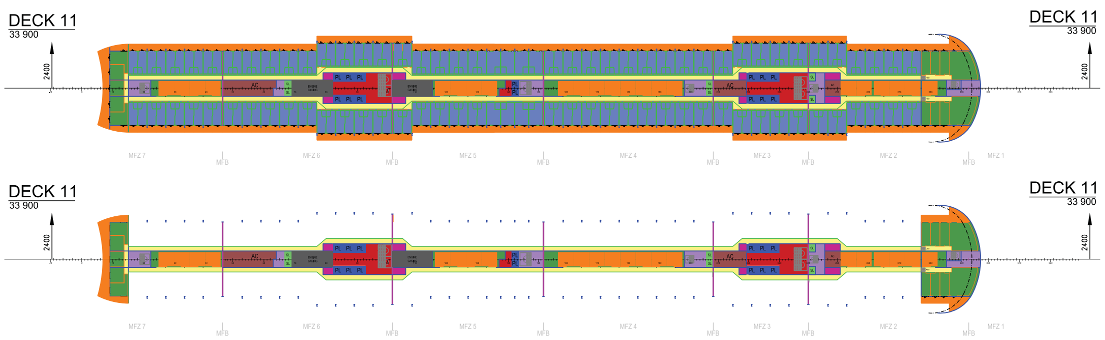

Figure 10. General arrangement

Complicated structures as well as special purpose spaces create challenges in the implementation of the modular approach at the aft and fore of the ship; therefore a conventional design has been preserved in these areas. Due to the larger deck height with the conventional design, the middle part of the ship has one deck more than the fore part to provide continuity within the structure; the solution shown in Figure 12 has been used. Additionally, the upper decks with public spaces are similar to a ship with the conventional cabin area design and are therefore kept identical.

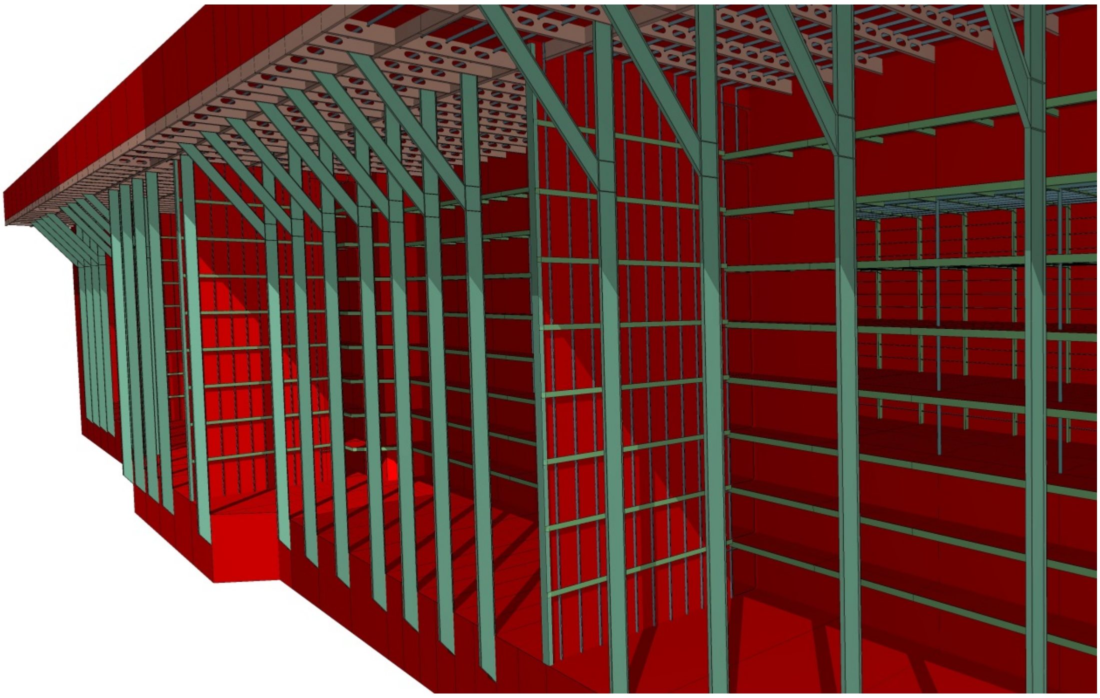

Figure 11. Steel structure

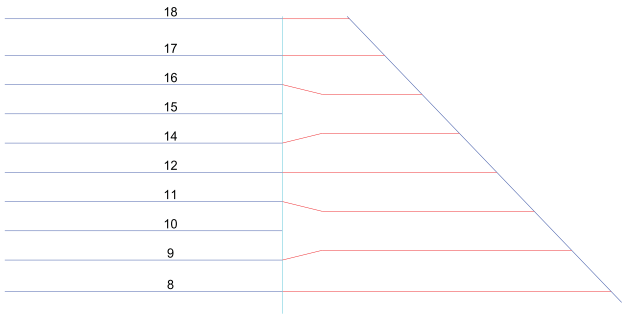

Figure 12. Steel structure in the fore

Several analyses have been carried out proving the feasibility of the structure. In cooperation with Foreship Ltd., a finite element analysis was conducted to evaluate the strength and deflections of a hull girder under longitudinal bending moment and torsion. Analysis showed that the problematic issues are torsional and horizontal stiffness. The same results were found by Oliver Parmasto's (2012) analysis of the almost identical structure of the m^{2}cell concept. This thesis relies on the analysis carried out by the aforementioned studies and therefore structure feasibility is not considered.

Outfitting principle

The usual outfitting practice is impossible when the deck height is reduced to 2400 mm since the lower deck height eliminates the space normally used for outfitting routing. This issue is solved by introducing a vertical routing for the systems.

All cabin outfitting components needed for two consecutive cabins are gathered into a single service module (see Figure 13). Service modules are fabricated at the dedicated manufacturing hall at the shipyard or turn-key delivered. When installed between the cabin doors, the modules form a vertical outfitting system where couplings have to be made only between the interfaces of the modules (see Figure 6). Finally, the vertical outfitting system is connected to the ship mains in the lower and upper part of the formed outfitting tower.

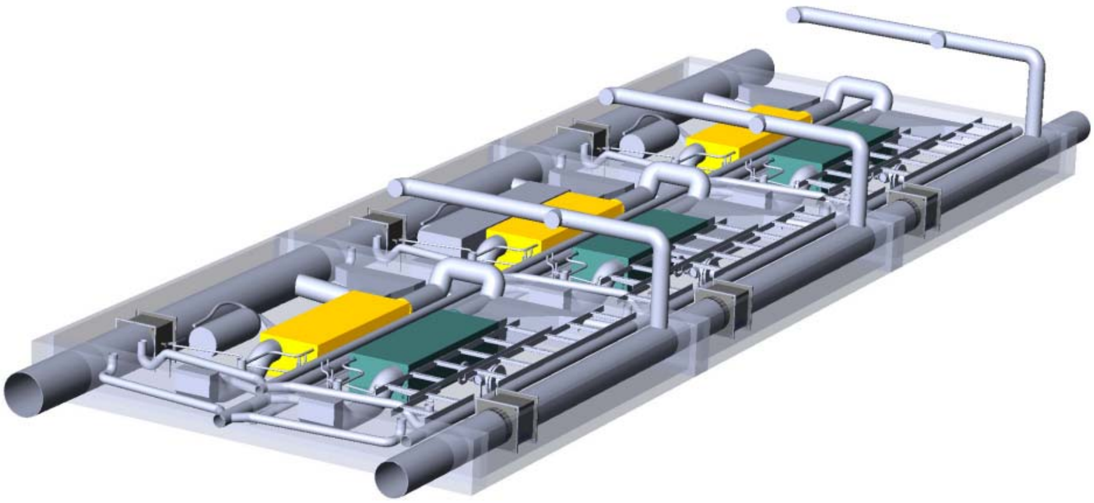

Figure 13. Maintenance space (Oy Shippax Ltd.)

Manufacturing

The advantage of the modular design is that the manufacturing of elements (modules) does not have to be located near the final assembly location. For example, if a macro-module's dimensions are within the limits of special road transportation, then the production could be established hundreds of kilometres from the shipyard. However, logistically it is easier if manufacturing is located on the shipyard territory, especially when a large number of macro-modules are required.

The preliminary manufacturing plan for the CC concept was made during the concept design stage. A manufacturing hall (see Figure 14 and Figure 15) has a length of 120 m, a width of 45 m, and a height of 13 m. According to the estimations of producing 18 cabins per week, three 2×3 type modules or one and a half 4×3 type modules can be manufactured.

The modules are manufactured using the assembly line principle. One side of the production hall (see Figure 14) is the *input* where all needed materials enter and another side is the *output* from which ready built modules are delivered. The four-step procedure starts with the panel assembly using a Fixcel Pro 2000 production line that is able to manufacture 500 m^2 of sandwich panel in one shift. Thereafter, macro-module erection starts with sandwich panel assembly at a production area that has three working platforms (stationary platforms on the sides and a portable middle working platform to allow the production line to be adjusted based on the size of the module under construction). Fabrication is continuous, with the installation of cabling, plumbing, and other systems all occurring in succession, and is accomplished with the outfitting of the cabin interior.

The placement of self-supporting macro-modules can vary; in the case of the CC concept, a stack is formed of three 2 × 3 type modules in the vertical and five to nine modules in the horizontal direction. The first row of the modules is welded to the eighth deck and backbone (the load-carrying construction of the superstructure) in the centre part of the ship. In the horizontal direction, the macro-modules are connected with elastic connections to compensate for ship hull deformations. Next, the modules are hoisted on top of their predecessors and similarly connected. After lifting and fixing the modules on-board, only corridor outfitting has to be finished.

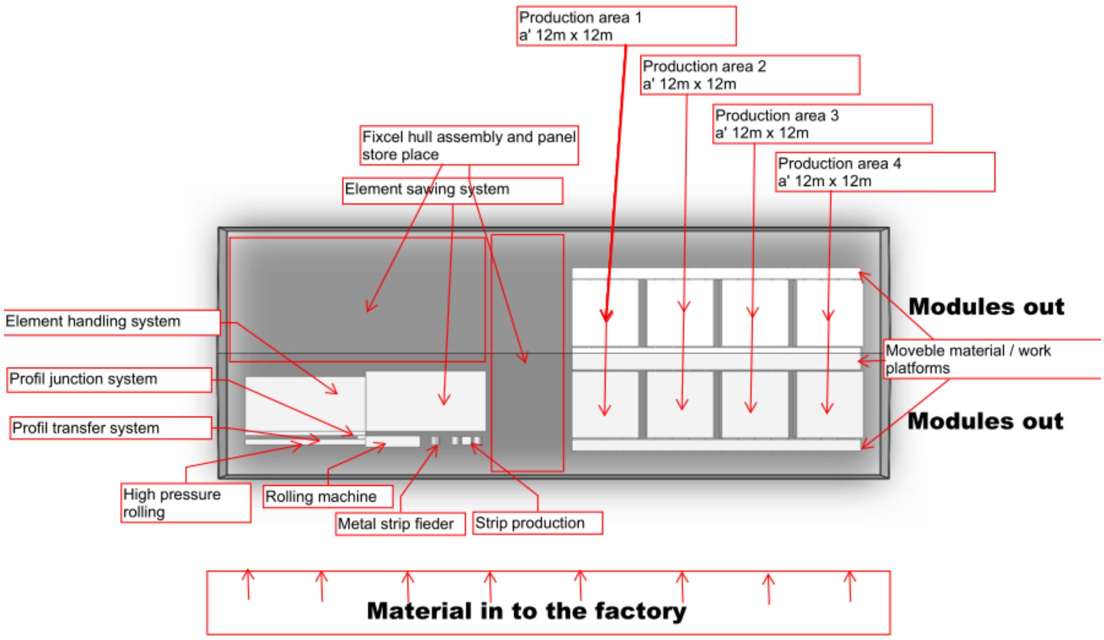

Figure 14. Manufacturing hall plan (STX Finland Oy)

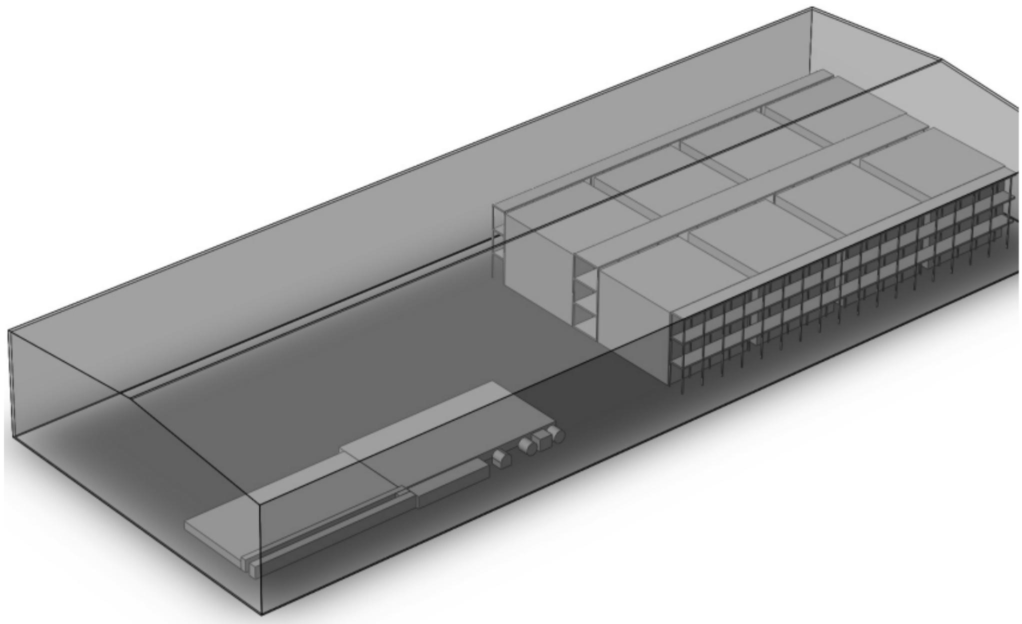

Figure 15. Manufacturing hall (STX Finland Oy)

1.3 Aim of the thesis

As described in the previous section, the macro-module based cabin area design has strong advantages; however, it also fundamentally changes the design of the superstructure, causing a series of challenges in the structural design and outfitting process. Although the project has already examined the feasibility of the CC concept, a number of issues remain unresolved.

This thesis aims to further elaborate and develop the CC concept and concepts with the macro-module based superstructure design in general. Since the macro-module based approach has major alterations compared to the conventional design, the utilisation of the conventional design assessment practice is not applicable; therefore, the evaluation of concept characteristics requires a distinctive systematic approach. The synthesis model has been developed for the evaluation of the technical and economic properties of the concepts with the macro-module based superstructure design. The synthesis model is then used to evaluate the CC concept as well as two additional proposed modifications. Finally, the feasibility of the CC and proposed concepts is evaluated against the conventional design.

To differentiate various parts of the research process, it has been divided into five phases. The first phase involves analysing and updating the earlier research. Since only a part of the documents concerning the CC concept could be acquired from STX Finland Oy, a part of the information had to be manually restored. Additionally, several important changes that were never included in the project report had to be added (Putaala, 2013, personal communication). Moreover, as the project was simultaneously carried out by four companies over an extended period of time, the project suffered from several errors that needed to be corrected.

The second phase develops the concept by expanding the technical and economic calculations. Well-established methods, discussed in the next chapter, are implemented to elaborate upon existing estimations and expand them.

A synthesis model is developed in the third phase. The synthesis model provides a framework, which offers the ability to develop design options and rationally select one of them (SNAME, 2003).

Fourth, two modifications of the CC concept are developed. Additional concept modifications explore and analyse available alternative design options.

Finally, the developed synthesis model is used to evaluate the CC concept and its modifications. The technical and economic feasibility of the proposed concepts is assessed by comparing them with the current method used in Finland.

The limitations of the thesis concern the area of assessment and the phase of the design process. The estimation of concept properties solely focuses on the superstructure below the sundeck. The design assessment concentrates mainly on the preliminary design.

2 Methods

This chapter describes the methods used in this thesis. The chapter is divided into two parts; the first part describes methods of the ship design process, concept evaluation, and the synthesis model and the second part discusses weight estimation, cost calculation, and other criteria that the concepts are assessed for.

2.1 Synthesis of the design process

2.1.1 Passenger ship design process

Although many of the tasks involved in the ship design process are interactive and decisions made during the design need to be amended frequently as the design develops, it is possible to suggest an order of attack which accelerates the design process and minimises the need for alterations (Watson, 1998).

The most common method used to describe the ship design process is a spiral model (see Figure 16). Given the objectives of the design, the design process follows an iterative path towards the best solution by adjusting and balancing the interrelated parameters (Eyres, 2012). The model illustrates how design evolves through three distinct and increasingly more definitive phases; these are concept, preliminary, and contract design. By the time the project development was taken over, the CC concept had already passed the first design evolution phase, so this thesis continues with the preliminary design phase.

The preliminary design phase is characterised by the increased level of detail. The focus is on identifying features which have significant effect on the characteristics of the ship. The outcome of the second phase should provide an adequate level of accuracy to verify the technical and economic feasibility of the ship (SNAME, 2003).

The spiral model cycle has twelve design disciplines, but not all of them are essential in the context of the current thesis. Since the research concentrates solely on the superstructure part of the passenger ship and concepts are based on the reference design, part of the disciplines can be excluded from the analysis. Vessel objectives, proportions, lines, hydrostatics, freeboard, and subdivision machinery as well as hull structure are identical to the reference ship and are therefore will be neglected. The relevant design parameters are general arrangement, structure, weight, capacities, and cost; these are discussed in the assessment criteria section of this chapter.

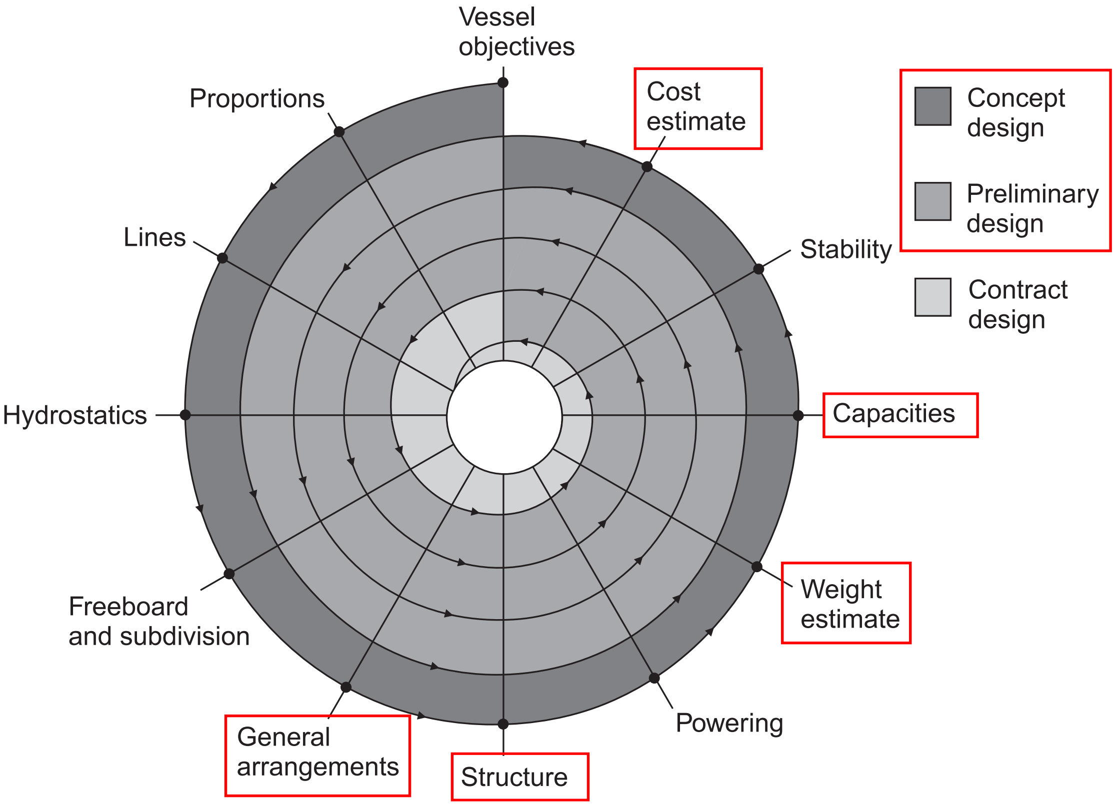

Figure 16. Design spiral (Eyres, 2012)

2.1.2 Concept evaluation

It is important to agree upon a common evaluation procedure that is known to all members of the design team. Mutual principles decrease the risk that individual members of the team will apply their own personal priorities as they evaluate design alternatives. The need for common rules is especially important when the number of designs is large or in the case of international teams.

Another reason to have a common evaluation method is that comparing single design parameters is often insufficient to adequately evaluate proposed concepts. To give profound insight into the strengths and weaknesses of the concepts, a systematic evaluation approach is required. The Pugh concept selection method (Pugh, 1991) is a commonly used technique for the evaluation of design concepts. The method compares concepts relative to a reference design by evaluating their properties.

The evaluation procedure can be divided into four steps (Figure 17):

- **Step 1:** Selection of the criteria and assigning weights,
- **Step 2:** Defining a reference and concepts to be evaluated,
- **Step 3:** Building the concept comparison matrix, and
- **Step 4:** Scoring design concepts.

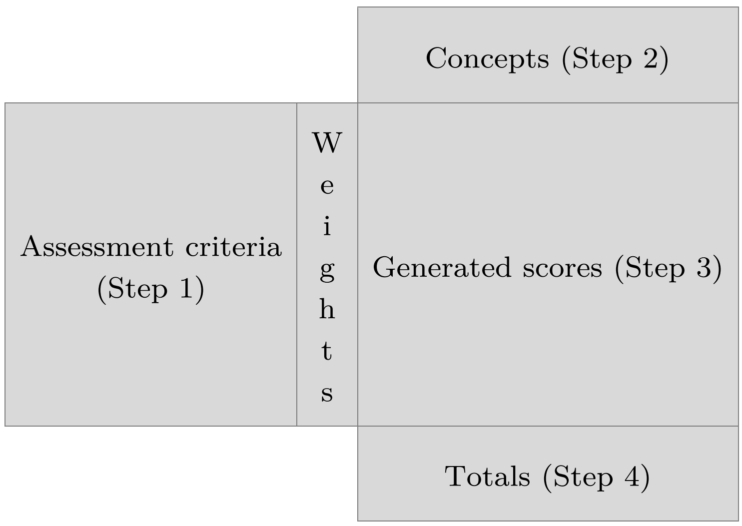

Figure 17. Pugh concept selection matrix

In the first step, a list of relevant criteria is compiled and weights are assigned to each based on their significance. The weights are calculated based on cost-benefit analysis which is discussed in sub-section 2.3.5 *Cost estimate.*

Comparable concepts are chosen in the second step; in the current work, the CC concept and its modifications are compared to the conventional concept. The weighted list of design criteria is used to score design alternatives in step number three. The scoring principle is based on relative change compared to reference design – a difference of one percent corresponds to one point. Positive change is marked with a positive score and negative, accordingly, with negative score. Finally, the scores of every concept are added and the final ranking can be observed.

In the following, a simple example intends to illustrate the evaluation procedure. If the increase of the total number of cabins by 1% is in the long-term economically twice as beneficial as a decrease of manufacturing cost by the same percentage, then the number for the cabin weight is 2 and the manufacturing cost weight is 1. For example, if the first of the compared concepts has 7% more cabins but is 5% more expensive when compared to the conventional design, and the second concept has corresponding values of 3 and 1, then the matrix shown in Figure 18 can be formed. Results indicate that the first alternative is significantly better.

Criterion	*Weights*	*Concept 1*	*Concept 2*
Number of cabins	$\boxed{2}$	$\boxed{2} \times 7 = 14$	$\boxed{2} \times 3 = 6$
Manufacturing cost	$\boxed{1}$	$\boxed{1} \times (-5) = -5$	$\boxed{1} \times (-1) = -1$
	Total	9	5

Figure 18. Example of a Pugh matrix

2.2 Synthesis model

A synthesis model is a tool for combining individual data into a common framework. In naval architecture, the ship design process synthesis model refers to the methods of calculation and combination of different design parameters. A synthesis model enables the determination of ship parameters in a systematic way, searching for attractive combinations of parameters. Properly designed synthesis models should produce an effective design with minimum effort in the shortest amount of time; it should give the opportunity to quickly compare modifications of the designs and illustrate sensitivity between various design parameters. In this research, the synthesis model is developed to provide a tool for the evaluation of ship concepts with macro-module cabin area design.

The major benefit of the synthesis model is that individual changes are automatically reflected on other fields, assuring that any given decision will not cause an adverse impact on other components of the system, e.g. increasing volume does not burst the total weight. It also gives the opportunity to easily update calculations as better information becomes available; this is especially important in the early stage of the design process, when input data is likely to be tentative. Another advantage is that the synthesis model accumulates knowhow in an organised format that simplifies the understanding of the design rationale and makes the process explicit for all members of the design team.

The Microsoft Excel spreadsheet application was used to develop a synthesis model for this research; it is widespread and easy-to-use software that has enough functionality for the given project. The synthesis model was developed with an emphasis on user experience and simplicity; the spreadsheet has dedicated input and output sheets, colour codes for cells with different purposes, and explanatory comments. A simplified synthesis model structure diagram is shown in Figure 19, with a detailed description of the synthesis model specified in Appendix 1. *Implementation of the synthesis model*. The following section describes the methods used in the developed synthesis model to assess the design concepts.

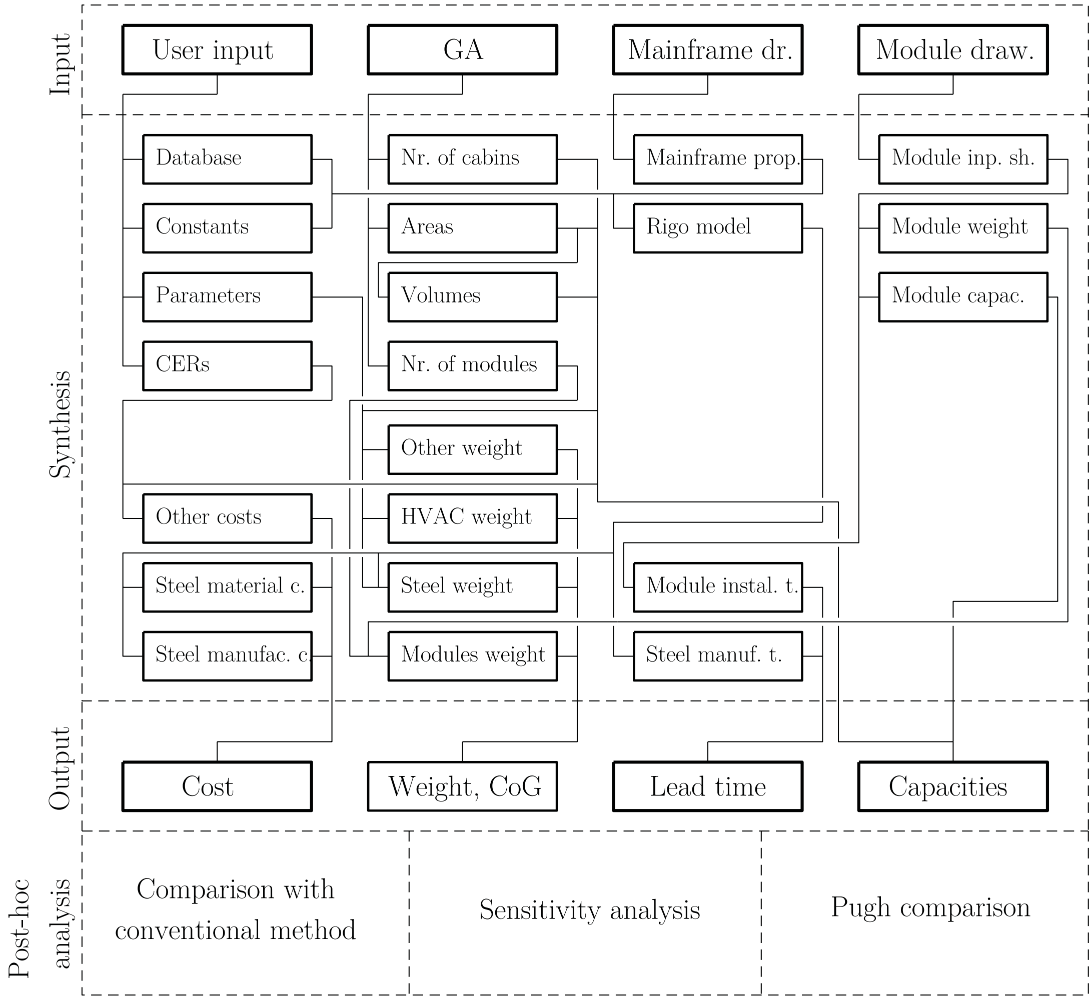

Figure 19. Simplified diagram of synthesis model structure

2.3 Assessment criteria

This section describes the criteria that the concepts are evaluated for. The criteria were adopted from the spiral model parameters, i.e. the new macro-module concept is evaluated for general arrangement design, structure, weight, capacities, and cost. Subsequently, three principles are followed throughout the assessment of all criterion:

- **Only areas affected by the introduction of the macro-module concept are assessed.** The macro-module based approach to hotel area manufacturing changes the structure and general arrangement of the ship; nevertheless, several areas remain identical to the conventional design. In order to simplify the assessment of the concept, areas not altered by the application of the macro-module concept are neglected.

- **Greater attention is paid to the aspects with a strong impact on the final result.** Various aspects of the design parameters have a different contribution to the final result; therefore, those parameters have to be treated differently as well. Insignificant parameters are generally ignored and important parameters are thoroughly considered.
- **Simple and logical methods are used when applicable.** Although elementary methods may not always be the most efficient and/or precise, the fact that simple methods can be easily verified, updated, and (if necessary) expanded outweighs their disadvantages.

2.3.1 General arrangement

The general arrangement (GA) of a ship is dictated by the service it provides; generally, the main objective of the passenger ship accommodation deck GA is to fit the maximum amount of cabins into a given space. This is due to the fact that the number of passenger cabins is directly proportional to the number of passengers that the ship is able to accommodate which has a strong link to the amount of revenue the ship can generate. However, several factors have to be considered:

- There are requirements of international agreements and a classification society that must be met in the design of general arrangements. The most important of which are SOLAS fire safety rules for fire safety bulkheads, escape routes, and corridors.
- The layout should be intuitive to navigate and have a sufficient amount of space for passengers to feel comfortable.

- GA has to include all service spaces necessary for the normal operation of a ship and maintenance of a convenient environment for the passengers.
- Balcony and luxury cabins are more profitable for the ship owner.

The macro-module concept was designed with the aim to retain maximum similarity with the reference design; therefore no significant changes were made to the GA. Even the most important modification – exchanging normal cabin areas with a macro-module based concept – does not particularly affect GA. The position of an engine casing, staircases, lifts, and several other spaces has been kept identical. Changes concerning the location and size of the air conditioning rooms, positions of fire safety bulkheads, and other minor modifications were needed. The modifications result from the usage of a vertical outfitting system that connects to the air conditioning (AC) rooms at the lower and upper part of the superstructure; this dictates the position of the AC rooms, which are therefore mainly located on the 8–9th and 16–17th decks. Another change was influenced by the fact that the macro-modules had to fit between bulkheads and the objective of minimising space that has no purpose.

2.3.2 Structure

Backbone

This work is not assessing the structural design; however it is essential to outline the main design principles of the load carrying part of the superstructure – the so-called backbone. The backbone is designed to be as light as possible while withstanding the design loads and being simple to manufacture; the design is driven by the macro-modules that have to fit between the fire safety bulkheads and be properly connected. With this consideration in mind, the distance between the bulkheads has therefore been adapted to multiples of the macro-module width.

The lowered deck height causes problems with the door opening. Namely, the steel strip above the door opening is reduced to the degree that it is not able to withstand the load it applies. The solution is the *checkerboard* pattern positioning of the doors and the stiffening of its surroundings.

Macro-module

The macro-module design includes several factors that have to be considered; the size of the macro-module is a major point among them. Larger macro-modules are generally preferable as bigger modules decrease the total number of units, therefore reducing the amount of double structures needed in the location of the module connections as well as the effort of lifting modules on board and their installation. However, while larger modules are more efficient, smaller modules add flexibility to the design and are easier to manufacture and operate. The size of the module is limited by several constrains; from the manufacturing point of view, the macro-module has to fit into the manufacturing hall, its weight has to remain within the crane’s lifting capacity, and its excessive size should not obstruct the installation process. For correct installation on-board, the depth of the macro-module is restricted to the distance between the side of the ship and its backbone.

The small variety of different types of macro-modules simplifies and shortens the manufacturing process; however, the need for different types of modules and the complexity of the passenger ship requires macro-modules of different sizes and structures. A proper balance should be found that offers sufficient variation between cabin types while retaining a reasonable number of different macro-modules.

Including the corridor as a structural part of the macro-module is another option that requires thorough analysis. The integration of a corridor with the module increases the level of prefabrication, but on the other hand, having corridors connected to the backbone of the ship increases structural rigidity and simplifies the module installation process. This thesis assumes that the macro-modules do not include a corridor part and leaves this question open for future research.

2.3.3 Capacities

The capacity of the passenger ship hotel area is regularly proportional to the amount of passengers the ship is able to accommodate; this is the reason why the expansion of this area is so desired. Concept capacities have to be measured to analyse how space on-board is used, have to check the fulfilment of regulations, and have to compare them with other concepts. The accurate assessment of areas and volumes is also essential since weight and cost estimations are largely related to the capacities based statistics. Additionally, the volume of any given space combined with the height from the bottom line of that space, gives a value for the centre of volume which is used as an approximation for a vertical centre of gravity.

Areas and volumes are measured directly from the general arrangement drawing using computer-aided design software. Measurements have been made separately for every deck and different type of space (see Table 1). Two types of cabin areas are distinguished: the useful cabin area is the space that a passenger can utilise and the total cabin area includes the area occupied by structures and outfitting spaces. This subdivision intends to show the share of the space that is used purposefully. Unused space includes all the space that has no purpose; it is aimed to show how much space can potentially be more usefully occupied.

The synthesis model has dedicated worksheets for entering the data of every room type on each of the decks. For this research, accounts of various areas were made manually, room-by-room, to demonstrate the source of the data and make the process very explicit; however, the required input data could also be obtained by other methods, for example, through NAPA software.

Table 1. Area and volume measurement groups

Cell cabins
Standard
Luxury
Traditional cabins
Balcony (standard)
Balcony (aft)
Window
Inside
Crew
Suite
Public areas
Public staircases
Public lifts
Corridors
Service spaces
AC rooms
Service staircases
Service lifts
Pool recess
Pool equipment
Wheelhouse
Navigation equipment
Offices
Engine Casing
Storage
Other
Balconies
Unused space

2.3.4 Weight estimate

The importance of the mass properties in shipbuilding cannot be overestimated. Increasing ship weight unleashes a chain reaction that has an adverse impact on the overall ship performance; increasing the total weight of the ship increases the draught, which has a negative influence on the resistance. A higher resistance results in increased fuel consumption which, in turn, raises operating costs. Weight is also strongly linked to manufacturing costs, requirements for hull girder strength, and power requirements. The vertical centre of gravity is another important parameter directly related to the weight and its location on the ship; decreasing the weight of the superstructure lowers the position of the vertical centre of gravity, which accordingly increases a ship's stability and passenger comfort.

In the concept design phase it is sufficient to divide the weight of the cabin area into three main groups – steel, interior, and HVAC. Each group is subdivided into smaller sub-groups. As the design process proceeds and more information becomes available, more groups and sub-groups should be added. For each weight group the most significant weight estimation method is used. Table 2 outlines weight groups and sub-groups, and the estimation methods used in the developed synthesis model.

Volume and area based statistics are the main method for obtaining the weight data. Statistics provide an easy and sufficiently precise way to estimate weight in the concept and primary design phase; however, the use of statistical data needs both an understanding of the statistical indicators' backgrounds as well as specifics for the designed ship. This is important since the use of some historical data for conventional designs is impractical for macro-module based design, while other data can be used without any restrictions. In the most important areas, more accurate, direct calculation is used. The latter involves a lengthy task, especially when the concept differs significantly from the conventional design, but it is the most desirable. Estimation methods for the main weight groups are explained below.

If weight saving is vital, the improvement work should be concentrated on the biggest weight factors. The steel weight is the dominant weight item in the deckhouse lightweight, accounting for approximately half of the conventional and a third of the modular design weight; therefore it is essential to estimate this figure precisely. The steel weight estimation can be done using several alternative methods including software, statistics, and direct calculation; all three are implemented in the current work.

Table 2. Summary of used weight estimate methods

	Weight group	*Estimation method*	*Source*
Steel	Steel (approximate)	weight per volume	STX Finland Oy
	Steel (more accurate)	direct calculation	Steel drawings
	Steel (verification)	CAD software	3D model
	Paint	weight per area	STX Finland Oy
Interior	Cell Cabin macro-module	weight per area	Oy Shippax Ltd
	Conventional cabin	weight per piece	STX Finland Oy
	Corridor materials	weight per area	STX Finland Oy
	Floor cover and insulation	weight per area	STX Finland Oy
	Other interior	weight per area	STX Finland Oy
	Windows & balcony doors	weight per piece	STX Finland Oy
	Balcony modules	weight per piece	STX Finland Oy
HVAC	AC devices and trunks	weight per piece	STX Finland Oy
	Cell Cabin	weight per area	Elomatic Oy

The first method is based on statistics from previous projects; the deckhouse volume is used for a quick approximate estimation of the steel structure weight. Direct calculation is used for more accurate estimation, while the steel cost estimation model, described in the next sub-section, is also appropriate for estimating the steel weight since it prerequisites the identification of structural dimensions for each of the steel elements. An accurate 3D computer-aided design (CAD) model (see Figure 11) primarily made for illustration purposes was used to extract the steel volume and the position of the centre of gravity. This method is not interactive but very accurate and was used to verify the precision of the previously outlined weight estimation methods.

Similar to steel weight, the weight of the macro-module has a significant role in the total weight of the superstructure. An estimation of the module weight was done in cooperation with Oy Shippax Ltd. The weight is based on the direct estimation of required material quantities and all cabin interior components and their weights. Since the weight of the macro-module does not increase linearly, the calculation was performed separately for different module sizes. Individual estimation was also done for the first row of the modules that are welded on the eighth deck and do not have a sandwich panel floor panel.

Heating, ventilation, and air conditioning (HVAC) weight calculation was done by Elomatic Oy. The estimation is based on the detailed estimation of all the parts needed to outfit one deck. Weight per area was then obtained by dividing the weight of the all components by the corresponding area. This parameter was then used to estimate the weight of all deckhouse outfitting.

In the case of areas such as storage rooms, staircases, or the control deck, a direct calculation is not reasonable. Therefore, statistical data was used for the weight estimation.

2.3.5 Cost estimate

The success of a commercial ship design is always measured by its economic outcome; economic profitability is also the main criterion for selecting the design concept and for the construction method for the next generation of passenger ships.

If the alternatives under consideration exist only as imaginary concepts, about which few details have been established, this suggests that the cost estimation technique should be relatively simple (SNAME, 2003). Moreover, in most cases, it is not necessary to worry about exact costs; relative costs are what matter (ibid.); in other words, the estimating should strive to emphasise differences in costs between various alternatives.

The difficulty lies in the necessity of estimating costs in the early phase of the design process. The common practice among shipyards in developing rational cost estimates is to catalogue historical costs data through some consistent work breakdown structure (WBS). The WBS has traditionally been a list of common ship systems (deckhouse structure, equipment, piping, paint, furnishing, etc.), augmented by ancillary shipyard services that are needed to support production.

Cost Estimating Relationships (CERs) provide the basic means for estimating costs (SNAME, 2003). CERs are basically statistics that are derived from the measurement of a single physical attribute or unit for particular shipbuilding activity and the cost of performing this activity. CERs have different types and levels of detail. Examples of CERs are:

- labour for steel block assembly at x man-hours/ton,
- material cost for pipe at y €/m, or
- the cost of a macro-module at z k€/module.

Weight is often used as the estimation parameter. The advantage of weight is that it applies to most of the components of the ship. However, some individual items are estimated on the basis of other parameters. For example, some costs are obtained from sub-contractor's quotations, while others are obtained by costing items on a cost per unit basis. Table 3 summarises the methods used for cost analysis in the developed synthesis model.

Steel

Rigo (2001) introduced the least-cost structural optimisation method but the cost estimation methodology introduced in this paper can be successfully applied to the preliminary design steel cost, weight, and manufacturing time estimations. The cost estimation method presented by Rigo has been adapted to the specific needs of the current work.

Table 3. Summary of used cost estimation methods

Attribute	*Estimation method*	*Source*
Approximate steel cost (material, design and production)	cost per weight	STX Finland Oy
More accurate steel cost (material, consumables, labour)	see sub-section below	Rigo (2001)
Painting (paint and painting)	cost per weight	STX Finland Oy
Cell Cabin macro-module	cost per piece	Oy Shippax Ltd
Turnkey of Cell Cabin area	cost per area	STX Finland Oy
Cost of conventional cabin	cost per piece	STX Finland Oy
Turnkey of conventional cabin area	cost per area	STX Finland Oy
Windows & balcony doors	cost per piece	STX Finland Oy
Balconies	cost per piece	STX Finland Oy
Cable trays	cost per area	STX Finland Oy
Other HVAC	cost per area	STX Finland Oy

According to Rigo (2001), global construction costs can be subdivided into the following three categories: the cost of raw materials, labour costs, and overhead costs. The cost of raw materials is based on the total volume of the steel and the price of a ton of steel. Labour costs estimation uses an analytic evaluation method; this approach requires quantifying the work time required to perform each of the manufacturing tasks and knowledge of the man-hour costs.

Overhead costs include insurances, utilities, rents, and other items that cannot be directly attributed to the construction process but are still linked to it. A step-wise description of the production weight and cost model is shown in Figure 20. The numbers in brackets refer to the formulas in Appendix 2, where a description of the used variables and constants is also provided.

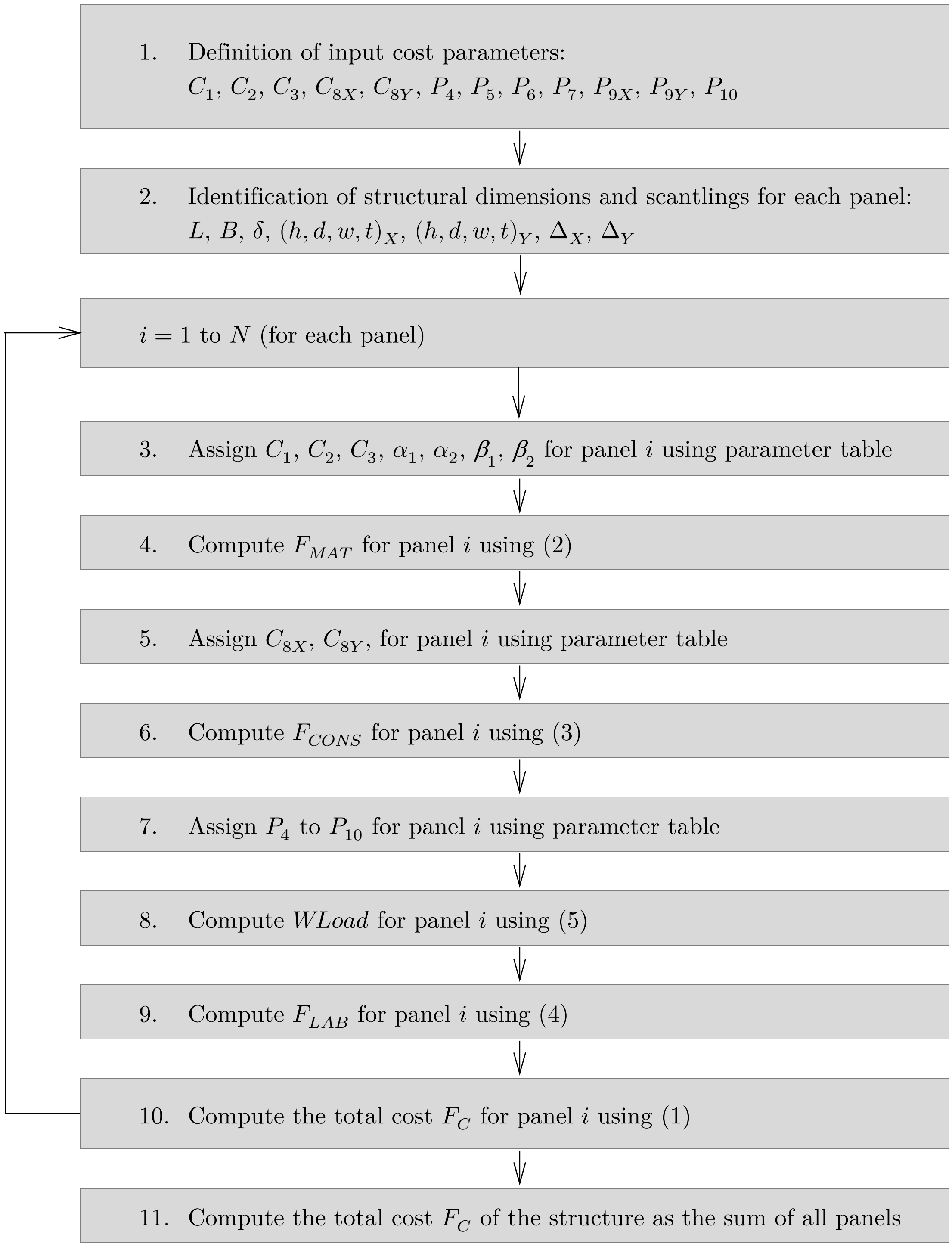

Figure 20. Step-wise description of production weight and cost model

A detailed estimation of all the small details of the steel structure is not reasonable. To simplify the estimation process, the assessment is limited to the central part of the steel structure, where the macro-modules would be installed. The aft and fore part of the ship are nearly identical and can be excluded from the analysis. The assessment of the central section is in turn divided into a wider part with the staircases and a narrower part with the inside cabins; the AC rooms are in the mid-part. The estimation process is repeated for each of the concepts.

Cost estimation model implementation in the synthesis model

This sub-section illustrates the Rigo cost estimation model's implementation in the developed synthesis model. For the effortless input of mainframe scantlings, a dedicated worksheet was developed where the user can choose characteristics for each of the longitudinal steel elements of the superstructure as well as specify deck heights (see Figure 21). The cost estimation model was compiled in a separate worksheet which is illustrated in Table 4. Variable values of the worksheet were gained automatically from the mainframe scantlings input (e.g. cells D6 and D5), acquired from the database (e.g. cells D20–D24), calculated (e.g. cell D31 = cells D17/D15), or determined using a formula (e.g. cell D38 = IF(D27 > 0;0;1)). Additionally, the user has to specify the longitudinal length of the section that the calculations are being made for (cell D2), the number of such stiffened panels (cell D14), and two parameters (cells D49–D50).

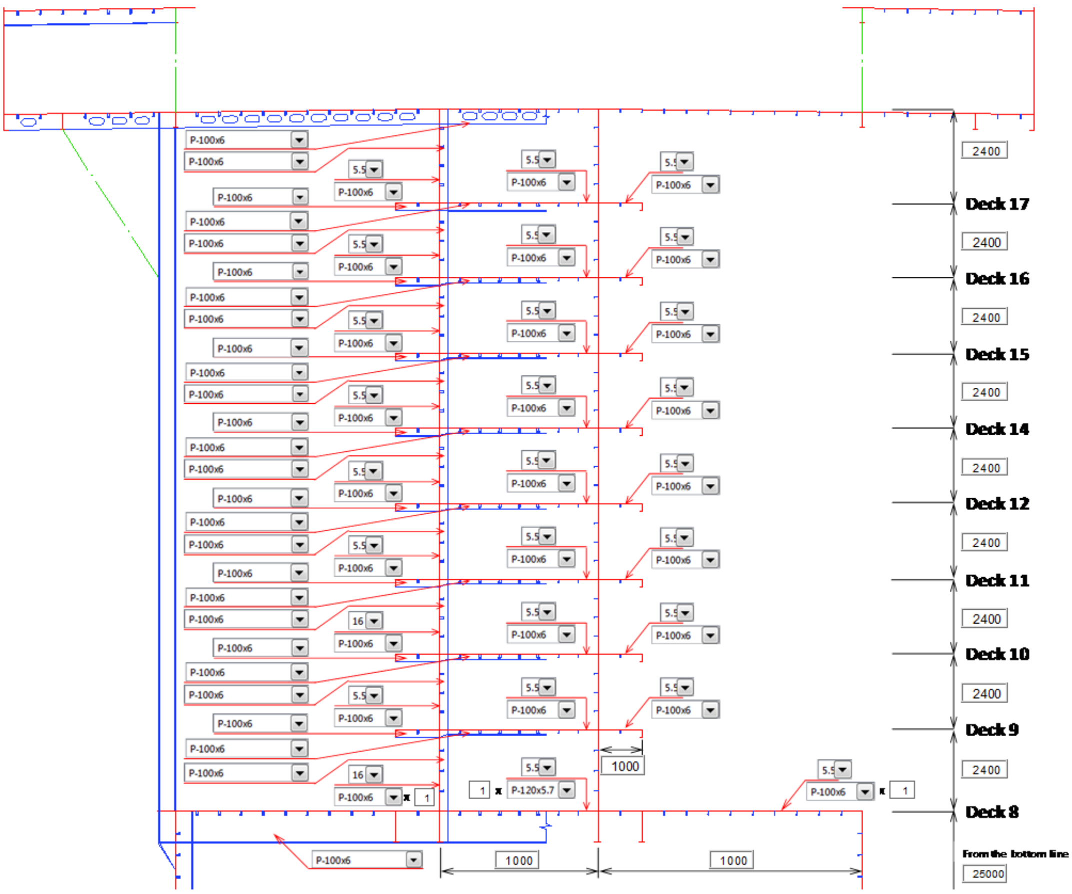

Figure 21. Mainframe scantlings input in synthesis model

Table 4. Calculation sheet example for one stiffened panel

	A	B	C	D
1		**Input data**		
2		Section longitudinal length	m	66.515
3				
4	Symb.	Description	Unit	Deck 8. Deck plating at CL
5		**Weight properties**		
6		Deck height from bottom line	m	26.5
7		Deck height	m	2.4
8		Weight	kg	3 465
9		Height of the centre of gravity	m	26.49
10				
11		**Total cost**	€	6 483
12				
13	F_{MAT}	**The cost of materials – for a stiffened panel**	€	1 833
14	-	Number of items	-	1
15	-	Number of longitudinal stiffeners	-	1

16	L	Stiffened panel length	m	66.515
17	B	Stiffened panel width (height)	m	1
18	d	Stiffened panel plate thickness	mm	5.5
19	-	Longitudinal stiffener type	-	P-120x5.7
20	A(x)	Longitudinal stiffener cross section area	m²	0.000896
21	H(x)	Web height	m	0
22	D(x)	Web thickness	m	0.0057
23	w(x)	Flange width	m	0
24	t(x)	Flange thickness	m	0
25	-	Transversal frame type	-	P-100x6
26	A(y)	Transversal frame cross section area	m²	0.000774
27	H(y)	Web height	m	0
28	D(y)	Web thickness	m	0.006
29	w(y)	Flange width	m	0
30	t(y)	Flange thickness	m	0
31	ΔX	Longitudinal stiffeners spacing	m	0.5
32	ΔY	Transversal frames spacing	m	2.73
33	C_1	Cost/kg of a plate with d thickness	€/kg	0.52
34	C_2	Cost/kg of longitudinal stiffeners	€/kg	0.57
35	C_3	Cost/kg of transversal frames	€/kg	0.57
36	**F_{CONS}**	**The cost of consumables – for a stiffened panel**	**€**	**26**
37	α_x	Binary coefficient related to stiffeners manufacturing	-	1
38	α_y	Binary coefficient related to frames manufacturing	-	1
39	C_{8X}	Cost/meter of the consumables related to long. stiffeners welding	€/m	0.28
40	C_{8Y}	Cost/meter of the consumables related to transversal frames welding	€/m	0.3
41	**F_{LAB}**	**The labour cost – for a stiffened panel**	**€**	**4 624**
42	η	Efficiency parameter for the considered production plan	-	1
43	Wload	Workload required for the fabrication of the stiffened panel	Man-hour	92
44	P_4	Workload per meter for the welding of longitudinal stiffeners web on the plate (preparation included)	Man-hour/m	0.457
45	P_5	Workload per meter for the welding of transversal frames web on the plate (preparation included)	Man-hour/m	1.104
46	P_{9X}	Workload required to build 1 meter of longitudinal stiffener – assembly of web - flange (preparation + welding)	Man-hour/m	0.100
47	P_{9Y}	Workload required to build 1 meter of transversal frame – assembly of web - flange (preparation + welding)	Man-hour/m	0.167
48	P_{10}	Workload required for the preparation of 1 m^2 of plate (cutting, positioning)	Manhour/m²	0.410
49	β_X	Ratio between the amount of intersections requiring longitudinal brackets and the total amount of intersections	-	1
50	β_Y	Ratio between the amount of intersections requiring transversal brackets and the total amount of intersections	-	1

Pugh concept evaluation

Sub-section 2.1.2 *Concept evaluation* described the Pugh concept evaluation method. This section describes the method to convert various criterion values to a common unit of measure for weighing the importance of concept criteria. Money is appropriate as a common unit; for the comparison, each criterion is converted to express daily cost/income value.

The income generated by additional cabins is estimated based on the extra number of passengers that the ship can accommodate due to additional cabin areas, which is then multiplied by the estimated average passenger daily contribution to cruise company profit (Cruise Market Watch, 2014) and the average occupancy rate (see equation (2.1)).

$$\begin{aligned} &Number\ of\ cabins\ change\ CER \\ &\quad = \frac{average\ profit\ per\ passenger\ per\ cruise}{median\ cruise\ length} \\ &\quad \times number\ of\ additional\ cabins \\ &\quad \times passengers\ \ per\ cabin \\ &\quad \times occupancy\ rate \end{aligned} \tag{2.1}$$

The increased manufacturing cost is divided by the time frame that the ship-owner is planning for his investment to pay him back.

$$Manufacturing\ cost\ change\ CER = \frac{\Delta C}{T \cdot 365} \tag{2.2}$$

where

ΔC	Total increase/reduction of the manufacturing cost	ton
T	Number of years that investment is intended to pay back	year

Sensitivity analysis

A sensitivity analysis was conducted to determine the responsiveness of the result to changes in key input parameters. The developed synthesis model performs sensitivity analysis for the total weight and cost by changing the most important input components. The total cost sensitivity has been tested for the impact of the macro-module, conventional cabin module, and steel structure cost change. The total weight responsiveness was analysed for the change in macro-module weight. The results were illustrated by plotting the relative change of the parameter against the relative change of the cost/weight.

Factors not considered in this thesis

The scope of this thesis and early design phase limit the aspects that can be assessed; however, several important issues are important to highlight.

A large investment is required to apply a new method of manufacturing. The shipyard would have to invest in building manufacturing halls, a production line, and other items. The estimation of initial investment requires a great deal of data that is challenging to obtain. Consideration of the initial investment is also complicated to take into account as it should not be taken as a one-time expense but as a long-term investment.

The advantage of the decreased manufacturing time is another characteristic that is difficult to estimate. A shorter manufacturing time can provide a shipyard with an advantage during negotiations; it also means that a shipyard can build more ships in the given time frame. If a shipyard needs to take a loan to afford the manufacturing process, then the shorter lead time decreases interest costs.

2.3.6 Manufacturing process

The design of the ship should be *production-friendly* to assure minimal vessel construction costs. The CC concept represents a substantial leap forwards in passenger ship manufacturing methodology. Due to the limited scope of this work, the manufacturing process analysis was done on the preliminary level. The macro-module installation and manufacturing time were estimated by Oy Shippax Ltd. The steel backbone manufacturing time was estimated, as previously discussed, via the Rigo cost estimation model.

3 Results

This chapter presents the results of this thesis. The chapter is divided into two parts; in the first part, comparable concepts are introduced and the particular choice made is justified. In the second part, the developed synthesis model is used to assess and compare conventional and macro-module based concepts.

3.1 Concepts

The developed synthesis model is used to compare four concepts – one concept with the conventional cruise ship design and three concepts with the macro-module based deckhouse design (see Figure 22). The macro-module concepts have a strong link with the conventional design since the aim was to keep the new concepts as similar as possible to the reference design while focusing on the identification and evaluation of the new concepts' influence on the weight, cost, and manufacturing process. The concepts used for the comparison are described below.

Reference concept. The conventional cruise ship concept serves as a reference for the comparison. The concept has a traditional general arrangement with public spaces located on the 5–7th decks as well as the top decks, while eight decks in between are occupied by cabins.

Cell Cabin (CC) concept with the 2×3 type macro-modules. The CC concept initially proposed by STX Finland Oy is based on the previously mentioned reference design that is modified between the eighth deck and sundeck. Traditional balcony cabins are replaced with macro-modules that have a width of two cabins and a height of three cabins (2×3). The deck height is reduced to 2400 mm and an additional cabin deck has been added.

CC concept modification with the 4×3 type macro-modules. This concept is the authors' proposed modification of the initial CC concept. The main difference lies in the size of the macro-module, which is doubled compared to the original design. The increased size of the macro-module reduces the number of double structures between the macro-modules, consequently saving weight, increasing the cabin area, and shortening the installation time. Another modification concerns luxury cabins at the mid-ship region that are exchanged with traditional cabins; this change is aimed to decrease the versatility of the modules. Moreover, the floor of the first row of macro-modules has been removed to eliminate the double structure and decrease the height of eighth deck. Additionally, several minor modifications were introduced to improve the utilisation of space, add additional cabins, and increase the area of the AC rooms.

CC concept modification with the 4×3 type macro-modules but without an additional deck. This concept is identical to the previous design but does not have an additional deck; instead, it has a similar amount of cabins as the reference ship. The aim of this concept modification is to provide an improved comparison to the reference design – since the number of cabins remains similar, the other properties can be directly compared.

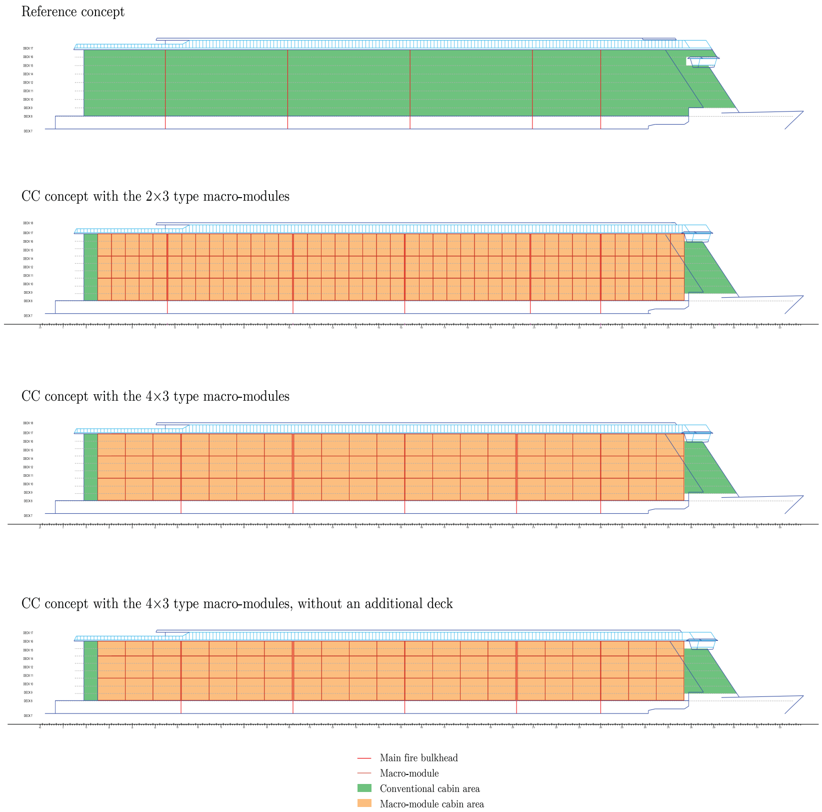

Figure 22. Reference design and Cell Cabin concepts

3.2 Comparison of traditional and macro-module concepts

Table 5 summarises the results of the concept comparison, followed by a discussion of each category of assessment.

Table 5. The comparison between traditional and macro-module concepts

	CC (2×3)	*CC (4×3)*	*CC (4×3) 8 decks*
Cabin decks	8	9	8
Cabins total	**8.5%**	**11.6%**	**-0.4%**
Balcony	7.9%	11.3%	-1.0%
Inside	16.4%	20.0%	11.8%
Window	0.0%	-57.1%	-71.4%
Height of the superstructure	1.2%	0.4%	-10.5%
Areas			
Cabin area (useful)	**12.8%**	**15.6%**	**3.1%**
Balcony cabin area	12.3%	15.3%	2.5%
Inside cabin area	16.4%	25.5%	17.3%
Window cabin area	40.3%	-47.9%	-68.5%
Service areas	**4.8%**	**6.8%**	**-0.2%**
AC	-3.4%	3.9%	-12.3%
Service staircases	-1.3%	-7.9%	-17.3%
Wheelhouse	-0.1%	-0.1%	-0.1%
Offices	-22.8%	-2.4%	-2.4%
Storage	146.3%	146.3%	117.9%
Pool recess and equipment	-3.8%	-3.8%	-3.8%
Unused space	92.2%	-76.2%	-88.4%
Total cabin area	18.0%	19.0%	6.1%
Total area	16.1%	16.8%	-3.8%
Volume			
Total volume	5.4%	5.4%	-6.0%
Weight			
Total	**4.6%**	**3.5%**	**-9.0%**
Steel (central part)	-35.7%	-35.6%	-37.6%
Steel (with aft and fore part)	-22.6%	-22.6%	-23.8%
Paint	-21.1%	-21.1%	-26.3%
Interior (incl. macro-modules)	45.7%	42.1%	20.3%
HVAC	-43.2%	-43.3%	-49.5%
Total weight / cabin	**-4.4%**	**-7.8%**	**-6.9%**
VCG	**-1.6%**	**-1.9%**	**-4.9%**
Cost			
Total cost	**10.8%**	**9.5%**	**-1.4%**
Total Cost / cabin	2.1%	-1.9%	-1.0%
Total Cost / cabin area	-1.8%	-5.3%	-4.3%
Total Cost /GT	4.9%	3.7%	5.0%
Steel	-40.6%	-40.3%	-42.5%
Manufacturing time			
Steel	-34.6%	-34.1%	-35.9%
Macro-modules manufact. time	reference	3.3%	-8.2%

3.2.1 Number of cabins

A significant increase in the number of cabins can be observed. The growth is higher among the inside cabins, which is adverse since the inside cabins are less valuable than the balcony and window cabins. However, it is important to acknowledge the fact that in case of concepts with 4×3 type macro-modules, a notable increase is partly achieved by exchanging the luxury cabins with standard cabins. If luxury cabins were not replaced, the actual change in the number of cabins would be 9.2% and –2.5% instead of 11.6% and –0.4%.

3.2.2 Area and volume

The significant growth of the total area (16.1%, 16.8%, and –18.3%) and the volume (5.4%, 5.4%, and –6.0%) can be examined. Additional space is a result of the additional deck and the wider superstructure design. A strong trend is apparent with the utilisation of the unused space. If the original CC cabin concept had a noteworthy amount of space without any purpose, then it has decreased with the concept modification (92.2%, –76.2%, and –88.4%). The area of the service staircases (–1.3%, –7.9%, and –17.3%) that were occupying significantly more space than necessary for convenient navigation or any required rules has also been decreased. The space acquired from the optimisation has been utilised to expand the cabin area and AC rooms.

The size of a cabin's effective area has also improved. A balcony cabin from the CC concept with a 2×3 macro-module layout is 3.93% larger than the same cabin with the conventional design; the same indicator for the larger macro-modules is 5.82%. A larger value for the 4×3 layout macro-module is a result of space saving from removing an additional sandwich panel between the macro-modules. If the additional space was used for extra cabins instead of increasing the area of the cabin, the growth of the total number of cabins would be even larger (12.2%, 17.3%, and 4.7%) instead of (8.5%, 11.6%, and –0.4%).

3.2.3 Weight

An additional deck and cabins come with extra weight. The total weight of the superstructure increases slightly in the cases of the first two concepts but the weight is lower for the third concept, which has the same number of decks as the conventional design (4.6%, 3.5%, and –9.0%). However, the more important indicator is the weight per cabin ratio which in contrast to the total weight decreases (–4.4%, –7.8%, and –6.9%). Achieving a lower weight per cabin ratio while increasing the cabin areas is a strong argument in favour of the new macro-module concept.

It should be mentioned that the weight distribution in Table 5 is somewhat misleading since some weight components are included in the macro-module weight. For example, a large decrease in the HVAC and steel structure weight is because those items are partly included in the macro-module weight, which is a part of the interior weight group.

A weight sensitivity analysis was carried out to determine the macro-module weight significance in the total weight. The results are illustrated in Figure 22; the figure reveals that macro-module weight contribution to the total weight is approximately 40%. The figure also exposes that the macro-module weight has a notable margin; the weight of the macro-module can increase by 20% before achieving a weight per cabin ratio similar to the conventional concept.

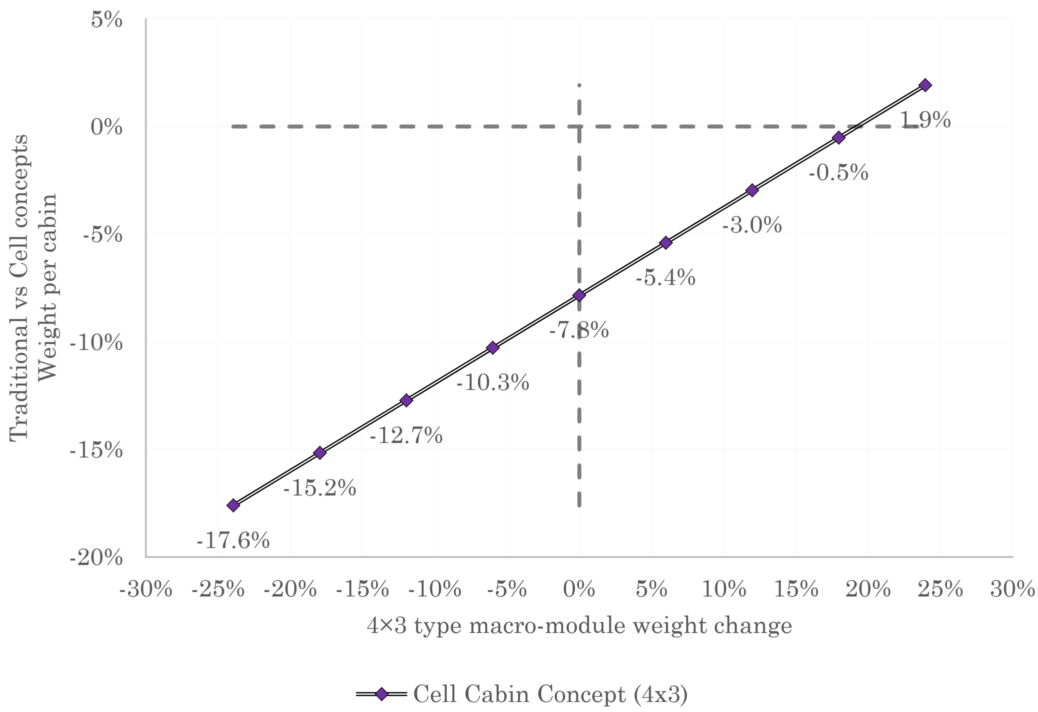

Figure 23. Sensitivity of macro-module weight change

The steel weight shown in the table row *Steel (central part)* has been obtained from a direct steel weight calculation and indicates a weight that includes only the longitudinal members of the mid-section of the deckhouse; the next row *Steel (with aft and fore part)* is acquired from a 3D model and also includes the fore and aft part of the deckhouse.

The weight decrease of the 4×3 type macro-module compared to a pair of 2×3 type macro-modules is moderate. The weight difference due to a removed structural panel between the modules decreases the weight per area unit by 1.92%. Additionally, in the case of 4×3 type macro-modules, the first row of the modules do not have a floor panel, which contributes to an additional savings of 1.1% of the total weight of the macro-modules.

3.2.4 Cost

The ratio of cost per cabin is an important indicator of the money making potential of the design. The results show that the difference between the cost per cabin ratio is insignificant with the aforementioned assumptions (2.1%, –1.9%, and –1.0%). The steel structure cost covers only the central section of the deckhouse where the difference between the conventional and macro-module based design is the most significant; the substantial difference in price (–40.6%, –40.3%, and –42.5%) would somewhat decrease if the complete deckhouse was included in the estimation.

Sensitivity analysis results can be observed in Figure 23, Figure 24, and Figure 25. Analysis shows that the macro-modules have the strongest impact on the total cost of the superstructure, while the conventional cabin cost has average importance and the steel cost has moderate importance.

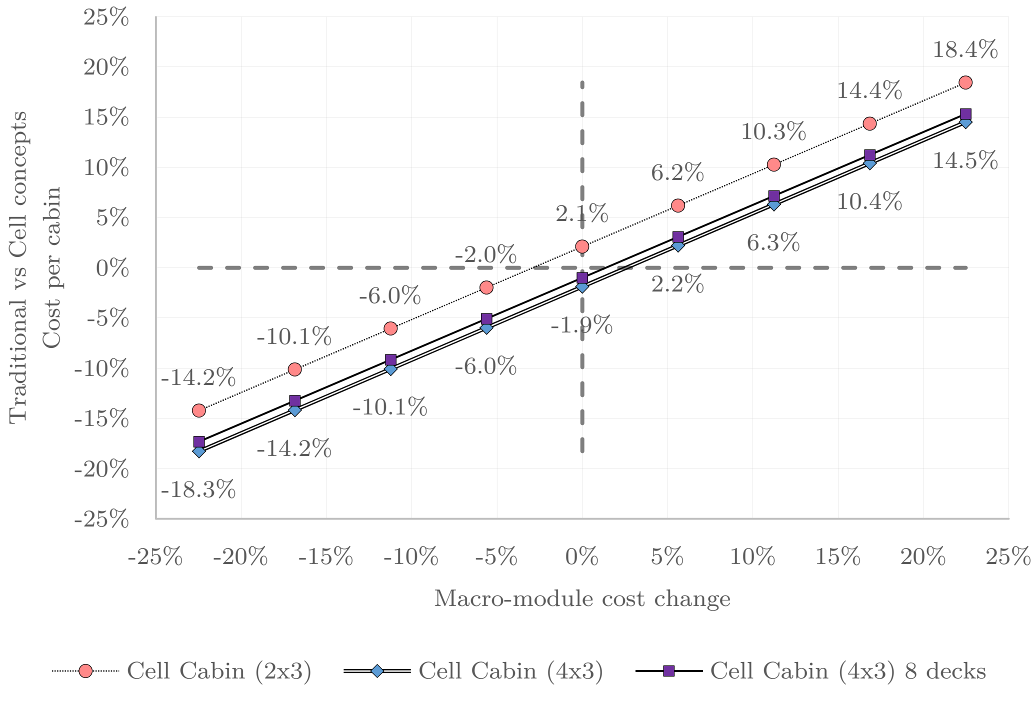

Figure 24. Sensitivity of macro-module cost change

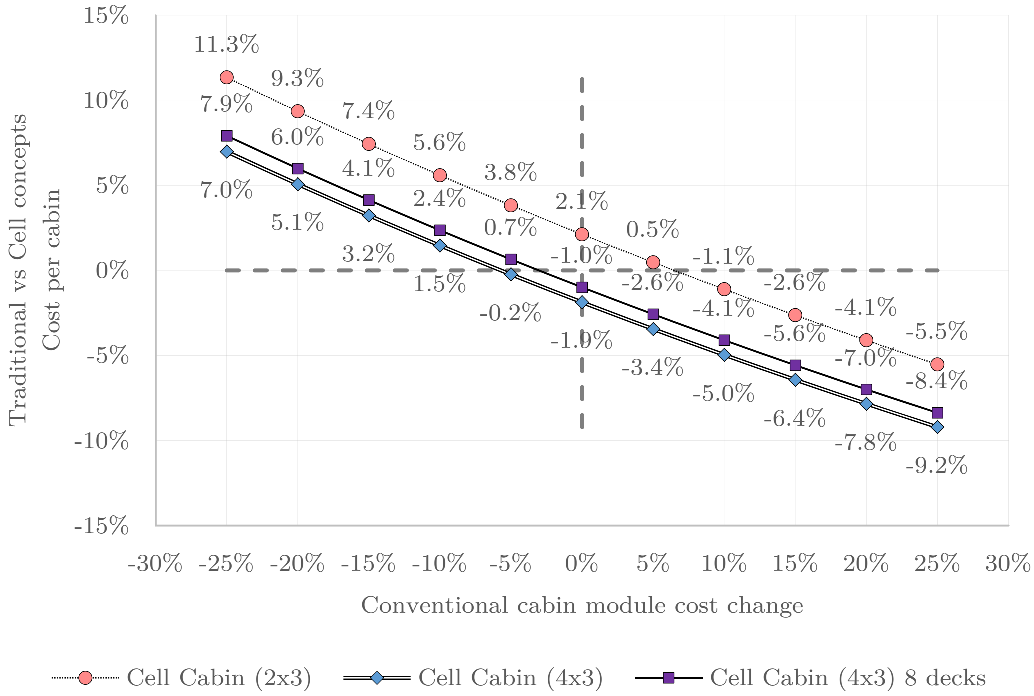

Figure 25. Sensitivity of conventional cabin module cost change

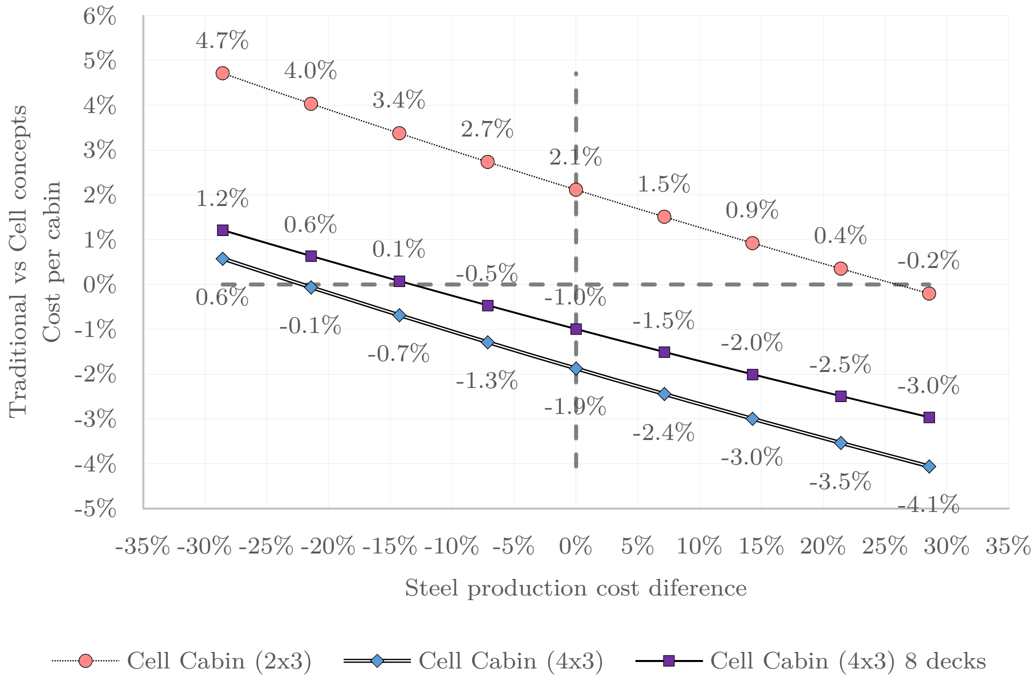

Figure 26. Sensitivity of steel structure cost change

3.2.5 Manufacturing

According to the Oy Shippax Ltd. estimation, 18 cabins per week, that is, three 2 × 3 type modules or one and a half 4×3 type modules, can be manufactured. With this manufacturing speed, all the required modules for the original CC concept can be produced in 81 weeks. The module manufacturing for the concept with 4×3 type modules would take three weeks more and for the last assessed concept, the period would be 75 weeks long. The Oy Shippax Ltd. estimation indicates that approximately 60–70% less labour is required for on-board construction of the cabin area and because of the increased level of prefabrication, the construction time for the ship would shorten by 2–3 months.

The steel manufacturing time estimation is derived from the Rigo cost estimation model and is similar to the weight and cost estimation of the steel part; the difference is that the central section of the deckhouse is taken into account. Still, the steel backbone is by far the largest steel construction part of the superstructure and the manufacturing time decreases by approximately 1/3, which is remarkable.

3.2.6 Pugh comparison

Comparison of the individual concept parameters is often misleading since individual parameters have different significance. Therefore, the Pugh concept comparison method has been used to systematically assess concept properties. The variables used for equations (2.1) and (2.2) are presented in the following table.

Table 6. Used variables

Average profit per passenger per cruise	€132.00
Median cruise length	7.0 days
Passengers per cabin	2 passengers
Occupancy rate	90%
Pay-back period	7 years

Two comparisons were carried out. The difference is in the extra criterion included in the second analysis, which characterises the situation where increased cabin area would have been used for additional cabins; in other words, if a single cabin area would have stayed identical to the conventional design cabin area, how many cabins could possibly fit and what would be their economic effect? Table 7 and Table 8 summarise the results of the Pugh concept comparison.

Table 7. Pugh comparison table

Assessment criteria	*Weight*	*CC (2×3)*	*CC (4×3)*	*CC (4×3) with 8 decks*
Number of cabins change	2.58	21.86	29.87	–1.00
Total cost	–1.58	–17.01	–14.99	2.18
	Total	***4.85***	***14.88***	***1.18***

Table 8. Pugh comparison table with extra cabin area

Assessment criteria	*Weight*	*CC (2×3)*	*CC (4×3)*	*CC (4×3) with 8 decks*
Number of cabins change	2.58	21.86	29.87	–1.00
Extra cabin area	2.58	9.60	14.67	13.04
Total cost	–1.58	–17.01	–14.99	2.18
	Total	***14.45***	***29.55***	***14.22***

The results of both the Pugh comparisons indicate that all the proposed concepts are better than the conventional concept. In particular, the CC concept with a 4×3 macro-module layout stands out. Analysis shows that with the given input data, additional cabins are worth the investment they require. However, more criteria (concerning weight and manufacturing time) are recommended in order to get a better overview of the feasibility of the concepts.

4 Discussion and conclusions

The problems associated with the current manufacturing technique of passenger ship cabin areas have motivated shipbuilding companies to seek new methods for cabin area manufacturing. Finnish maritime companies have proposed a ship concept whose hotel area is assembled from functionally complete and self-supporting macro-modules. The aim of this thesis was to develop a synthesis model in order to assess the technical and economic feasibility of the macro-module concept and its two modifications and compare them with the conventional design concept.

The developed synthesis model combines individual design parameters in a common framework. The model couples the technical analysis with an economic analysis and provides an opportunity to compare design alternatives and illustrate the sensitivity of various design parameters. Individual changes made to the synthesis model are automatically reflected in other fields, offering a great overview of the impact that parameter changes cause. Another advantage is an opportunity to easily update calculations as better information becomes available. Additionally, the synthesis model accumulates knowhow in an organised format that makes the design process explicit for all members of the design team.

The concepts were assessed for weight, cost, and manufacturing time. The results indicate that in most areas, the macro-module based concept has moderate but certain clear advantages over the current concept. Even though the total weight and cost somewhat increase, the amount of additional cabins makes the concept still feasible. The cost per cabin ratio stays within $\pm 2\%$ limits. The weight per cabin ratio of the deckhouse value varies from –4.4% to –7.8%, which is notable but minor when the total weight of the ship is considered. The Pugh concept comparison indicated that all the analysed concepts are better than the conventional concept, especially the Cell Cabin concept modification with a 4×3 macro-module layout.

The conducted study confirms that macro-module based passenger ship hotel area manufacturing is a potential direction for cabin area manufacturing method development. However, despite the achievement of satisfactory results, the developed synthesis model and macro-module based concepts remain in the preliminary design phase. In order to increase the precision of the feasibility assessment, the concept, together with the synthesis model, should be further developed. The most important part that stayed out of the scope of this thesis is the manufacturing process. A detailed evaluation of the manufacturing and installation process is essential for several reasons; it has a strong influence on the lead time and cost estimation, workforce requirements, and many other issues. The cost estimation is another topic that requires development if the concept is further studied.

Additionally, it is essential to note that the new concept involves a great amount of innovations that may be excessive for the conservative shipbuilding industry. Moreover, a significant initial investment is required to update shipyard facilities in order to enable the implementation of the new approach.

Proposal for future development

Three recommendations for future research on the Cell Cabin concept are subsequently presented.

- The CC concept is based on the conventional design, which also dictates the general arrangement design. Since a macro-module based design has many specialities, a general arrangement designed with a focus on macro-modules is required to utilise all the benefits of the new concept.

- Combining a corridor with a cabin increases the level of pre-outfitting; however, the installation process of the macro-modules would be more challenging. Both mentioned aspects should be studied to decide the feasibility of including corridors as part of the macro-module.
- Research has indicated that the cost and weight of the macro-module has the strongest effect on the total cost and weight. Further investigation of the macro-module design is therefore the most potentially helpful in further highlighting the advantages of the new concept.

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List of Appendices

Appendix 1. Implementation of the synthesis model

The Microsoft Excel spreadsheet application was used to develop a synthesis model for this research; it is widespread and easy-to-use software that has enough functionality for the given project. The synthesis model was developed with an emphasis on user experience and simplicity; the spreadsheet has dedicated input and output sheets, colour codes for cells with different purposes, and explanatory comments. All data analysis is done in the single Excel file that joins different research parts into complete, convenient and easy to update system. Table 9 outlines worksheets and their purposes.

Table 9. Worksheets

Workseet	*Content/Purpose*
Input	Various input data required in different parts of the synthesis model. For example steel density, web-frame spacing etc.
Summary	Worksheets gathers and presents output data (see Table 5)
Pugh comp.	Pugh concept comparison matrix and calculations for it.
Weight summary	Worksheets gathers weight calculation and presenting it with user friendly manner
Weight - sensitivity	Weight sensitivity analysis and output graphs
Weight - module	Macro-module weight properties input and synthesis. Mainly done by Oy Shippax Ltd.
Weight - HVAC	Heating ventilation and air conditioning weight estimation for macro-module based cabin area. Mainly done by Elomatic Oy.
Weight - interior	Interior weight that does not fit under other sub-groups. For example elevators, passenger stairs etc. Mainly done by STX Finland Oy.
Cost calculation	Cost estimation for all concepts. Also includes sensitivity analysis.
Rigo summary	Worksheets gathers Rigo model output data.

Rigo – calculations	Rigo model calculations (see Table 4)
Rigo – mainframe input	Mainframe scantlings input (see Figure 21)
Rigo – data	Worksheets that collects data entered by used to *Rigo – mainframe input* worksheet and provides opportunity to easily recover any previously entered mainframe specification.
Database	Worksheet gathers stiffener data, parameters etc.
Counting	Summary of area and volume data from general arrangement drawing and their synthesis
Data from GA	Input from GA
Archive	Input data from various tested concepts is archived for quick recovery

Appendix 2. Modelling of the steel structure cost

The total production cost

The total production cost is the sum of three components:

$$F_C = F_{MAT} + F_{CONS} + F_{LAB} \tag{1}$$

where

F_C	The total production cost	€
F_{MAT}	The cost of materials	€
F_{CONS}	The cost of consumables	€
F_{LAB}	The cost of labor	€

The Cost of Materials

The cost of materials means the steel acquisition cost. For a stiffened panel, this cost is directly derived from the structural weight using the following formula:

$$F_{MAT} = \rho LB \left\{ C_1 \delta + C_2 \frac{A_X}{\Delta_X} + C_3 \frac{A_Y}{\Delta_Y} \right\} \tag{2}$$

where

F_{MAT}	The cost of materials for a stiffened panel	€
ρ	Steel density	kg/m^3
L	Stiffened panel length	m
B	Stiffened panel width	m
δ	Stiffened panel plate thickness	m
A	Stiffener/frame cross-section area	m^2
Δ_X	Longitudinal stiffeners spacing	m
Δ_Y	Transversal frames spacing	m
X	Index of longitudinal stiffeners	-
Y	Index of transversal frames	-
C_1	Cost/kg of a plate with δ thickness	€/kg
C_2	Cost/kg of longitudinal stiffeners	€/kg

C_3	Cost/kg of transversal frames	€/kg

The values of the parameters C_1, C_2, C_3, A should be extracted from the previously defined table of parameters.

The Cost of Consumables

The cost of consumables means the cost of welding except the labour cost and it is composed by the cost of energy, gas, electrodes, provision for equipment depreciation. The cost of consumables for a stiffened panel is calculated as follows:

$$F_{CONS} = LB\left(\left[\frac{2-a_X}{\Delta_X}\right]C_{8X} + \left[\frac{2-\alpha_Y}{\Delta_Y}\right]C_{8Y}\right) \tag{3}$$

where

F_{CONS}	The cost of consumables – for a stiffened panel	€
L	Stiffened panel length	m
B	Stiffened panel width	m
Δ_X	Longitudinal stiffeners spacing	m
Δ_Y	Transversal frames spacing	m
a_X	Binary coefficient related to stiffeners manufacturing	-
α_Y	Binary coefficient related to frames manufacturing	-
C_{8X}	Cost/meter of the consumables related to long. stiffeners welding	€/m
C_{8Y}	Cost/meter of the consumables related to transversal frames welding	€/m

The values of the parameters C_{8X} and C_{8Y} should be extracted from the previously defined table of parameters.

The Labour Cost

The labour cost is related to the workload for welding and welding surface preparation. For a stiffened panel, the labour is estimated as follows:

$$F_{LAB} = \eta \cdot k \cdot WLoad \tag{4}$$

where

F_{LAB}	The labour cost – for a stiffened panel	€
η	Efficiency parameter for the considered production plan	-
k	Man-hour cost at the considered shipyard	€/man-hour
$WLoad$	Workload required for the fabrication of the stiffened panel	man-hour

The amount of workload should be calculated with the formula:

$$WLoad = LB\left[\frac{1}{\Delta_X}P_4 + \frac{1}{\Delta_Y}P_5 + \frac{1}{\Delta_X\Delta_Y}(P_6 + \beta_X\beta_Y P_7) + \frac{1-\alpha_X}{\Delta_X}P_{9X} + \frac{1-\alpha_Y}{\Delta_Y}P_{9Y} + P_{10}\right] \tag{5}$$

where

$WLoad$	Workload required for the fabrication of the stiffened panel	man-hour
L	Stiffened panel length	m
B	Stiffened panel width	m
Δ_X	Longitudinal stiffeners spacing	m
Δ_Y	Transversal frames spacing	m
P_4	Workload per meter for the welding of longitudinal stiffeners web on the plate (preparation included)	man-hour/m
P_5	Workload per meter for the welding of transversal frames web on the plate (preparation included)	man-hour/m
P_6	Workload required for the welding and	man-hour/

	preparation of one intersection between long. stiffeners and transversal frames	intersection
P_7	Workload required for fixing the brackets at one intersection between longitudinal stiffeners and transversal frames	man-hour/ intersection
P_{9X}	Workload required to build 1 meter of long. stiffener – assembly of web - flange (preparation + welding)	man-hour/m
P_{9Y}	Workload required to build 1 meter of transversal frame – assembly of web - flange (preparation + welding)	man-hour/m
P_{10}	Workload required for the preparation of 1 m^2 of plate (cutting, positioning)	man-hour/m^2
β_X	Ratio between the number of intersections requiring long. brackets and the total amount of intersections	-
β_Y	Ratio between the amount of intersections requiring transversal brackets and the total amount of intersections	-
a_X, α_Y	Binary coefficient related to stiffeners manufacturing. $a_X, \alpha_Y = 0$, if the members are manufactured on the yard from standard plates. In this case, the welding costs are considered separately. $a_X, \alpha_Y = 1$, if the members are standard members (HP etc.).	-

The values of the unitary cost parameters involved in the equation (5) should be extracted from the previously defined table of parameters.