ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A UNIVERSAL SHIP DESIGN NETWORK

M.Sc. THESIS

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Department of Shipbuilding and Ocean Engineering

Shipbuilding and Ocean Engineering Programme

NOVEMBER 2017

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TÜMSEL GEMİ TASARIM AĞI

YÜKSEK LİSANS TEZİ

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KASIM 2017

Baran Serdar SARIOĞLU, a M.Sc. student of İTU Graduate School of Science Engineering and Technology student ID 508141111, successfully defended the thesis entitled "A UNIVERSAL SHIP DESIGN NETWORK", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my curiosity and road,

FOREWORD

This paper presents the study about the possible role of artificial intelligence in the life cycle of ship. It shows that the wider decision making environment can be succeed by using investigated methods in this thesis. This study just tiny example of artificial intelligence power and the further studies will discover the unbelievable real world applications.

I would like to thank Ferhat ABUL from DNV-GL Company, Mevlüt CİVELEK from MAN Diesel & Turbo Company and Hüseyin GÖREN from Arkas Holding. Their valuable sharings gave me needful data to complete the research and write this thesis. Finally I would like to express my deepest gratitude to my parents and my advised friends who endured this long process with me.

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Baran Serdar SARIOĞLU
Ship Building & Ocean Eng.

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ABBREVIATIONS

PLM **:** Product Life Cycle Management
AI **:** Artificial Intelligence
DI **:** Design Intelligence
DE **:** Design Exploration
DO **:** Design Optimization
API **:** Application Program Interface

SYMBOLS

L : Rule Length
L_{LL} : Freeboard Length
L_{PP} : Length Between Perpendiculars
B : Moulded Breadth of Ship
D : Moulded Depth of Ship
T : Moulded Draft
T_{SC} : Scantling Draft
T_{Full} : Full Load Design Draft
T_{Design} : Design Draft
Δ : Moulded Displacement at Draft T_{SC}
C_B : Block Coefficient T_{SC}
V_S : Maximum Service Speed
x,y,z : X,Y,Z Coordinates of the Calculation Point with Respect to the Reference Coordinate System

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A UNIVERSAL SHIP DESIGN NETWORK

SUMMARY

This thesis describes the developed software to manage design phase of ship's project lifecycle by using artificial intelligence with the participation of entire stakeholders of this lifecycle. The lifecycle of a ship project includes design phase, building phase, operation phase and recycling phase. There are links between these phases. On the other hand, there are different stakeholders inside of these phases such as owner of ship, class societies, national or international authorities, suppliers, shipyards, design offices and ship operators. A ship project must contain these phases and stakeholders.

The main objective for the realization of a ship project is to obtain desired gain as an economic investment. This gain may be military force for a navy ship or economic profit for a merchant ship. Life time of a ship is longer than 25 years now and there are various studies to extend this life time. In this point, a ship is the long term economic investment.

The long duration life cycle of ship starts with design phase and feasibility studies together. Every design decision affects the rest of life cycle of the ship. After the design phase, building phase begins and important point of this phase is to build the ship exactly the same with detailed designs in agreed time. Ending up building phase means operation phase. Operation phase is the longest period in the whole life cycle of a ship. Economic return of a ship investment is the subject of this phase so in this phase a ship should be run in the most profitable level. End of the ship operation period, the ship goes to recycling shipyard for disposal process and this generates the final economic return of the ship. Also, this phase is the finalization of a ship project as an economic investment.

There are various stakeholders in the life cycle of a ship. They have conflicted objectives sometimes. For example, a ship owner wants minimum number of personnel in the operation of the ship to decrease crew cost. On the other hand, this situation increases the operational risk of a ship and this is an unwanted circumstance for international or national authorities.

The management of a ship project is a complex task and resources should be used efficiently by whole stakeholders. The decision of any stakeholders can affect the others mostly.

An artificial intelligence can help to manage a life cycle of ship project to increase efficiency for whole stakeholders by using holistic ship synthesis model. There are two main approaches for AI such as weak AI and strong AI. Strong AI is the simulation study of human intelligence by using computers. On the other hand, weak AI aims to solve industrial, scientific or other problems by using different intelligence approaches inspired by nature. In this study, a solution is investigated for ship design problem by using weak AI approaches on holistic ship synthesis model.

Ship design basically is a combination of selection problem from finite space and exploration problem from infinite space, so evaluation of entire variables is impossible. At this point, AI should take rational decisions to find feasible or optimum solutions. AI will search suitable variables on a finite database and explore optimum variables by using holistic synthesis model. Also, AI could help to management of ship project in every phases of life cycle by using this synthesis model.

Holistic synthesis model includes entire phases of a ship project from initial decision of design to disposal of ship. This model enables to evaluate all phases of ship together. Different and also conflicted objectives of stakeholders could cause to decrease total benefit of a ship in the end of her life time. Holistic view has gained popularity to avoid from this situation. Also, this view is kind of basement for decisions to manage ship life cycle.

In this thesis, a framework is offered to manage lifecycle of ship by using AI. Design module of offered framework is realized for concept design of a container ship in the scope of this study. Also, this study will be foundation for further studies.

TÜMSEL GEMİ TASARIM AĞI

ÖZET

Bu tezde bir geminin yaşam döngüsünün tasarım fazını belirli bir kapsamda, yapay zekâ ile birlikte ve bu yaşam döngüsünün bütün paydaşlarının katılımıyla yönetmek için geliştirilen bir yazılım tanıtılmaktadır. Geminin yaşam döngüsü kısaca tasarım fazını, inşaat fazını, operasyon fazını ve geri dönüşüm fazını kapsar. Bu fazlar arasında bağlantılar mevcuttur. Öte yandan, bu fazların içerisinde geminin sahibi, klâs kuruluşu, ulusal ve uluslararası otoriteler, tedarikçiler, tersane, tasarım ofis ve gemi işleticileri gibi farklı paydaşlar vardır.

Bir gemi projesinin hayata geçmesindeki ana amaç ekonomik bir yatırım olarak istenilen kazancı elde etmektir. Bu kazanç bir askeri gemi için askeri güç ya da ticari bir gemi için ekonomik kâr olabilir. Ticari gemiler özel olarak ele alınırsa kar, yatırım ve işletme maliyetleri çıkarıldıktan sonra geminin yaptığı toplam kazançtır. Bu şekilde formüle edildiğinde, kar arttırımı için iki yol rahatlıkla görünmektedir.Birincisi masrafların azaltılması ve ikinci olarak ta gelirin arttırılmasıdır. Buradaki temel problem; masraflar ve gelirler arasındaki doğrusal olmayan ilişkinin ortaya çıkarılmasındaki güçlüklerdir. Gemilerin ekonomik kullanım ömürleri artık 25 yılı geçmiştir ve bu sürenin daha uzun olması için çeşitli çalışmalar da sürdürülmektedir. Bu yönüyle bakıldığında gemiler nispeten uzun süreli ekonomik yatırımlardır.

Geminin bu uzun süreli yaşam döngüsü belirli fizibilite çalışmalarıyla beraber tasarım süreci ile başlar. Tasarım sürecinde verilen her karar geminin bütün bir kullanım süresi boyunca etkisini gösterir. Tasarım sürecinden sonra inşaat aşamasına geçilir. İnşaat aşamasında artık proje üzerinde genel tasarımı etkileyecek değişiklikler yapmak çoğu zaman çok maliyetli olduğu için mümkün değildir. İnşaat aşamasının önemli noktası gemiyi detay tasarım planlarına birebir uygun şekilde gemi sahibi ile anlaşılan sürede ortaya çıkarmaktır. İnşaat süresinin uzaması gemi sahibinin gemisini işletmeye başlamasını geciktirecektir. Bu da yapılan ekonomik yatırımın karlılığını düşürecektir. İnşaat aşaması ile ilgili bahsedilen bu iki önemli nokta bu sürecin çok iyi yönetilmesi gerektiğini ortaya koymaktadır. İnşaat aşamasının son bulması ile beraber geminin çalışma hayatı başlar. Artık gemi, sahibine yaptığı ekonomik yatırımın geri dönüşünü kazandırmaya başlar. Bir gemi projesi yatırımının en uzun fazı artık 25 yılı aşan süreler ile operasyon aşamasıdır. Bu aşamanın en önemli noktası da geminin karlılığını olabildiğince yüksek seviyede tutarak çalıştırılmasıdır. Bahsedilen kârı en üst düzeye çıkarmak için iki önemli etki noktası vardır. Birinci etki noktası geminin bütün bir çalışma süresinde oluşacak piyasa koşullarını ön görüp tasarım aşamasında en çok kazanç getirecek ve piyasa koşullarının olumsuz etkilerinden en az etkilenecek projeyi ortaya çıkarmaktır. İkinci etki noktası ise geminin işletme potansiyelini en üst düzeyde kullanmaktır. Bu iki önemli etki noktası geminin yaşam döngüsünde çok iyi değerlendirilmelidir. Gemi işletme ömrünü tamamladığında artık geri dönüşüm için söküme gönderilir. Gemi

sahibi son olarak bu geri dönüşüm aşamasında bir kazanç elde eder ve gemi sahibinin ekonomik yatırımı böylece son bulur.

Yukarıda açıklandığı üzere geminin yaşam döngüsü tasarım, inşaat, operasyon ve geri dönüşüm fazlarını kapsar. Bu fazlar arasında çeşitli etkileşimler mevcuttur. Bu etkileşimin temel sebebi, geminin yaşam döngüsünde karşılaştığı her bir fazda farklı paydaşların yer almasıdır. Her paydaş bu ekonomik yatırımı farklı şekillerde etkilemektedir. Gemi sahibinin projeye etkisi, geminin yaşam döngüsü boyunca yatırım gücüne bağlı olarak kârı en üst düzeye çıkarmak için çabasıdır. Ulusal ve uluslararası otoriteler belirledikleri kurallarla toplum ve gemi sahibi için risklerin minimum seviyede tutulmasını sağlar. Klâs kuruluşları da kendi yönergeleri ve denetimleri ile diğer paydaşların risklerinin azaltılmasına yardımcı olur. Tersane ve tedarikçiler, hem iş sürelerini kısaltarak kazançlarını arttırmaya çalışırlar hem de mümkün olan en az hata ile işlerini tamamlamak isterler. Tasarım ofisi, gemi sahipleri için en karlı tasarımı ortaya çıkarmaya çalışırlar. Gemi işleticileri ve personeli, kârlılığı mümkün olan en üst seviyede tutarak geminin ömrünü tamamlamasına çalışırlar. Paydaşların hedefleri bazen paralellik gösterir bazen birbirleri için kısıt oluşturur bazen de birbirlerini ters yönde etkilerler. Örneğin otoritelerin belirlediği kurallar bütün paydaşlar için birer kısıttır. Gemi işleticileri giderleri azaltmak için mümkün oldukça az personel ile gemiyi işletmek isterler. Bu hem mevcut gemi personeli için iş yükünün artması demektir, hem de risklerin artması demektir. Bu durumda gemi işleticileri ile gemi personelinin hedefleri birbirlerini ters yönde etkiler. Bir geminin çelik tekne ağırlığı ne kadar az olursa taşıyabileceği yük kapasitesi de o kadar fazla olacaktır. Gemi sahibi, gemisinin yük kapasitesinin fazla olmasını isteyecektir ama hafif bir yapı çeşitli mukavemet problemleri ile karşılaşacaktır ve tasarım ofisi için bunlar çözülmesi gereken yeni sorunlar demektir.

Gemi projesinin yönetimi oldukça karmaşık bir iştir ve bu karmaşıklığın çeşitli sebepleri vardır. İlk olarak bir gemi projesi yukarıda açıklandığı üzere yaşam döngüsü boyunca birçok paydaşa sahiptir. Paydaşlar arası bilgi aktarımı ve bu bilgilerin yönetimi zordur. Herhangi bir paydaşın proje üzerinde yaptığı bir değişiklik çoğunlukla diğer paydaşları da etkilemektedir. Etkilenen her alan tekrar revize edilerek işlenmelidir. Bu da tekrarlamalı bir süreci zorunlu kılmaktadır. Ayrıca işlenen veriler çoğunlukla karmaşık mühendislik veya işletme verileridir ve bu verileri işleyip anlamlı bilgiler çıkarmak uzunca süreler gerektirmektedir. Geminin yaşam döngüsü uzundur ve herhangi bir kararda uzun bir süreci göz önünde bulundurmak gerekmektedir. Yaşam döngüsünün uzunluğu karar vermeyi zorlaştırmaktadır. Gemi sahibinin hedefi yaptığı ekonomik yatırımın geri dönüşünün olabildiğince yüksek olmasıdır. Bir gemi projesinde yaşam döngüsü boyunca bu hedefi belirli kısıtlar altında gerçekleştirmek zordur. Gemi sahibinin kar hedefi, uluslararası otoriteler tarafından toplumun faydası için belirli güvenlik kuralları ile sınırlandırılmıştır. Bütün bu sınırları göz önünde tutarak, birden çok paydaş ile beraber uzun bir süre için kazanç iyileştirmesinin karmaşıklığı ortadadır. Bu noktada bir çeşit uzun süreli ekonomik yatırım olan gemi projelerinin yönetimini kolaylaştırmak için çözümler aranmaktadır. Bu çözümlerin bazıları bütün bir yaşam döngüsüne etki edebildiği gibi bazıları yaşam döngüsünün belirli fazlarında kullanılabilmektedir. Bu çalışmanın temelinde gemi projesinin yönetim karmaşıklığına çözüm olarak sunulan tümsel gemi ağı fikri bulunmaktadır. Yalnız tez süresinin yeterli olmamasından dolayı sadece tasarım aşaması belirli ölçüde gerçeklenebilmiştir. Burada şu ayırımı açıklamak gerekmektedir. Literatürde henüz tasarım aşamasında geminin yaşam döngüsünü göz önüne alan çeşitli çalışmalar zaten mevcuttur. Bu çalışmanın temel farkı geminin yaşam döngüsünü diğer fazlar ile birlikte bir bütün olarak ele almasıdır. Burada paydaşlar arasında yaşam döngüsü boyunca kesintisiz bilgi akışı önerilmektedir ve bu bilgi akışı bir yapay zekâ tarafından işlenmektedir. Buradaki çalışma kapsamında da tümsel ağın tasarım kısmı ele alınmıştır ve yapay zekâ ile ilişkisi işlenmektedir.

Temelde yapay zekâ için iki temel yaklaşım veya tanımlama vardır diyebiliriz. İlki, kuvvetli yapay zekâ ile insan zekâsının bir donanım üzerinde gerçeklenmesi hedeflenmektedir. Zayıf yapay zekâda ise daha çok doğadaki zekâ esaslı davranışların modellenerek endüstriyel, bilimsel ve diğer birçok probleme çözüm bulunması hedeflenmektedir. Bu çalışmada da zayıf yapay zekâ yaklaşımları ile geminin yaşam döngüsü sentez modelinde ele alınarak gemi tasarım problemine bir çözüm aranmaya çalışılmıştır. Gemi tasarım problemi temel olarak, sonlu ve sonsuz iki kümeden birbirleri ile uyumlu değişkenlerin seçilerek bir araya getirilmeleri problemidir. Burada sonlu değişken kümesinin büyüklüğü yapılabilecek alternatif seçimlerin sayısını doğrudan arttırsa da, sonsuz değişken uzayının tüm elemanları incelenemeyeceği için bu uzaydan mümkün olan en uygun değişkenlerin seçilmesi problemini ortaya çıkarmaktadır. Buda tabi ki yapay zekânın rasyonel kararlar vermesi, çıkarımlar yapması ve sonsuz bir uzayda arama yapması gibi temel özelliklere sahip olmasını gerektirmektedir. Yapay zekâ, gemi tasarımını ortaya çıkaracak değişkenleri bir veri tabanı üzerinde modellenen sonlu bir uzayda ve holistik sentez modeli ile sonsuz bir uzayda arayacaktır. Ayrıca oluşturulan yapay zekâ bütün paydaşlar için verimi arttırmakta holistik sentez modeli kullanarak bir gemi projesinin yaşam döngüsünü yönetmekte yardımcı da olabilir.

Holistik sentez modeli, bir geminin tasarım aşamasının ilk adımından geri dönüşümde tamamen yok edilene kadar ki geçen sürecin tamamını ifade etmektedir. Geminin bütün bir yaşam döngüsünü ele alan bu yaklaşım, geminin geçirdiği aşamaların bir arada değerlendirilmesine olanak vermektedir. Geminin geçirdiği aşamalarda paydaşların farklı hedefleri öncelemesi geminin yaşamının sonunda ortaya çıkarmış olacağı toplam faydayı azaltmaktadır. Bu durumun önlenmesi için holistik bakış açısı popülerlik kazanmıştır. Ayrıca bu bakış açısı geçirdiği bütün aşamalarda geminin yönetilmesi için alınacak kararlara rasyonel bir temel oluşturmaktadır. Son yıllarda popülerlik kazanan holistik bakış açısı, birçok tasarım yöntemi ile birlikte kullanılmaktadır. Yinelemeli yöntemler ile kullanımı zor ve uzun süre alsa da, eş zamanlı yöntemlerle kolaylıkla kullanılabilinmektedir.

Bu tezde, geminin yaşam döngüsünü yönetmek için yapay zekâ temelli çerçeve bir sistem önerilmiştir. Önerilen çerçeve sistemin tasarım kısmı bir konteyner gemisi konsept dizaynı üzerinde gerçeklenmiştir. Konunun çok geniş bir alanı içermesiyle beraber süre yetersizliği nedeniyle bu çerçeve sistemin temel olarak tasarım kısmı yapılan çalışma kapsamında incelenmiştir.Geminin yaşam döngüsünün inşaat, operasyon ve geri dönüşüm fazları ile tasarım fazı arasındaki ilişkilerde yapılan çalışma içerisinde temellendirilmiştir. Fazlar arasındaki etkileşim, yapay zeka ve sentez modeli üzerinde incelenmesi gereken yeni problemler ortaya çıkarmıştır. Ortaya çıkan bu problemlerin bir kısmı yapılan tez içerisinde cevaplanmaya çalışılmıştır. Burada sunulan çalışma aynı zamanda ileride yapılacak daha kapsamlı araştırmalara temel oluşturacaktır.

1. INTRODUCTION

1.1 Background of the Study

Marine vehicles such as passenger vessels, naval vessels, cargo ships or other self propelled ships have different operation capabilities according to their intended purposes. Operation capacity requirements reveal various design priorities. Also, there are stakeholders of a ship design process like owner, shipyard, design office, class society etc. Stakeholders can be extended by taking into account entire ship value chain. To define all stakeholders, ship value chain can be divided into design, building, operation and recycling phases. Brokers, charterers, recycling requirements, ship officers and main suppliers are also important to optimize economic return of a merchant ship. In the last instance, a ship project is an economic investment for owner but this project should correspond to priorities of other stakeholders; therefore, life cycle of a ship should be taken into consideration at the design phase and also a project should give the optimum respond to related stakeholders of following phases. Optimization of all phases means maximization of incomes, and minimization of costs during the life cycle from economic investment view. Also, a ship project should ensure some criteria and constraints for different stakeholders. For example, international regulations are constraints and risk, performance and environmental effects properties of a ship are criteria for a ship projects. Goals, criteria and constraints can be variable for different projects. Income is the goal of a cargo ship, on the other hand; performance is the goal of the naval vessel.

1.2 Statement of the Problem

The current design tools just consider limited space originated by design phase of a ship project. A ship project has also other phases such as building, operation, and recycling so actual solution space is wider than space that is generated by current design tools. All phases can be considered together in the design process and this view enables the more efficient design. Also, a good design does not mean the efficient life for a ship. Design particulars of a ship should be performed properly so every phases of a ship should be managed in conjunction with design.

1.3 Aim and Research Questions

This study is conducted to develop and improve a system for optimization of ship lifecycle by using adequate tools and methods. This objective is translated in the following questions:

- What is the scope of ship lifecycle?
- What is the scope of ship lifecycle's optimization?
- What are the adequate tools and methods for optimization of ship lifecycle?

The lifecycle of ship shortly involve entire meaningful things which have affect on business volume related to design, building, operation and recycling phases of a ship project and stakeholders of these phases, so this new system should involve entire phases and stakeholders of lifecycle. Optimization of ship lifecycle means minimization of cost, keeping risk and environmental effect at a certain level, also maximization of economic revenue and performance in every related phase. To accomplish the optimization of lifecycle, the system should answer different duties in several phases for same objective; for example, the holistic design space exploration in concept design, decision support system for operation and optimization framework for preliminary design are important tasks to keep lifecycle of ship optimum as possible as. The relationships between stakeholders also phases are permeable; therefore, a ship project should be considered together with whole stakeholders and phases. This requires adequate tools such as an artificial intelligence for administration and optimization, the data management for collection and keeping of informations and the ship synthesis model for link between artificial intelligence and data management and also related methods. The aim of this thesis is to investigate the main question of this study which is presented below:

"How can life cycle of a ship be managed by a system which is composed of the artificial intelligence, the data management and the ship synthesis model to maximize economic return of a ship and performance, also minimize cost, risk and environmental effect?"

A possible answer of above question is investigated in this study and the pieces of the answer can be found in the following sections.

1.4 Scope and Delimitations

The scope of this thesis is to develop advanced ship design synthesis model that takes into account all phases of ship life-cycle, data management system that is accessible by stakeholders through the life-cycle and to integrate artificial intelligence algorithms for optimization/exploration and management by using synthesis model and data management system. The main system is developed by considering all phases of life-cycle but thesis duration is short to verify entire system, therefore building, operation and recycling modules are released for further research. The links between phases are kept in design module to enable further extensions for the rest of modules.

1.5 Methodology

Firstly, life-cycle of ship is investigated. Essential subjects are defined to consider current situation of ship design problem. Related literature is scanned deeply to utilize current answers for design problem of ship. An artificial intelligence based holistic approach is offered to solve ship design problem. Required tools for defined subjects are developed. Tools are integrated to create a system. Finally, the system is validated by a series of test cases for the container ships. Results are analyzed and research questions are answered.

1.6 Thesis Structure

The following paragraphs provide general views for subsequent chapters and the outlined of this thesis can be seen in Figure 1.1.

Chapter 2 (Life cycle of ship) describes the life cycle of ship. Design, building, operation and recycling phases are identified. Processes in these phases are explained.

Chapter 3 (A universal ship network) is the background idea of this study. A universal ship network is offered to manage a ship project as an economic investment. Because of the broad subject, the scope of this study is limited with design phase of life cycle.

Chapter 4 (The design of ships) describes the particulars of ship design. It introduces the basis knowledge to develop a design approach for life cycle management.

Chapter 5 (Review of design methods) presents an overview of literature for ship design. At the end of the chapter, design methods are reviewed and strengths-weaknesses of design methods for life cycle management process are discussed.

Chapter 6 (A universal ship design network) demonstrates main subject of study. Also, offered approach for ship design is investigated in this chapter. Firstly, holistic ship synthesis model is described. Components of synthesis model are created. Secondly, database structure is explained to take into account life cycle of ship. Thirdly, artificial intelligence implementation is presented. Finally, structure and particulars of system is submitted.

Chapter 7 (Application, developments and results) describes possible applications. A container ship project is selected as a case study to show application process. Various developments are explained to improve system stability. Results of conducted case study are investigated in the scope of thesis.

Chapter 8 (Discussion and conclusion) draws limitations and conclusions from experiences in this research and also related future research areas are suggested.

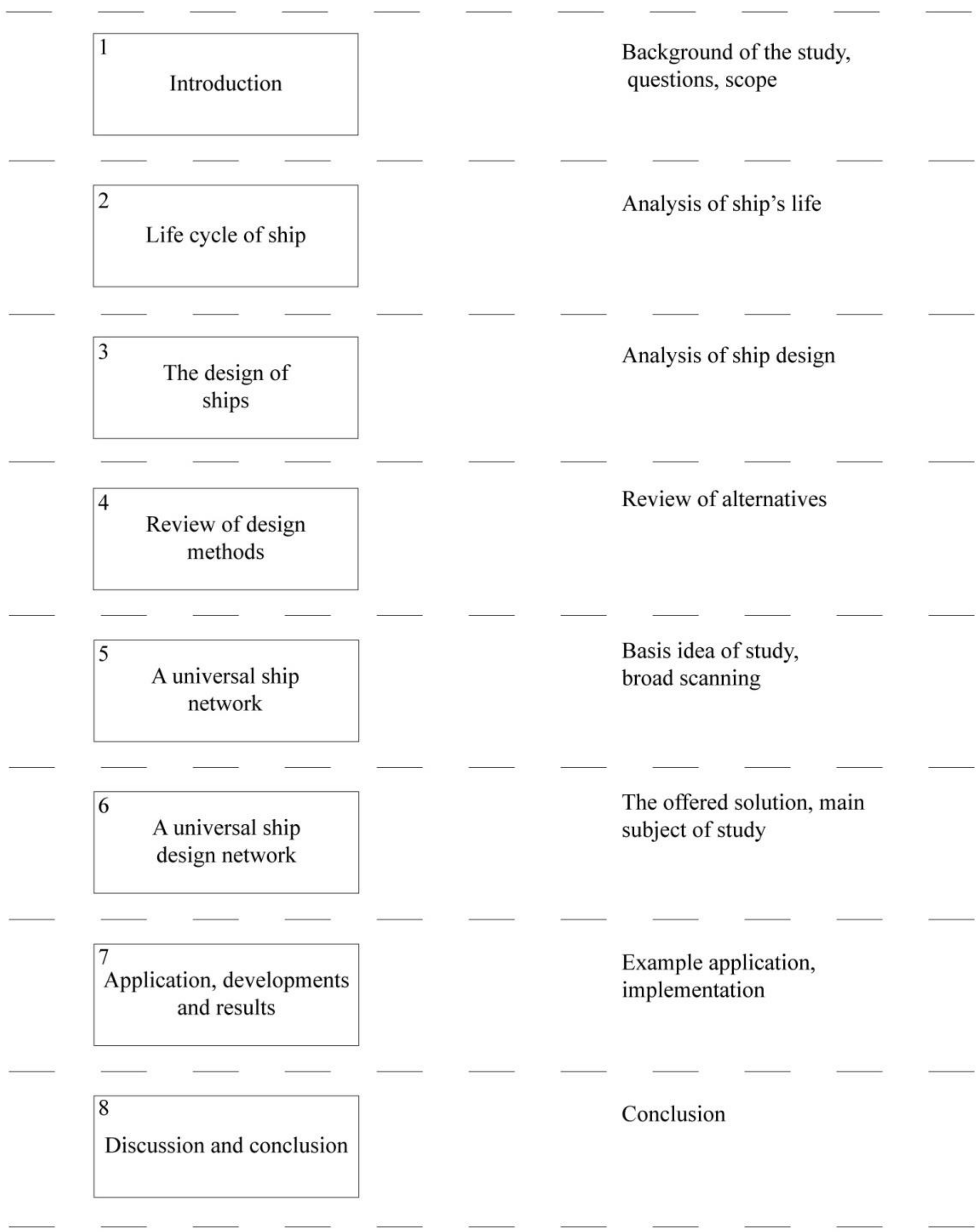

Figure 1.1 : Organization of thesis.

2. LIFECYCLE OF SHIP

According to Stark (2011), product lifecycle management (PLM) is the management of processes and their own activities from initial idea to disposal point. Most of engineering products are same or similar life. Lifecycle of ship contains design, building, operation and recycling phases. Managing and connection of whole informations related to project data to conduct to these phases mean product lifecycle management for a ship project, too. All knowledge is centralized in PLM concept to increase efficiency. Connection, organization, control, tracking and management of data are important steps of PLM. Also, high collaboration is necessary in PLM. Created knowledge in design phase is tracked through following building, operation and recycling phases. On the other hand, knowledge of building, operation and recycling phases are used as an input in the next design phase. This means that there is a cycle between value chains of project. This concept is used for every phases, respectively.

Tracking of knowledge requires the collaboration between customers, suppliers, partners and other stakeholders in all phases. Tracked knowledge may be the engineering bill of materials (EBOM), manufacturing bill of materials (MBOM), calculations, analyses, technical drawings, productions plans, etc. in accordance with function of stakeholders.

Some purposes of lifecycle concept are listed below;

- Better project development with regards to related criteria
- Comparison and selection of products
- Improvement of project chain
- Improvement of project performance
- Development of management routines

PLM can be seen as an architecture which is composed of tools and methodologies integrated to single system for connection and management of the entire process. This means that there are different programs and sub-programs for design, building, operation and recycling phases and PLM is the integrated shape of them. Scope of PLM can be varied for different companies. To manage a project, in general PLM includes;

- Management of data
- Product families and related data
- Process documents
- Assets
- Service information for after sales
- Visualization tools
- Digital manufacturing tools
- Simulation tools
- Process and product analysis tools

These tools can be decreased or increased according to specific requirements of firm and project so, there are many different models of PLM. Lifecycle of ship will be investigated below to define suitable PLM models.

Lifecycle of a ship starts with design phase than building, operation and recycling phases follow to design phase, respectively. Every phases has own sub-processes which can be seen in Table 2.1.

Table 2.1 : Life cycle of a ship.

Design	Building	Operation	Recycling
Basic design	Building planning	Operation	Decomposition
Detailed design	Contracts	Maintenance	Disposal
Class approval	Purchasing	Repair	
Resources planning	Supply		
	Construction		
	Tests		

2.1 Design Phase

Firstly, optimum basic design should be found in design phase. There is a high effort to decrease the difference between basic and final design for a long time. In other words, final optimum design should be estimated in basic design step more precisely. Basic design may be the most important design step, because; the most of important decisions related to project are taken in this step and it is costly to change these decisions in further steps. Therefore, uncertainty of basic design should be low.

End of the optimum basic design, ship owner negotiate with ship yard for contract. Once the contract is signed with shipyard, ship owner orders the main engine and main propulsion parts. Also, ship owner and ship yard decide on makers lists.

After the contracts are signed, detailed design process starts and technical drawings, part lists, construction plans are generated. Technical drawings are utilized by class society, and after the class approval, building phase can start. Timeline of design phase can be seen in Figure 2.1.

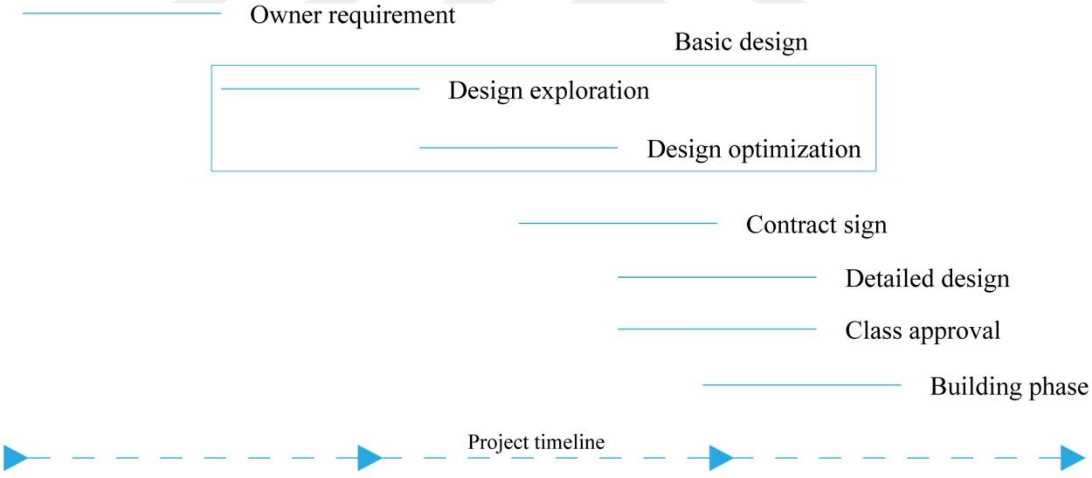

Figure 2.1: Ship design process.

In the design phase generally, calculations, analysis, drawings and documents which are related to following list should be completed. Some of them can be unnecessary according to project type and class regulations. In the different step of design phase, various items of mentioned list are finished.

- Hydrostatic, stability, resistance, seakeeping, and manoeuvering calculations
- Form plans
- Strength, vibration, and fatigue calculations of structure

- Propulsion calculations and engine selection
- Subdivision and tank plans
- Outfitting
- Fire fighting plans
- Risk analysis
- Part and material lists
- Manufacturing drawings

2.2 Building Phase

In building phase, production plan of ship is organized by shipyard. Yard purchases all equipments and materials in accordance with design plans. Delivery dates of equipments and materials with design plans develop the production plan. Production plan is the most important step of building for yard because of manufacturing efficiency. After the purchasing, following sub-processes will start.

- Cutting, bending and welding
- Construction of blocks
- Outfitting of blocks
- Controls of blocks
- Class survey of blocks
- Joining of blocks
- Launching

After launching the vessel, finishing of vessel will be start. Every equipments and sections are checked and controlled in practice as the harbor acceptance testing. Before the delivery, ship and equipment performance should be tested at sea trial for acceptance.

In the building phase, ship yard should organize, supervise, manage, and control all the processes of building. This require huge amount of work volume. The most complex work volume of ship’s lifecycle is in the building phase, so collaboration is important to accomplish all processes properly.

2.3 Operation Phase

Operation phase is the longest period of the ship's lifecycle. Modern vessels have 25-30 years of life. In this phase, the ship earns the money as the return of the investment. Efficiency of operation is important to keep return at the maximum level. During the operation phase, maintenance and repair of ship generates the disabled periods. Also, the bad weather conditions create the inefficiency for operation phase.

2.4 Recycling Phase

Repair and maintenance cannot be affordable to keep ship in service and after 25-30 years of service, the ship is recycling. Equipments and extracted steels are sold in the secondhand market. IMO has regulations for environmental issues during the ship recycling process. Recycling yard should manage and control the process according to regulations.

Sub-processes of ship life cycle can be seen in Figure 2.2. PLM model should contain the tools to interact with these processes Offered PLM model may be named as a universal ship network and it is investigated in next section.

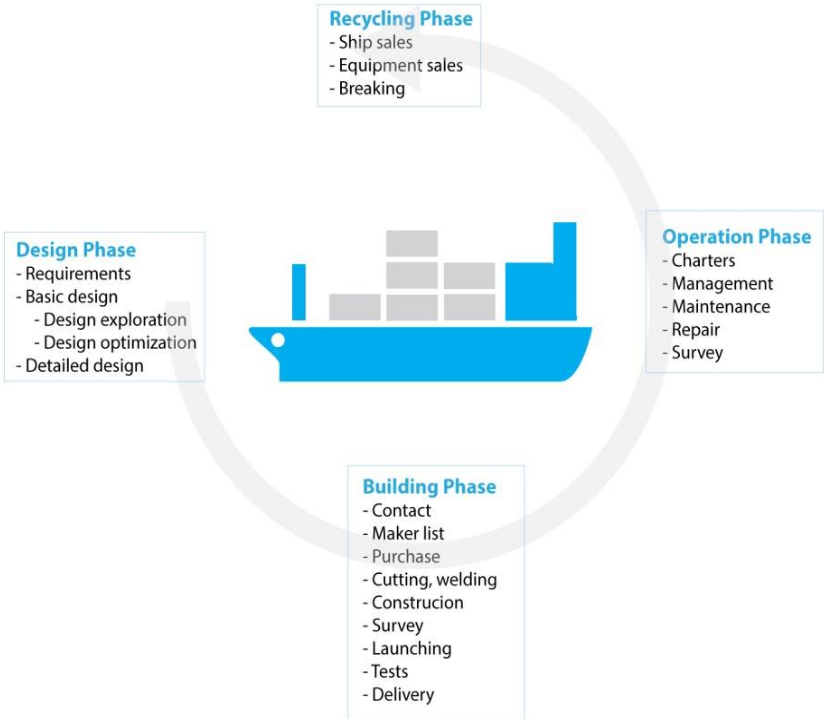

Figure 2.2: Life cycle of a ship.

3. A UNIVERSAL SHIP NETWORK

There are plenty of different PLM models; companies can use specific PLM model in accordance with their own necessities. The exclusive PLM model is created for this study. Life cycle of a ship is considered to keep applicable this PLM model for ship problems. Life cycle of ship includes design, building, operation, and recycling phases which are investigated previous chapter. Every phases of lifecycle is considered as a module of total PLM model. The interface between phases is provided with *"CORE"* which is shown in Figure 3.1. This approach makes easier the solution of total life cycle problem. Design module and *"CORE"* are investigated deeply in the scope of this thesis; other modules are left for further study because of the time constraint. In this chapter, general concept of regarded PLM model is summarized.

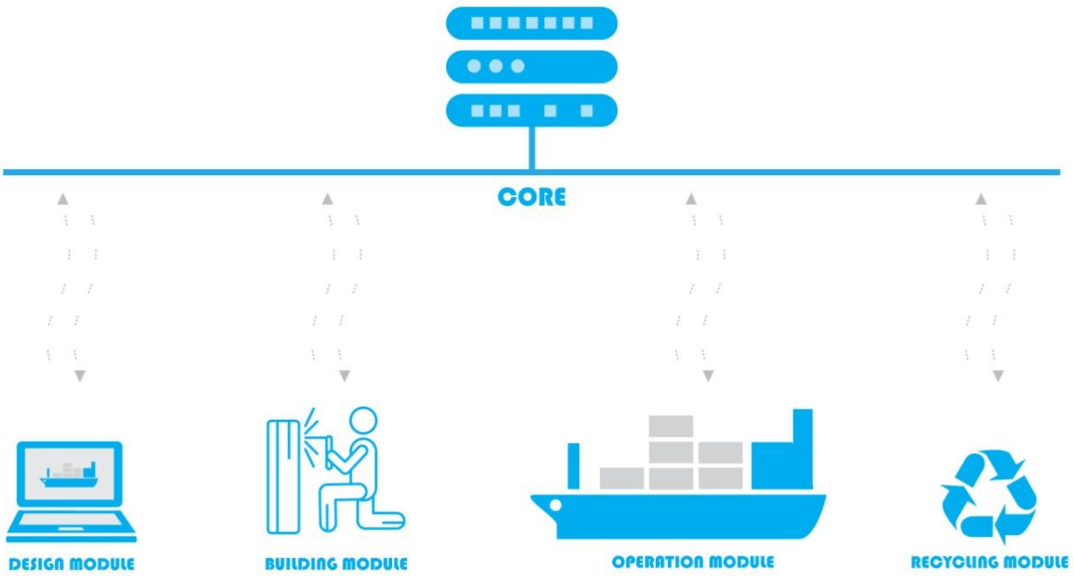

Figure 3.1 : Modules of total PLM model.

"CORE" is the brain of the total PLM model and it includes kernels related to interfaces, libraries, and databases. In other words, *"CORE"* can be defined as the base of total PLM model. Modules can be added or updated in time, this gives flexibility for changes.

3.1 Design Module

Design module is composed of the ship synthesis model, database, and artificial intelligence algorithms. Objective of design module is to help the ship owner to find optimum project considering entire life cycle of a ship. This objective is solved by using the design exploration and optimization framework. This framework is created by combining a holistic ship synthesis model and exploration-optimization tools.

Ship synthesis model has different engineering calculation tools to evaluate generated design alternatives. Hydrostatics, stability, resistance, seakeeping and strength functions are some of the engineering calculation tools. Modular structure of total PLM model gives permission to add other functions in time.

Design exploration and optimization tool includes searching algorithms of Kennedy and Eberhart (1995) like particle swarm, criteria, constraints and some statistical techniques like Latin hypercube (McKay et al, 1979).

3.2 Building Module

Building module manages sub-process of building phase such as construction, supply-chain, and purchase processes. Program, resource, strategy, and portfolio managements are based on *"CORE"*. Building module is very similar with classical PLM architecture. The only difference between classical PLM approach and building module which is considered in this thesis scope is the artificial intelligence capability for undesired situations like supply delay, labor deficiency etc. In undesired situations, optimum path should be found quickly to keep project delay as minimum as possible and artificial intelligence can help to show the best alternatives for decision making process.

3.3 Operation Module

Objective of operation module is to keep performance of ship inside the border of design predictions. It includes decision support and tracking systems. Tracking system keeps engine, route, propeller, vibration etc. data and this builds up basement for further estimations of decision support system with combination of initial design parameters. Decision support system helps ship officer to increase operation efficiency.

3.4 Recycling Module

Ship can have dangerous materials and equipments for disposal so recycling module is important to manage disposal process. Also, recycling module increase the efficiency of process. Management and control of recycling process via this module decrease environmental and safety risks.

4. THE DESIGN OF SHIPS

Ship is a floating vessel which has own propulsion system to cross waters. There are various usage purposes of ships such as naval, merchant, luxury, scientific etc. For example, merchant ships are used for commercial earnings by performing her tasks. Primarily, ship owner approves the maritime for economic investment and then, selects the most profitable and suitable task to earn money for him. Requirements for selected task shape the design of ship. Sometimes different designs can answer the same purposes. There are various examples for SWATH and monohull wind farm service vessels as an instance.

First point of the design process is the determination of concept. After the concept design, preliminary design, contact design, and detailed design follows respectively in the design process. Sum of whole design process means final design of a ship.

In this point, these questions arise for more specific definition;

What is the design of a ship?

The design of ship is the creative process to generate building, operation and recycling knowledge of the ship by using selected suitable parameters according to requirements of predetermined task. Selection of suitable parameters actually is enough to accomplish a design.

What is the better ship?

Better ship can be defined as a ship performs her duty successfully than alternatives. If this ship is a merchant ship, better ship means a ship provides more total commercial earnings than alternatives in the final of her life cycle.

What is the better design?

Better design is the finding of essential knowledge to create a better ship, therefore; better design is related to economic meaning in the merchant ship.

These questions obviously show that the main definition of better ship design is exploration of more profitable ship in the end of her life cycle. Another important deduction from these questions is any ship design method can be applicable to design a ship but any design method cannot be suitable for the exploration of better design. This deduction will be investigated in the literature survey chapter.

Selection and exploration are related to different problem concepts. Selection is element of a decision problem and design of a ship is a decision problem for the basic approach. In the decision problem, alternatives are selected from finite set. Combination of suitable alternatives from finite set to generate the best possible design is relatively easy. On the other hand, there is a problem in this approach and this arises from some infinite sets like hull forms, weight distributions, inertia moments etc. For example, it is possible to create infinite number of hull forms and how we can be sure used hull form is the best alternative. This is obviously impossible and so finding better design is a recursive exploration process. The process is the view of optimization problem concept. The ship design should be thought as the union of decision and optimization problems.

Now, objective of ship design can be defined easily, this is selection and exploration of suitable design variables combination to generate the best possible ship which gives the highest economic profit in the end of her life. Every step of design should be compatible with this main objective.

After the main objective is determined, ship design process can be investigated in detail. The ship design process can be divided into concept design, preliminary design, contract design, and detailed design stages. Sometimes, concept design as a feasibility study and preliminary design are used together as the basic design phase. Each stage of design process affects the big part of the following stages. There are different sub-objectives of these mentioned stages of design process. Concept design aims the exploration of suitable alternatives for the main concept of design requirements. Objective of preliminary design is the finding out the most economic design solution which provides the highest return of investment by compounding the various conflicting requirements (Papanikolaou et al, 2009). The goal of contract design stage is to generate irreplaceable detailed definition of design project. This stage involves all necessary calculations and drawings to pass the detailed design stage as the next step. Hull form, exact power estimation, seakeeping, maneuvering analysis, details of structural design, selection and design of propulsion and auxiliary systems and detailed weight distribution are finalized in the end of contract design.

In the detailed design stage as the finalization of the design process, whole informations of design process to construct a ship are generated as the outcomes such as drawings and specifications. Detailed design stage is the longest period of the total design process. Changes of design basis mean to return to the preliminary design step; therefore, preliminary design is the most important design stage to determine the life-cycle of ship economically.

4.1 Particulars of Ship Design Problem

In the most of classical design approaches, design requirements such as ship type, speed, payload, range etc. are determined by the ship owner as the first stage of the design process. These approaches do not answer some of important decision problems, quickly. For example, is the final design of catamaran vessel better than the final design of monohull vessel for the crew service purpose? Number of hulls, hull form type, building material, type of propulsion, and type of powering are important particulars which are shared in Table 4.1 as the initial design requirements. Also, speed, range, and payload choices affect the entire life cycle of a ship project like previous important particulars. This situation forces the design methods to concurrent approaches rather than iterative in accordance with design exploration-optimization frameworks.

Table 4.1 : Initial requirements.

No. of hulls	Hull form type	Building material	Propulsion	Powering
Monohull	Displacement	Steel	Single propeller	Diesel
Catamaran	Planing hull	Aluminium	Twin propeller	LNG
Trimaran	Hydrofoil	Composite	Waterjet	Steam turbine
Pentamaran	Swath	Wood	Podded propulsion	Electrical
	Hovercraft		Azimuth propulsion	Combined
	SES		Voith Schneider	

Stability, resistance, propulsion, structure and others are the subjects which should be utilized in every ship design process. Each decision for these subjects affects the rests so they should be considered together. This problem is related to multidisciplinary nature of ship design process which can be seen in Figure 4.1; therefore, concurrent solutions answer faster than iterative solutions to ship design problems.

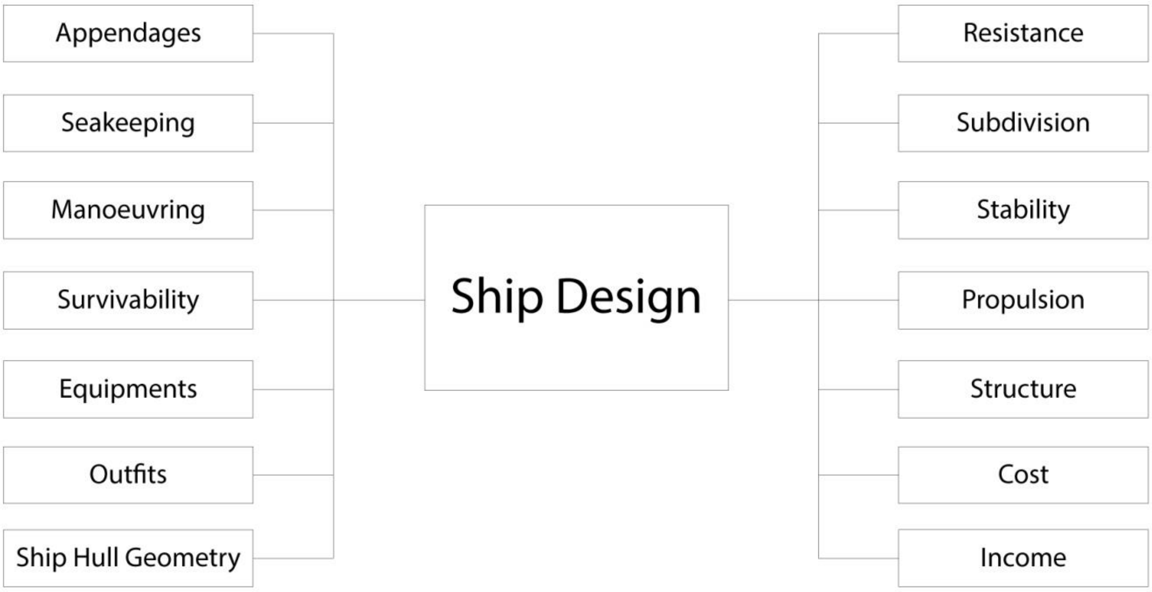

Figure 4.1 : Multidisciplinary nature of ship design.

A ship design may be based on multiple objectives related to usage purpose. For example, high speed, high seaworthiness, low wake, and high propulsion efficiency are expected for a frigate. On the other hand, maximum return and minimum risk are expected for a cargo ship. This situation enlarges the single objective-multidisciplinary problem to multiobjective - multidisciplinary problem.

A ship design should follow the international, national and class regulations. These are constraints of any ship design projects. At this point, class society and flag authority are incorporated to ship design project as the stakeholders. Also, there are other stakeholders which can be seen in Figure 4.2. Whole stakeholders have important effects on design so they should transfer own knowledge to design process.

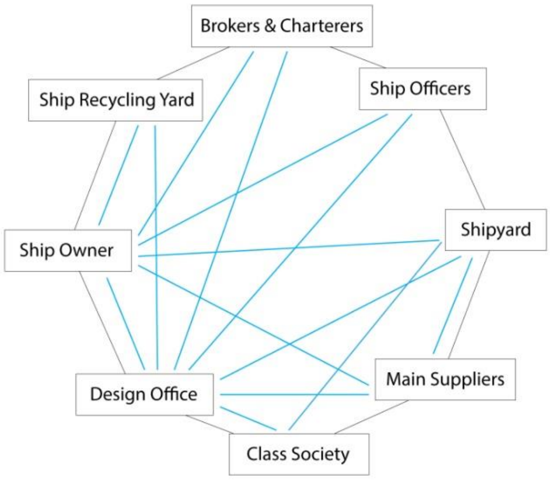

Figure 4.2 : Stakeholders of ship design process.

The design of ship affects whole life cycle of ship from first operation day to end of dismantling. Therefore, holistic view should be applied to ship design process. Every discipline of design is utilized for entire life cycle of ship in holistic design. In fact, the holistic design is a parallel view with product life cycle management, so they complete each other.

There can be multiple solutions based on considering criteria. Some of them can be non-dominated and this means none of them can be improved without decreasing some criteria. The name of this problem is Pareto optimality. Entire Pareto optimal solutions are considered equally good and this is the area of multiple criteria decision making.

4.2 Mathematical Formulation of Ship Design Problem

Ship design study can be formulated as maximization or minimization problem of a function. In this study, purpose of ship design is considered as the maximization of economic profit. Formulations are shared below;

X is the vector of design variables. X_i^L and X_i^U are lower and upper bounds of design variables. h_k and g_j are constraints of problem. F is the objective function. Structure of objective function specifies the design problem. In the ship design, objective function has multi-disciplinary nature. Actually, design problem is exploration of desired variables which give the feasible designs in the design space.

$$Max\ F(X) \quad (4.1)$$

$$g_j(X) \leq 0 \quad \text{j=1,….l} \quad (4.2)$$

$$h_k(X) = 0 \quad \text{k=1,… l} \quad (4.3)$$

$$X_i^L \leq X_i \leq X_i^U \quad \text{i=1,….l} \quad (4.4)$$

In ship design problem, lower and upper bounds of global design variables are defined in the initial state as the first set bounds, bounds of local variables are determined in accordance with global design variables as the second set bounds. Design variables are related just one discipline considered local to that discipline. Global design variables affect more than one discipline. Variations of global variables change the bounds of local bounds. Also, same situation is applicable for constraints, because ship design problem has non-hierarchic structure.

On the other hand, generation of design variables and bounds are sequential in some portion of problem like first length of ship is sampled and then L/B > 4.5 condition specify bound of B. Generation of B comes after L. They are sequential variables.

Effect of lifecycle approach on design problem is the time dependence (t) of objective function, variables, constraints, and bounds.

$$Max\ F_t(X_t)\ ,\ X_t = \left[X_{1_t}, X_{2_t}, X_{3_t}, X_{4_t} \dots X_{n_t}\right] \quad (4.5)$$

$$g_{j_t}(X_t) \leq 0 \quad \text{j=1,….l} \quad (4.6)$$

$$h_{k_t}(X_t) = 0 \quad \text{k=1,… l} \quad (4.7)$$

$$X_{i\ t}^L \leq X_{i_t} \leq X_{i\ t}^U \quad \text{i=1,….l} \quad (4.8)$$

Different design methods explore limited portions of design space. Some design methods generate an intersection set. Power of design method means the capacity of exploration to generate feasible portion of design space and to determine solution space’s behavior. Figure 4.3 shows exploration of two design methods in the design space. Obviously, there are two difference sets. This means that these two methods searched different portions of design space but not entire space.

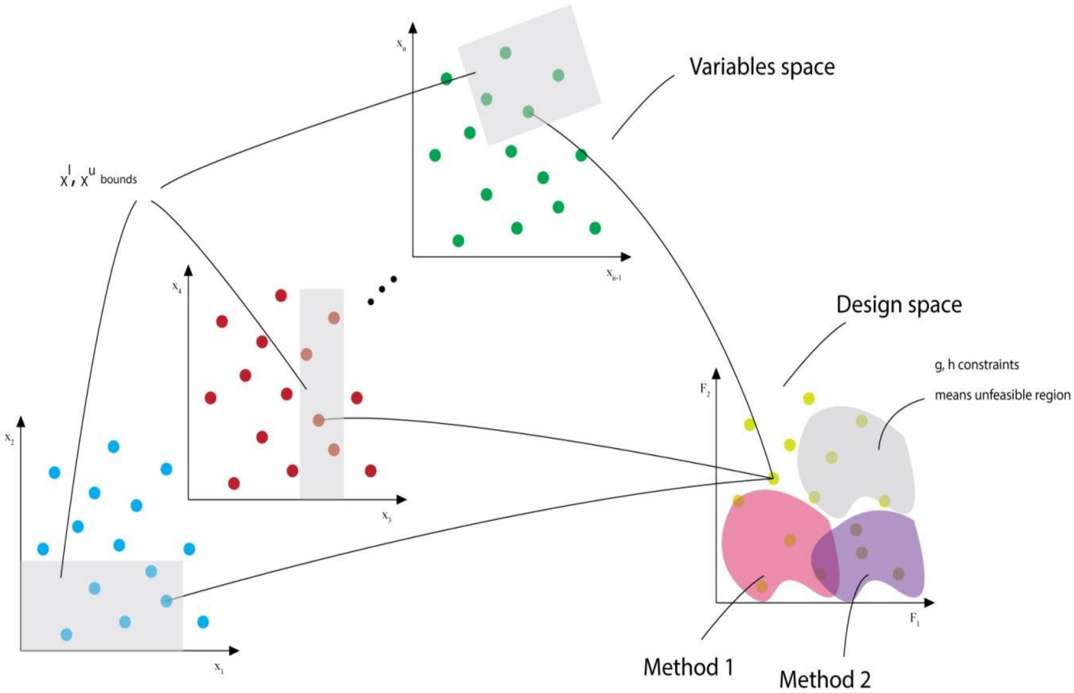

Figure 4.3 : Variable, design spaces and their particulars.

5. REVIEW OF DESIGN METHODS

5.1 Design Methods

Ship design spiral was first presented in 1959 by Evans (1959). Actually today, this approach is the still most common, knowingly or unknowingly used method from designers or design offices in ship building industry. Design spiral can be seen in Figure 5.1 described by Evans is the methodical form of the natural sequential steps. Later on, economics of project was added to the spiral by Buxton (1972). Quality of this method is based on utterly designer's experience and also, success of the final design has strong relationship with iteration and cycle number of design process.

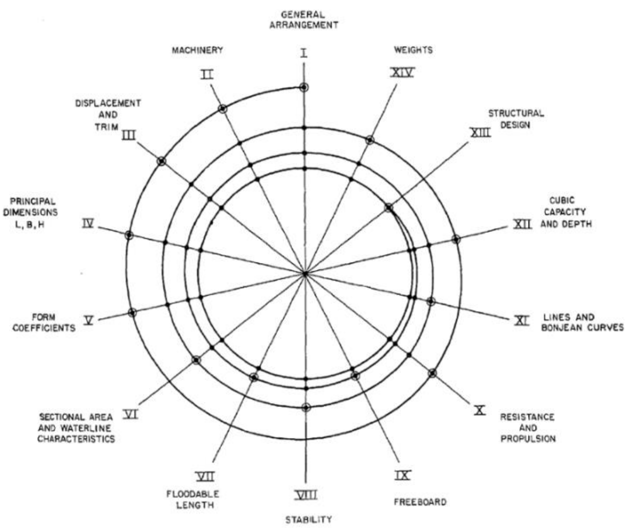

Figure 5.1 : Design spiral (Evans, 1959).

During the design process, changing systems force the reconsideration of all design again and again so this means long design time and this approach is incapable of responding to today's design considerations. Enhanced design spiral can be seen in Figure 5.2 was presented in 1981 by Andrews (1981) according to Mistree et.al. (1990). Andrews added the time effect to design spiral; so, design spiral expands to three dimensions. In the different level, design project continues the development. Convergence of the process is directly related with low level decisions because of sequential activity and iteration.

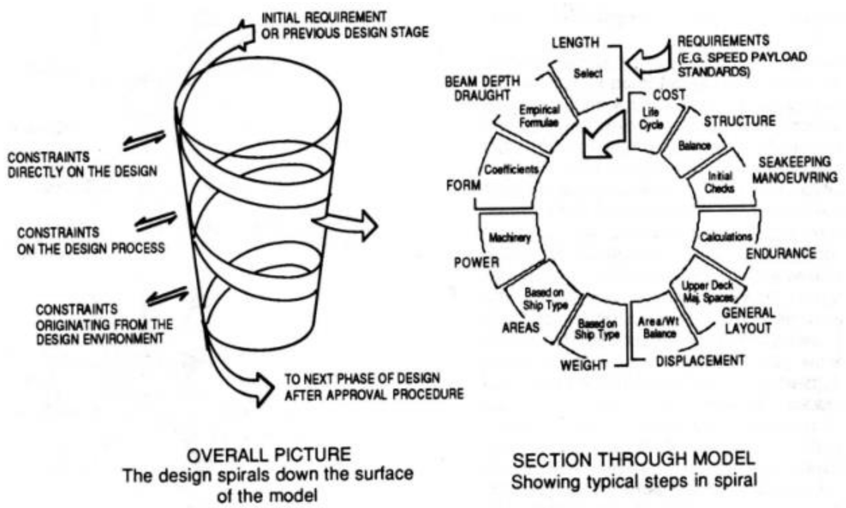

Figure 5.2 : Enhanced design spiral (Andrews, 1981).

Expert system in ship design was presented in 1982 by MacCallum (1982) according to Helvacıoğlu and İnsel (1998). Actually, expert system is the subfield of artificial intelligence and based on decision-making ability of computer by using knowledge inputs of human. Furthermore, expert systems try to solve complex problems by reasoning of human expert's knowledge. Expert system is also known as knowledge based design system. Although rule based frameworks of ship design such as regulations and class rules are suitable, expert system does not become popular in ship design community. One of the common applications of expert system in ship design process is the layout design solution. Figure 5.3 gives an example of expert system layout design application from an expert system program package called ALDES (Accommodation Layout Design Expert System) which is developed by Helvacıoğlu and İnsel (2003).

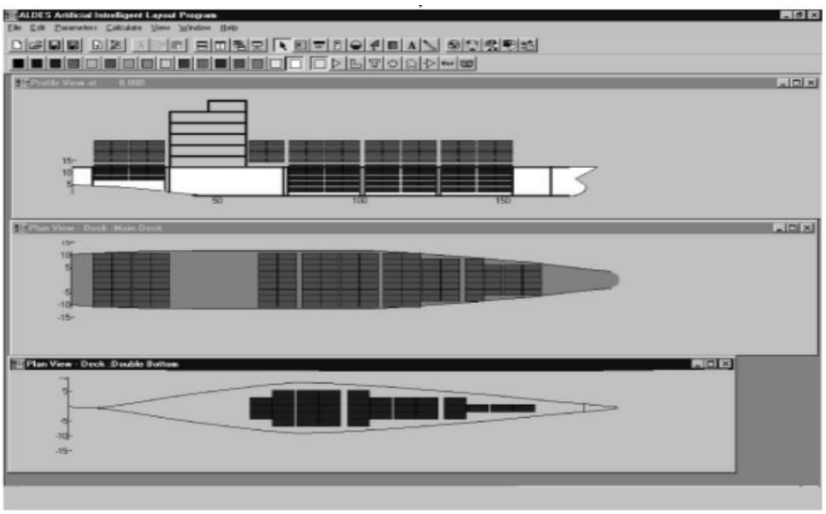

Figure 5.3 : Expert system layout application (Helvacıoğlu and İnsel, 2003).

Further information related to expert system applications in marine technology can be found of study of Helvacıoğlu and İnsel (2008).

Decision-Based design was first presented by Mistree et al. (1990) for ship design. This approach offers concurrent engineering design for the life-cycle by using rational decision based system thinking. There is no just one model for decision based design. The Decision Support Problem Technique is the one example of decision based design application (Mistree et al., 1990).

Decision based design has different role from computer-aided or computer based design methods. This method actually is a perspective to implement an approach for design. Main properties of decision based design method are heterarchical system construction, product’s life-cycle consideration, meeting or exceeding criteria and concurrent system solution. Figure 5.4 shows “The Frustum of a Cone” offering of Mistree et al. (1990). This approach differs from Evans, Buxton and Andrew’s spiral by using heterarchical and concurrent system.

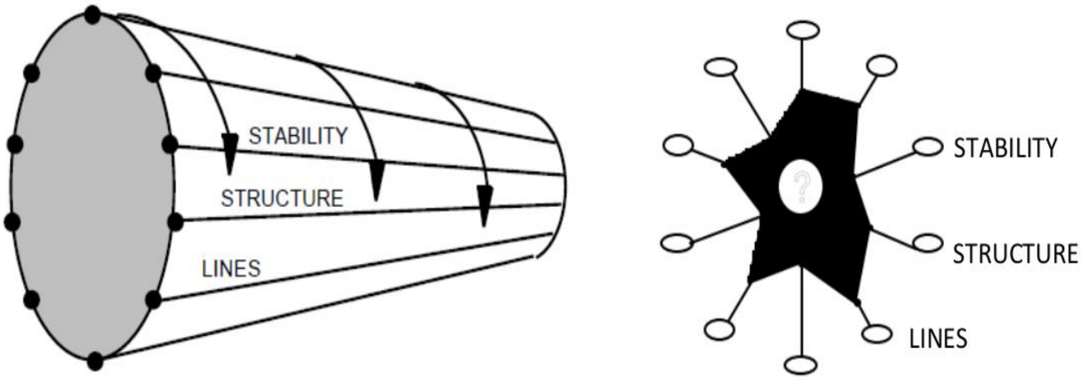

Figure 5.4 : “Frustum of a Cone” and cross section (Mistree et al., 1990).

System based design was first presented by Levander (1991). This method is in essence the improved version of the design spiral by attaching some definitions such as mission, function, form, performance and economics. System based design still has the sequential and iterative nature of the process. Main feature of this approach is the functional breakdown structure capacity. This capacity allows the more extensive perspective for ship design process management. First step of the design should be mission definition for the ship according to Erikstad and Levander (2012) and steps of design process can be seen in Figure 5.5.

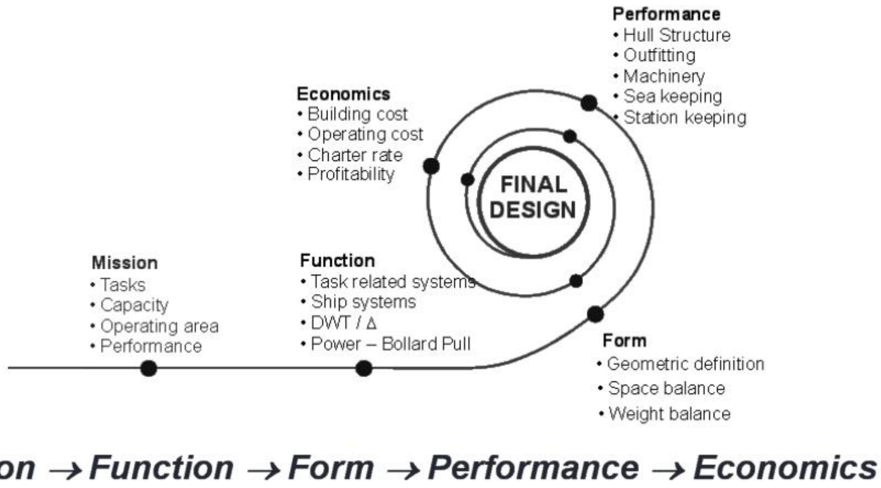

Figure 5.5 : The system based design process (Levander, 1991).

More recent applications for offshore vessels are presented in 2011 by Vestbøstad (2011) and by Erikstad and Levander (2012). System based design approach was used as a decision support tool in these studies. Special functions are described for offshore vessels and initial sales process is supported by this approach.

Case-based design actually is a case based reasoning approach of Artificial Intelligence. Rule based expert systems have several problems for shallow, implicit problem domain knowledge. In this situation, it is difficult and time consuming to construct knowledge base system, deal with problems and learning facility of expert system is limited. In this point, case-based reasoning approach solves new implemented problems by adapting and modifying previously feasible and successful solutions to similar problems. Schabacher et al. (1994) offered learning prototype-selection rules for case-based iterative design for example yacht design process. Obviously, cased-based design underlies today’s global and local optimization studies such as common global or local hydrodynamic optimization of ship hull form.

Figure 5.6 shows an example of used B-Spline surface in study of Schabacher et al. (1994). In this study, course time optimization problem was solved by using four different surface modification approaches and velocity prediction program.

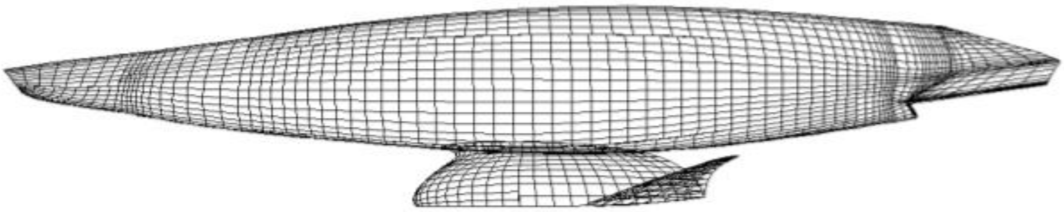

Figure 5.6 : The Stars and Stripes ‘ 87 (Schabacher et al, 1994).

Simulation-based design was first presented by Boudreaux (1995) for naval ships. This method contains simulations and virtual environment with the integration of CAE/ CAD/ CAM systems and databases network Boudreaux (1995). Main feature of this method is collaborative concurrent engineering and integrated product and process development approach. Offered system architecture in this method can be seen in

Figure **5.7**.

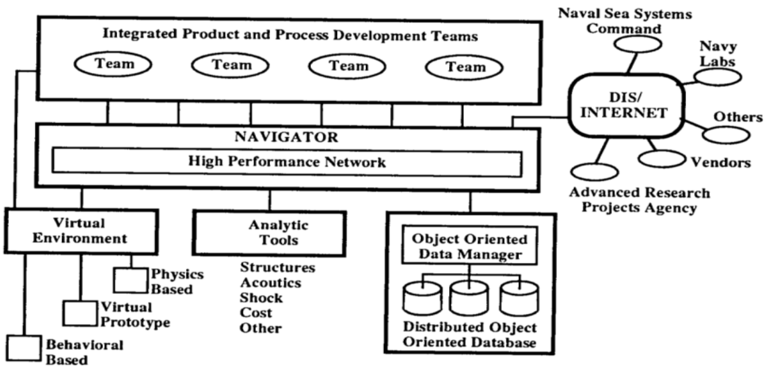

Figure 5.7 : System architecture for the simulation based design system Boudreaux (1995).

Today, simulation-based design mostly means individual applications and computer aided calculations such as FEM and CFD calculations. Bertram and Thiart (2005) investigated the simulation-based ship design and show recent applications like Figure 5.8 and Figure 5.9.

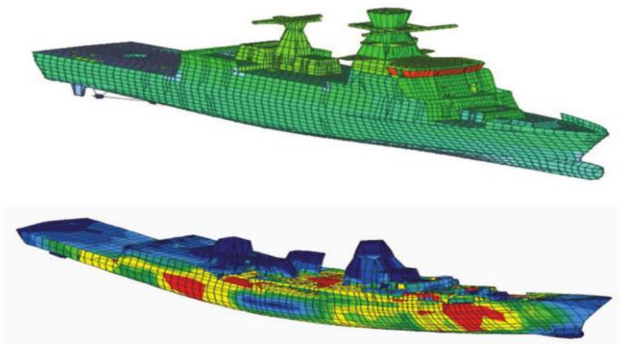

Figure 5.8 : FEM structural simulation. (Bertram and Thiart, 2005).

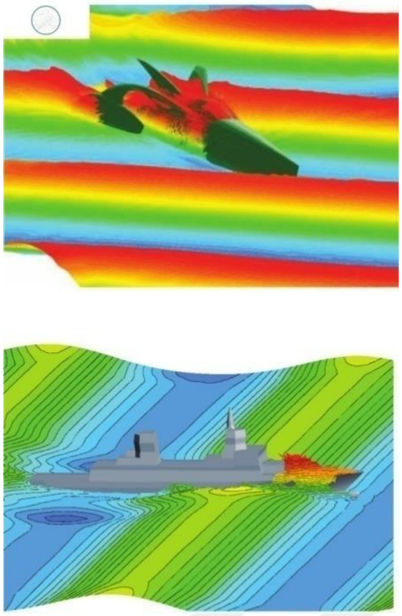

Figure 5.9 : CFD hydrodynamic simulation (Bertram and Thiart, 2005)

Axiomatic design principles were outlined by Brown and Thomas (1998) as a naval ship design process by Whitcomb and Szatkowski (2000). Axiomatic design approach maps customer needs to functional requirements, design parameters and process variables in seen Figure 5.10.

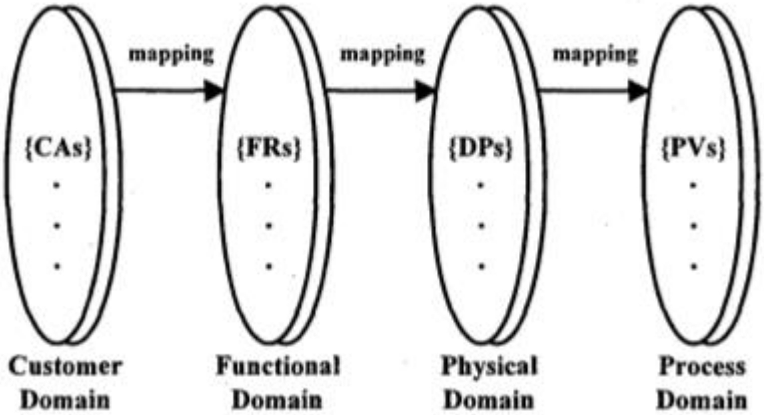

Figure 5.10 : Design Domains including Characteristic Vectors (Szatkowski, 2000).

The axiomatic design converts complex engineering problems into simple sub-problems by decomposing design domain from customer domain to process domain. It allows to concurrent design process to achieve the requirements. Axiomatic formulation example of concept ship design by using ship synthesis model can be found in study of Whitcomb and Szatkowski (2000).

Design for X concept means optimization of ship for specific important properties, like design for safety, design for efficiency, design for arctic operations and design for production (Papanikolaou et al, 2009). Life cycle of ship is important in design for X approach and ship design problem is handled as a holistic ship design optimization. This optimization consists of exhaustive multi-objective and multi-constrained optimization procedures as shown in Figure 5.11.

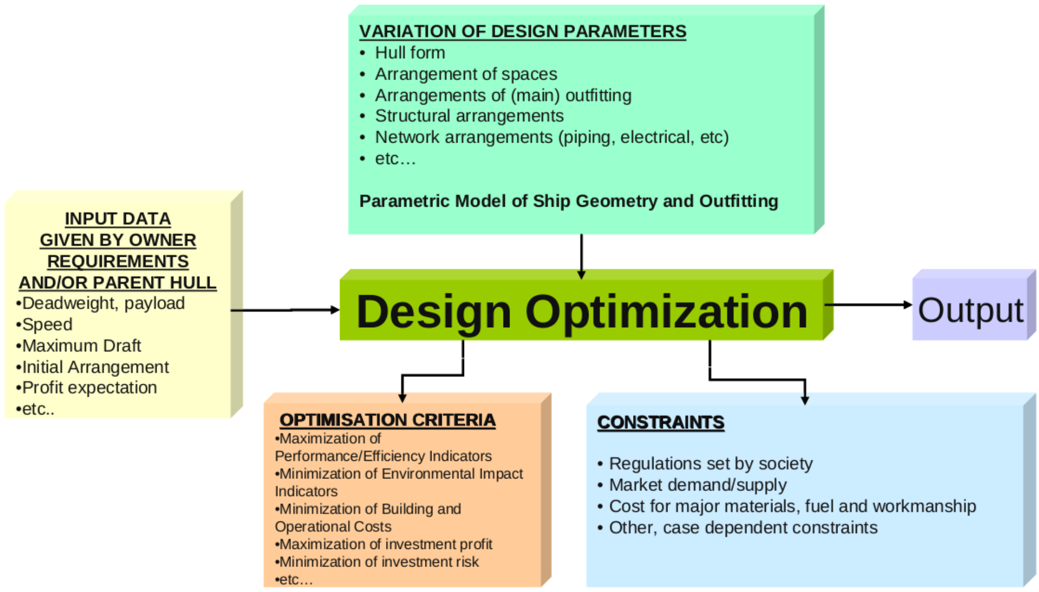

Figure 5.11 : Generic Ship Design Optimization Problem (Papanikolaou, 2008).

Library based approach was presented by McDonald (2010) in his doctorate thesis. This approach offers large exploration of alternative hull form styles in preliminary design stage with generated a library sub-options to allow examination of possible options with a set of initial design requirements (McDonald, 2010). Searching to find potential options in a library of design data is easier and faster than stochastic or deterministic optimization for explore alternative hull forms. Offered approach is based on two processes. First process consists of creating and evaluating a number of options to create a library. The second process is the designer examination as part of the design process. McDonald suggests library with separation and combination approach rather than simple library to reduce pre-calculation complexity in his thesis (McDonald, 2010).

Figure 5.12 shows relative complexity with an increased number of styles. In this point, obviously there is trade-off problem between run-time complexity and pre-calculation complexity.

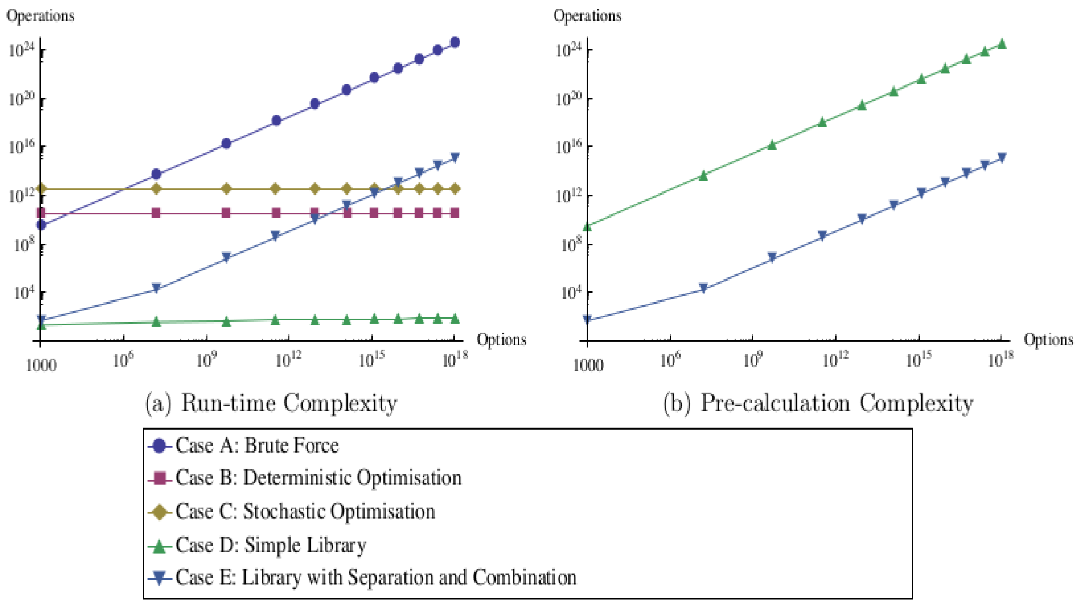

Figure 5.12 : Relative complexity with an increased number of styles (McDonald, 2010).

C-K Theory or Concept-Knowledge theory propounds an important relationship between the Concept-Space and Knowledge-Space; furthermore, the Concept-Space has all concepts that are not created in Knowledge-Space which contains truths of designer yet (Van Bruinessen et al, 2013). Without concept-space, the design process turns into optimization or rational problem solution. Also, concept space brings creativity to design process. Van Bruinessen investigated ship design process as an example of innovation with C-K theory in his study (2016). Figure 5.13 and Figure 5.14 show knowledge based and conceptual elements in radical Innovation design process (Van Bruinessen et al, 2013).

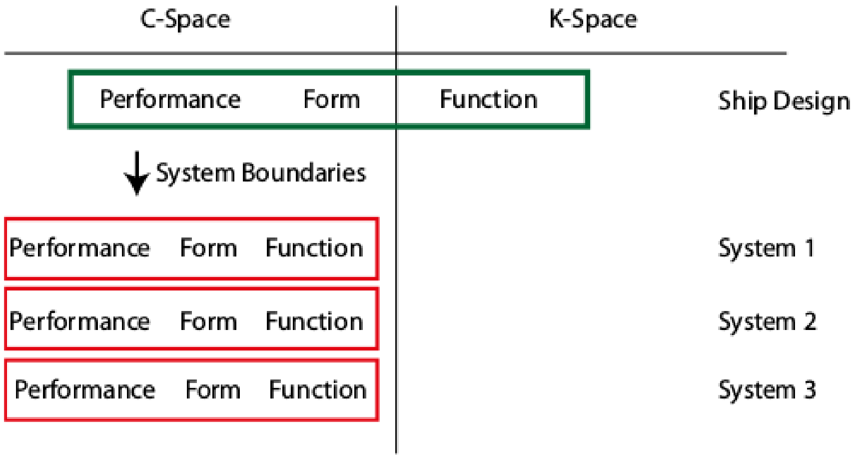

Figure 5.13 : Radical Innovation, Phase 1 (van Bruinessen et al, 2013).

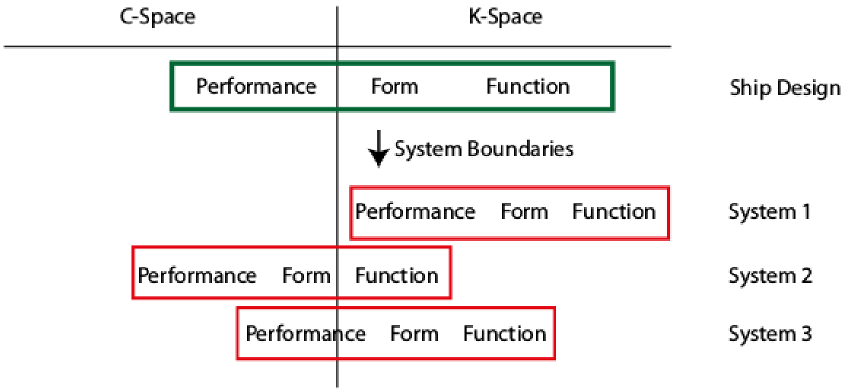

Figure 5.14 : Radical Innovation, Phase 2 (van Bruinessen et al, 2013).

Set based design was investigated firstly by Milanovic (2016) for offshore supply vessel. In this approach, multiple feasible solutions sets are evaluated simultaneously in parallel and weakest sets are eliminated by using accumulated knowledge from previous successful designs while converging towards a final solution (Milanovic, 2016). Set based design consists of three main principles according to Sobek et al, (1999) as seen in Table 5.1.

Table 5.1 : The three principles of set based design (Sobek et al, 1999).

Map the design space	1. Define feasible regions 2. Explore tradeoffs by designing multiple alternatives 3. Communicate sets of possibilities
Integrate by intersection	1. Look for intersections of feasible sets 2. Impose minimum constraint 3. Seek conceptual robustness
Establish feasibility before commitment	1. Narrow sets gradually while increasing detail 2. Stay within sets once committed 3. Control by managing uncertainty at process gates

Sets of possibilities are communicated to each other and evaluated by using associated requirements related to engineering disciplines. Feasible regions are assessed and generated intersection of independent solutions. The design space is reduced by eliminating subsystem solutions that do not contribute to total system solution. Set based design process can be seen in Figure 5.15.

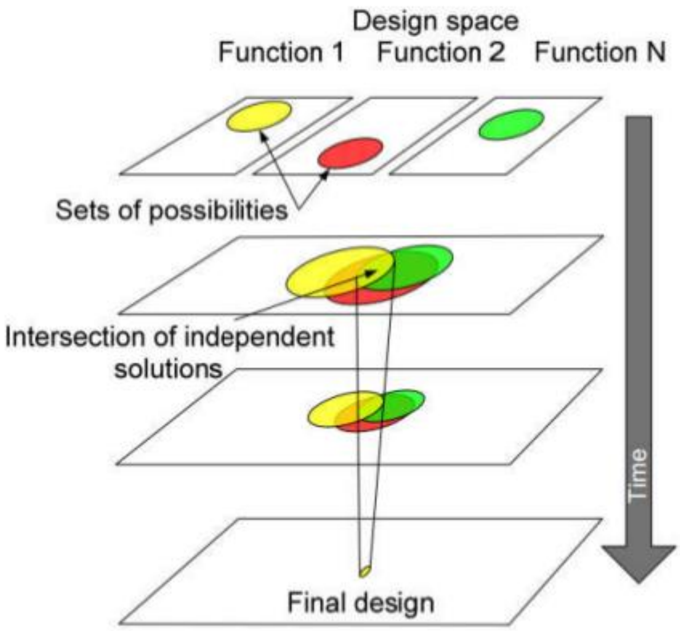

Figure 5.15 : Set based design approach (Raudberget, 2012).

5.2 Discussion of Design Methods for Implementation

Various design methods are presented as a literature study in previous section. Fifty-eight years passed from first published design method to today, and design methods are evolved to different ways. Evolution of design methods in the timeline can be seen in Figure 5.16. Main contributors of these evolutions are the increased power of computers, the enlarged concept of decision theory, and the demand for efficient ships.

Design spiral which is the first design method can be considered as the parent of other design methods. Its iterative and sequential concept is basic form of the design. After that, variations of design spiral are published like Buxton's method (Buxton, 1972). Modular approach is added to design spiral by Jolliff (Cook, 1976). Cook investigated modular approach for lifecycle of ship (1976) but still design method was sequential. Modular approach is important perspective and it keeps still own significance. Enhanced design spiral of Andrews (1981) has time effect but still iterative and sequential. Expert system of MacCallum (1982) is one of the initial attempts to combination artificial intelligence with ship design. Weak part of this system is the inputs for functional relationships. It can be practicable for some design sub-fields. Decision based design of Mistree et al. (1990) offers concurrent engineering design. It can be useful for lifecycle consideration. This method actually is a perspective to implement an approach for design. System based design of Levander (1991) is sequential and iterative method like other design spirals. The difference between system based design and other spirals is the functional definition of process. Case-based design of Schabacher et al. (1994) is the basis of today's optimization approaches. Most of contemporary design methods contain case-based approach in themselves. Simulation based design (Boudreaux, 1995) is the wider form of case based design. This form is collaborative and it has system architecture for product development environment. Axiomatic design of Brown and Thomas (1998) is important to convert complex engineering problem into simple sub-problem. Actually, it is more suitable for pre –design or first step of design study. Design for X concept of Papanikolaou et al. (2009) is the holistic form of the combination of decision and simulation based design approaches. Library based approach of McDonald (2010) is actually the solution for problems of large exploration study. Any design method can be combined with library based approach. Purpose of C-K theory of Van Bruinessen et al. (2013) is to found innovative solution for ship design problem. This methodology does not give solutions in the known space. Founded concepts by using C-K theory can be integrated with classical design exploration approaches. Set based design of Milanovic (2016) is a method to enlarge explored space and it is useful to overcome some of classical exploration method's problems. These methods are not suitable alone to integrate with PLM structure but good part of these methods can be subtracted and combined into new approach. Actually, most of them are combination approach and the difference between them is the dominant side of design method. Our need is convenience for intelligence capacity in the lifecycle management.

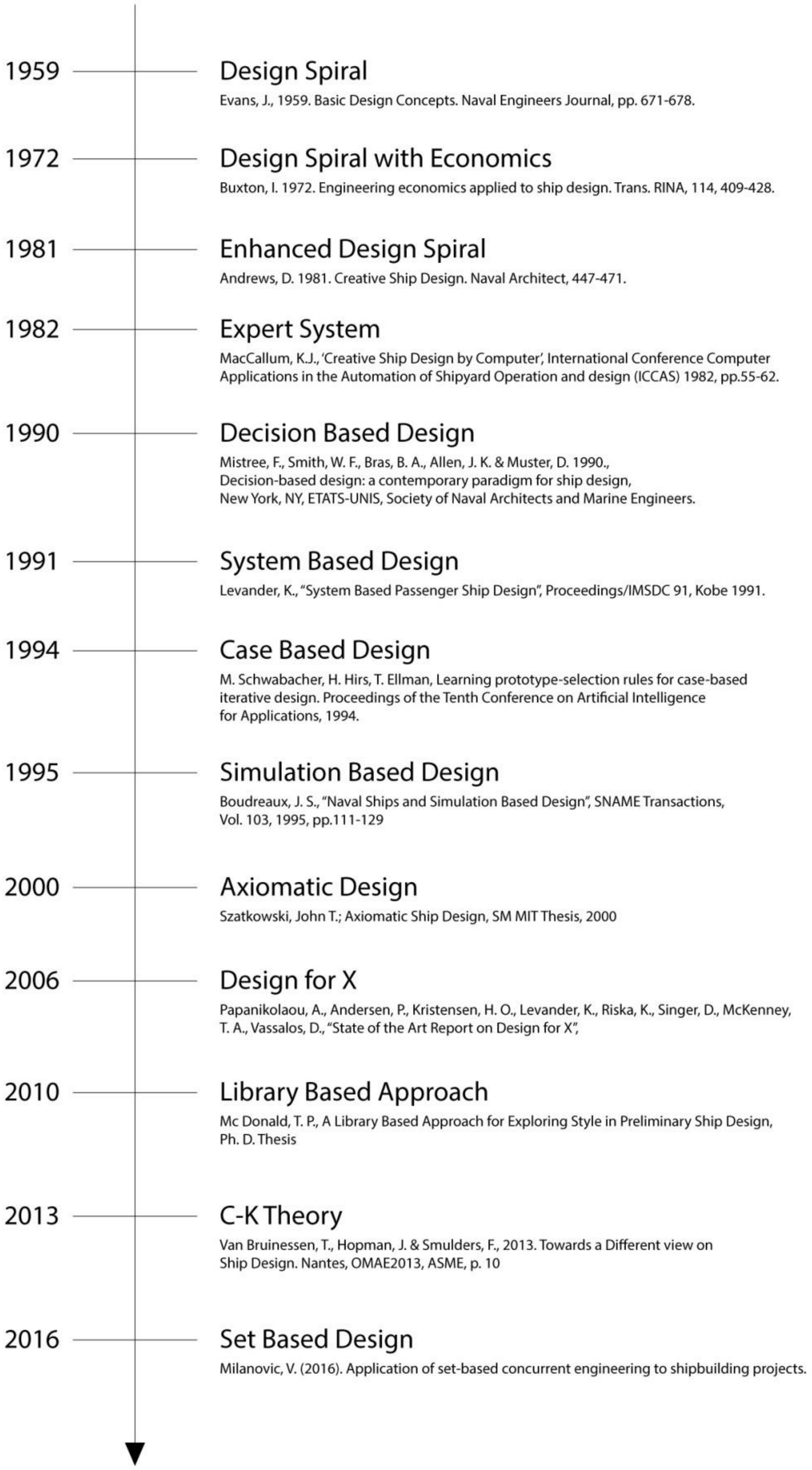

Figure 5.16 : Timeline of design methods.

6. A UNIVERSAL SHIP DESIGN NETWORK

The design nature of ship and mathematical formulation of design problem are investigated in section 4. The universal ship design network approach is offered as a design module of the universal ship network, to consider all particulars of ship design nature in a lifecycle. Offered design network includes holistic ship synthesis model, database, and artificial intelligence which are linked with *"CORE"*. In the previous section, phases of design process are mentioned as the concept, preliminary, contract and detailed design stages. Reviewed design methods contain various phases and the most of them are a solution for preliminary design. In this study, offered design method just includes the outcomes of preliminary and contract design phases. To use this method, concept should be determined firstly and in this study a container ship concept is used to investigation of method. In the universal ship network, detailed design phase should communicate with created design network and building, operation and recycling phases but this is not subject of this study.

Followings are the sample outcomes of the universal ship design network for the preliminary and contract design phases;

- General arrangement
- Hull form
- Tank plan and stability calculations
- Power estimation
- Seakeeping calculations
- Design of propulsion system
- Selection of auxiliary systems
- Weight distribution estimation
- Economic return estimation

Objective of design network is to explore design space in accordance with incoming data of other modules, database, ship synthesis model and artificial design intelligence. Offered design network enables integration of the produced knowledge in building, operation and recycling phases with design process. Design network uses produced knowledge of other phases as an input and it generates new designs continuously. Bad designs are removed from database and feasible designs are kept in database. Also, design process knowledge is kept in database to improve next design cycle. Components of offered design network which can be seen in Figure 6.1 and details of them are explained in the following sections, also detailed figure of offered design network can be seen in Figure D.

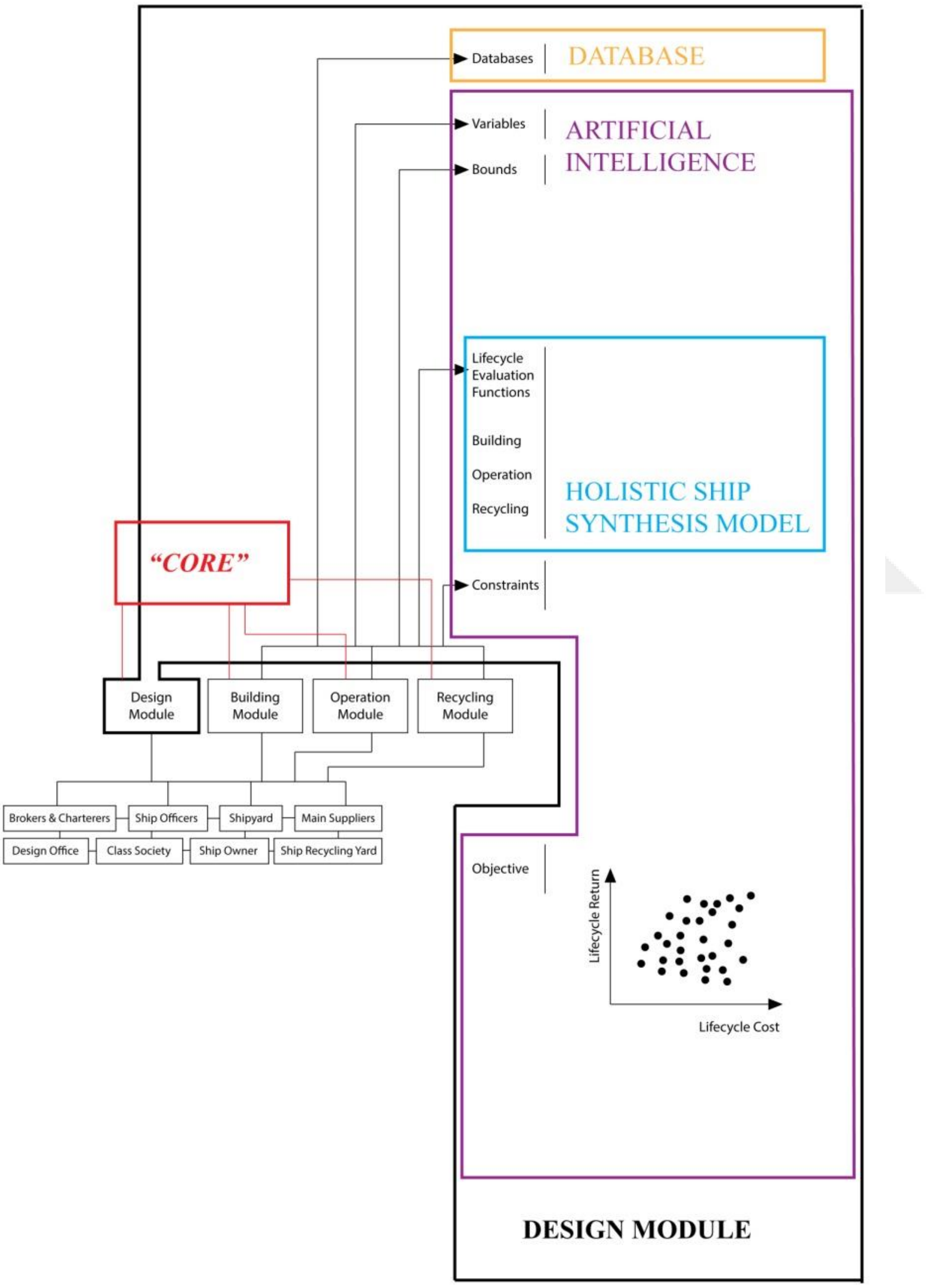

Figure 6.1 : Structure of the universal ship design network.

6.1 Holistic Ship Synthesis Model

Papanikolaou states that optimum design means result of optimization for the entire lifecycle consideration of the ship (2012). Actually, this definition is parallel with PLM approach. For the design exploration, all phases of a ship life should be considered in the design process. Holistic ship synthesis model means that the synthesis model of a ship is enlarged with the lifecycle integration by improving evaluation function towards to building, operation and recycling phases. For example, ship resistance is normally calculated for the contract speed in the calm water – full loaded condition. On the other hand, ship resistance is time-varying because of fouling, operation profile, loading conditions etc. Holistic view enables taking into account of changing evaluations during the lifecycle. Holistic ship synthesis model can be detailed considerable. In the scope of this study, just main functions are considered in the synthesis model to illustrate behavior of the ship design network. Used evaluation functions in the holistic ship synthesis model are described in the following sections.

6.1.1 Life cycle budget estimation

Economic purpose of a merchant ship is to derive profit for ownership. For non-commercial ships such as naval vessels, yachts etc., the economic purpose of ships can be the least cost. Profit is the total income minus expenditures. These economic purposes are taken into consideration during the ship design process. The best design ship means that a ship maximizes the income and minimizes the cost during the life cycle of ship for an ownership. To maximize the profit, incomes should be increased and costs are diminished for ship's life cycle. On the other hand, environmental impacts and safety of ship during its life cycle should be kept in acceptable region in conformity with international or national regulations, society standards and academic researches etc. Figure 6.2 shows the budget phases of ship during its life cycle. All phases have impacts with revenue and cost on budget and all of them should be considered in the design phases.

Figure 6.2 : Budget phases of ship during its life cycle.

In this study, an analytical budget model is used to implement into *"Core"*. Detailed investigation about budget model is proposed followed sections. Another important subject is the data communication between phases. Suitable data can help to diminish design, building, operation and recycling costs.

6.1.1.1 Life cycle income estimates

Total income of ship during its life cycle results from two phases. First one is operation phase and second is the recycling phase. Goal of the merchant ship is to provide the income to owner so actually, life cycle income estimate is the important part of the decision process. Implemented estimation models to "Core" are described followed topics.

$$\text{Total revenue} = \text{Revenue}_{\text{Operation Phase}} + \text{Revenue}_{\text{Recycling Phase}} \qquad (6.1)$$

Operation Phase

Revenue of operation phase can results from sales of ship, charter fare and other operating revenues such as ticket revenue of passenger vessels, towage rate of tugs etc. Revenue of operation phase is the main part of the revenue of ship in its life cycle and also revenue is the main building purpose of merchant ships. Equation (6.2) describes the possible components of operating phase revenue. These components do not occur in the same time and they depend on market conditions.

$$\text{Revenue}_{\text{Operation Phase}} = \text{Revenue}_{\text{Ship sales}} + \frac{Revenue_{\text{Charter fare}}}{Revenue_{Operating}} \tag{6.2}$$

Revenue of ship sales depends on market condition constitutively. Income from sales of a ship is not a direct objective of the owner. This chance arises in rare times in accordance with market conditions. Due to these reasons, revenue of ship sales is not modeled in the implemented function of *"Core"*.

Revenue from charter is the main objective of a ship investment so income of operation phase is implemented by using equation (6.4). To use this equation, route of ship, loading and offloading capacity of terminals should be known before the design.

$$N_{\text{a-service}} = \frac{1}{24} \cdot \frac{1}{365} \left(\frac{Route\ distance}{Ship\ design\ speed} + \frac{Container\ capacity}{Loading\ capacity\ of\ terminal} + \frac{Container\ capacity}{Offloading\ capacity\ of\ terminal} \right) \tag{6.3}$$

$$\text{Revenue}_{\text{Operating}} = (\text{N}_{\text{a}-\text{service}} \cdot \text{Container capacity} \cdot \text{Freight rate of a container}) \cdot y \tag{6.4}$$

y = Estimated technical working life

$N_{\text{a-service}}$ = Number of voyage in a year

When we analyze equation (6.4), it is obvious that three parameters which are related to ship design mainly affect the revenue of operation phase. These are ship design speed, container capacity and working life of the ship. Ship design speed and container capacity are dependent parameters in the negative direction. More container capacity means slow ship because of extra weight.

Recycling Phase

Recycling decision is taken by ship owner when the recycling revenue is higher than potential operation revenue of ship in the rest of the life or revenue from selling of ship to second hand market except force of regulations. Revenue of ship owner from sales of ship to recycling company depends on light weight ton of ship. Potential recyclable units are steel scrap, re-rollable steel, engines, chilling compressors, spare parts, pipes, electrical cables, motors, kitchen ware and furniture. 95% of waste ships is steel and about 98% of this steel is recyclable and Figure 6.3 shows the recycling process of a ship's steel structures. Jain, Pruyn and Hopman state the prices per light weight ton (LWT) offered by recycling yards such as Indian sub-continent yards

USD 380-420, Chinese yards USD 55-80, and Turkish yards (USD 55-60) lower than Chinese yards (2014). Because of process mechanization, Chinese and Turkish yard's price lower than Indian yards (Jain, Pruyn & Hopman, 2014). Eq. (6.5) is used for recycling revenue calculations.

$$\text{Revenue}_{\text{Recycling Phase}} = \text{LWT of ship x unit price (USD/LWT)} \tag{6.5}$$

Unit price is used as USD 55 in this study.

Figure 6.3 : Recycling process of ship (Netpeckers recycling yard).

6.1.1.2 Life cycle cost estimates

$$\text{Total cost} = \text{Cost}_{\text{Design Phase}} + \text{Cost}_{\text{Building Phase}} + \text{Cost}_{\text{Operation Phase}} \tag{6.6}$$

Design phase cost

$\text{Cost}_{\text{Design Phase}}$ is divided into detailed design and class approval costs. Generation of technical drawings by design office is important cost part of design phase; also most of the drawings should be approved by a class society. They are implemented by using following equations.

$$\text{Cost}_{\text{Design Phase}} = \text{Cost}_{\text{Design}} + \text{Cost}_{\text{Class}} \tag{6.7}$$

Detailed design:

$$\text{Cost}_{\text{Design}} = (\text{L} \cdot \text{B} \cdot \text{D}) \cdot C_f \cdot U_{pDesignOffice} \quad (6.8)$$

C_f: Complexity factor

$U_{pDesignOffice}$: Unit price of design offices for detailed design process (\$/m3)

Complexity factor which is shared in Table 6.1 is derived from engineering price calculation forms of Turkish Chamber of Naval Architects and Marine Engineers (2010) for members, and unit price can be varying for different design offices.

Class approval of drawings:

Complexity of ships changes the class approval costs;

$$\text{Cost}_{\text{Class}} = (\text{L} \cdot \text{B} \cdot \text{D}) \cdot C_f \cdot U_{pClass} \quad (6.9)$$

U_{pClass} : Unit price of Class societies for approval process (\$/m3)

Table 6.1 : Complexity factor.

Ship type	Complexity factor
Naval vessels	2.0
Container ships	1.1
Bulk carriers	1.0
Chemical tankers	1.2
Tugs	1.3
Passenger ships L > 50m	1.3
Passenger ships L < 50m	1.1
Special ships	1.3

Yachts	1.1
Fishing vessel	0.6

Building phase cost

Building phase cost could be divided into financial cost, yard cost, material cost, labor cost, armament cost, and overheads. Related equations which are shared below are borrowed from study of Chen (1999) and Ventura (2017) and then combined.

$$\text{Cost}_{\text{Building Phase}} = \text{Cost}_{\text{Yard Building}} + \text{Cost}_{\text{Yard Profit}} + \text{Cost}_{\text{Financial}} + \text{Cost}_{\text{Aux.Machinery}} + \text{Cost}_{\text{Engine}} \quad (6.10)$$

Ship owners take a loan out to finance ship building cost. Typically, 70% loan to deposit ratio and 3-4% interest are common. Ship owners pay these loans in 5-10 years, so to minimize building cost cause to decrease loan cost.

$$Budget_{Total} = \text{Capital} + \text{Loan} + \text{Interest} \quad (6.11)$$

$$Payment_{Total} = \text{Installment} \cdot \text{Number of installment} \quad (6.12)$$

$$\text{Installment} = \text{Loan x CRF} \quad (6.13)$$

$$\text{CRF (Capital recovery factor)} = \frac{r\ x\ (1+r)^n}{(1+r)^n - 1} \quad (6.14)$$

n = number of installment

r = interest rate

$$\text{Cost}_{\text{Financial}} = \text{Interest} = Payment_{Total} - \text{Loan} \quad (6.15)$$

Number of interest is taken as 10 and interest rate is taken as 3%. Loan to deposit rate is 70%.

$$\text{Cost}_{\text{Yard Profit}} = 0.05 \cdot \text{Cost}_{\text{Yard Building}} \quad (6.16)$$

$$\text{Cost}_{\text{Yard Building}} = \text{Cost}_{\text{Hull Material}} + \text{Cost}_{\text{Hull Labor}} + \text{Cost}_{\text{Outfit}} + \text{Cost}_{\text{Overhead}} \quad (6.17)$$

$$\text{Cost}_{\text{Hull Material}} = W_H \cdot UP_{Material} \quad (6.18)$$

$$\text{Cost}_{\text{Hull Labor}} = Cmhs \cdot \left(\frac{W_H}{1000}\right)^{0.85} \cdot UP_{Labor} \tag{6.19}$$

$$\text{Cost}_{\text{Outfit}} = 8000 \cdot \left(\frac{W_O}{100}\right)^{0.90} \cdot UP_{Labor} + W_{Outfit} \cdot UP_{Outfit} \tag{6.20}$$

$$CFE = 350 \cdot L \cdot \sqrt{B} \cdot UP_{Labor} \tag{6.21}$$

$$\text{Cost}_{\text{Aux.Machinery}} = \left(W_{Aux.Machinery}\right)^{0.95} \cdot UP_{Aux.Machinery} + CFE \tag{6.22}$$

$$\text{Cost}_{\text{Overhead}} = 0.70(\text{Cost}_{\text{Hull Labor}} + \text{Cost}_{\text{Outfit Labor}} + \text{Cost}_{\text{Engine Labor}} + \text{Cost}_{\text{Aux. Machiner Labor}}) \tag{6.23}$$

W_o is the outfit weight and W_s is the steel weight of ship. Cmhs is the yard effectiveness coefficient.

Operation phase cost

Turan et al. (2009) divided operation phase cost into operating cost, periodic maintenance cost and voyage cost.

<u>Operating (Running) cost:</u>

Crew cost, stores, lubricants, supplies, management costs, insurance, and routine maintenance and repair which doesn't make ships unavailable are considered as operating cost.

$$\text{Crew cost} = \sum \text{Np x Fs x Ap} \tag{6.24}$$

Np : Number of personnel

Fs : Salary factor (see Appendix-I)

Ap : Annual total cost of a personnel includes entire related parts ($/year)

Crew cost is modeled by using above equation. Minimum personnel number is related to ship and its equipment according to international and national regulations. For example; Table A.1 shows the minimum personnel number according to Marshall Islands Maritime Regulations (Chapter7, 2012).

Supplies for crew are implemented by using equation (6.25) as provision cost.

$$\text{Provision} = Np \cdot Unit\ Cost_{\text{Provision}} \cdot 365 + 75000 \tag{6.25}$$

Ship engine, ventilation system, anchor motor etc. need routine maintenance in compliance with service life of parts. Manuals of systems, components or parts show the service life and cost of maintenance can be estimated in design phase. Also, sometimes failures can appear because of wrong or cursory maintenance, wrong usage or overuse of systems or other reasons. Collected data from operation phase of ships to "Core" can help to foresee the failures and some of them can be prevented in new design phases or operation phases. This process obviously reduces the routine maintenance and repair costs. Scope of this study is limited with design phase so routine maintenance cost is just modeled by using equation (6.26) which is borrowed from Ventura with insurance cost formula.

$$\text{Maintenance cost} = 0.0035 \ \cdot C_S + 105 \cdot (P_{\max})^{0.66} \tag{6.26}$$

$$\text{Insurance cost} = 0.006 \ \cdot V + 2.5 \cdot Gross\ Tonne \tag{6.27}$$

When the ship owner employs the own ship for the shipping, ship owner legally responsible for the damage of freight so ship owner must prefer the insurance for both own ship and freight. Also there are other accident risks during the transportation. Cost of insurance depends on the value of ship, cargo capacity, factor related to transported freight, equipment of ship, performance of ship etc.

Periodic maintenance which makes ships unavailable:

This maintenance is necessary for periodic survey and foul cleaning. In every four year, ships must be controlled in the docking by class societies. During the docking, ships are unavailable for operating so it means deficiency for income. Structural design, selected equipments and safe operation are important to keep maintenance short as possible as. Docking cost which is eq.(6.28) borrowed from Ventura (2017) is the important periodic expense.

$$\text{Docking maintenance cost} = 0.006 \text{ x } C_S \tag{6.28}$$

Voyage cost:

Fuel cost, canal dues, port charges and cargo handling costs are considered as voyage cost. Turan et al. (2009) stated following equations to calculate annual cost of fuel for main engine(s).

$$ACOF = D_{sea} \times DFC \times PR_{fuel} \times N_{main} \times Oil_{corr} \quad (6.29)$$

$$DFC = P_{max} \times SPOC_{main} \times 10^{-6} \times F_{mean} \times 10^{-2} \times 24 \quad (6.30)$$

Where:

D_{sea} : Days at sea in a year

DFC : Daily fuel consumption (Tonnes)

Pr_{fuel} : Fuel price ($/ton)

N_{main} : Number of main engines

Oil_{corr} : Correction ratio for lubrication oil and diesel oil

P_{max} : Maximum power of main engines (Kw)

F_{mean} : Percentage of maximum speed (%)

$SPOC_{main}$: Specific fuel oil consumption of main engines (g/kWh)

Pr_{TEU} : Loading/ Offloading price per a container ($/TEU)

Canal dues, port charges and cargo handling costs are variable for different routes. They should be utilized for specific route case and before design. Canal and ports specify fees in accordance with ship size and displacement. Cargo handling costs depend on ship's container number. They are basically implemented by using equation (6.31) and (6.32).

$$\text{Port Charges} = \text{Gross Tonnage} \times \text{Price per unit gross tone} \quad (6.31)$$

$$\text{Cargo Handling Cost} = \text{Container capacity} \times Pr_{TEU} \quad (6.32)$$

6.1.2 Surface modification

Effective and proper hull surface representation plays a significant role to reach desirable optimum surface with used modification techniques and also smooth meshing process. In order to allow global or local variation of hull form, NURBS representation of hull form is used in this study.

NURBS is a very common technique in most of CAD software. Rhinoceros software is used for NURBS representation and surface modification. Generated hull form may be directly visualized in the Rhinoceros. It allows parametric geometric modeling via Python programming for ship hull in surface modification procedure. Also, this software is capable of triangular surface generation. Triangular surface representation is used in meshing procedure for hydrodynamic analysis of ship hull form. Figure 6.4 and Figure 6.5 show the NURBS and triangular surface representations of a ship hull form.

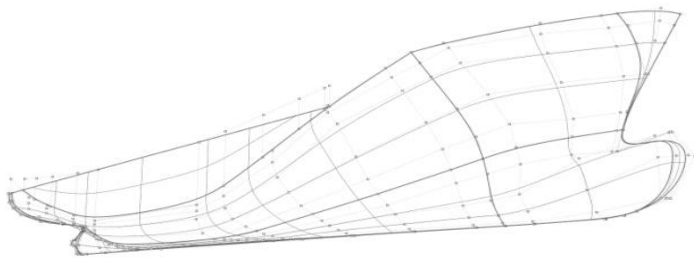

Figure 6.4 : NURBS Representation.

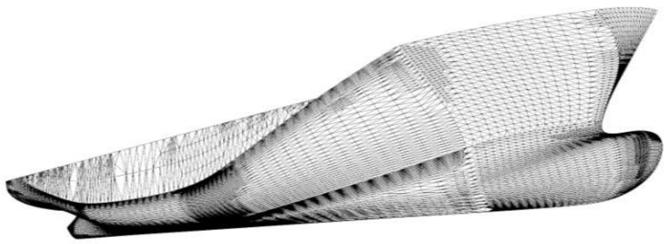

Figure 6.5 : Triangular surface representation.

The accuracy of geometry is important in converting surface from NURBS to triangular representation. Triangular surface representation should ensure smooth surface with the proper accuracy level for true grid generation. ITTC recommend the tolerances which are shared in Table 6.2 for the geometry based on the length between perpendiculars (2011).

Table 6.2: Geometry tolerances.

Scale	L_{pp}(m)	Re	Tol. (m)
Model	$1 < L_{pp} < 10$	$10^6 – 10^7$	10^{-5}
Intermediate	$10 < L_{pp} < 50$	$10^7 – 10^8$	5×10^{-5}
Full	$50 < L_{pp} < 250$	$10^8 – 10^9$	10^{-4}

The first problem of surface modification method is the exploration of whole solution space. Infinitely many hull forms can be generated and some of them have better hydrodynamic performance than initial hull form. Also, rests of them have same performance or worst performance than initial hull form. Exploration of better hull forms is the desired objective surface modification method. Selected method can give the better hull forms but this does not mean that generated hull forms are the bests. There is always a possibility to find better hull form unless search the entire solution space. Obviously, exploration of entire solution space is the impossible and impractical.

The second problem of surface modification method is to generate always producible hull forms. Because, the hull forms which have high curvatures are hard to produce and this cannot be feasible. Selected method should always generate hull forms which have better performance and smooth surface.

There are various surface modification techniques for ship hull form optimization in the literature. Some of them such as Lackenby method, Moor method, radial basis function interpolation and weight-based shape modification are discussed for sail yacht hull form in study of Kükner and Sarıoğlu (2014).

Surface modification methods can be divided into two categories such as global and local surface modifications. Lackenby and Moor methods are global surface modification methods; on the other hand radial basis function interpolation and weight-based shape modification allow to local modifications. In this study, written Python module on Rhinoceros software which allows both the partially and the fully parametric techniques is used for global and local surface modifications. The classical parametric modification approach stands for design exploration in the large space. Figure 6.6 and Figure 6.7 show the initial and modified bow part of parametric hull forms.

Figure 6.6 : Initial hull form.

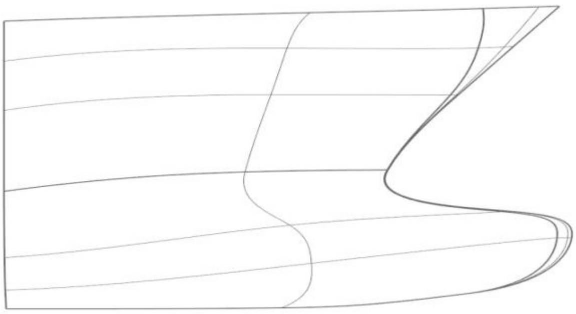

Figure 6.7 : Modified hull form.

There are two types input for Python surface modification module such as global and local parameters. Local parameters are basically related control points of NURBS curves which can be seen in Figure 6.8. On the other hand, global parameters are based on ship synthesis model which are seen in Figure B (Appendix II). Main global parameters as the design variables required to generate lines drawing are:

- Beam (Function of transverse container number)
- Depth (Function of vertical container number)
- Double bottom height
- Length of bulb
- Height of bulb
- Beam of bulb
- Length of engine room
- Length of cargo hold
- Length of collision bulkhead

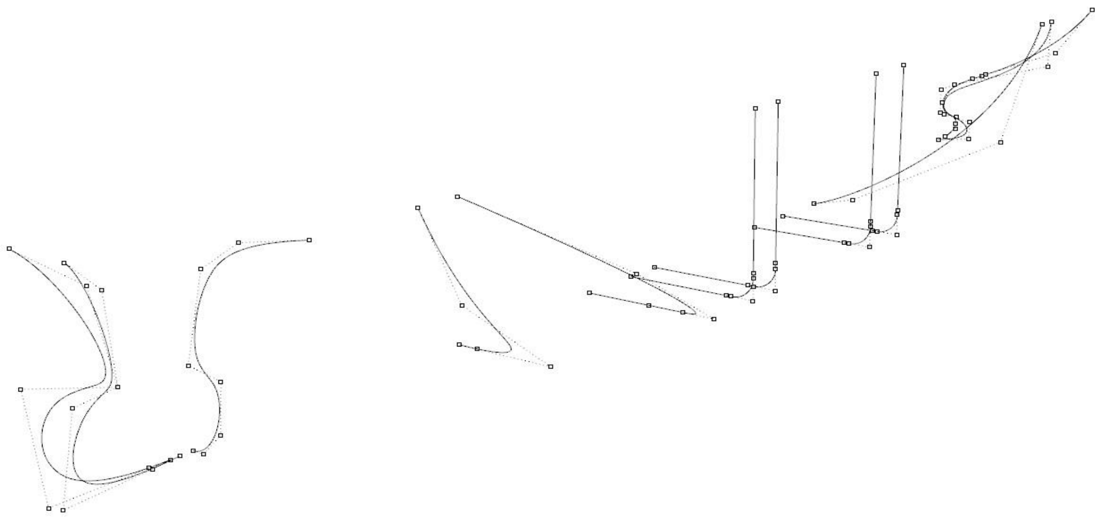

Figure 6.8 : Local surface parameters.

6.1.3 Hydrostatics

The determination of hydrostatic forces and moments acting on ship hull surface is the subject of hydrostatic calculations. The assessment of a ship hydrostatic shortly aims following information.

- Displacement volume of ship
- Center of some points
- Waterplane area
- Form coefficients

The outputs of hydrostatic solver which is shown in Figure 6.9 can be used to assess the hydrostatic equilibrium and stability. These hydrostatic properties are also important during the operation phase for loading, grounding, etc. operations.

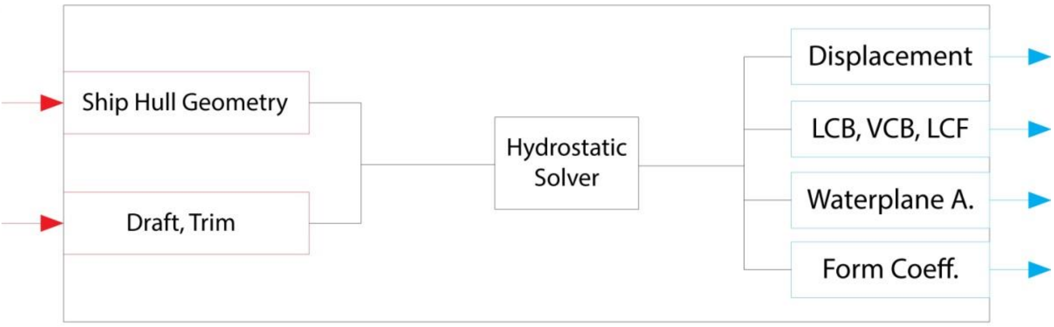

Figure 6.9 : Hydrostatic solver module.

Detailed information for calculation procedures can be obtained from the book of Letcher Jr. (2009)

Hydrostatic solver is written in Rhinoceros software by using Python language. Inputs of this module are hull form id and draft value. Outputs of module are main hydrostatic values as a function return and data inputs for database file.

6.1.4 Stability

The ships must satisfy the static equilibrium condition against external forces. The ship stability calculations are concerned with this problem. The external forces can be wave forces, external weights and flooding weights by collision, grounding or other accidents. The ship stability problem can be divided two sections as intact stability and damaged stability. In this section, intact stability problem is discussed and damage stability problem will be investigated in subdivision section.

Intact stability subject concern with heel and trim movements of a ship until the equilibrium condition. Metacentric height (GM) is the shows the initial transverse stability of ships and it can be calculated by following formula for small angles of heel (0° to $7^{\circ} - 10^{\circ}$)

$$GM = KB + BM - KG \tag{6.33}$$

KB: the height of centre of buoyancy above the keel

BM: the metacentric radius is the between the centre of buoyancy and the metacentre

KG: the height of the ship's centre of gravity above the keel

Also, large angle stability should be checked to measure ability of ship to return to upright position. The righting moment can be estimated by using following formula for a requested heel angle and loading condition. For

$$M_T = \Delta GZ = \Delta(BM\text{-}BG\text{+}MN)\ \sin\varphi \tag{6.34}$$

The righting moments are calculated for a range of displacement usually from the lightship condition to full load condition. The calculated moments are plotted as a set of cross curves to determine the length of the righting arm and heel angle for requested displacement. Then, statical stability curve is generated for requested displacement to evaluate the righting arm. Detailed information related to calculation procedures can be found in the book of Moore and Paulling (2010).

After the required criteria are implemented according to properties of ship, stability of ship should be evaluated by using stability module of the ship synthesis model. The structure of ship stability module can be seen in Figure 6.10 and this figure shows that there are four parameters to change stability results. If results are not satisfy the stability criteria, the most adjustable parameter to carry the results of solver beyond to required values of criteria is weight distribution especially cargo loads; because, decreased cargo loads enhances the freeboard height and so GM and GZ values directly.

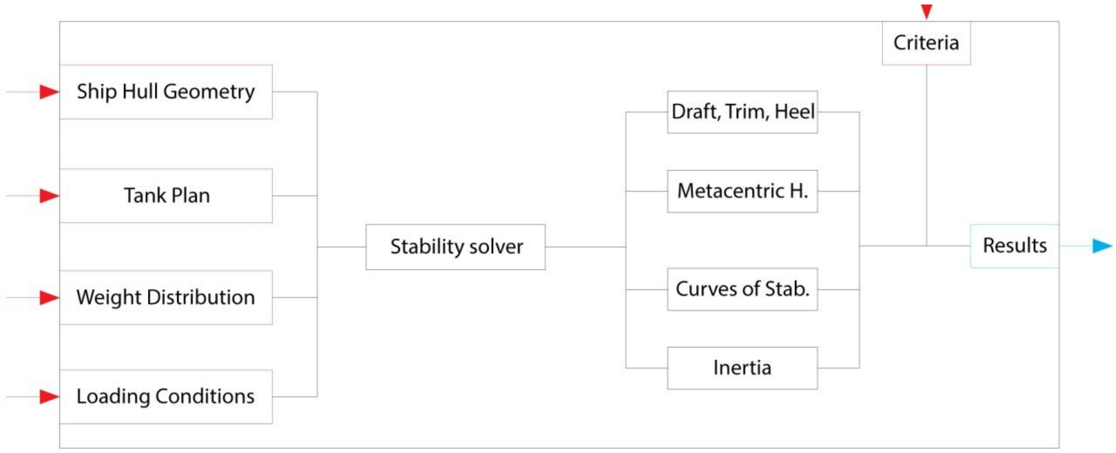

Figure 6.10 : Intact stability solver module.

Stability module is written by using solid modeling of Rhinoceros software and Python language. Tank modeling of ship is generated by solid modeling after the subdivision and structure process. Figure 6.11 shows the tank modeling. Weight distribution and loading conditions are numeric inputs of module. Stability values of hull form are calculated via recursive usage of stability module and at the end, final results are checked with implemented criteria.

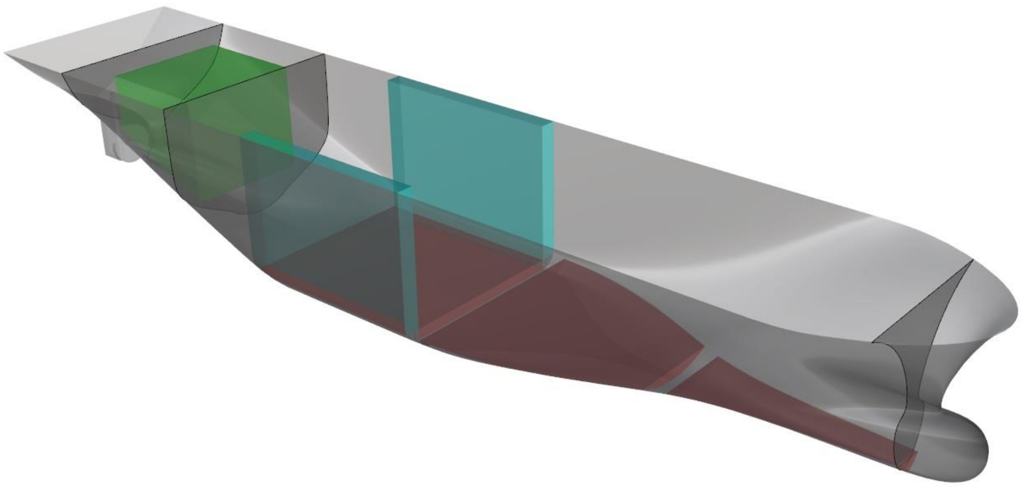

Figure 6.11 : Solid tank modeling on Rhinoceros.

6.1.5 Subdivision

Subdivision of a ship should be arranged to satisfy related international/ national regulations and class rules. These regulations and rules contain strength, floatability and stability of a ship. For example, some rules obtained from DNV-GL (2017) are shared in this part.

- All ships shall have one collision bulkhead, one aft peak bulkhead and one bulkhead at each end of engine room.
- In the case of ships with an electrical propulsion plant, both the generator room and the engine room shall be enclosed by watertight bulkheads.
- For vessels where no damage stability calculations have been carried out the total number of watertight transverse bulkheads shall not be less than given in Table 6.3.

Table 6.3 : Number of transverse bulkheads.

Ship length in m	Engine room	
	Aft	Elsewhere
L ≤ 65	3	4
65 < L ≤ 85	4	4
85 < L ≤ 105	4	4
105 < L ≤ 125	5	5
125 < L ≤ 145	6	6
145 < L ≤ 165	7	7
165 < L ≤ 190	8	8
190 < L ≤ 225	9	9
L > 225	specially considered	

Position of collision bulkhead;

$x_{c-min} = 0.05L_{LL} - x_f \qquad L_{LL} < 200\ m$

$x_{c-min} = 10 - x_f \qquad L_{LL} \geq 200\ m$

$x_{c-max} = 0.05L_{LL} + 3.0 - x_f \qquad L_{LL} < 100\ m$

$x_{c-max} = 0.08L_{LL} - x_f \qquad L_{LL} \geq 100\ m$

Where:

x_f = adjustment of reference point due to bulbous bow in m.

Without bulbous bow; x_f= 0

With bulbous bow; x_f= min (0.5x_{be}; 0.015L_{LL}; 3.0)

x_{be} = the distance in m from FP_{LL} to the extreme forward end of the bulb extension which is shown in Figure 6.12.

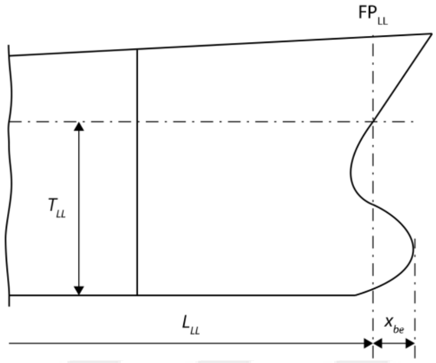

Figure 6.12 : Bulbous bow shape (DNV-GL, 2017).

Watertight bulkheads should be arranged in accordance with damage stability calculations according to related SOLAS rules (IMO, 2009). Support bulkhead should support transverse strength of ship. Aft peak bulkhead should enclose the stern tube and rudder trunk in a watertight compartment. These arrangements can be seen in Figure 6.13. The distances between transverse bulkheads are adjusted by parametric layout module.

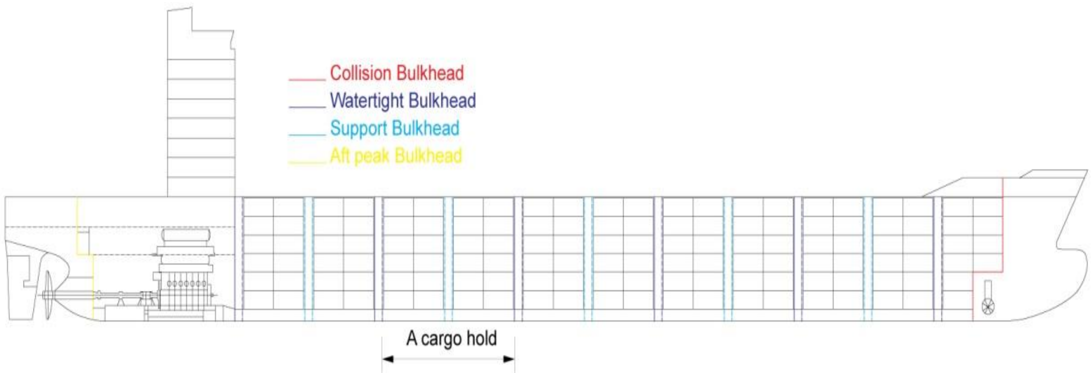

Figure 6.13 : Bulkhead arrangement.

For passenger vessels and cargo ships other than tankers, a double bottom shall be fitted, extending from the collision bulkhead to the aft peak bulkhead, as far as this is practicable and compatible with the design and proper working of the ship and this rule can be seen in Figure 6.14. The height of the double bottom can be calculated by the following formula according to DNV-GL, Chapter 4 (2017). Also this related rule says that the height can be taken minimum 760 mm and maximum 2000 mm.

$$h_{DB} = 1000 \cdot B/20 \tag{6.35}$$

Figure 6.14 : Double bottom arrangement.

Longitudinal side bulkheads which can be seen in Figure 6.15 separate the cargo holds from the hull skin. Wing tanks are located in these separated volumes. These volumes provide extra strength and also safety in case of damage situation. Also, bottom watertight girders generate separated double bottom tanks which have same purposes with wing tanks. Following the mid-ship section figure shows the longitudinal subdivision of ship by side bulkheads and girders. Dimensions of bulkheads and girders are adjusted according to scantling and damage stability calculations.

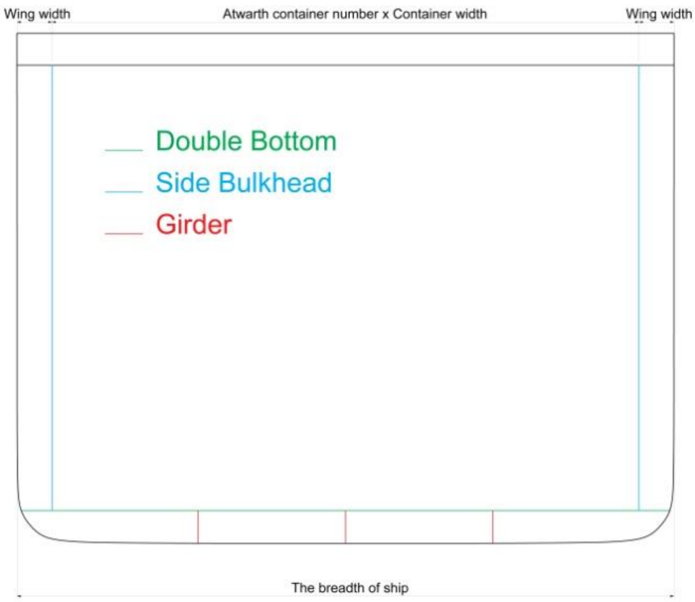

Figure 6.15 : Longitudinal subdivision.

After the subdivision process, cargo volumes will be appeared and tonnage calculations can be completed. Tonnage calculations are important to determine canal dues, pilotage charges, safety requirements, technical equipment, crew size, fleet and transport statistics, and insurance, among others for a vessel. Requested tonnage may be gross tonnage or net tonnages which are shown the following Figure 6.16.

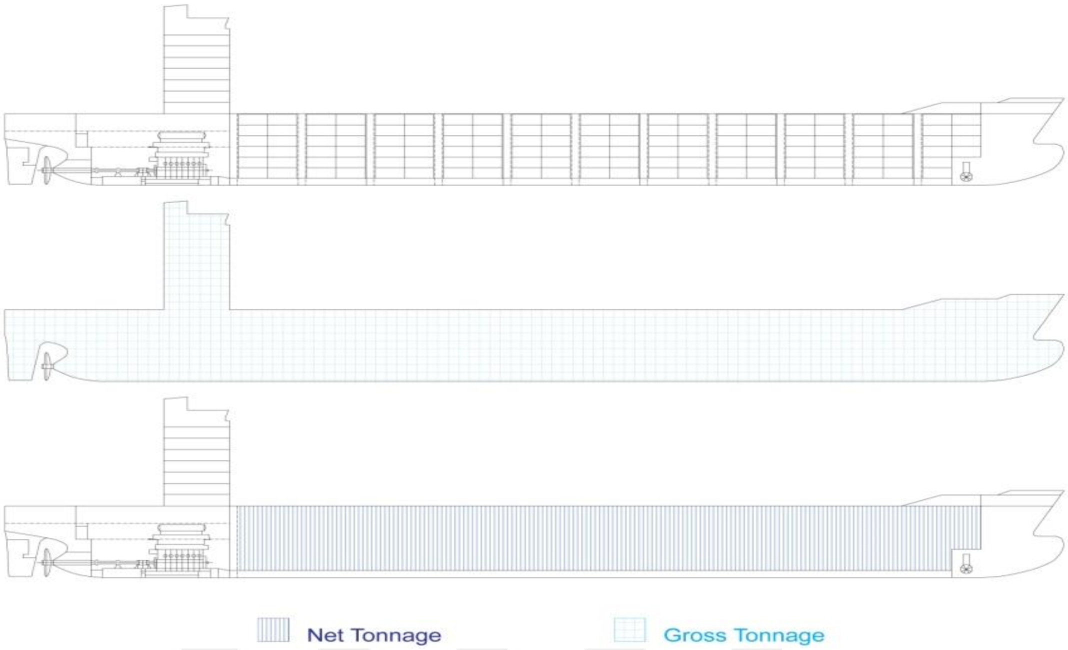

Figure 6.16 : Tonnage calculation.

Parametric subdivision module is created to generate subdivided structure of ship on Rhinoceros. After the scantlings and number of bulkheads are determined, optimized hull form is used as an input than bulkheads and girders are created to specify cargo and tank volumes. Subdivided structure which can be seen in Figure 6.17 can be checked to satisfy damaged stability rules. Any further modification can be performed by changing parameters. In this study, damaged stability calculations are not implemented.

After the cargo volume generation, total container number is calculated in this module. Figure 6.17 also shows the calculation surfaces. Firstly, sections are generated for unit container length. Secondly, intersections between container surfaces and hull surface are checked. If there are intersections, these are removed by decreasing containers from related sections. In the end, deck container plan is generated by using final row of inside container stowage.

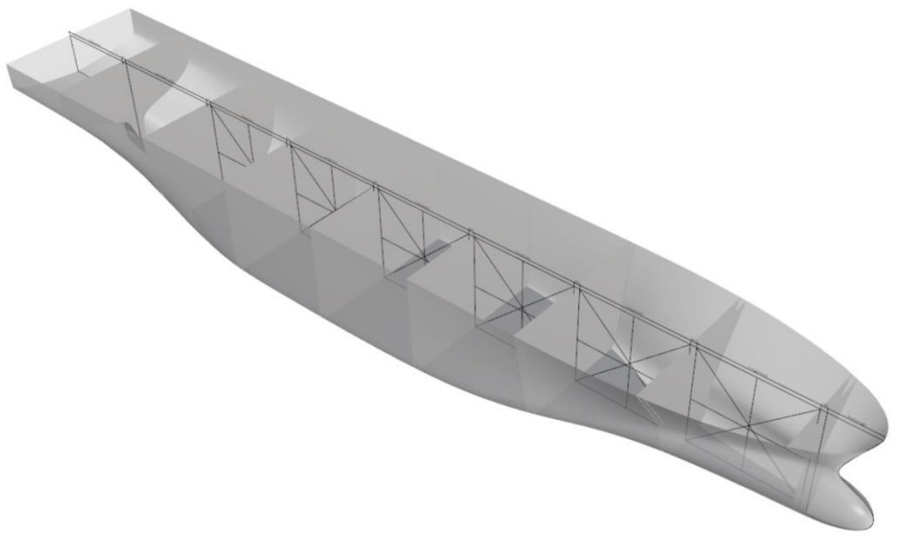

Figure 6.17 : Parametric subdivision structure.

6.1.6 Hydrodynamics

6.1.6.1 Resistance

The determination of forces acting on the ship hull to estimate the effective power required to drive the ship at a certain speed in the calm water is the subject of resistance calculations. The assessment of a ship resistance characteristic is shortly related to following four factors. Also, related module is shown in Figure 6.18.

- Size, dimensions, form characteristics
- Draft and trim
- Ship’s speed
- Appendages

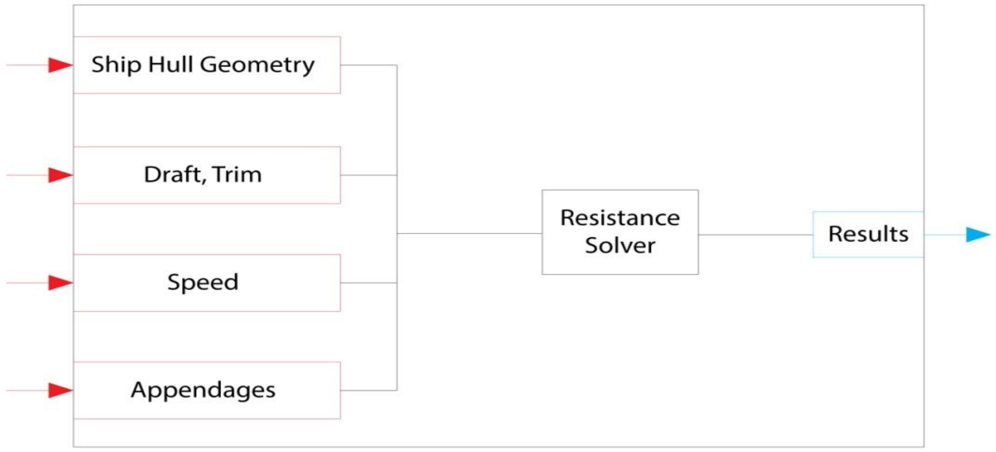

Figure 6.18 : Resistance performance assessment module.

Ship resistance in calm water can be decomposed into components. Figure 6.19 shows these components according to Molland (2008). Total resistance can be found by two ways. First one is to sum up pressure with skin friction resistance or second way is to sum up wave making resistance with viscous resistance.

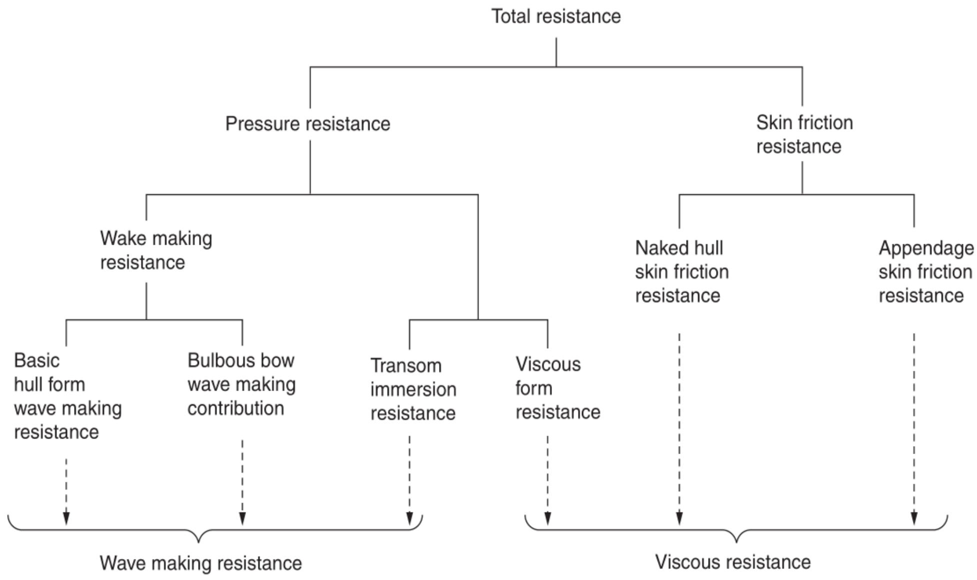

Figure 6.19 : Components of ship resistance.

A ship which advances in the ocean environment experiences force more than calculated total forces. The difference between calculated total force in calm water and real total force in ocean environment is the added resistance which is caused by ship motion in the seaway. To estimate added resistance, ship motions should be calculated via seakeeping analysis. Generally, calculated total resistance in calm water is increased by 15% as a sea margin to take into account added resistance and other uncertainties originated by calculations, fouling, paint and the propulsion system in the most of design project.

Today it is possible to decrease frictional resistance by using modern paints. These paints reduce the surface roughness of ship. Also, increment of the resistance originated by the fouling should be considered in a life cycle of a ship. These two subjects should be taken into account in the cost calculations.

Resistance characteristics of sea vehicles can be calculated in different uncertainty which is shown in Figure 6.20 as regards used methods. Suitable methods can be changed in compliance with desired calculation time, type of sea vehicles and capacity of methods. These methods might be empirical or numerical. Problem type and level specify the methods. Model test is impossible for offered design approach in this thesis. Actually, the most accurate method is the DNS solution but this approach is impossible with today's computer power. URANS calculation may be suitable solution with highly parallel computation environment. Less accurate approach may be 3D panel method plus empirical form factor as a computational tool. Also, computational tools can be used with surrogate models. The best approach may be usage of various methods together based on their accuracy and improvement of results iteratively. This mentioned method is named as multi-fidelity approach. For example, an empirical method may be used to catch first optimum dimensions, than 3D panel method plus form factor approach gives the more accurate results. Finally, RANS simulations with few variations give acceptable design space with tolerable uncertainty. In this thesis, just Holtrop and Mennen (1982) method is used to keep simple. In the further research, more accurate methods will be added in accordance with shared strategy above.

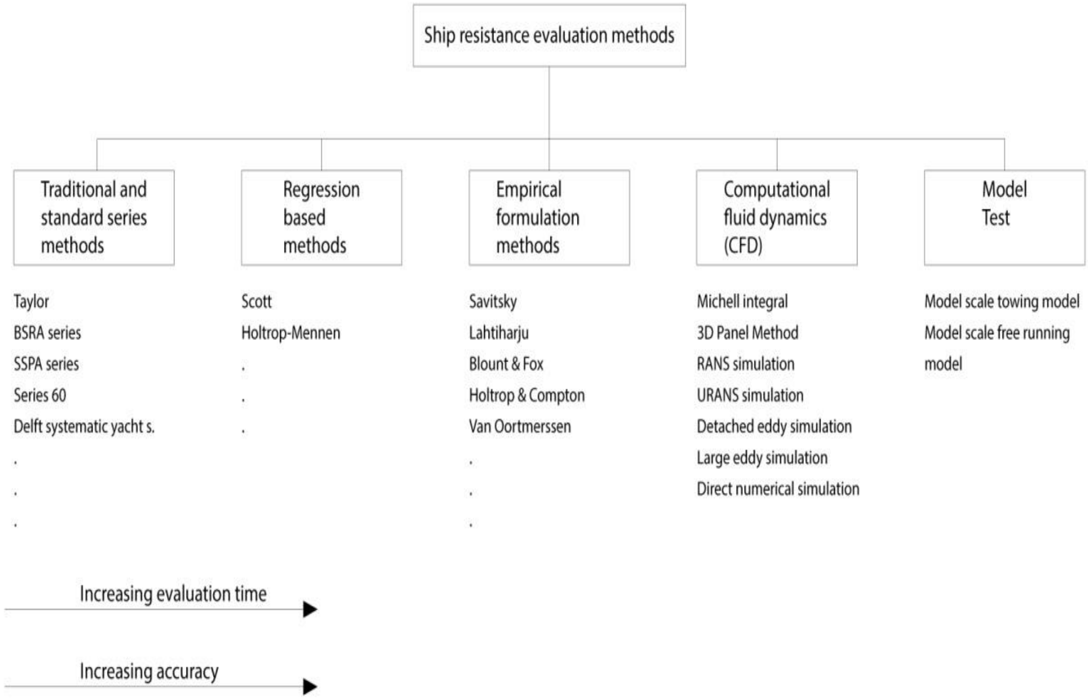

Figure 6.20 : Ship resistance evaluation methods.

Holtrop and Mennen published the power prediction method based on regression analyses of many model test results (1982). In that study, authors proposed following ship resistance equation and the total resistance of a ship has been subdivided into:

$$R_{total} = R_F (1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \quad (6.36)$$

Where:

R_F : Frictional resistance according to the ITTC- 1957 friction formula

1+k_1 : Form factor describing the viscous resistance of the hull form in relation to R_F

R_{APP} : Resistance o f appendages

R_W : Wave-making and wave-breaking resistance

R_B: Additional pressure resistance of bulbous bow near the water surface

R_{TR} : Additional pressure resistance of immersed transom stern

R_A : Model-ship correlation resistance

In equation (6.36) the frictional resistance R_F is calculated according to the 1957 ITTC friction formulation which is stated in equation (6.37) and the hull form factor 1+k_1 which is equation (6.38), is based on a regression equation and is expressed as a function of breadth, length of run, prismatic coefficient, longitudinal center of buoyancy, draught and stern shape coefficient.

$$C_F = \frac{0.075}{(\log_{10} R_n - 2.0)^2} \tag{6.37}$$

$$1+k_1 = c_{13}\left\{0.93 + \ c_{12}\,(\frac{B}{L_R})^{0.92497}\,(0.95 - \ C_p + 0.0225\ lcb)^{0.6906}\right\} \tag{6.38}$$

The appendage resistance according to the Holtrop and Mennen (1982) approach is evaluated from the equation (6.39);

$$R_{APP} = 0.5\,\rho V^2 S_{APP}(\,1 + k_2)_{eq} C_F \tag{6.39}$$

where p is the water density, V the speed of the ship, S_{APP} the wetted area of the appendages, $1 + k_2$ the appendage resistance factor which is shared in Table 6.4 and C_F the coefficient of frictional resistance of the ship according to the ITTC-1957 formula.

Table 6.4 : $1 + k_2$ the appendage resistance factor (Holtrop and Mennen, 1982).

Approximate $1 + k_2$ values	
rudder behind skeg	1.5 - 2.0
rudder behind stern	1.3 – 1.5
twin-screw balance rudders	2.8
shaft brackets	3.0
skeg	1.5 – 2.0
strut bossings	3.0
hull bossings	2.0
shafts	2.0 – 4.0
stabilizer fins	2.8
dome	2.7
bilge keels	1.4

The wave resistance can be determined from equation (6.40), equation (6.41) gives the additional resistance due to the presence of a bulbous bow near the surface. There are various methods to calculate added wave resistance but simple approximation is enough for this study.

$$R_W = c_1\, c_2\, c_5\ \nabla\, \rho g \exp\{m_1\, F_n^d + m_2\ \cos(\lambda F_n^{-2})\} \tag{6.40}$$

$$R_B = 0.11 \exp(-3\ P_B^{-2})\, F_{ni}^3 A_{BT}^{1.5}\, \rho g \,/\, (1+ F_{ni}^2) \tag{6.41}$$

Immersed transom causes the additional pressure resistance and equation (6.42) gives the this additional resistance, also equation (6.43) gives the model-ship correlation resistance R_A

$$R_{TR} = 0.5\, \rho V^2\, A_T c_6 \tag{6.42}$$

$$R_A = \frac{1}{2}\, \rho V^2 S\, C_A \tag{6.43}$$

Coefficients of formulas and detailed information can be obtained from the original study of Holtrop and Mennen (1982).

6.1.6.2 Seakeeping

The determination of a ship behavior in the wave environment of the ocean is the subject of seakeeping calculations. The assessment of a ship seakeeping performance is shortly related to following four factors according to Sarıöz and Narlı (2005).

- Size, dimensions, form and weight distribution characteristics
- Sea environment
- Ship's speed and heading
- Seakeeping criteria

Seakeeping performance assessment module which is shown in Figure 6.21 needs four factors defined above as inputs. Seakeeping calculations are occurred inside of the module by using strip method. Strip method has shown mostly well agreement with experimental results in the literature up to now. One of them is the study of Palladino et al. (2006) which is validation of PDSTRIP for some standard test cases. Palladino et al. (2006) compared the seakeeping calculations results of PDSTRIP code with experimental results in that study. PDSTRIP which is developed by Bertram et al. (2006) is a freely available strip method code for seakeeping calculations. This code is open-source, public domain and workable in Windows and Linux systems.

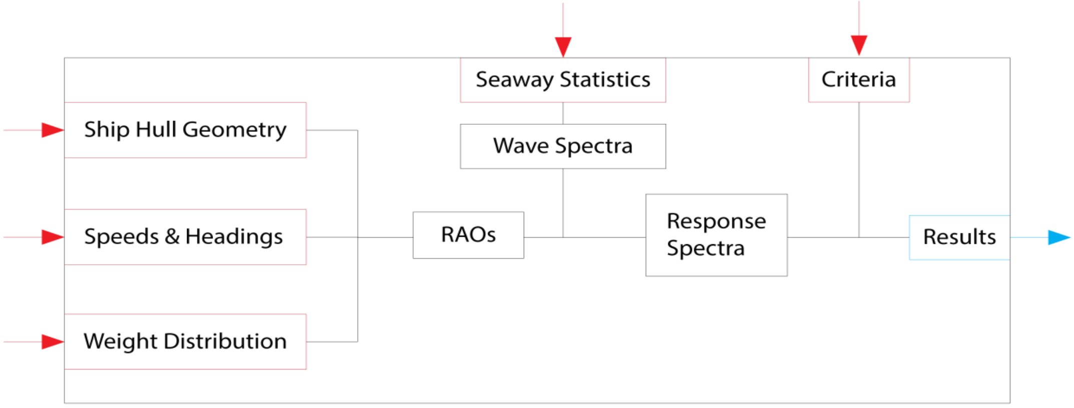

Figure 6.21 : Seakeeping performance assessment module.

Bertram et al. (2006) stated that the PDSTRIP based on the Söding's (1969) slightly different method than strip method proposed originally by Korvin-Kroukowski and Jacobs (1957) for motions and PDSTRIP uses the procedure of Hachmann (1991) for the pressure. Basically, strip method converts a 3D problem into 2D independent problems by using strip sections which are shown in Figure 6.22 and has the capacity to calculate the linear responses in regular waves as transfer functions. These transfer functions allow calculating ship responses in a specific seaway.

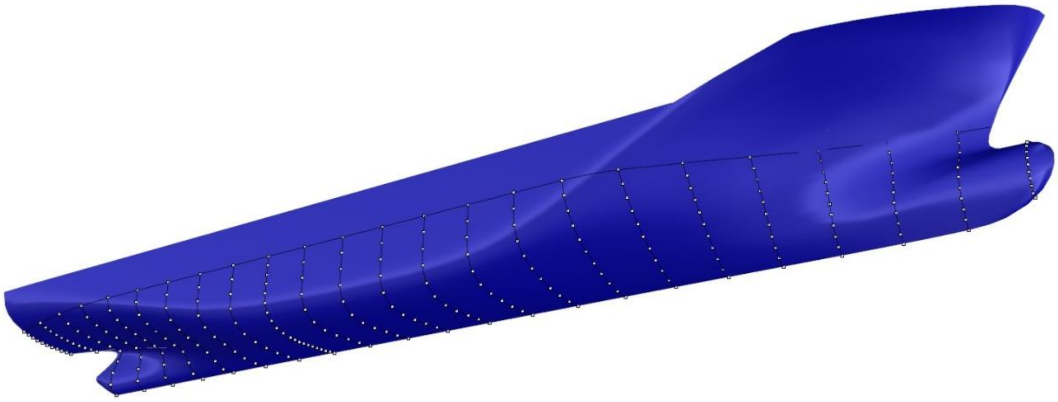

Figure 6.22 : Half body strip sections.

In the first calculation, unknown value of weight distribution characteristics is estimated by using well known formulas which are shared in Table 6.5.

Table 6.5 : The radius of gyration.

k_{xx}	0.4 B
k_{yy}	0.25 L
k_{zz}	0.25 L

It is important to calculate actual motion responses of ship in real seaway condition. Real sea has irregular waves as basically superposition of regular waves. These irregular waves can be expressed statistically by using wave spectra. Calculated motions responses can be closer to real ship motion responses by using adequate wave energy spectrum. Wave energy spectrum may be defined in terms of the zero crossing periods, significant wave height or the other measures. If necessary quantities are known, wave energy spectra can be constructed for any point in the ocean. There are many lines of merchandise for cargo ships. A ship in these lines can cross different wave characteristics. For example, wave statistics of Istanbul-Rotterdam line is different wave statistics of Istanbul-Yokohama line. To compare wave statistics of different lines, global wave statistics which is prepared by Hogben et al. (1986) and map of lines are shared in Figure 6.23 and Figure 6.24. Also, any other route for same line may generate different spectrum. There are more specific maps may be obtained from satellites and direct measurements of ocean buoys to generate more realistic spectrum by using detailed statistics.

Figure 6.23 : Different lines of merchandise.

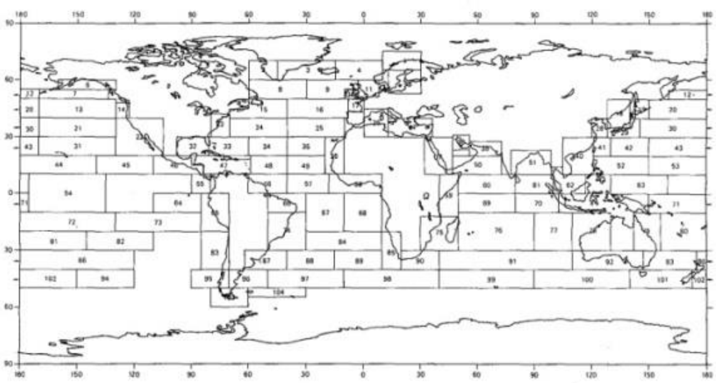

Figure 6.24 : Global wave statistics.

There are various seakeeping criteria related to different subjects such as comfort, propeller load variations, bow emergence, added resistance etc. After the response spectra calculation, preferred criteria can be implemented to the system. Used criteria are explained in criteria section 7.

6.1.7 Propulsion

Hull form design from the point of propulsion system is shown in Figure 6.25. To increase total propulsion efficiency, hull form, propulsion system and propeller are considered together.

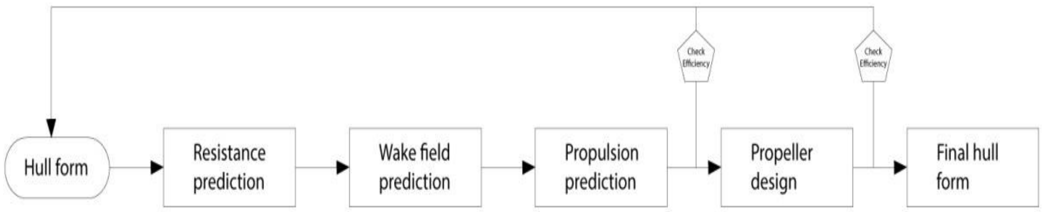

Figure 6.25 : Hull form design for propulsion system.

Effective power is obtained from product of total resistance and ship speed by using Eq. (6.44).

$$P_E = R_T \text{ x } V_S \tag{6.44}$$

R_T = Total resistance of ship in calm water [kN]

V_S = Velocity of ship [m/s]

P_E = Effective power [kW]

Brake horse power of engine can be obtained by using (6.45). Required efficiencies should be known by using suitable approach.

$$P_B = P_E x \frac{1}{\eta_H \, \eta_0 \, \eta_R \, \eta_S} \tag{6.45}$$

η_H= Hull efficiency

η_0 = Open water propeller efficiency

η_R = Relative-rotative efficiency

η_s = Shaft efficiency

Ratio between the effective power(P_E) and the thrust power (P_T) can be defined hull efficiency and the ratio of power absorbed by the propeller in open water of speed V_a to mixed wake field of mean velocity V_a is defined as the relative-rotative efficiency. These efficiencies are calculated by using well-known Holtrop (1988) formulas.

The open water efficiency of a propeller is defined the ratio of the thrust power to delivered power;

$$\eta_0 = \frac{THP}{DHP} = \frac{TV_a}{2\pi nQ} \tag{6.46}$$

T = propeller thrust

V_a= speed of advance

n = revolution per minute

Q = torque

J = advance coefficient

D = diameter

The open water efficiency can be written as following equation by using variable transformation; K_{To} is the open water thrust coefficient and K_{Qo} is the open water torque coefficient. This transformation is important to define propeller characteristics by using the open water diagram. This diagram is used to determine open water propeller efficiency in the next chapter.

$$J = \frac{V_a}{n\,D} \tag{6.47}$$

$$\eta_0 = \frac{J}{2\pi}\frac{K_{To}}{K_{Qo}} \tag{6.48}$$

The shaft efficiency depends on the reduction gear and shaft bearings. The shaft efficiency is normally around 0.98, and depends of propeller shaft length for directly mounted propeller. The lost in a gearbox is normally around 4% and the lost is 2% for a shaft bearing depends on its alignment and lubrication. Also shaft generator can be installed in a propulsion system. Total shaft efficiency depends on number of shaft bearing, gear box, shaft generator and their losses. In this system, reduction gear is not used because of slow speed engine and just two bearings are used. Shaft efficiency of this system can be calculated by the ratio of power delivered to the propeller to engine brake power $\left(\eta_s = \frac{P_D}{P_B}\right)$ which is shared in following Table 6.6.

Table 6.6 : Shaft efficiency calculation.

	Factor	Power	
Effective Power (P_E)		2400.00	kW
Thrust Power (P_T)	1.1	2181.82	kW
Power delivered to the propeller (P_D)	0.55	3966.94	kW
Shaft bearing losses	0.98	4047.90	kW
Stern tube losses	0.98	4130.51	kW
Engine brake power (P_B)		4130.51	kW

The optimum propeller should have desired thrust and best open water efficiency value and also satisfy some constraints such as cavitation, noise, strength, weight and price. The design of a propeller can be based on systematic propeller series, wake adapted design or design optimization method.

Famous Wageningen-B for fixed pitch propeller, Wageningen-C and D for controllable pitch propeller series of the Maritime Research Institute Netherlands (MARIN) are good example for systematic propeller series. It is possible to design new propeller which has desired diameter, number of blades, blade area and mean pitch by using characteristics of systematic series. In this study, Wageningen-B screw series are used to design propeller. Wake adapted design and design optimization method can be combined with systematic series in further studies.

Working propeller generates the pressure impulse to the hull and this causes the vibration on the hull. To keep this effect under the limits, a proper distance should be between the hull and propeller which is termed as propeller clearance. Babicz (2015) suggests a tip clearance which is 20-25% of the propeller diameter for non-skew propeller or 15-20% D for high skew propeller and minimum base line clearance should be 50-100 mm, they are showed in Figure 6.26. Also, these clearances generate the maximum diameter of propeller for design.

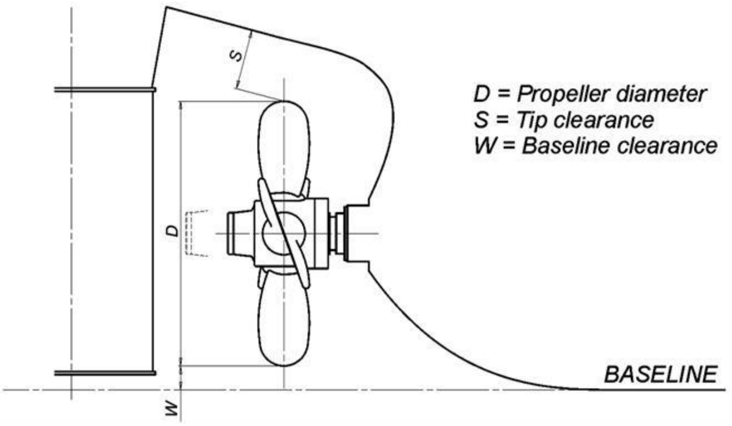

Figure 6.26 : Propeller clearances (Babicz, 2015).

After the calculation of effective power and maximum diameter, propeller design based on Wageningen-B series is conducted by using procedure which is shown in Figure 6.27. Optimum η_0 is found by using K_T-J curves and controlled the cavitation by using Keller method. If selected propeller is cavitating, next propeller is selected until the finding of non-cavitating propeller.

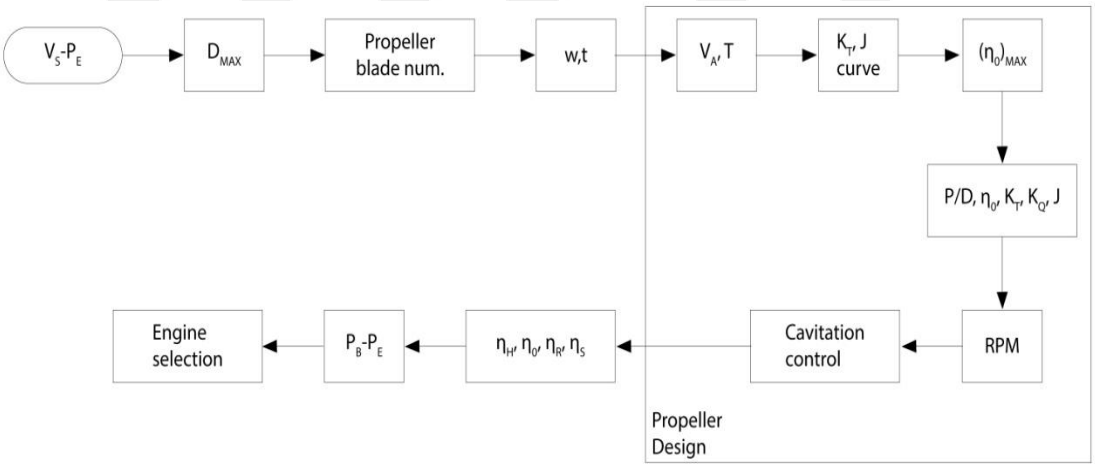

Figure 6.27 : Propeller design framework for Wageningen-B screw series.

After the propeller design, total propulsion efficiency can be calculated and engine can be selected by using engine brake power (P_B). Calculated brake power should be inside of the selected engine power borders. Figure 6.28 shows the engine power graph which is obtained from engine catalog and engine power at 85% MCR should satisfy brake power in the best case.

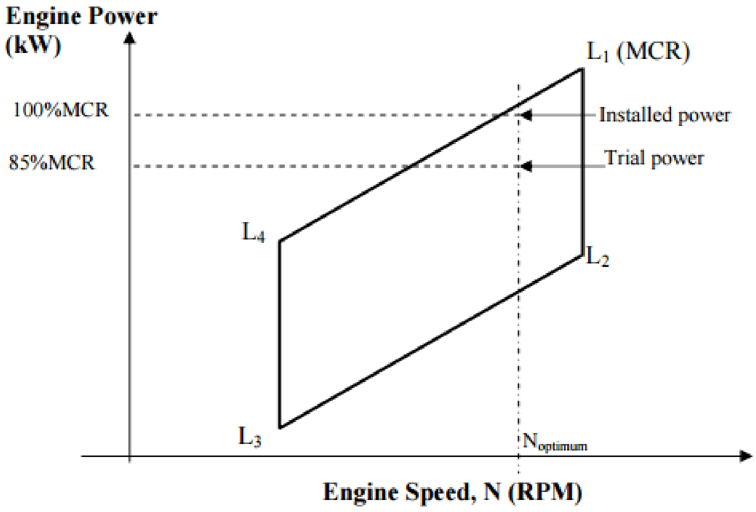

Figure 6.28 : Engine poer borders.

After the selection step of propeller, other properties of selected propeller such as weight, maintenance etc. should be considered for holistic ship design.

6.1.8 Structure

The structure of ship should have enough strength for the different load combinations. On the other hand, the ship should have minimum weight to increase cargo tonnage and the one of the biggest weight group is the structural weight; therefore, there is a conflict between strength and weight for optimum structural design. Also, cost, fabrication, maintenance and repair are other conflicted objectives related to structural design. The optimum structural design should satisfy all these objectives inside acceptable tradeoffs in the end. Structural design of ship can be based on class formulations, direct calculations by using FEM or combination of both. Figure 6.29 shows the basic structural design process.

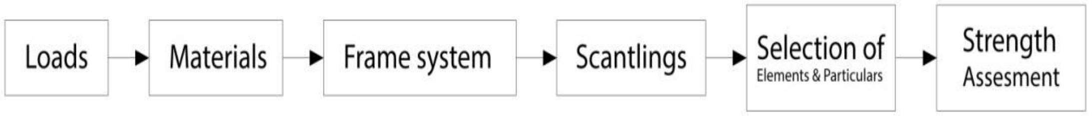

Figure 6.29 : Structural design process.

The ship structure design which has sufficient strength also should overcome other problems such as fatigue, corrosion, welding deformation etc. Some of these problems can be estimated in the design phase by using simulations but some of them like corrosion, collision etc. are hard to predict and class rules based on past experience is usable in the design.

Different ship types may have unique structure sections. Figure 6.30 shows the mid-ship sections of container ship and bulk carrier. Basement mid-ship sections are used in this study to design ship structure.

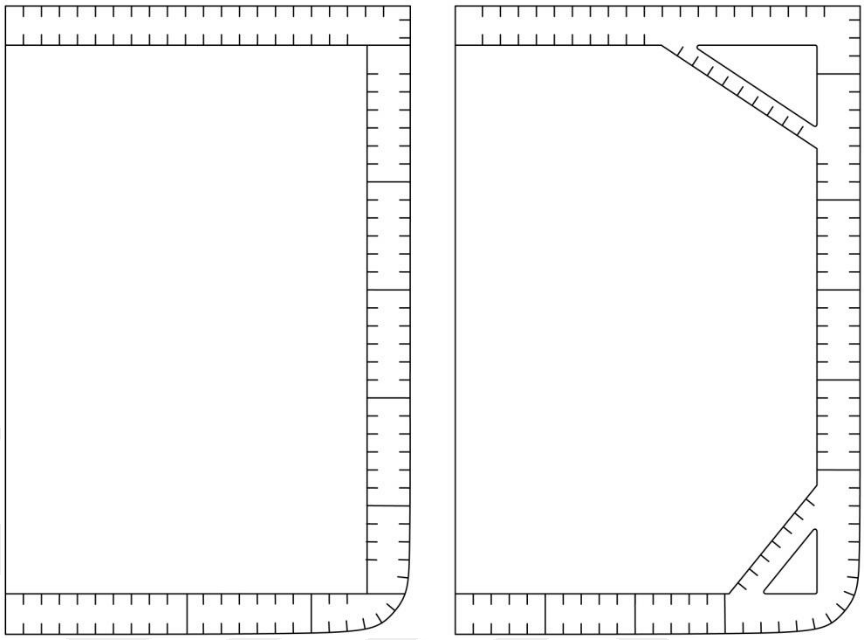

Figure 6.30 : Container (left) and bulk carrier (right) ships mid-ship sections.

In this study, DNV-GL (2017) formulations are followed to design and assess ship structures. FEM module can be added easily in the further research.

6.1.9 Weight

Weight calculations are necessary to check buoyancy - displacement equality, trim by using weight distribution and generate cargo capacity.

Displacement tonnage is the;

$$\Delta = LBTC_B\rho = Deadweight\ tonnage\ (DWT) + Lightshipweight\ (LS)$$

Light ship displacement is the weight of the ship excluding tank loads, cargo, passengers and crews. The lightship weight of a ship is the sum of all fixed weights such as weights of structure, outfit, main and auxiliary engines, and other equipments. Figure 6.31 shows the weight group functions that are implemented into ship synthesis model.

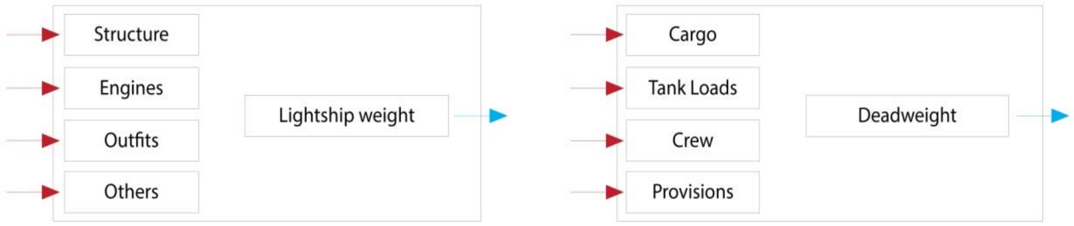

Figure 6.31 : Weight groups.

In the number of design step, weight calculation is important, and determined items are taken into account to calculate total weight and weight distribution more precisely. The weight and moment of determined items about referenced origin are simply added to total weight in every step. For example, Table 6.7 shows the weight of a main engine items. The information from the database may be used by *"Core"* in the exploration of new design. Every part or system can have own weight properties labels in the database.

Table 6.7 : Main engine weight information.

Group	Item	Volume	Sub-volume	Weight [t]	G(x,y,z)	L(x,y,z)
Machinery	Main Engine	Engine Room	-	400	22,0,8	3,0,2

Some of weight groups like cargo, tank loads, crew, and structures are calculated directly; on the other hand, rest of weight groups are estimated by using empirical formulas. The scope of this thesis is to show results of offered design approach, so entire weight groups can be calculated in the further studies.

The weight of ship should be monitored through life cycle of ship. Weight classification provides the organization to enter items into the database for weight calculations. The database important for weight control process to verify final weight of delivered ship within the limits of design phase. The database will be used also operation and recycling phase so it is important to enable the inheritance of true information during the life cycle of a ship. Changed steel weight in the operation phase for repair can be calculated easily via weight database as an example.

6.1.10 Control surfaces

Control surface enables to control the motion of ship by generating and steering force. There are both fixed and movable control surfaces such as rudders, fin stabilizers, transom flaps etc. In this study, just rudder is used as a control surface to keep design space small.

Rudder is the main control surface for the manoeuvring of ship. To satisfy manoeuvring criteria such as turning diameter, yaw checking, stopping, hydrodynamic design of rudder is important; furthermore, rudder and hull form should be considered together in hydrodynamic design step. When rudder satisfies the criteria, the structural design of rudder can be practiced. The dimensions of rudder are important for aft ship design and arrangement of propeller. The following equation offered by DNV (2000) is used to obtain total rudder area which is shown in Figure 6.32.

$$A = \frac{TL}{100}\left[1 + 50{C_B}^2\left(\frac{B}{L}\right)^2\right](m^2) \qquad (6.49)$$

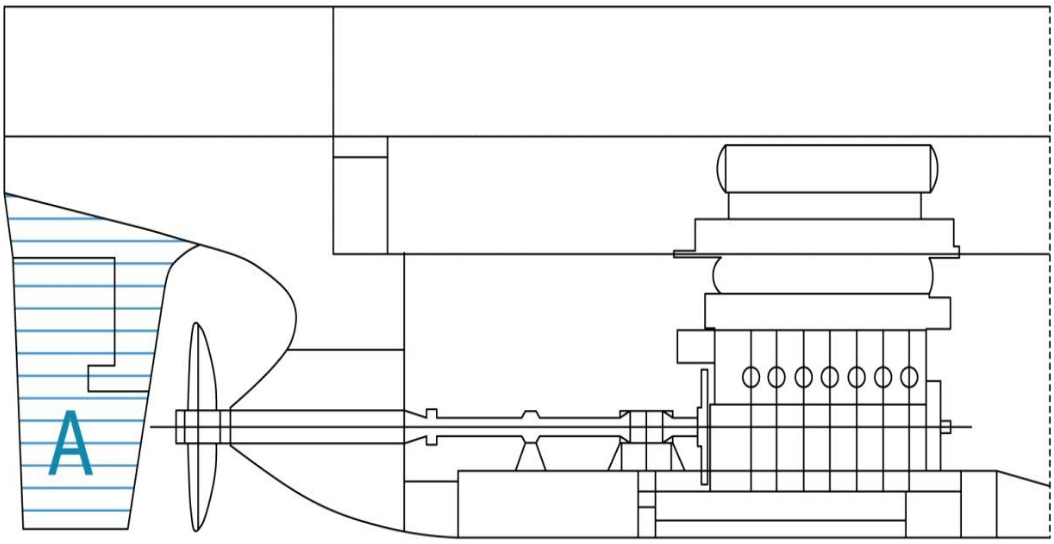

Figure 6.32 : The semi-spade rudder behind the screw propeller.

The main dimension of rudder is necessary for preliminary design but hydrodynamic and strength of rudder should be calculated for detailed design. These calculations will be implemented in future research. Also, there are different types of rudder besides the semi-spade rudder and these are should be considered as design variables. Selected rudder type absolutely affects the project life cycle of ship. For example, the bad directional stability of ship increases the fuel cost of ship because of extra effort keeping ship in the route. Other rudder types are also should be added in the future research.

6.2 Database

There are two kinds of variables spaces in the design exploration. One of them is continuous space and the second is discrete space. Design exploration in the discrete space requires predefined variables. These variables are defined in a database before design exploration study. Database also enables the collaboration between stakeholders during the life cycle of ship. The database should include mainly following items.

- Equipment library
    - Main engine
    - Propeller
    - Generator
    - Shaft generator
    - Boiler
    - Compressor
    - Heat exchanger
    - Pump
    - Purifier
    - Paint
    - Coupling
    - Specific weights
    - Others
- Hull form library
- Material library
    - Normal strength steel and grades
    - High strength steel and grades
    - Extra high strength steel and grades
- Construction elements library
    - Sheet metal
    - Profile
    - Bracket

Input formats of items are based on used utility functions in ship synthesis model. For example, Table 6.8 shows data format for hull form library and Table 6.9 shows the main engine library example. These inputs can be extendable for further different utility functions.

Table 6.8 : Data example for hull form library.

No. of parent hull		1
No. of hull		1
Displacement	[ton]	14500
LOA	[m]	150
LWL	[m]	135
LBP	[m]	132
Beam	[m]	16
Depth	[m]	12
Reference draft	[m]	6
LCB	[%]	-0.4
Deck area	[m2]	2304

A web based SQL database is generated to enable collaboration between stakeholders and “CORE”. www.madid.ist web site is developed to make online data entries of suppliers. SQL database is in the backend of this web site. Figure 6.33 shows the framework from suppliers to “CORE”. Also, Python API is developed to access directly SQL database from PC during design process. Related functions of equipments are defined in this API which is can be seen in appendix.

Table 6.9 : Data example for the main engine library.

Max power	[kW]	80520
RPM	[r/min]	84
Mass of engine	[ton]	2088
SFOC	[g/kWh]	166
Steam	[kg/h]	13490
Length	[m]	22.495
Beam	[m]	5,450
Depth	[m]	15
Tier		II
No. turbocharger		3
Price	[$]	…

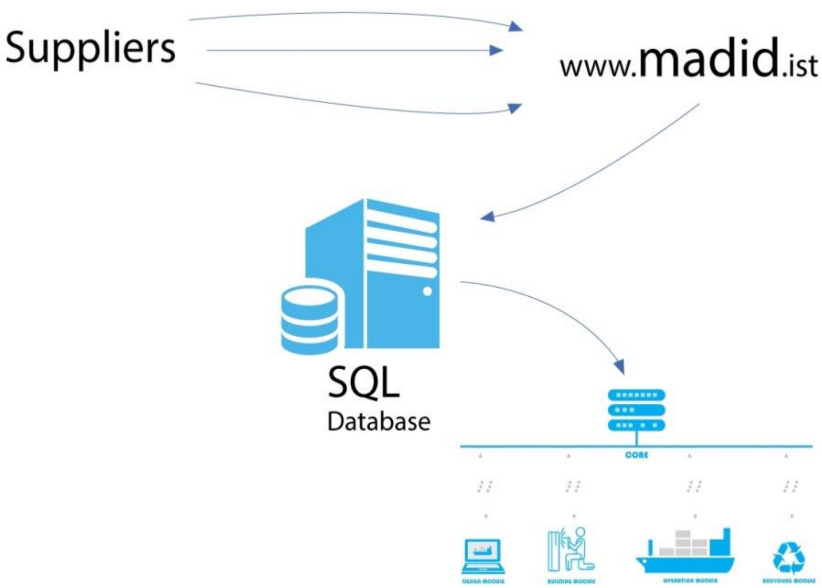

Figure 6.33: Data communication framework.

6.3 Artificial Intelligence

Artificial intelligence (AI) is the simulation of human intelligence according to Jackson (1985), and thinking of machine like a human and replication of human brain function can be defined as strong artificial intelligence according to Warwick (2012). In this study, the role of AI is the design intelligence (DI) and offered idea is that the design module of the universal ship network is simulated by design intelligence.

Duties of DI are exploration of feasible designs, selection of optimum designs, processing of data obtained by other modules, and manage the design process. Suitable design method should be established for success of DI on its job. The design problem of ship is investigated in section 5. The design problem of ship based on the lifecycle has multidisciplinary nature. Ship synthesis model should be decomposed to solve multidisciplinary design problem which is formulated in section 5.1. After the decomposition, suitable method should be selected to solve generated synthesis model.

6.3.1 Decomposition of ship synthesis model

A ship synthesis model has various disciplines like hydrostatics, stability, hydrodynamic, structure, layout design, subdivision, and propulsion. Detailed investigations of regarded disciplines can be found in section 6.1. The multidisciplinary system should be decomposed to see possible implementations. Decomposition reduces the complexity and maximizes efficiency. There are three decomposition models, and they are hierarchic, non-hierarchic and hybrid-hierarchic decomposition. Type of decomposition specifies the solution method for multidisciplinary design problem.

Output/s of each disciplines and sub-disciplines are input/s of others so this means that the synthesis model is non-hierarchic and information flow is multi-directional. Non-hierarchic decomposition model can be seen in Figure 6.34.

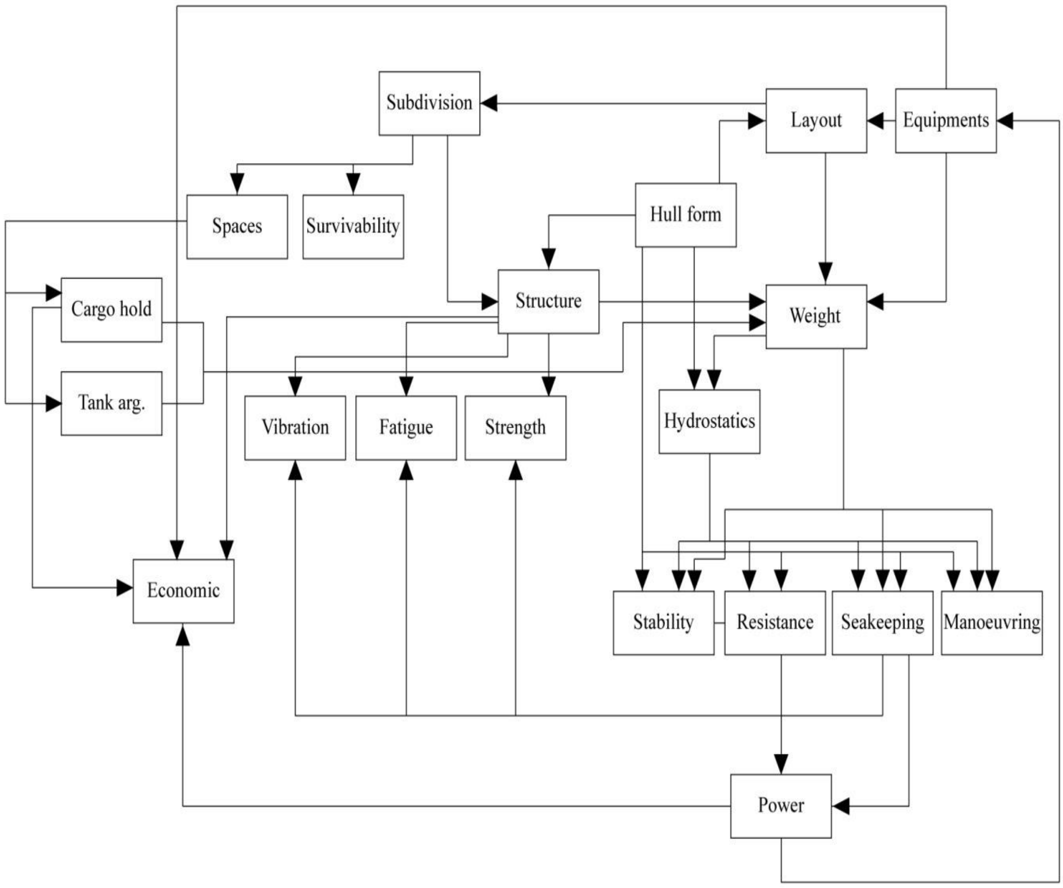

Figure 6.34 : Non-hierarchic decomposition of ship synthesis model.

For example, output of hull form, weight and hydrostatics are input of seakeeping. Seakeeping is the input of strength, fatigue and vibration thereby seakeeping actually input of structure. Structure is the input of weight and weight is the input of seakeeping. On the other hand, whole disciplines affect the others directly or indirectly. It shows that this flow is the non-hierarchical.

There are various methods for multidisciplinary design problems of non-hierarchic synthesis model in the literature. Concurrent subspace optimization and global sensitivity equation approach are some of them according to Bloebaum et al, (1993).

In this study, multidisciplinary design problem is considered both exploration and optimization cases to implement more powerful design intelligence. Design exploration and design optimization are different concepts and these are explained in next section.

6.3.2 Design exploration and design optimization

Design exploration (DE) and design optimization (DO) are different concepts in design study. The purpose of design exploration is to search and characterize the solution space. On the other hand design optimization study aims to find optimum design. To create the design intelligence for ship design problem, both of them are necessary. They are two abilities which design intelligence should have them.

DE uses divergent-iterative scheme to explore entire solution space which can be seen in Figure 6.35; on the other hand, DO uses convergent-iterative scheme to determine optimum design, Figure 6.36 shows the solution space of design optimization study. DE can be used in explore entire solution space of ship projects and DO can be used to find optimum solution in the disciplines. For example, bad hull forms are unnecessary, and a hull form which has better performance with equal displacement is preferred solution so DE and DO can be used together.

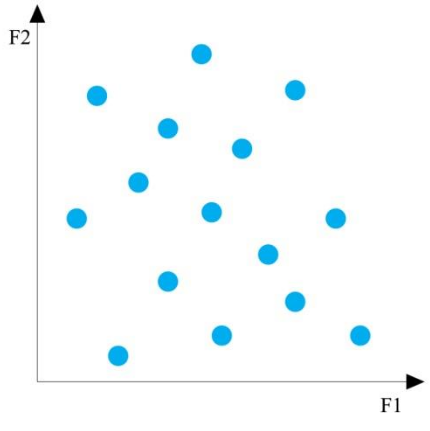

Figure 6.35 : Design exploration.

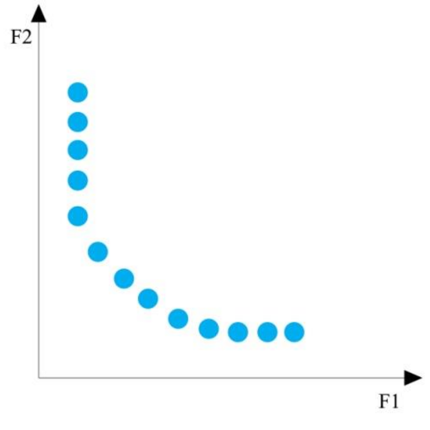

Figure 6.36 : Design optimization.

There are various design exploration and design optimization algorithms. Concerned problems specify the used algorithms. DE algorithm should have fast and efficient multi-dimensional sampling particulars. Design optimization algorithm should be used both single and multi objective optimization problems. In the ship design problem, there are constraints and bounds which are variables in different level of problem. For example, a length is selected as an initial sampling. Hull form is generated based on this length and initial design variable control points should be suitable with length. Every step of design constraints and bounds are changed in accordance with other design variables.

6.3.3 Algorithms

In this study, Latin hypercube sampling (LHS) is used as design exploration algorithm and particle swarm optimization (PSO) algorithm is used for design optimization algorithm. Selection reasons of these methods are easy implementation, usability in different problems and fast response. These algorithms are investigated in following section.

6.3.3.1 Latin hypercube sampling

Design optimization usually has poor quality to explore design space ;because, it requires a loarge number of simulations. On the other hand, feasible solutions can be missed because of optimization study's nature. Suitable design exploration method gives good improvement to design intelligence algorithm. McKay et al. (1979) propesed the Latin hypercube sampling method as a solution for disadvanteges of optimization study. LHS is a better choice than random distribution to explore design domain uniformly. Figure 6.37 shows this situation. Blue points have a uniform distribution but red points are very close in some portion of design domain. Mathematical formulations and algorithm procedure can be found on study of McKay et al. (1979). The selection reason of LHS algorithm is the easy implementation for exploration study. Because of limited computer power, population of particle swatm algorithm is restricted as 50 but to see distribution of design space Latin hypercube sampling is used with 250 sample points.

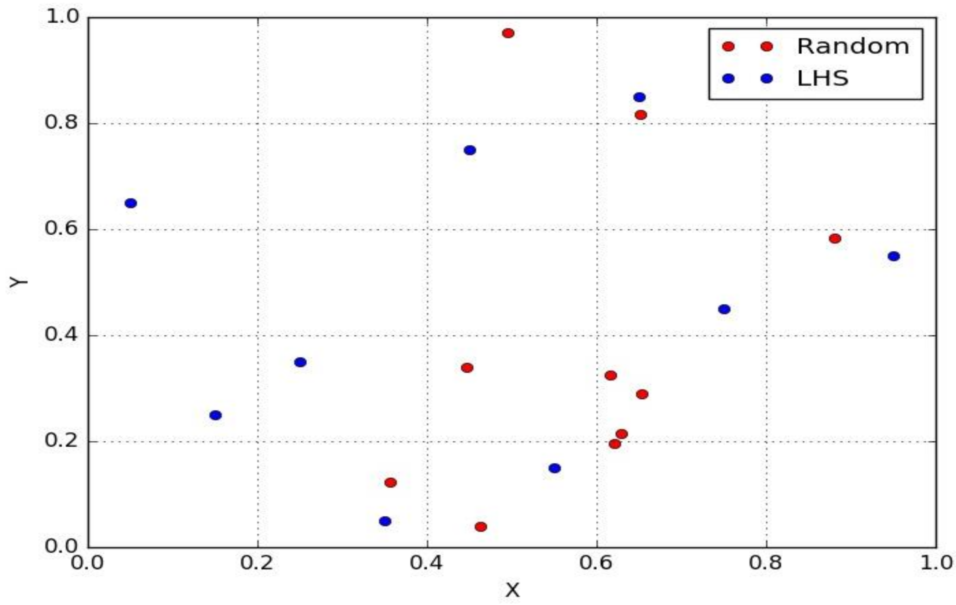

Figure 6.37 : LHS sampling versus random sampling.

6.3.3.2 Particle swarm method

The Particle Swarm Optimization algorithm (PSO) is a kind of population-based stochastic search algorithms. The PSO algorithm is generally suitable for complex black-box non-linear optimization problems. The PSO algorithm was first introduced by Kennedy and Eberhart (1995) and its basic idea was originally inspired by simulation of the social behavior of animals like bird flocking, fish schooling etc. Each member of population shares individual knowledge when population search food and it is the natural process of group communication. If any member can find out the food, the rest of population will follow inherently.

In PSO, each member of the population is called a particle and the population is called a swarm. Food means the finding of fitness function and the position of particles corresponds to design variables of fitness function. Particles search food randomly, and keep the knowledge the best previous positions of itself and its neighbors so they can adjust their own position and velocity by using the best position of swarm. Velocity update and position update are two primary operators of PSO algorithm. Iteratively, all particles try to find better and better positions the searching for optimum result of fitness function during until a minimum error or iteration number is achieved.

There are variations of PSO algorithm but all of them can be implemented easily. PSO algorithm does not use any gradient information so it is suitable for black-box optimization problems. Generally, PSO algorithm can be used to solve the non-linear, non-convex, continuous, discrete and integer variables type problems by modifying small portion of codes. It requires low computer power by comparison with other heuristic algorithm and few lines of code are enough to setup algorithm so it is not complex to use.

Basic equations to calculate velocity and position of particles are share in below.

$$v_i^{k+1} = v_i^k + c_1 r_1 (Xpb_i^k - x_i^k) + c_2 r_2 (Xsb^k - x_i^k) \quad (6.50)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (6.51)$$

Where x_i^k and v_i^k are the position and velocity vectors of i'th particle, respectively. k is the iteration number. $r_1$and $r_2$are two random numbers uniformly distributed in the range (1,0). Xpb_i^k is the best fitness value of particle and Xsb^k is the best fitness value of whole swarm so far. c_1 and c_2 are velocity components to control exploration tendency. Particles move to optimum points mainly by using equation (6.50) and (6.51). Also, there are alternative formulations for position and velocity vector but in this study basic forms are used. Movement illustration of particles is shared in Figure 6.38.

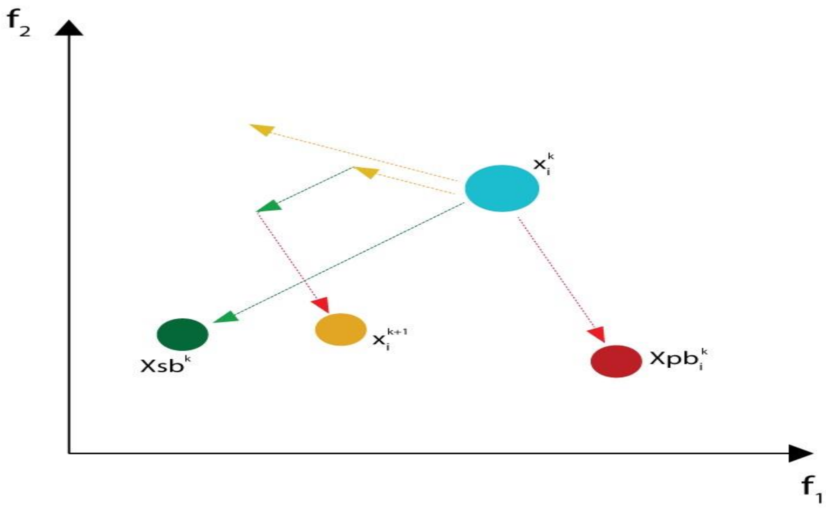

Figure 6.38 : Particle movement scheme.

Main part of PSO algorithm is the movement of particles by using position and velocity equations. Rest of the algorithm is quite similar to general recursive algorithms. The basic structure of PSO algorithm is as follows:

Initialize all particles with random positions (x_i^0) in search space and velocities (v_i^0).

Initialize best known positions of particles (Xpb_i^0) by using its initial positions.

Calculate the first best known position (Xsb^0) of swarm.

repeat

for all Particle i in the swarm **do**

Pick random numbers: r_p , r_g ϵ (0,1)

Update the particle's velocity by using equation (2.1)

Compute the particle's new position by using equation (2.2)

if $fitness\left(x_i^{k+1}\right) > fitness\ (Xpb_i^k)$ **then**

Update the particle's best known position: $Xpb_i^{k+1} = x_i^{k+1}$

end if

if $fitness\ \left(Xpb_i^{k+1}\right) > fitness\ (Xsb^k)$ **then**

Update the swarm's best known position: $Xsb^{k+1} = Xpb_i^{k+1}$

end if

end for

until error criterion or iteration number is met

return

The general concept of particle swam algorithm can be also seen in Figure 6.39 as the flowchart.

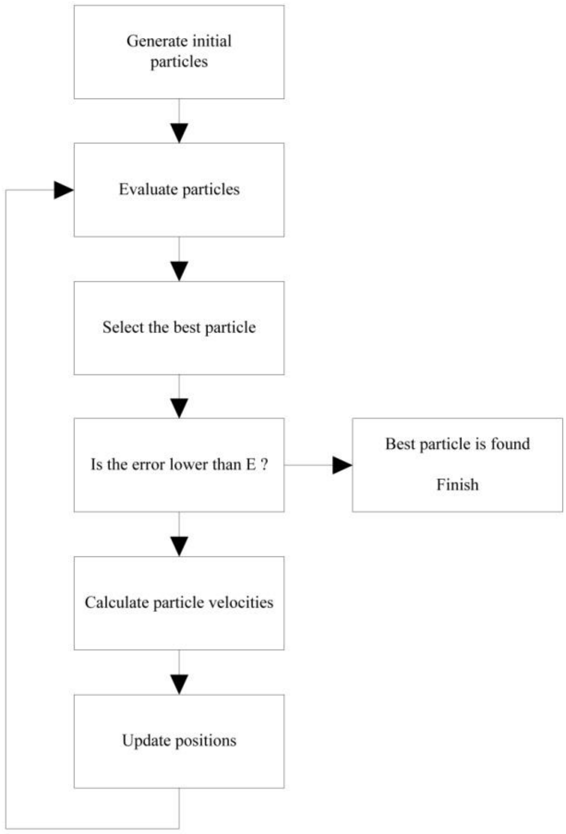

Figure 6.39 : The basic scheme of particle swarm algorithm.

There are different variations of particle swarm algorithm. The basic concept is implemented in this study.

Parameters of PSO Algorithm

PSO algorithm mainly has various parameters such as swam size (total number of particles), number of iteration, velocity components coefficients such as cognition and social behavior coefficients (c_1 and c_2), acceleration coefficients. Also, PSO algorithm can be improved by using extra parameters such as inertia weight, velocity clamping, velocity constriction etc. Number of iteration could be replaced with other termination criterion like error value, velocity etc. values of parameters could be fixed during the optimization process as an off-line strategy of values or they depend to optimization process as an online parameter tuning strategy. Optimal values of parameters are another optimization problem and in this study fixed values strategy is used. Basic parameters of algorithm are investigated below.

Swarm size

Swarm size is the number of particles in the population. A large number of particles can seek out the larger parts of the search space. On the other hand, this increases the computation time per iteration.

Iteration number

The number of iteration determines how many times swarm will be generated. The low number of iterations causes the early stopping before the optimum solution. The high number of iteration with appropriate stopping criteria is better for searching without unnecessary source usage.

Velocity Components

Particles velocity has three components which are inertia, cognitive, and social components. They generate the learning capacity of algorithm.

7. APPLICATION, DEVELOPMENTS AND RESULTS

Basement of ship design network is developed in the previous sections. Evaluation functions are described in section 6.1 and implemented design intelligence is investigated in section 6.3. Created framework is limited in the scope of this study for just container ship. By using evaluation functions, a holistic synthesis model is built which can be seen in Figure C (see APPENDIX); also small portion of synthesis model is shared in Figure 7.1.

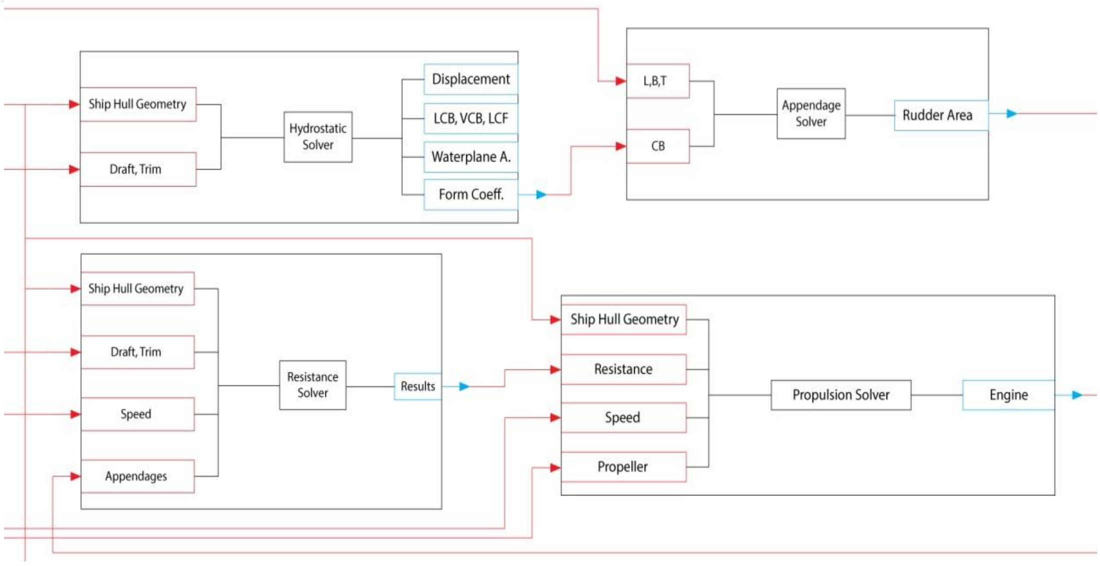

Figure 7.1 : A portion of holistic ship synthesis model.

Exploration design space by using synthesis model is duty of design intelligence. Latin hyper cube sampling and particle swarm algorithm are used as a basis to implement design intelligence.

A container ship project is studied as a sample case. The purpose of case study is to explore the design space for preliminary ship design of a container ship. Operational profile for case study is shared in the next section. Also, generated designs are investigated in section 7.6. Objective function, constraints, design variables and bounds of this exploration are shared in following sections.

7.1 Definition of the Case Study

The preliminary design problem of a container ship is adapted in here as a case study. An operational profile is set up at the case study to calculate some semi-empirical formulations like ship cost, financial cost; weight etc. Table 7.1 shows used values for the operational profile.

Table 7.1 : Operational Simulation Input Parameters.

Variable	Value	Unit
Route distance (One way)	14000	Nautical miles
Port numbers	1	
TEU loading time	43	TEU/hour
TEU offloading time	43	TEU/hour
Loading price	24	$/TEU
Offloading price	24	$/TEU
Port price	0.002	$/Gross tone
Fuel price	520	$/Tone
Management cost	120000	$/ year
Unit provision cost	15	$/ day

The goal of design study is to explore the design solution space. This exploration is derived by programmed design intelligence on ship synthesis model. Entire design of a ship or various sub-disciplines of ship design can be modeled as the exploration and optimization problem. In this study, ship design problem is considered as the part of the life cycle of a ship project as an economic investment. Main purpose of a ship design is to gain maximum return for total life cycle of ship to her owner so design problem is modeled as single objective multidisciplinary optimization problem. The formulation of the optimization problem consists of three parts: formulation of objective function, determination of constraints and the selection of design variables and boundaries.

7.2 Formulation of Objective Function

In the most of the container ship design problem, required freight rate is used as minimum cargo price without any profit to solve optimization problem. This approach misses some part of the life cycle budget. For example, recycling income or irregular operation cost like dock survey; therefore, the maximization of total life cycle return is used an objective function. Other criteria like efficiency, comfort etc. actually have positive effects on return so in the optimum solution, their values will be high. The objective function for the MDO project is formulated as follows:

$$Max\ f(x) = \ Return_{Life\ cycle} = Income_{Life\ cycle} - Cost_{Life\ cycle}$$

7.3 Constraints

Constraints help extraction of infeasible regions from solution space. This defines a subset of an optimization space. This condition enables the efficient usage of resources avoiding of infeasible region search. They are also part of the learning behavior of the optimization algorithm. There are two types of constraints: equality and inequality. Equality constraints reduce the dimensionality of the optimization space by one. On the other hand, inequality constraints which are shown in Figure 7.2 define geometric limitations without reduction of dimensionality. Formulation of equality and inequality constraints are also basically shared in equation (7.1) and (7.2), respectively.

$$A = B \tag{7.1}$$

$$A - B \leq 0 \tag{7.2}$$

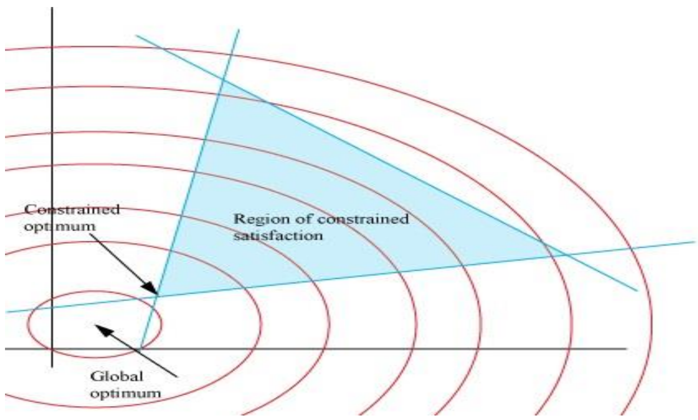

Figure 7.2 : Inequality constraints.

In this study, both constraint types are used. For example, buoyancy force should be equal to weight, LCB and LCG should be equal to avoid from trim etc. This kind of constraints can be modeled equality functions. Physical design restrictions are one example of the equality constraints. Also, there are some design boundaries such that freeboard should be higher than calculated value by using related rules. This type constraint is modeled as inequality formulation. Used constraints are shortly summarized in Table 7.2.

Table 7.2: Determined constraints.

Constraint	**Formulation**	**Type**
Displacement and weight	$F_B - F_W = 0$	Equality
Untrimmed condition	$LCB - LCG = 0$	Equality
Freeboard	$Freeboard_{rule} - Freeboard_{design} \geq 0$	Inequality
GM	$GM_{rule} - GM_{calculated} \geq 0$	Inequality
DNV-GL (2017, Chapter 4)	$C_B > 0.6$	Inequality
DNV-GL (2017, Chapter 4)	L < 500 m	Inequality
DNV-GL (2017, Chapter 4)	L/B > 4.5	Inequality
DNV-GL (2017, Chapter 4)	B/D < 2.5	Inequality

Summarized constraints can be extended with various international and national regulations in the further research. For example;

- SOLAS (2012)
- International Convention on Load Lines (1966)
- MSC/Circular.608/Rev.1 – Interim Guidelines for Open-top Containerships – (Adopted on 5 July 1994)
- DNV-GL Rules
- MII, MSI
- IMO A751, Manoeuvring criteria

In this study, above constraints are not used but these constraints are important to show the effects of stakeholders in the design process. Developed rules by Class societies, national or international authorities should be implemented into *"CORE"* as the boundaries of explored design space.

7.4 Design Variables

Design variable is actually main control mechanism of the optimization problem; because, the solution of design problem is the finding of the variables which give the optimum result. There are two type variables: discrete and continuous. Ship design problem has these two types. For example, hull form optimization requires continuous space for surface modification. On the other hand, finding of optimum engine means discrete variables space. Usage of continuous and discrete spaces together can be defined as mixed type optimization problem and related algorithms should be used to solve this kind of problem. There are various bounds for variables originated by design boundaries or regulations. For example, the selected propeller should give the minimum required thrust for desired speed. On the other hand, propeller diameter should be suitable between hull and draft. Other example is that regulations impose restrictions to some variables. According to DNV-GL (2017, Chapter 4), height of double bottom should be between 0.76 m and B/20.

Discrete and continuous design variables may be independent and dependent. For example maximum diameter of propeller is restricted by the limit of the hull form. For every different hull forms, bounds of design variables for propeller will be changed so diameter of propeller is the dependent design variables. Furthermore, main engine is the other dependent design variable. Resistance of hull form specifies the bounds of variables for main engine selection subspace. Continuous independent design variables are shared in Table 7.3. Continuous dependent variables like control points of hull form, discrete dependent variables like propeller or main engine spaces are created by using evaluation functions and independent design variables.

Table 7.3 : Continuous independent design variables.

Design variable	Lower bound	Upper bound
Bays	100	500
Rows	0.6	0.9
Tiers in hold	4.5	10
Tiers in deck	1	2.5
Double bottom (m)	0.76	B/20
Double side (m)	1.1	2.55
Speed (knot)	15	25
Draft (m)	0.45D	0.8D
Length of engine room(m)	10	25
Length of forward(m)	5	15
Length of aft(m)	9	15
Length of bulb(m)	7	20
Height of bulb(m)	0.4D	0.6D
Width of bulb(m)	0.1B	0.175B

7.5 Parameters

Parameters actually mean settings of design intelligence. Combination of Latin hypercube and particle swarm optimization algorithm is the basis for design intelligence. Shared parameters in Table 7.4 are particulars of these algorithms. Values of these algorithms are important to determine convergence speed and to explore uniformly the solution space.

Table 7.4 : Parameters definition of algorithms.

Parameter	Definition	Value
S	Sample size of LHS algorithm	250
v_i^{n+1}	Particle velocity for next iteration	Varies
w^n	Weight function	0.729 and varies
v^i	Particle velocity for current iteration	Varies
c^1 *and* c^2	Cognitive and social parameters	1.49
r_1^n *and* r_2^n	Randomly generated constant, bounds [0, 1].	Varies
x_i^n	Design variable vector for current iteration	Varies
P	Maximum iteration	50

7.6 Results

The case study conducted on holistic ship synthesis model. 250 designs are generated during the exploration study as a case study for a container ship. Used objective function, design variables, bounds, constraints and parameters are shared in the previous sections. Followings are the sample outcomes of the universal ship design network for the preliminary and contract design phases;

- General arrangement
- Hull form
- Tank plan and stability calculations
- Power estimation
- Design of propulsion system
- Selection of main engine
- Weight distribution estimation
- Economic return estimation

The results obtained from this preliminary design exploration can be seen on the following figures and tables. Figure 7.3 shows the operation revenue of explored design versus lengths. There is one and a half difference roughly between the most and the least operation revenue for the same length. The lowest boundary increases for the growing length.

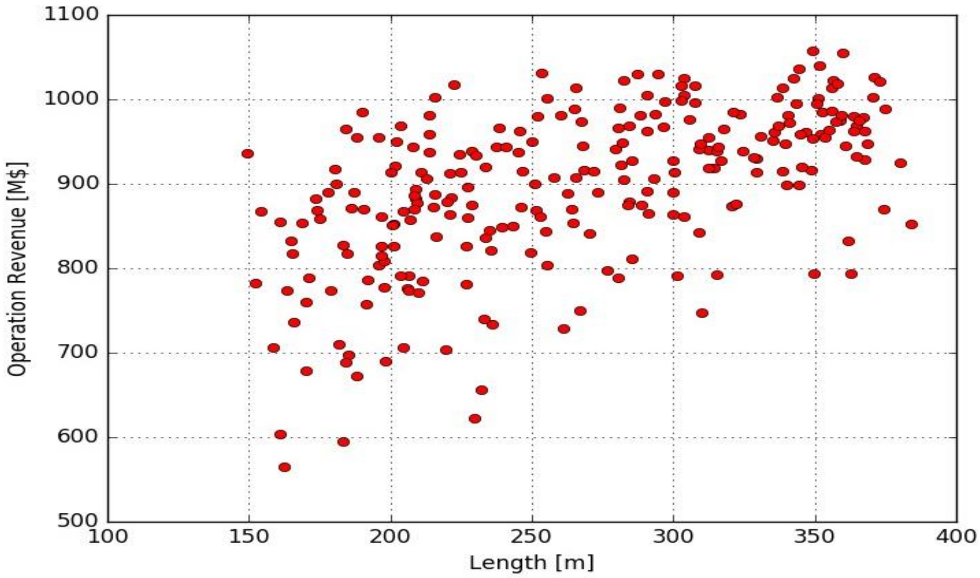

Figure 7.3 : Operation revenue – length.

Figure 7.4 shows the operation revenue versus displacement of ship. Obviously, the highest revenues are in the biggest displacement region. Intensive region is between 50000 and 150000 tones.

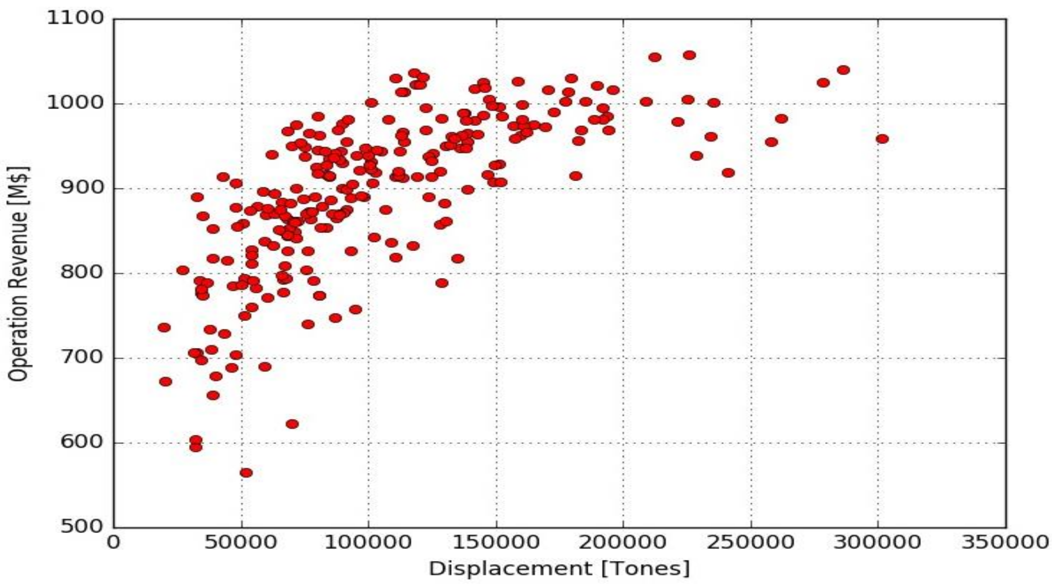

Figure 7.4 : Operation revenue – displacement.

Figure 7.5 shows the operation revenue versus total container capacity. Used container capacity means the full loaded operation. The speed, loading and offloading capacity generates the revenue differences for the same container capacity values.

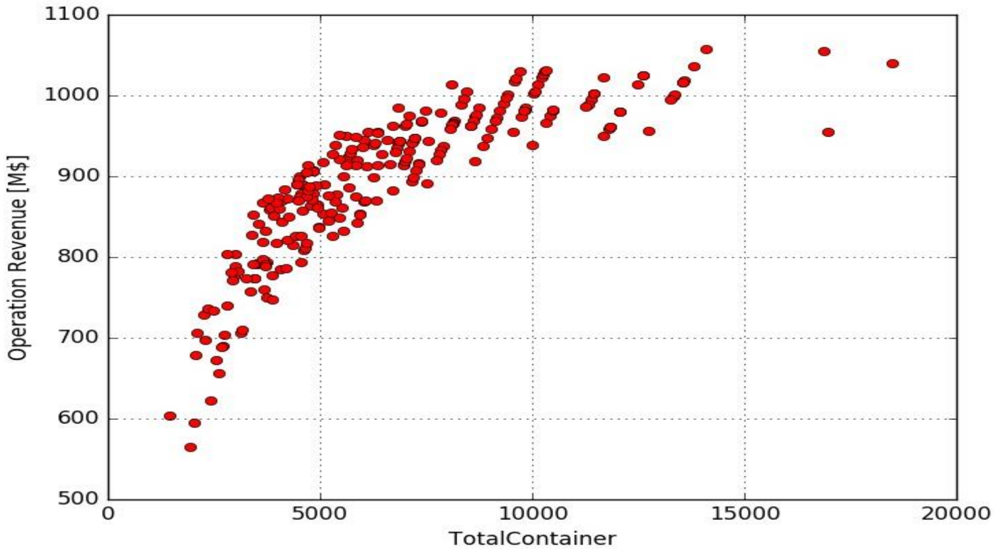

Figure 7.5 : Operation revenue - total container capacity.

Figure 7.6, Figure 7.7, Figure 7.8 and Figure 7.9 show the variation of the explored designs main dimensions and displacement. The wide spectrums are investigated in these figures. These spectrums produce the different cost and revenue results. One of the usage objectives of the offered approach is to help designer as a decision support system. Generated figures explain revenue and cost results of different main dimension selections.

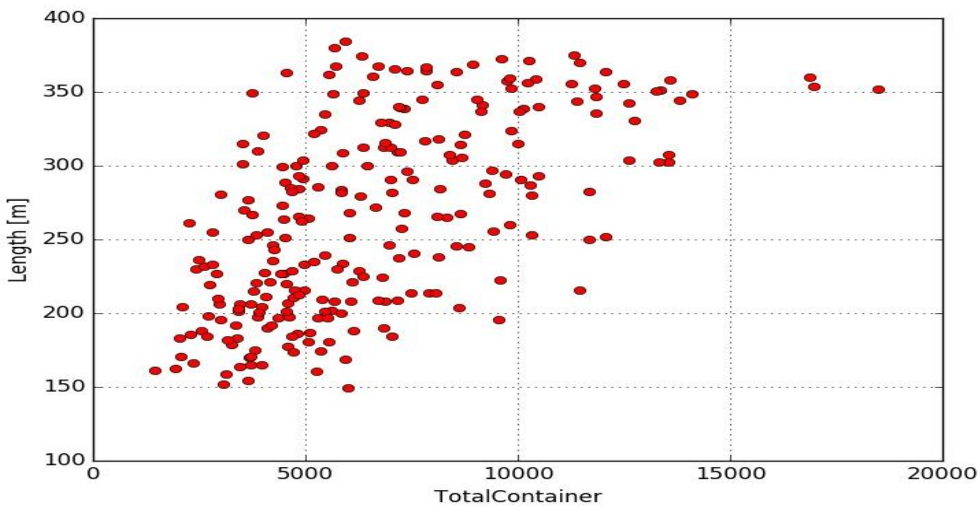

Figure 7.6 : Length – total container capacity.

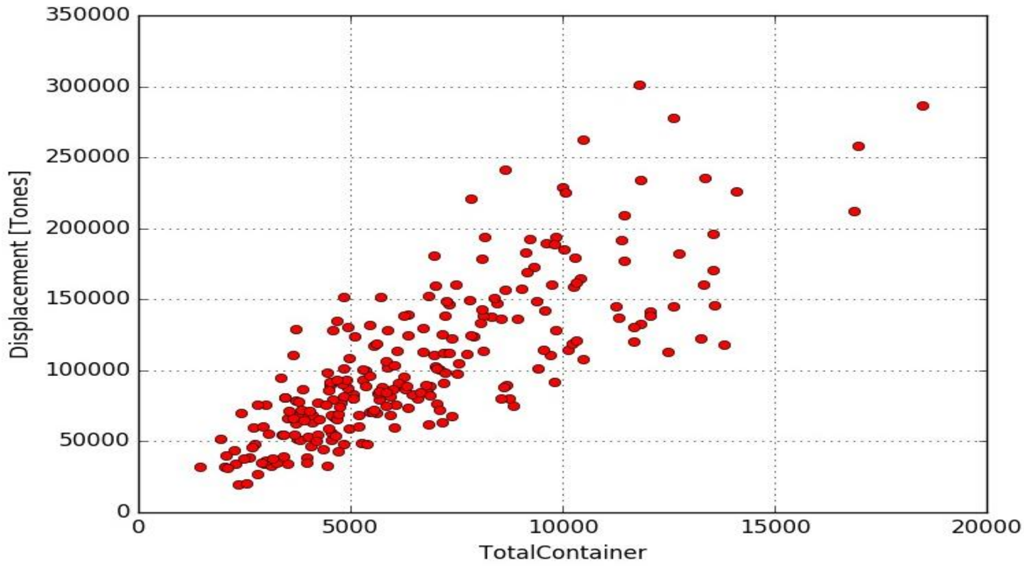

Figure 7.7 : Displacement – total container capacity.

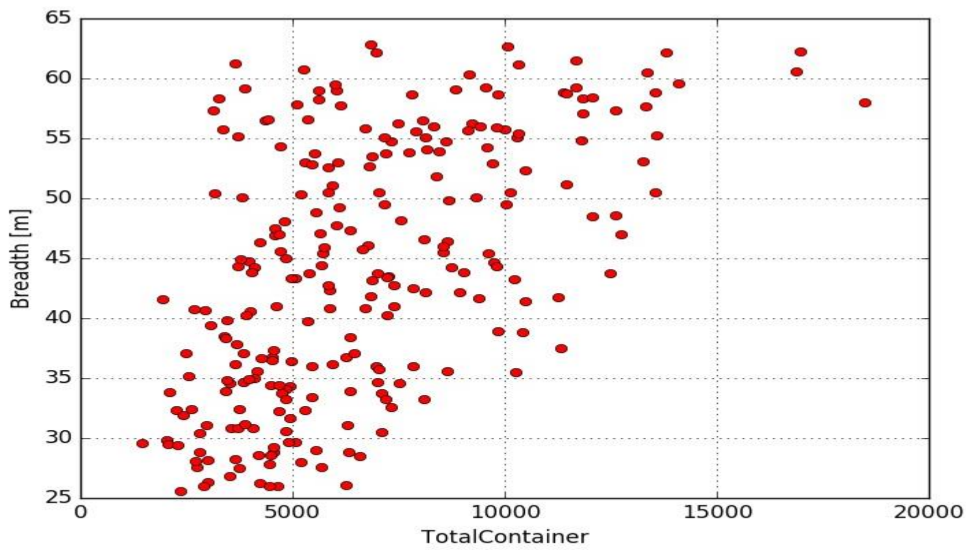

Figure 7.8 : Breadth – total container capacity.

Figure 7.10, Figure 7.11 and Figure 7.12 indicate costs of phases for the life cycle of ship. Operation phase cost rise with increased container capacity. Obviously, the trend of operation phase cost says it generally. There is a linear similarity between building phase and design phase; on the other hand, operation phase cost main source of nonlinearity.

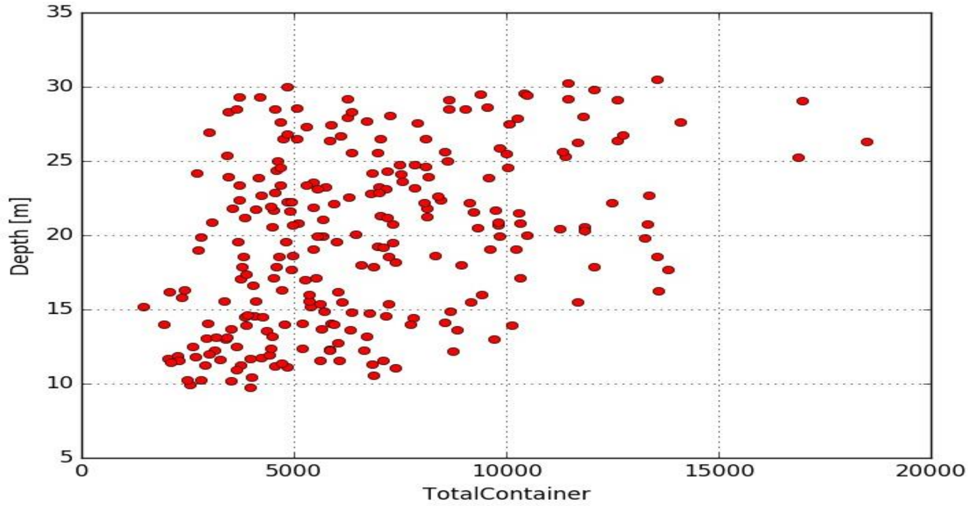

Figure 7.9 : Depth – total container capacity.

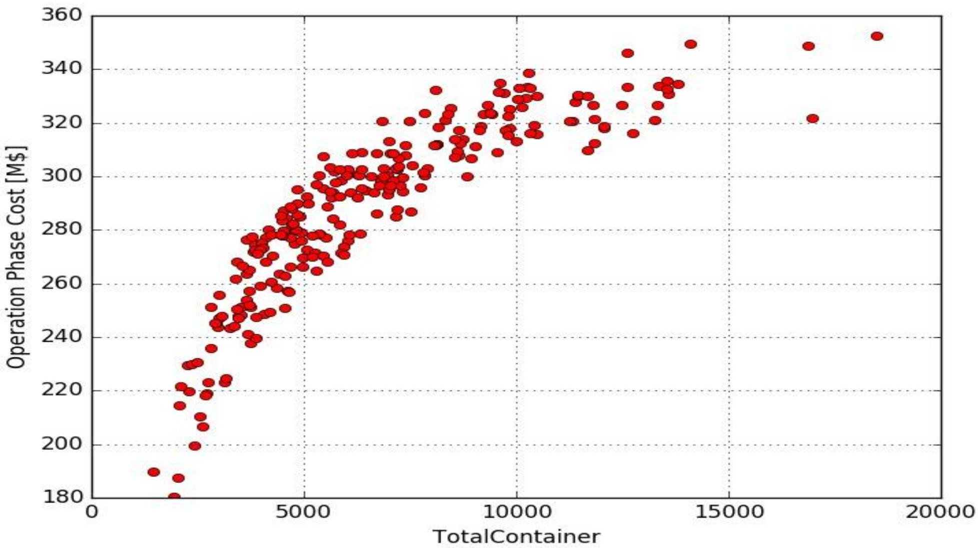

Figure 7.10 : Operation phase cost – total container capacity.

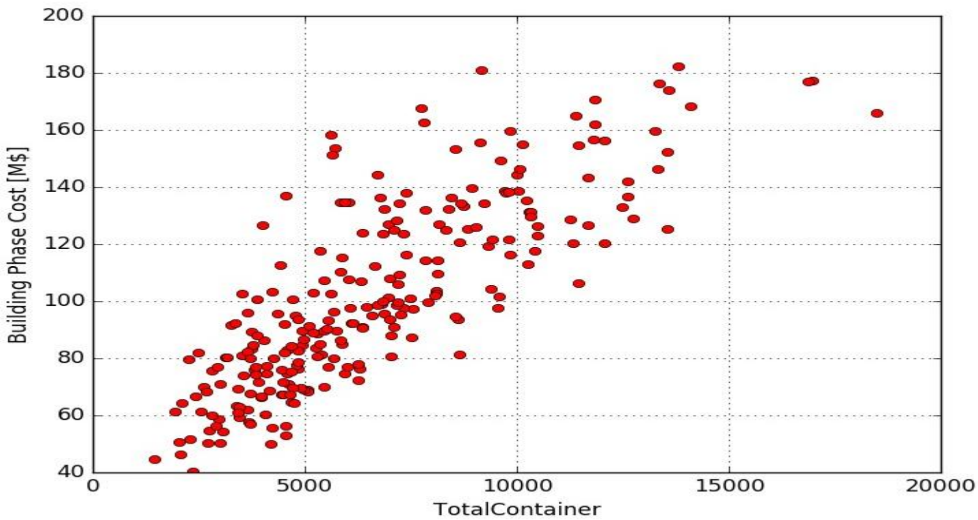

Figure 7.11 : Building phase cost – total container capacity.

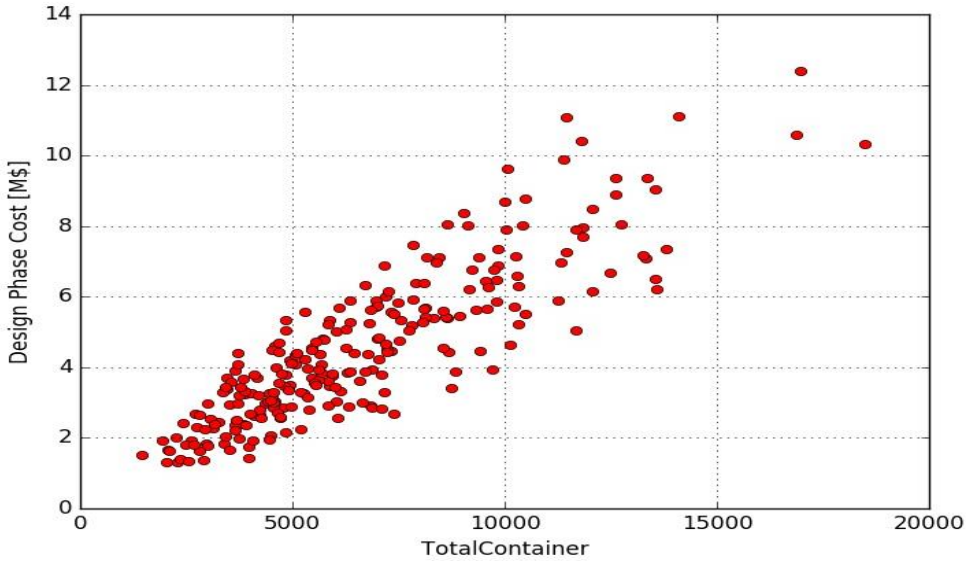

Figure 7.12 : Design phase cost – total container capacity.

The main objective of design exploration is to generate life cycle cost and life cycle revenue of designs. Figure 7.13 and Figure 7.14 show main results of this exploration study. Approximately, these two graphs have same trends. This similarity illustrates the unit cost per TEU in the Figure 7.15. The trend of this figure expresses the decreasing cost of a container with increasing ship size.

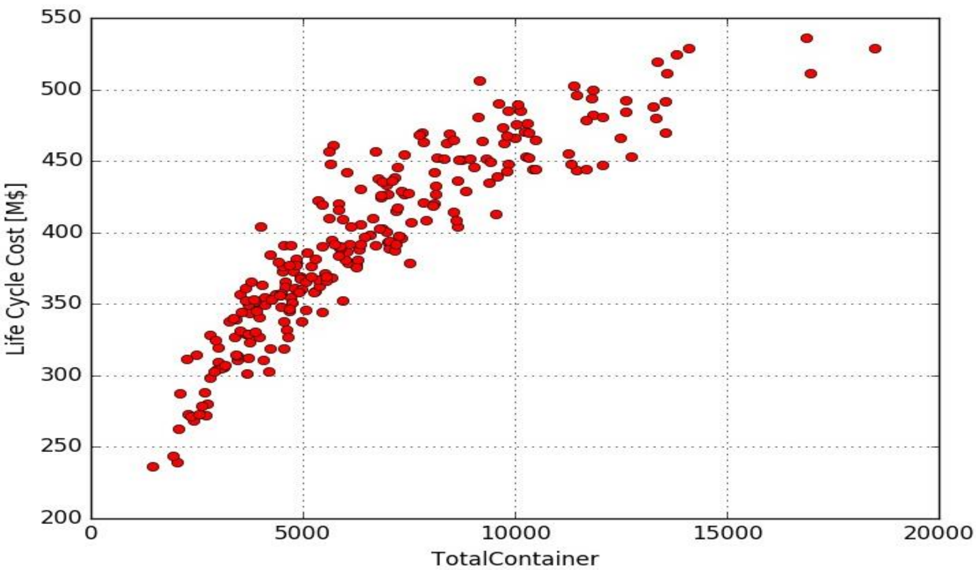

Figure 7.13 : Life cycle cost – total container capacity.

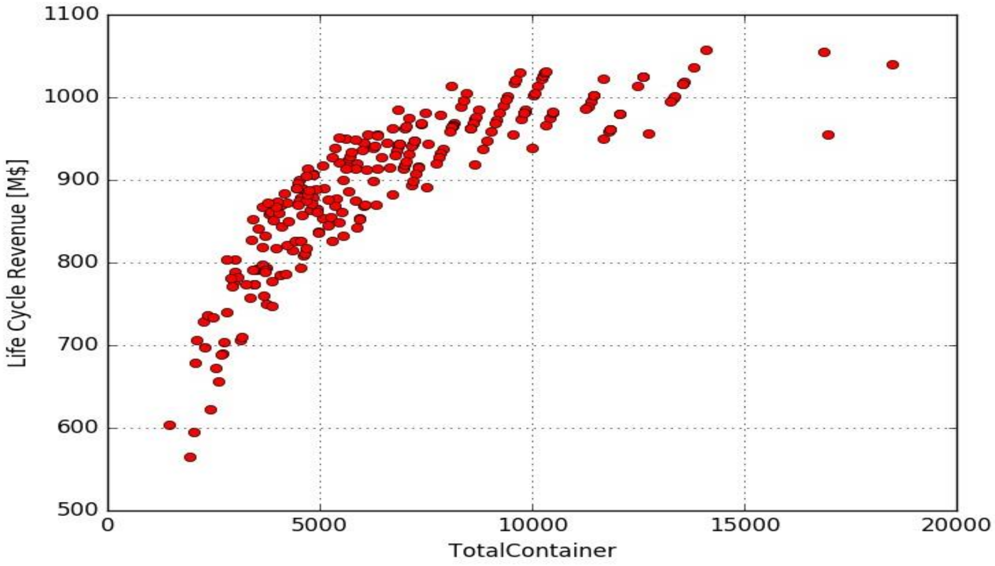

Figure 7.14 : Life cycle revenue – total container capacity.

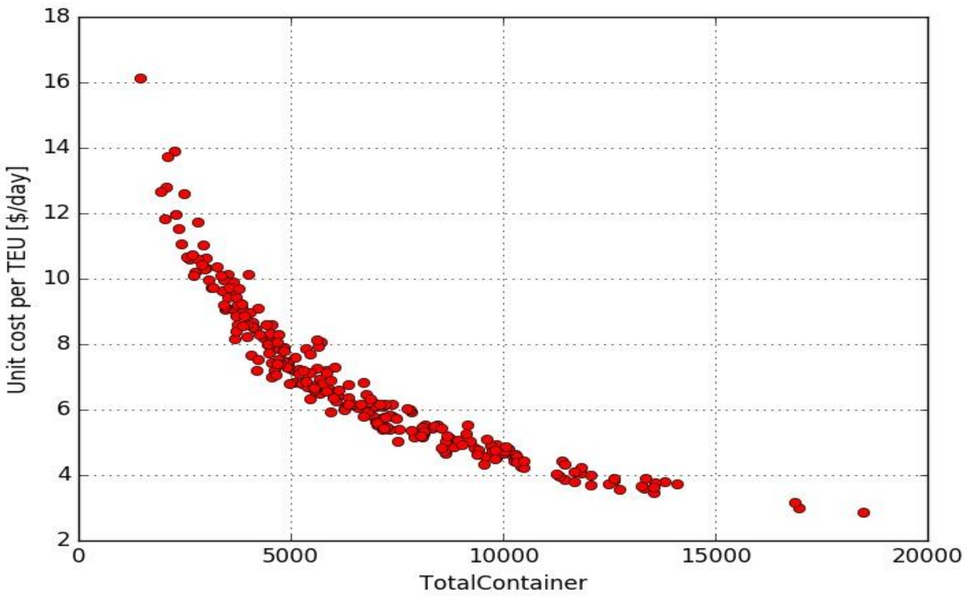

Figure 7.15 : Unit cost per TEU – total container capacity.

8. DISCUSSION AND CONCLUSION

This section describes the limitations, future developments and main conclusions of this study.

8.1 Limitations

Computer power is the first limit to search big design space. Implementation of low fidelity solver increases the uncertainty in generated design. High uncertainty causes restriction in the catching of some designs.

8.2 Future Developments and Research

For future development suggestions are shared below.

- Improving the searching algorithm, different algorithms can converge faster.
- Development of the synthesis model; some parts of real ship project are simplified.
- Real prices can be used for further studies; some prices in this study are used as generic.
- Building, operation and recycling module can be integrated the design module
- More information can be added to database.
- High fidelity solvers can be used for evaluation functions.
- More equipment would provide better design solutions.
- Probabilistic approach can be implemented to generate robust design.

8.3 Conclusion

A universal ship design network is presented in this study as the design module of wider approach for a universal ship network. This module makes it possible to explore design space in PLM concept. It includes holistic ship synthesis model, database and artificial intelligence. The model is tested in a container ship case with small space generation.

The holistic ship synthesis model includes main evaluation functions such as resistance, cost, revenue, structure etc. Synthesis model enables the knowledge basin for simulation of artificial intelligence. The difference of evaluation functions from classical approaches is the lifecycle consideration of calculations. The synthesis model is programmed with modular approach to upgrade or update functions easily. Decomposition of synthesis model shows the non-hierarchic system. This requires special attention in searching the design space. Formulation of synthesis model can decrease the solution time. Lifecycle approach requires inputs from building, operation, and recycling phases to synthesis model. Used model enables parameters refinement with lifecycle approach.

The small database is created to feed synthesis model during the exploration process. The database communication is fast enough to keep design cycle stable. Concurrent approach is used for hull form exploration. Better hull forms are searched separately than design exploration. Feasible hull forms from generated space are collected and added to database. In the design exploration, artificial intelligence used directly the hull form library from database. This model decreased the evaluation time considerably.

The last part of the design network is the artificial intelligence as a brain of framework. Actually, created thing is design intelligence. Main duty of design intelligence is to search design space. The design intelligence makes decisions by using swarm intelligence and Latin hypercube sampling methods to determine design directions. Also, design intelligence manages the hull form library in the database.

Following points are succeed in this study;

- Cost, Revenue, resistance etc. holistic evaluation functions
- Ship synthesis model
- Latin hypercube algorithm
- Particle swarm optimization algorithm
- Design intelligence
- Design intelligence database
- Preliminary design tools

- Design exploration procedure
- Related APIs, source codes

Finally, the created design framework is tested for a container ship design case. 250 sample designs are explored. The determined bottlenecks of design cycle are evaluation functions and searching directions. The same approach with suitable evaluation functions on the synthesis model can be reused for different cases.

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APPENDICES

APPENDIX A

Table A.1 : Minimum safe manning req. (Marshall Islands Maritime Regulations).

Application	Scale
Vessels over 3000 GT but under 5000 GT	Master Chief Mate Two (2) Officers in Charge of a Navigation Watch (OICNW) Radio Officer/GMDSS Two (2) Able Seafarers or Able Seafarers Decks Two (2) Ordinary Seafarers
Vessels under 3000 GT but over 500 GT	Master Chief Mate One (1) Officer in Charge of a Navigation Watch (OICNW) Radio Operators(s)/GMDSS Two (2) Able Seafarers or Able Seafarers Deck One (1) Ordinary Seafarer

Table A.2 : Salary factor.

Job	**Factor**
Master	10
Chief Mate	6.5
Officer in Charge of a Navigational Watch	4.0
Radio Officer	2.25
Seafarer Deck	1.1
Ordinary Seafarer	1.0
Chief Engineer	3.5
1st Assistant Engineer	3.0
Officer in Charge of an Engineering Watch	2.5
Seafarer Engine	1.1

APPENDIX B

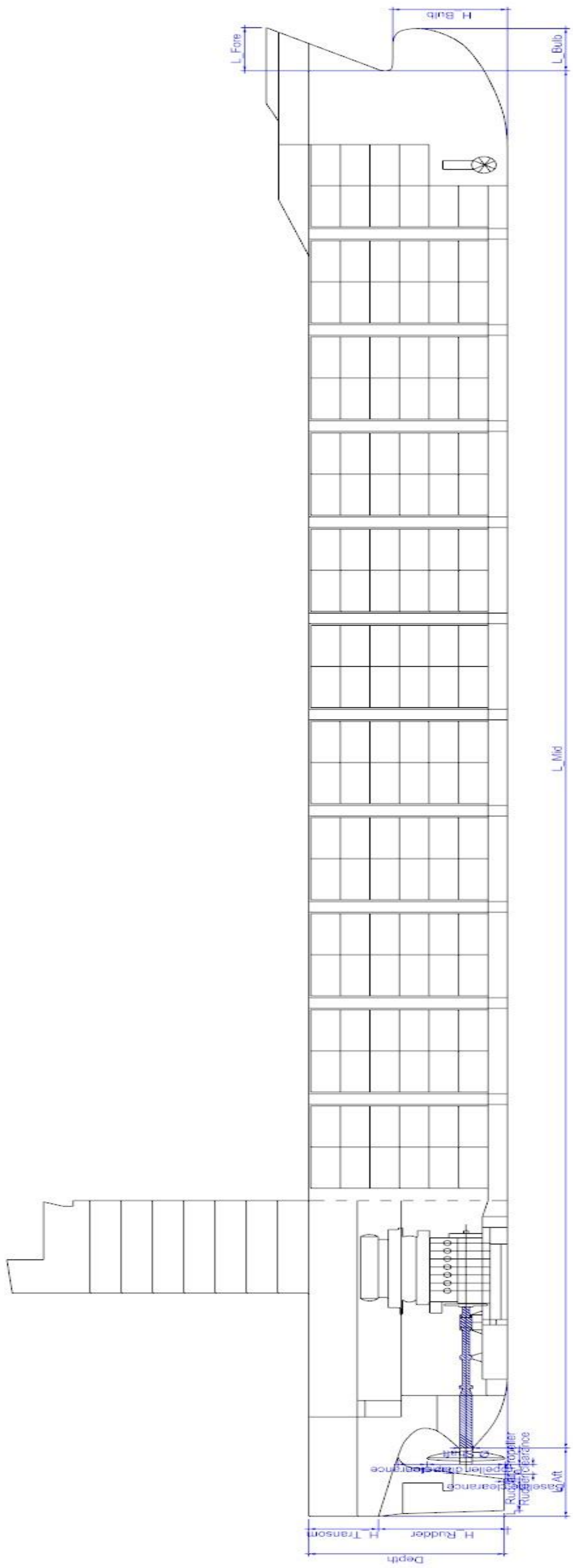

Figure B.1 : Global parameters of surface modification.

APPENDIX C

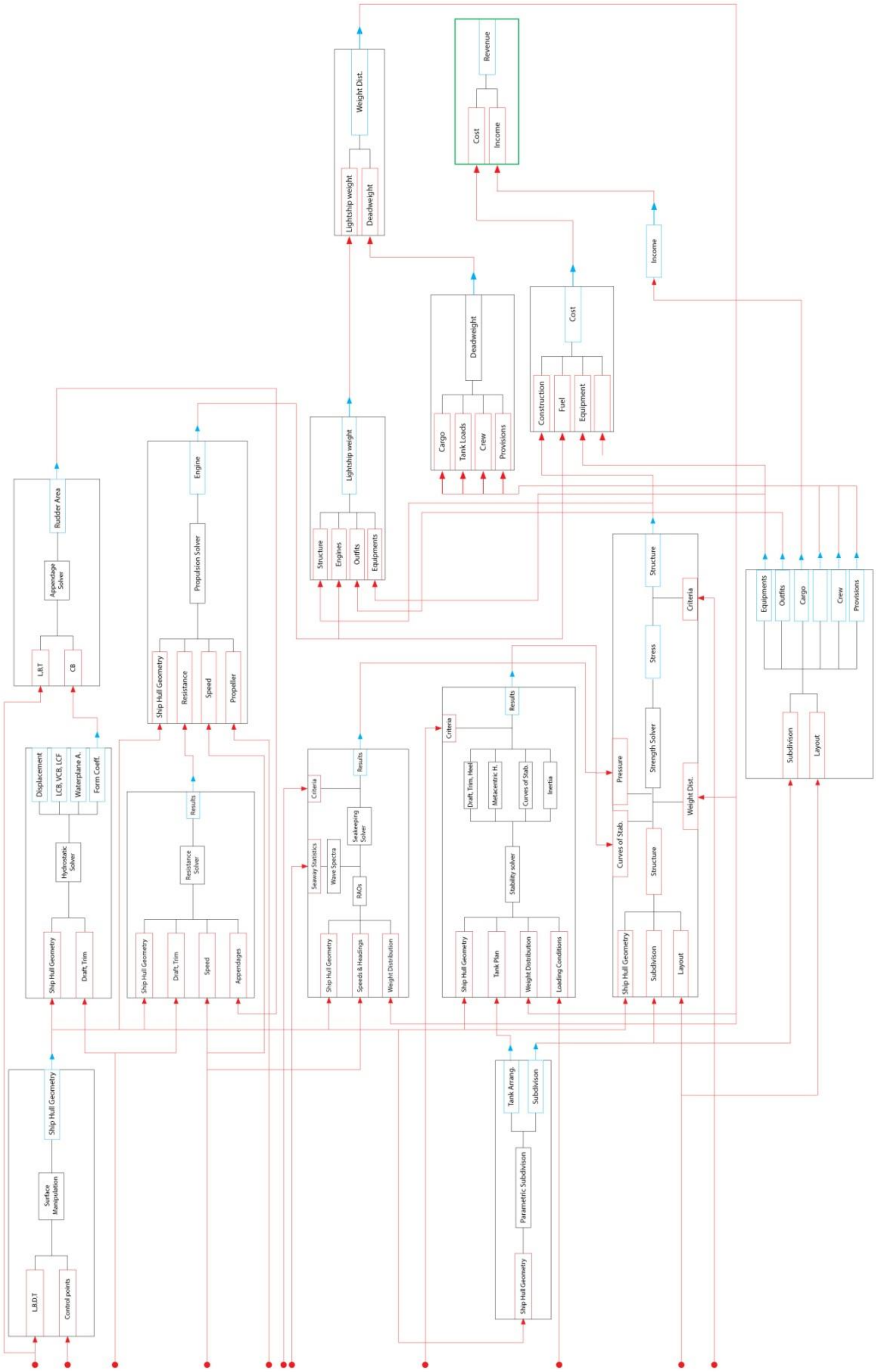

Figure C.1 : Ship synthesis model.

APPENDIX D

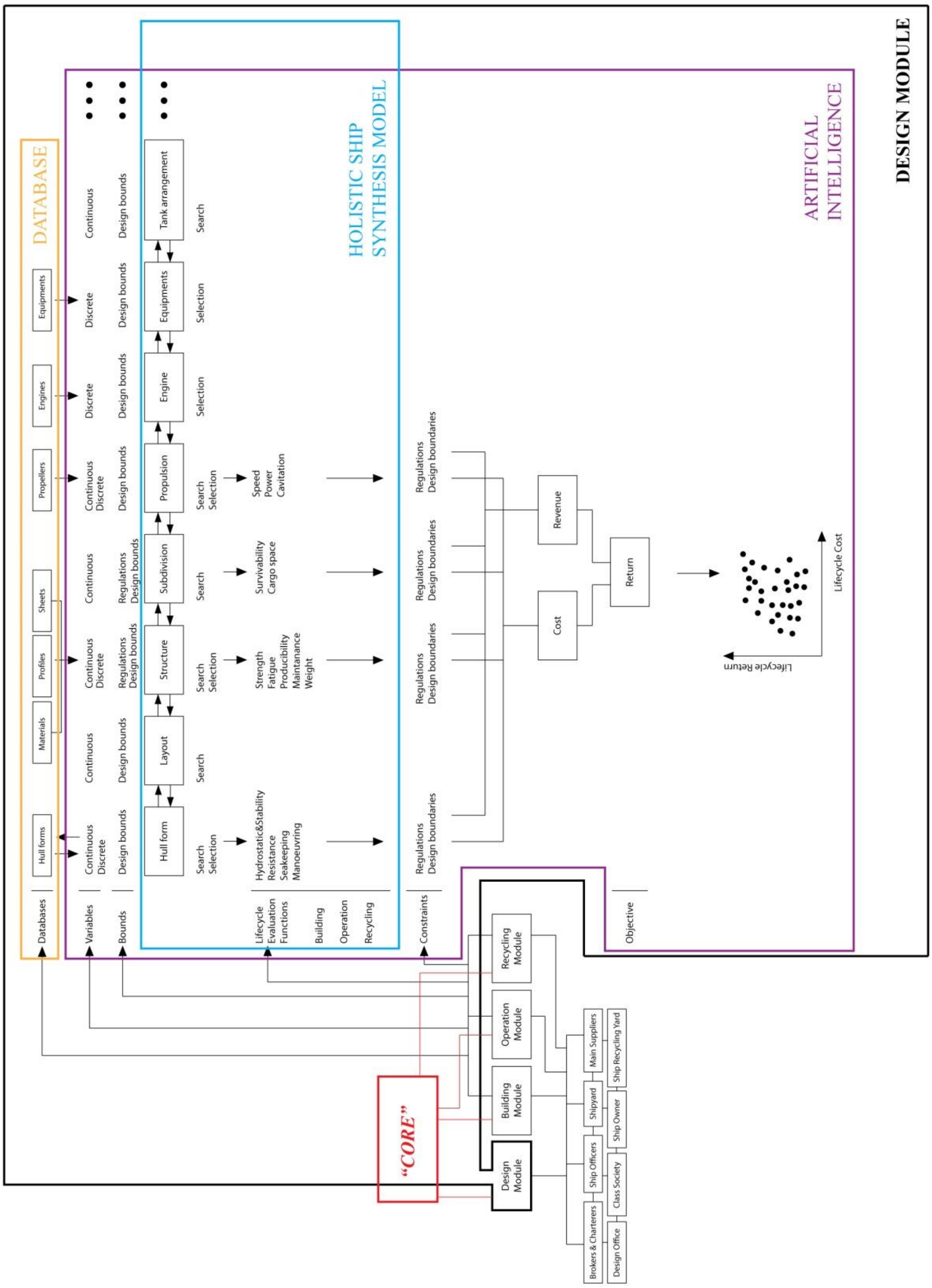

Figure D.1 : Detailed structure of the universal ship design network

Table D.1 : Explored preliminary design results – main parameters.

	Design I	Design II	Design III
Container capacity (TEU)	16400,00	12100,00	6800,00
Length overall (m)	350,04	289,56	180,04
Length waterline (m)	338,26	279,42	172,62
Beam (m)	48,20	32,20	26,40
Depth (m)	28,60	24,49	17,26
Draft (m)	15,25	13,80	11,46
Draft / Depth	0,53	0,56	0,66
Beam/Depth	1,69	1,32	1,53
Freeboard (m)	13,35	10,69	5,80
Deadweight (t)	106291,35	54265,24	20377,42
Lightweight (t)	42358,65	22478,58	10027,64
Displacement (t)	148650,00	76743,82	30405,06
Froude number	0,22	0,24	0,31
Speed (knot)	24,30	24,60	24,40
Waterline coeff.	0,698	0,655	0,699
Prismatic coeff.	0,571	0,524	0,569
Midship coeff.	0,983	0,965	0,971
Block coeff.	0,613	0,633	0,597

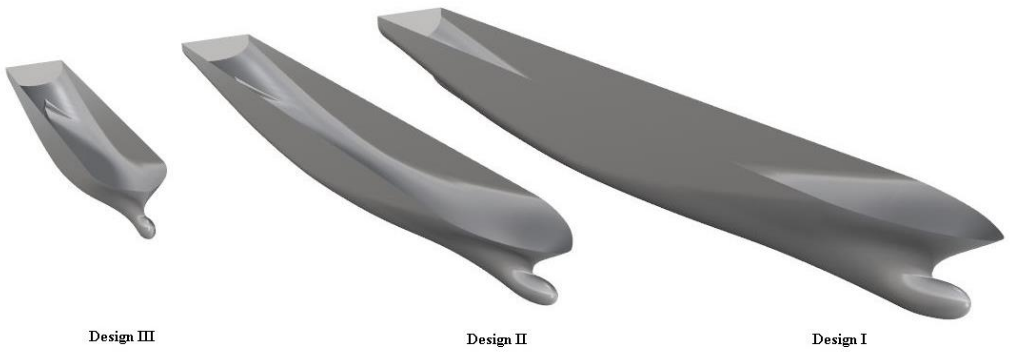

Figure D.2 : Explored hull form samples.

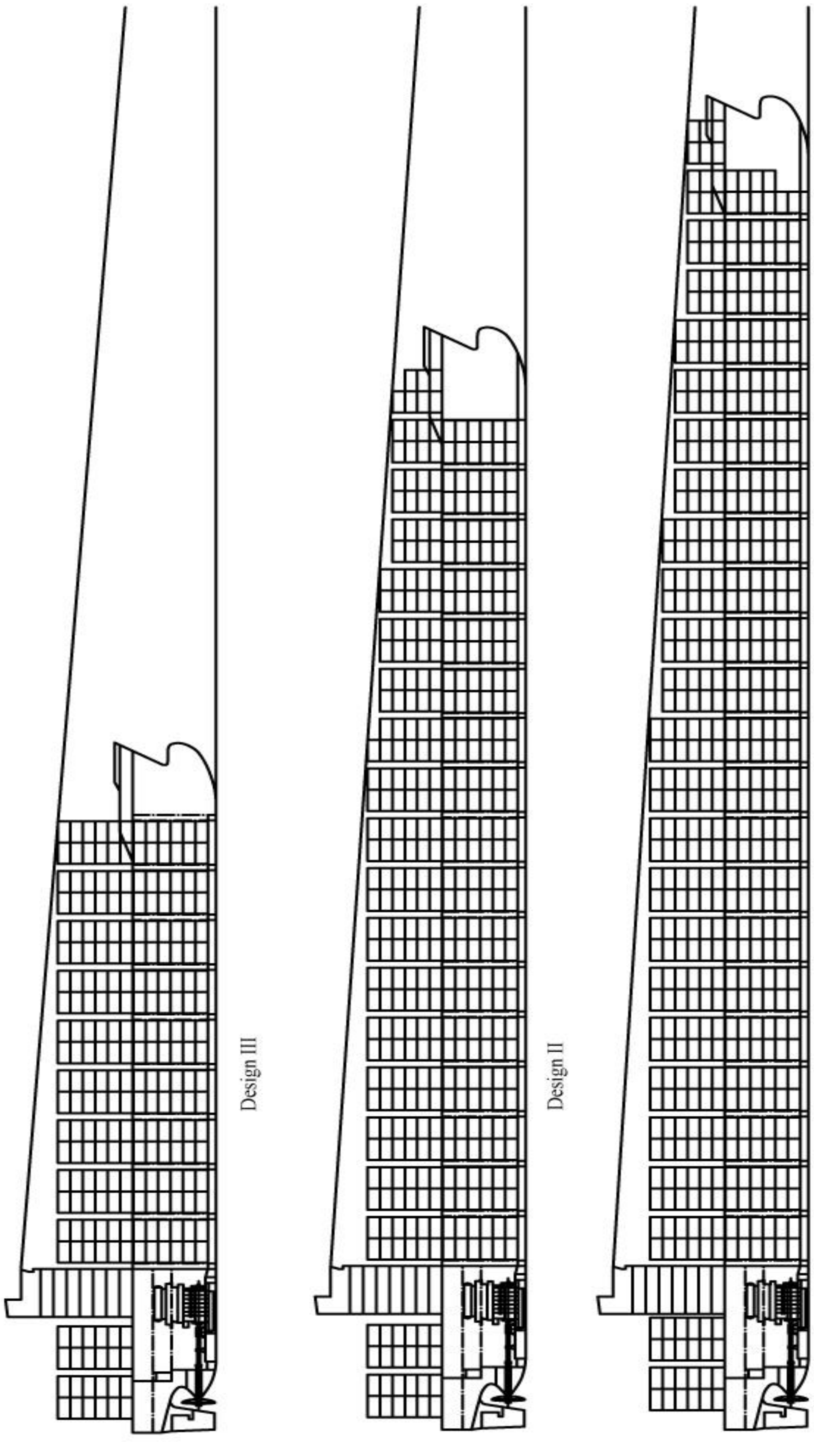

Figure D.3 : Explored general layout samples.

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- Kükner, A., Sarıoğlu, B.S., 2017. Numerical Evaluation of Resistance for Turkish type Bodrum Gulet by using OpenFOAM, Ocean Engineering (on Review)

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