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Cruise Ship Preliminary Design: The Influence of Design Features on Profitability

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Cruise Ship Preliminary Design: The Influence of Design Features on Profitability

Thesis

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Dedication

I dedicate this thesis to those who think unconventionally and aspire to do more than what is expected.

Acknowledgement

I would like to acknowledge the faculty and staff at the University of New Orleans whose support was pivotal in this project's completion. I am very grateful to Dr. McKesson and Dr. Taravella for providing me with exceptional guidance throughout my project. Also, I appreciate them and Dr. Birk for serving on my thesis committee.

Lastly, I would like to acknowledge my parents who have always unequivocally supported my passion for Naval Architecture and inspired me to fulfill my dreams.

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Abstract

This thesis provides a means to estimate the physical and performance characteristics of a preliminary cruise ship design. The techniques utilized to estimate these characteristics are showcased in the user-friendly interface known as the Cruise Ship Analysis Tool (CSAT). Using the CSAT, the implications that design feature decisions in the preliminary design stage have on a cruise ship's profitability is analyzed. Then, the most profitable design feature assemblage among a finite number of varying design feature combinations is estimated and compared among cruise ship designs with different passenger carrying capacities. Profitability is analyzed using the measure of merit (MOM) known as net present value (NPV). If a preliminary cruise ship design has a positive NPV at a reliable rate of return and ship operating life, the design is considered to be a profitable investment if implemented. The greater the NPV, the more profitable the investment is considered to be.

Cruise Ship, Preliminary Ship Design, Design Feature, Net Present Value, Cruise Ship Analysis Tool, Profitability, Cruise Ship Physical and Performance Characteristics

Chapter 1 – Introduction

The goal of this thesis is to provide a means to evaluate the implications of selecting various design features for a cruise ship in the preliminary design stage. Techniques are derived to estimate the physical and performance characteristics of a cruise ship design. These techniques are then showcased in the Cruise Ship Analysis Tool (CSAT) that provides a clear, concise, and user-friendly interface to analyze the ship's characteristics. By utilizing the techniques provided in the CSAT and the net present value (NPV) model, the implications of selecting particular design features in the preliminary design stage on a cruise ship's profitability can be evaluated.

In the preliminary design stage often some dimension, parameter, quantity, quality, or some other form of value is analyzed to distinguish a project that is most favorable among alternatives. These are known as measures of merit (MOM). A major aim in the cruising industry is to design a ship that is conducive to profitability. Profitability is the ability to yield profit. Profitability of a ship design is particularly important to a cruise company since without it they would be unable to generate the revenue needed to support their operations. According to Lamb (2003), "Engineering success depends largely on economic success" (p. 6-3). To this point, it is important for ship designers to consider the consequences of selecting a particular design feature in the preliminary design stage on the ship's potential profitability if it were actually implemented. For example, say a customer in the commercial sector contracts a Naval Architecture firm to design a ship for a particular mission. It would behoove the Naval Architects of that firm to consider the implications on profitability of selecting particular design features (e.g. hullform and engine type) in order to provide a more favorable ship design for their customer. By doing so, the relationship between the customer and the Naval Architecture firm can be strengthened and the customer has greater financial resources to promote future contractual agreements.

NPV is the most widely used MOM to analyze profitability of a potential investment. Its popularity is attributed to it being user-friendly and its effectiveness in comparing the cost characteristics among design alternatives. The NPV model analyzes the profitability of a project by considering the net benefits of the project for a specified rate of return and project life. Net benefits include the construction costs, operating costs, and revenue generated from the project over its life. Rate of return is a profit on an investment over some period of time expressed as a percentage of the amount invested. Typically, the rate of return is set at the minimum rate of return (also known as a hurdle rate) a company is willing to accept before implementing a project. Thus, if NPV is positive, the project is considered favorable and is likely to be a profitable investment if implemented. Negative NPV has the opposite effect. The higher the NPV, the more profitable the investment is likely to be. In regards to the cruising industry, the rate of return utilized in the NPV model is often based on the profitability of a built cruise ship that is considered economically successful. Thus, if a preliminary cruise ship design has a positive NPV with this rate of return it is likely to be a profitable investment as well since the built cruise ship was. In fact, cruise companies such as Carnival Corporation & plc often set a hurdle rate that subsidiary brands must surpass in order for them to increase their capacity (Buck & Conrady, 2009).

In order to analyze the NPV of a cruise ship in the preliminary design stage in this thesis, physical and performance characteristics of a cruise ship design are first estimated using the techniques discussed in Chapters 3 and 4. Many of the physical parameters of a cruise ship design are estimated via statistics of 21 different classed, built cruise ships. These cruise ships vary in a wide spectrum of gross tonnage (GT) and passenger carrying capacity that represent ships from 12 different cruise lines. Nonetheless, these parent cruise ships are not the only means utilized to estimate the physical and performance characteristics of a cruise ship design. For example, residual resistance of a cruise ship design is estimated using model data provided in the publication *Ship Resistance – Effect of Form and Principal Dimensions* (Guldhammer & Harvald, 1974).

The CSAT is a clear, concise, and user-friendly interface constructed in Microsoft Excel in order to provide a means to analyze the physical and performance characteristics of a cruise ship in the preliminary design stage. Also, the CSAT can be used to analyze the profitability of a cruise ship design via utilization of the NPV model. Although, the CSAT was constructed for this thesis's goals, nevertheless, the tool is comprehensive enough to be utilized for various analyses in regards to preliminary cruise ship design. This is because the CSAT's ability to estimate an array of cruise ship parameters which were needed to estimate NPV of that design.

To analyze the implications of selecting a particular design feature in the preliminary design stage on a cruise ship's potential profitability, NPV is analyzed for a finite number of cruise ship designs of varying design feature assemblages using the CSAT. A cruise ship design is defined by its passenger carrying capacity at double occupancy. A design feature is defined as a finite design decision that will influence a cruise ship's physicality and/or performance in some facet. For example, the selection of a diesel engine design feature instead of a gas turbine engine will influence a cruise ship's performance in terms of fuel consumption and its physicality in terms of needed fuel tankage size. A design feature assemblage is defined as the synthesis of design features.

By surface plotting NPV as a function of the possible design feature assemblages of a cruise ship design, the particular design feature assemblage that exhibits the greatest NPV of that cruise ship design can be quantified. This design feature assemblage is then considered the most profitable of that cruise ship design. The design feature assemblage that is considered most profitable for cruise ship designs are compared to analyze the influence of passenger carrying capacity on a cruise ship's potential profitability.

Chapter 2 – Background

A cruise ship is characterized as a vessel related to leisure activities (Lamb, 2004). Typically, a cruise ship returns to the same port at which it embarked from after its voyage is completed. A cruise ship differs from an ocean liner in that an ocean liner's main mission is to transport passengers from one port to another (e.g. transatlantic voyage). As of 2013, the average length of a cruise ship voyage is 7.3 days.

A cruise ship's size is most commonly measured and referred to in terms of gross tonnage (GT). GT is a dimensionless quantity that describes the volume of all enclosed spaces a ship has and serves as the basis for ship regulations and assessment of taxes and fees (Scull, 2007). Although, the actual form of GT does not include balconies, sundecks, or similar areas, cruise line marketing departments will often include these spaces to promote their ship as being larger, thus, promoting ticket sales. Nonetheless, cruise lines will use the actual GT of a cruise ship when taxes and fees are being assessed since the cost will be less. GT is not to be confused with the measurement of gross register tonnage (GRT). GT refers to the convention system derived from the provisions of the International Convention on Tonnage Measurement of Ships in 1969 (Coast Guard Marine Safety Center, 2004). GRT refers to the regulatory system and is calculated in units of register tons of 100 ft^3 per ton. The regulatory system is composed of the standard, dual, and simplified sub-systems. The standard sub-system dates back to the 1860's and is based on the British "Moorsom" system. The dual sub-system was developed in the mid-20th century to benefit shelter deck ships since it provided alternatives to fitting them with tonnage openings. The simplified sub-system was authorized by Congress in 1966 for recreational boats to reduce the cost burden for owners and the measurement workload on the government. The simplified sub-system was later extended to cover certain commercial ships.

Historically, the average GT among cruise ships delivered over the last 20 years has increased each year. This correlation is attributed to cruise companies trying to maximize profit per ship. Figure 1 illustrates the GT of Carnival Cruise Lines, Norwegian Cruise Line, and Royal Caribbean International cruise ships plotted for the year at which they were delivered (i.e. between the years 1990 and 2014).

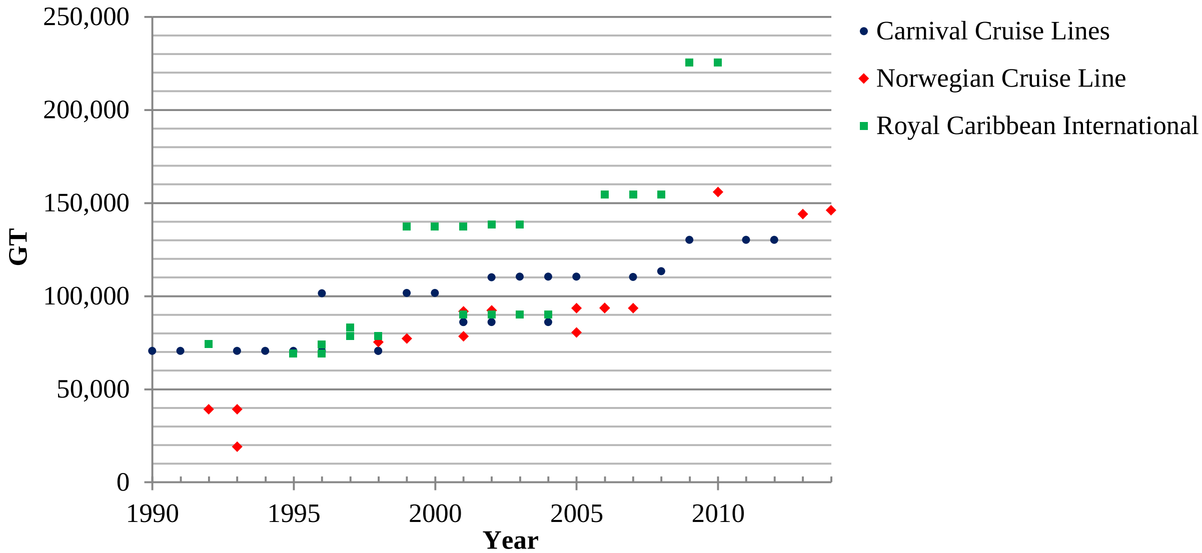

Figure 1. GT and delivery year of built cruise ships. The cruise ships of Carnival Cruise Lines, Norwegian Cruise Line, and Royal Caribbean International delivered between the years 1990-2014 are plotted.

The major cruise lines types are contemporary, premium, and luxury which are mainly distinguished by their luxuriousness and space ratio (i.e. GT per passenger). In more detail, contemporary cruise lines are considered to be amenity-packed that offer a plethora of activities in a casual environment at a great value (“Types of Cruise Lines,” n.d.). Ships in this cruise line type typically have greater GTs when compared to other cruise ships, however, lower space ratios. Examples of contemporary cruise lines are Carnival Cruise Lines, Norwegian Cruise Line, and Royal Caribbean International. Premium cruise lines are typically more upscale and elegant than contemporary cruise lines, offering greater space and comfort per passenger in a semi-formal environment; however, at a greater cost for the passenger. Also, they are typically more refined in regards to passenger services. Ships in this cruise line type typically have moderate to large GTs when compared to other cruise ships. Examples of premium cruise lines are Celebrity Cruises, Holland America Line, and Princess Cruises. Luxury cruise lines are considered to be even more upscale and elegant then premium cruise lines, offering a formal environment and personalized services in order to create a greater experience for passengers on and off the ship. These cruises will typically be at a higher cost for a passenger. Ships in this cruise line type typically have lower GTs than that of other cruise ships. Examples of luxury cruise lines are Crystal Cruise Lines, Seabourn Cruise Line, and Silversea Cruises.

Chapter 3 – Physical and Performance Estimation Techniques

Overview

The primary objective of Chapter 3 is to provide techniques to estimate the physical and performance characteristics of a cruise ship in the preliminary design stage. This includes the dimensions, power requirements, manning, and etc. of a cruise ship design. The techniques in this chapter are then utilized in the CSAT to evaluate the implications of selecting a particular design feature in the preliminary design stage on a cruise ship's potential profitability.

Parent Cruise Ship Data

Many of the techniques used to estimate the physical and performance characteristics of a cruise ship design in the CSAT are based on statistical data of built cruise ships. The built cruise ships analyzed are listed in Table 1 and are referred to as parent cruise ships in this thesis. The list consists of 21 different classed cruise ships of 12 cruise lines which were constructed between the years 1996 and 2014. These ships vary in GT between 30,277-225,282 and have electric machinery. The table lists the GT, passenger carrying capacity at double occupancy ($N_{Passengers}$), length overall (L_{OA}), length between perpendiculars (L_{PP}), beam at the waterline (B_{WL}), and draft (T) of each ship. By using a large variation of GT among different classed cruise ships of varying cruise lines that have varied luxury standards and attributes, a more accurate predictive method is made to estimate the physical and performance characteristics of a cruise ship design. Note that cruise ships within the same class were not analyzed because of data skewing concerns.

Table 1
Technical Particulars of the Parent Cruise Ships

Parent Cruise Ship	**Cruise Line**	**GT**	$\mathbf{N_{Passengers}}$	$\mathbf{L_{OA}}$ **(m)**	$\mathbf{L_{PP}}$ **(m)**	$\mathbf{B_{WL}}$ **(m)**	**T (m)**
AIDAaura	AIDA	42,289	1,266	202.8	182.0	28.1	6.19
AIDAluna	AIDA	69,203	2,050	252.0	226.0	32.2	7.30
Azamara Journey	Azamara	30,277	710	180.4	157.9	25.6	6.05
Carnival Destiny	Carnival	101,353	2,642	272.2	230.0	35.5	8.23
Carnival Dream	Carnival	128,251	3,646	305.6	269.2	37.2	8.20
Carnival Miracle	Carnival	85,942	2,124	292.5	262.7	32.2	7.90
Carnival Splendor	Carnival	113,323	3,006	290.2	247.7	35.4	8.30
Celebrity Solstice	Celebrity	121,878	2,852	317.2	293.6	36.8	8.30
Costa Luminosa	Costa	92,600	2,260	294.0	265.4	32.3	8.00
Disney Dream	Disney	128,000	2,500	339.5	303.0	37.0	7.90
Nieuw Amsterdam	HAL	86,273	2,106	285.3	254.0	32.3	7.80
MSC Magnifica	MSC	93,330	2,518	292.9	269.1	32.2	7.85
MSC Opera	MSC	59,058	1,712	251.2	222.3	28.8	6.81
Norwegian Breakaway	NCL	145,645	3,969	324.0	300.1	39.7	8.30
Norwegian Epic	NCL	155,873	4,228	330.0	288.8	40.6	8.70
Pride of America	NCL	80,439	2,186	280.6	257.6	32.2	7.99
Royal Princess	Princess	141,000	3,600	330.0	306.0	37.5	8.53
Ruby Princess	Princess	113,561	3,070	289.6	245.0	36.0	8.50
Freedom of the Seas	RCI	154,407	3,634	338.8	303.2	38.6	8.50
Oasis of the Seas	RCI	225,282	5,412	361.6	330.0	47.0	9.10
Seabourn Quest	Seabourn	32,346	450	198.2	169.2	25.6	6.40

Note. The cruise line, GT, $N_{Passengers}$, L_{OA}, L_{PP}, B_{WL}, and T of the parent cruise ships are listed the table.

Stateroom Luxury Factor

The concept of stateroom luxury factor (SLF) is utilized in this thesis to estimate the GT of a preliminary cruise ship design.

A cruise ship's GT can be estimated by relating GT to the summation of all passenger stateroom volumes (V_{St}). This concept is known as SLF. A stateroom of more luxuriousness is considered to be one of larger volume and more amenities than that of a stateroom with less luxuriousness.

Consider two cruise ships with the same $N_{Passengers}$; however, different levels of luxuriousness based on their respective stateroom arrangement. That is, one ship is composed mostly of staterooms of lower luxury while the other of higher luxury staterooms. The enclosed volume of crew and public spaces most likely would not differ drastically between the two ships because $N_{Passengers}$ is constant; however, V_{St} can be much higher for the ship that is more luxurious. Therefore, the difference in volume between these two ships is primarily due to the difference in V_{St}. Since GT describes the volume of all enclosed spaces a ship has, V_{St} can be used to estimate GT.

To determine the relationship between V_{St} and GT, V_{St} of 14 of the 21 parent cruise ships listed in Table 1 is determined. This is accomplished by first determining the total floor area (A_{St}) of all passenger staterooms. When calculating this summation, each stateroom type's respective size (i.e. "luxuriousness") is considered. Then, assuming the floor-to-ceiling height is 2.8 m for all passenger staterooms, V_{St} is estimated for these parent cruise ships. The results of this analysis are shown in Table 2.

Table 2
A_{St} and V_{St} for the Passenger Staterooms of the Parent Cruise Ships

Parent Cruise Ship	**A_{St} (m^2)**	**V_{St} (m^3)**
Azamara Journey	7,519	21,053
Carnival Dream	34,935	97,818
Carnival Miracle	21,534	60,295
Carnival Splendor	28,405	79,534
Celebrity Solstice	26,992	75,577
Disney Dream	30,230	84,644
Nieuw Amsterdam	24,326	68,113
MSC Magnifica	22,236	62,261
MSC Opera	12,143	34,000
Norwegian Breakaway	36,519	102,253
Norwegian Epic	39,080	109,424
Pride of America	16,211	45,391
Oasis of the Seas	60,930	170,604
Seabourn Quest	8,397	23,512

Note. It is assumed $V_{St} = 2.8 * A_{St}$.

The values of V_{St} for the 14 parent cruise ships listed in Table 2 are plotted as a function of their respective GT values, as shown in Figure 2. As the figure indicates, a linear relationship exists between V_{St} and GT in which a linear-fit of the data points exhibits a R^2 value of 0.97. Due to this strong correlation, the following equation of the linear-fit is used to estimate GT:

$$GT = 1.406(V_{St}) \tag{1}$$

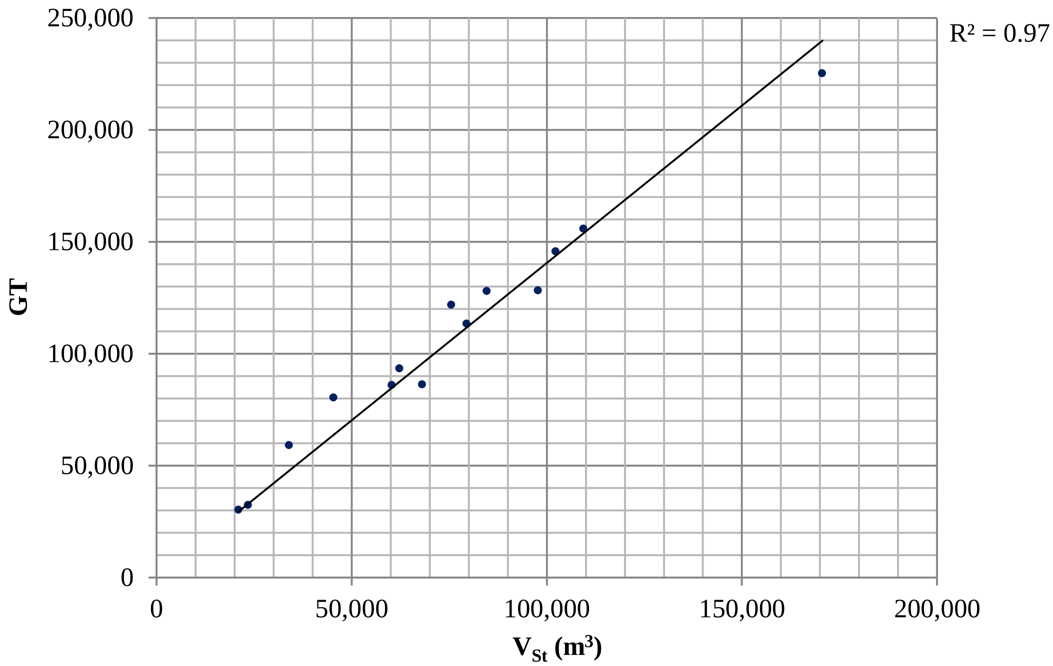

Figure 2. Correlation between V_{St} and GT. This is analyzed for the 14 parent cruise ships listed in Table 2.

Equation (1) is used in the CSAT to estimate GT for a preliminary cruise ship design. That is, a user inputs $N_{Passengers}$ and the stateroom type(s) desired. There are three options to select from which are distinguished by their luxury level. The first option is considered the least luxurious of the three and is defined as a Lower Luxury Stateroom (LLS). A LLS is characterized as having a smaller volume and fewer amenities than the other stateroom types. Examples of this would be a normal-sized interior stateroom or a normal-sized window stateroom. The second option is considered moderate in terms of luxuriousness and is defined as a Moderate Luxury Stateroom (MLS). A MLS is characterized as having a moderate volume and more amenities than a LLS, but less than that of the even more luxurious stateroom type. An example of this would be a normal-sized balcony stateroom. The last option is characterized as being the most luxurious of the three and is defined as a Higher Luxury Stateroom (HLS). A HLS is characterized as having the largest volume and the most amenities of the three options. An example of this would be a balcony suite. A MLS or a HLS is considered to have an accompanying balcony while a LLS does not have one. The stateroom types and their respective floor areas and volumes analyzed in this thesis (and CSAT) are listed in Table 3. These values are based on averages obtained among the 14 parent cruise ships analyzed for A_{St} and V_{St} (see Table 2).

Table 3
Floor Area and Volume of Each Stateroom Type

Stateroom Type	**Floor Area (m^2)**	**Volume (m^3)**
LLS	14.50	40.60
MLS	23.50	65.80
HLS	39.95	111.86

Note. These stateroom types and respective floor areas and volumes are used in the CSAT.

Displacement Volume

Each parent cruise ship's displacement volume (∇) is estimated via the following equation in units of m^3:

$$\nabla = C_{B,PP}(L_{WL} B_{WL} T) \tag{2}$$

In equation (2), L_{WL}, B_{WL}, and T are known for each parent cruise ship via Table 1. Thus, the only unknown in the equation is the block coefficient based on L_{PP} ($C_{B,PP}$). $C_{B,PP}$ can be estimated using the Alexander formula (van Lammeren, et al, 1948) as follows:

$$C_{B,PP} = 1.08 - \frac{1}{0.595}\left(\frac{v_{Trial}}{\sqrt{g * L_{PP}}}\right) \tag{3}$$

v_{Trial} in equation (3) is the trial speed of the ship in units of m/s. g is gravitational acceleration with a value of 9.81 m/s^2. The estimated $C_{B,PP}$ for each parent cruise ship is shown in Table 32 in Appendix A.

∇ can now be estimated via equation (2) for each parent cruise ship, as shown in Table 32 in Appendix A. The correlation between GT and ∇ for the parent cruise ships is plotted in Figure 3. A power-fit of the data points exhibits a R^2 value of 0.98. Due to this strong correlation, this equation of fit is used to estimate ∇ in units of m^3:

$$\nabla = 1.365(GT)^{0.912} \tag{4}$$

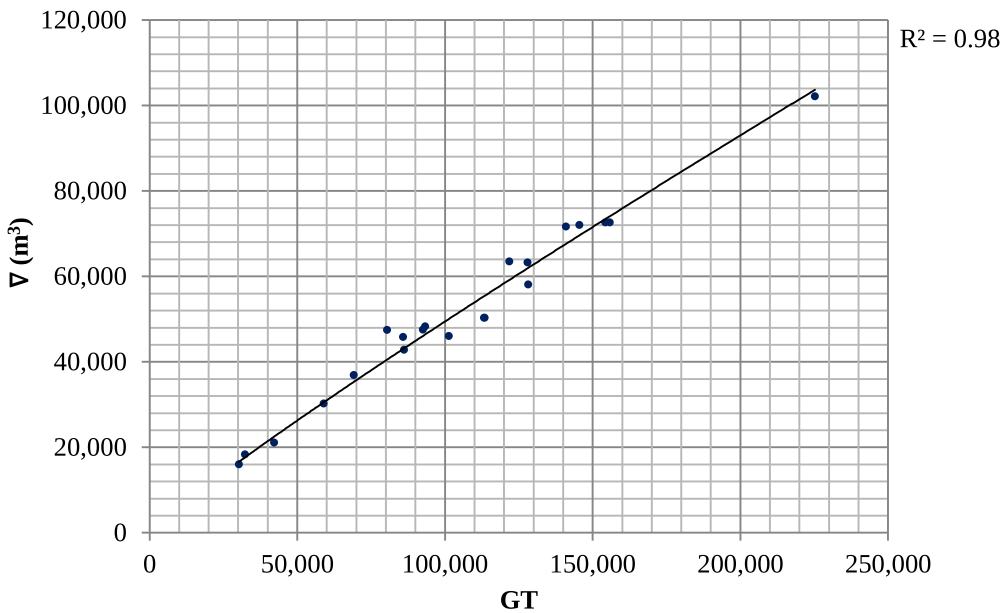

Figure 3. Correlation between ∇ and GT. This correlation is exhibited among the parent cruise ships.

Displacement Weight

Since cruise ships are buoyantly lifted, by balancing the weight of the ship with buoyancy forces, the displacement weight (Δ) of a cruise ship design can be estimated by the following equation using ∇ solved via equation (4):

$$\rho_{sw} g \nabla = \Delta g \quad \rightarrow \quad \Delta = \rho_{sw} \nabla \tag{5}$$

ρ_{sw} in equation (5) is the density of saltwater having a value of 1025 kgm^{-3} at 15ºC. Dividing this equation by 1,000 gives the weight of the ship in units of metric tons. See Table 32 in Appendix A for the Δ estimations of the parent cruise ships.

Beam, Length, Draft, and Hull Depth Dimensions

Beam

A correlation between B_{WL} and GT exists among the parent cruise ships, as shown in Figure 4. A power-fit of the data points exhibits a R^2 value of 0.95. Thus, the equation of this fit is used to estimate B_{WL} as follows:

$$B_{WL} = 1.304(GT)^{0.285} \tag{6}$$

One interesting feature of Figure 4 worthy of noting is the cluster of data points corresponding to cruise ships of varying GT that have values of B_{WL} just below 32.3 m, as circled in the figure. This is likely attributed to the limitations of the Panama Canal which requires ships to have a B_{WL} less than 32.3 m in order for them to fit through the canal's locks.

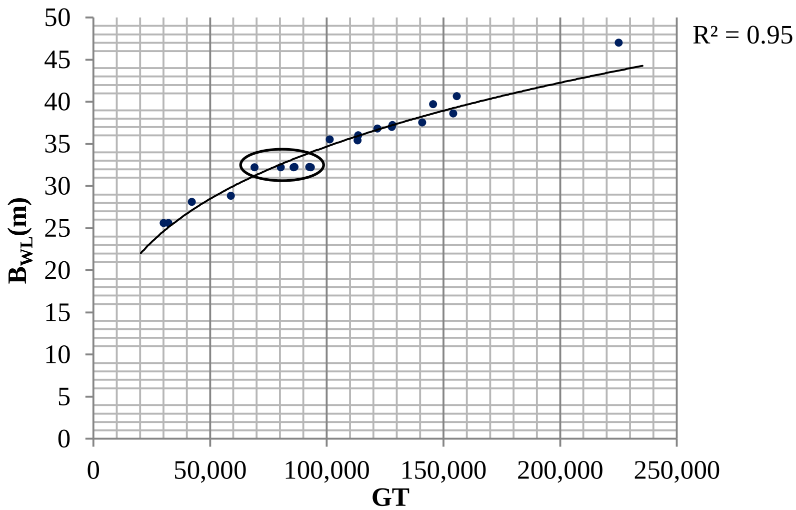

Figure 4. Correlation between B_{WL} and GT. This correlation is exhibited among the parent cruise ships.

Length

A correlation between L_{OA} and $\nabla^{1/3}$ is evident among the parent cruise ships, as shown in Figure 5. A linear-fit of the data points exhibits a R^2 value of 0.96. Thus, the following equation of this fit is used to estimate L_{OA} of a cruise ship design in units of m:

$$L_{OA} = 7.904(\nabla)^{1/3} \quad (7)$$

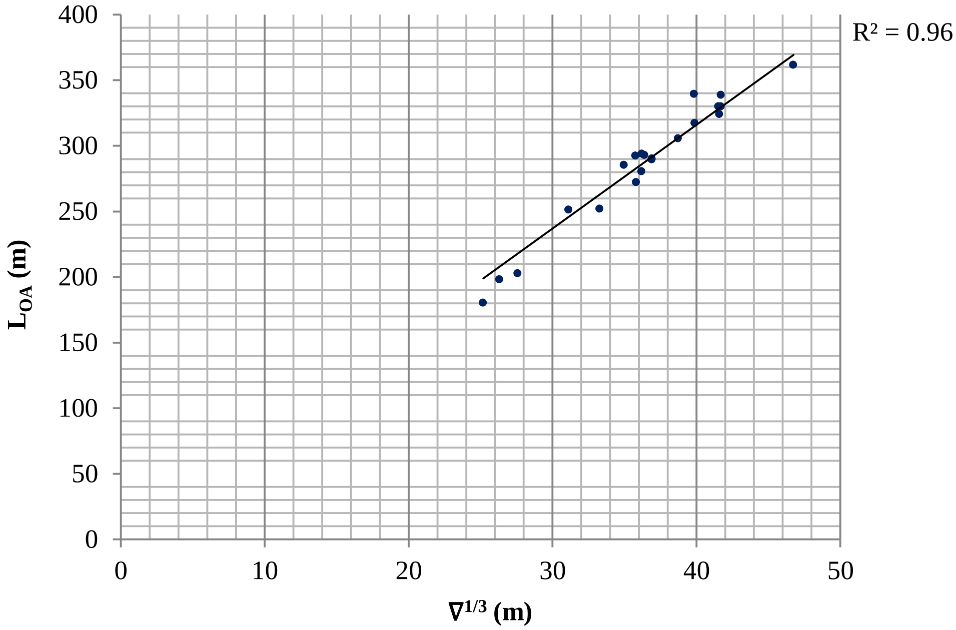

Figure 5. Correlation between L_{OA} and $\nabla^{1/3}$. This correlation is exhibited among the parent cruise ships.

A strong correlation between L_{PP} and L_{OA} among the parent cruise ships is exhibited, as shown in Figure 6. A linear-fit of the data points exhibits a R^2 value of 0.97. Using the estimated L_{OA} via equation (7), L_{PP} can be estimated via the following equation of this fit in units of m:

$$L_{PP} = 0.894(L_{OA}) \quad (8)$$

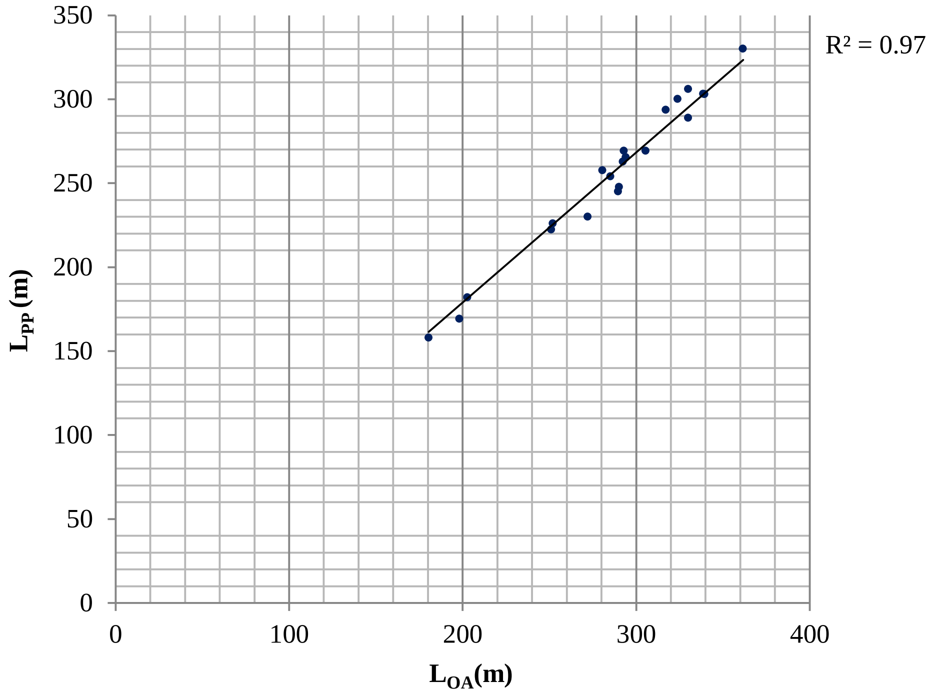

Figure 6. Correlation between L_{PP} and L_{OA}. This correlation is exhibited among the parent cruise ships.

In regards to length at waterline (L_{WL}) of a cruise ship design, it is assumed L_{WL} is 102% of L_{PP}.

Draft

Since L_{WL}, B_{WL}, $C_{B,PP}$, and ∇ can now be estimated via the previous relationships, T can be estimated in units of m by rearranging equation (2) as follows:

$$\nabla = C_{B,PP}(L_{WL}B_{WL}T) \quad \rightarrow \quad T = \frac{\nabla}{C_{B,PP}(L_{WL}B_{WL})} \tag{9}$$

Hull Depth

A correlation between L_{OA} and D among the parent cruise ships is exhibited, as shown in Figure 7. A power-fit of the data points in the figure exhibits a R^2 value of 0.90. The following equation of this fit is used to estimate D in units of m:

$$D = 0.26(L_{OA})^{0.782} \tag{10}$$

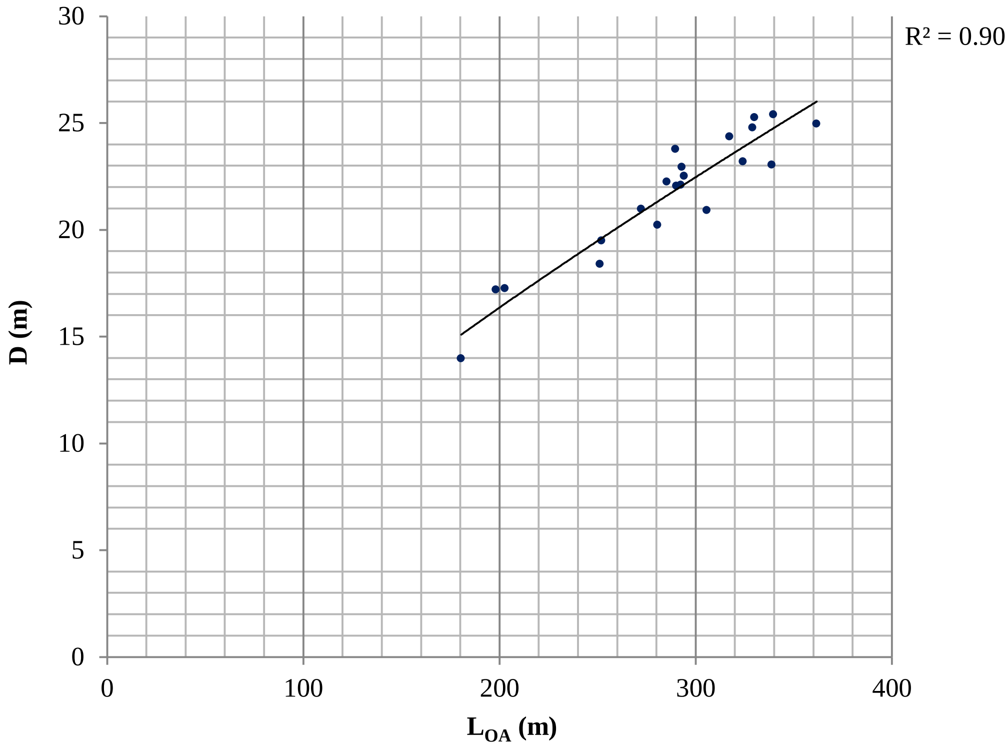

Figure 7. Correlation between D and L_{OA}. This correlation is exhibited among the parent cruise ships.

Volume

The total volume in m^3 of all enclosed spaces on a cruise ship (V_{Tot}) can be related to GT by the following summation:

$$GT = K * V_{Tot} \qquad \text{with:} \quad K = 0.2 + 0.02 * \log_{10}(V_{Tot}) \tag{11}$$

V_{Tot} is estimated for a cruise ship design by rearranging and approximating equation (11) as follows:

$$V_{Tot} \approx 3.17(GT) \tag{12}$$

A cruise ship design's hull volume (V_H) in units of m^3 can be estimated utilizing the following equation provided in *The Maritime Engineering Reference Book* (Molland, 2008):

$$V_H = C_B'(L_{OA}B_{WL}D) \qquad \text{with:} \quad C_B' = C_B + (1 - C_B)\left(\frac{0.8D - T}{3T}\right) \tag{13}$$

Since V_{Tot} and V_H can now be estimated via equations (12) and (13), the superstructure volume (V_{SS}) of a cruise ship design can be estimated in units of m^3 by rearranging the following equation:

$$V_{Tot} = V_H + V_{SS} \quad \rightarrow \quad V_{SS} = V_{Tot} - V_H \tag{14}$$

Resistance and Power

Resistance

To estimate the amount of power needed for propulsion of a cruise ship design, the total ship resistance (R_T) is first estimated. R_T is represented mathematically by the following equation:

$$R_T = C_T\left(\frac{1}{2}\rho_{sw}v^2S\right) \tag{15}$$

In equation (15), C_T is the total ship resistance coefficient, v is the ship speed, and S is the wetted surface of the ship. In this thesis, S is estimated in units of m^2 using the following formula provided in the publication *An Approximate Power Prediction Method* (Holtrop & Mennen, 1982):

$$\begin{aligned} S = {} & L_{WL}(2T + B)\sqrt{C_M}[0.453 + 0.4425C_B - 0.2862C_M \\ & - 0.003467(B/T) + 0.3696C_{WP}] + 2.38\ (A_{BT}/C_B) \end{aligned} \tag{16}$$

In equation (16), C_M and C_{WP} are the midship and waterplane coefficients respectively. C_M and C_{WP} are estimated via the following formulas provided in *Ship Resistance and Propulsion* (Hudson, Molland, & Turnock, 2011) and *Ship Design and Performance for Masters and Mates* (Barrass, 2004) respectively:

$$C_M = 0.80 + 0.21(C_B) \tag{17}$$

$$C_{WP} = \frac{2}{3}(C_B) + \frac{1}{3} \tag{18}$$

The last term in equation (16) is for consideration of the wetted surface of a bulbous bow. In regards to this term, A_{BT} is the cross-sectional area of the bulb at the fore perpendicular. A_M is the midship section area which is needed to estimate A_{BT} as follows:

$$A_M = C_M(B * T) = [0.80 + 0.21(C_B)](B * T) = \frac{A_{BT}}{C_{ABT}} \tag{19}$$

As equation (19) indicates, the cross-section parameter of the bulb (C_{ABT}) needs to be known to estimate A_{BT}. A value of C_{ABT} is selected such that the residual power reduction coefficient ($\Delta C_{P\nabla R}$) is maximized. $\Delta C_{P\nabla R}$ is a measure of the percentage reduction in power using a bulb compared with a normal bow in which a larger value indicates a greater power reduction. Kracht (1978) provides values of $\Delta C_{P\nabla R}$ as a function of C_{ABT} for a range of Froude numbers (F_n), as shown in Figure 8. This figure is applicable for C_B equal to 0.7. Since the average C_B among the parent cruise ships is 0.68, it is assumed this figure is also applicable for cruise ship designs analyzed in the CSAT as well. The figure indicates the greatest $\Delta C_{P\nabla R}$ for all F_n curves is approximately at C_{ABT} equal to 0.125. Therefore, this value is assumed and A_{BT} can now be estimated via rearranging equation (19).

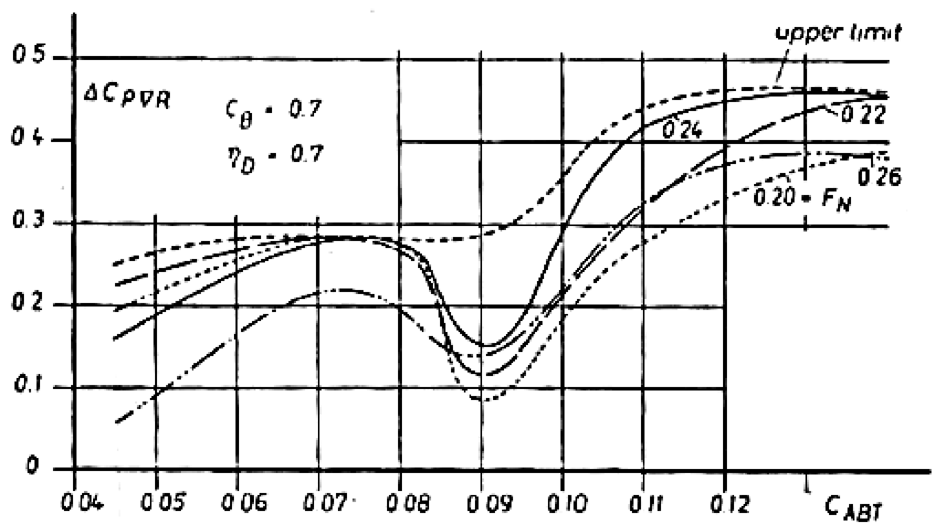

Figure 8. $\Delta C_{P\nabla R}$ as a function of C_{ABT}. Reprinted from *Ship Resistance and Propulsion* (p. 327), by D.A. Hudson, A.F. Molland, & S.R. Turnock, 2011, New York, NY: Cambridge University Press. Copyright 2011 by D.A. Hudson, A.F. Molland, & S.R. Turnock, 2011.

Equation (16) used to estimate S needs to be corrected (i.e. S_{Corr}) for consideration of the type of appendages a cruise ship design can have. A cruise ship design can have either a traditional or pod propulsion and maneuvering system in this thesis. The wetted surface of the appendages associated with traditional propulsion and maneuvering system (e.g. shafts, rudders, and etc.) will differ from that of the pod propulsion and maneuvering system (e.g. pods). To estimate S_{Corr} for traditional ($S_{Corr,Trad}$) and pod ($S_{Corr,Pod}$) propulsion and maneuvering systems, the following equations are used:

$$S_{Corr,Trad} = S(1 + 0.0075 * N_{Rudder} + 0.03 * N_{Shaft}) \quad (20a)$$

$$S_{Corr,Pod} = S + 87.2 * N_{Pod} \quad (20b)$$

In equation (20a), N_{Rudder} and N_{Shaft} are the numbers of rudder(s) and shaft(s) the cruise ship is designed to have. The values of 0.0075 (0.75%) and 0.03 (3%) represent the percent increase that each appendage will have on the ship's overall wetted surface. For this equation, it is assumed a cruise ship design will not have bossings. In regards to equation (20b), N_{Pod} is the number of pod(s) the ship is designed to have. The value of 87.2 in this equation represents the approximate wetted surface of each pod in units of m^2. With consideration of these corrections, R_T is now defined as follows:

$$R_T = C_T\left(\frac{1}{2}\rho_{sw}v^2S_{Corr}\right) \quad (21)$$

To estimate R_T, the total ship resistance coefficient is first estimated via the following equation:

$$C_T = C_F + C_R + C_A + C_{AA} + C_{AS} \quad (22)$$

In equation (22) C_F, C_R, C_A, C_{AA}, and C_{AS} are the frictional, residual, incremental, air, and steering resistance coefficients respectively. The calculations regarding each component of C_T are detailed in the following paragraphs.

The frictional resistance coefficient is estimated using the ITTC 1957 model-ship correlation line which corresponds to the following equation:

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2} \quad (23)$$

In equation (23), R_n is the Reynolds number (vL_{WL}/υ) where υ is the kinematic viscosity of saltwater ($1.188 * 10^{-6} m^2/s$ at 15ºC).

Since the residual resistance coefficient of a ship will be equivalent to that of its model, model test data is used to estimate C_R. Model test data provided in the publication *Ship Resistance – Effect of Form and Principal Dimensions* (Guldhammer & Harvald, 1974) is used to estimate C_R since model test data is obviously not available for a cruise ship design generated in the CSAT. This empirical method is based on an extensive analysis that is comprised of many documented model tests. In this publication, diagrams of C_R plotted as a function of F_n (between 0.15 and 0.45), prismatic coefficient (C_P), and $L_{WL}/\nabla^{1/3}$ are provided. Each C_R diagram is applicable to a specific $L_{WL}/\nabla^{1/3}$ between 4.0 and 8.0. Each curve in a diagram is applicable to a specific C_P between 0.50 and 0.80. The C_R diagrams pertaining to $L_{WL}/\nabla^{1/3}$ between 6.5 and 8.0 are utilized in thesis (see Appendix B) since all parent cruise ships have values of $L_{WL}/\nabla^{1/3}$ in this range. Therefore, it is assumed any cruise ship design generated in the CSAT would also have values of $L_{WL}/\nabla^{1/3}$ in this range.

The model hullforms used to predict C_R could have different aspects than that of a cruise ship hullform. Guldhammer and Harvald (1974) recommend that if a hullform is different from the model hullforms in the following aspects, C_R should be corrected:

- $\Delta C_{R,B/T\neq 2.5}$: B/T deviation from 2.5 (C_R diagrams are applicable for ships with a beam/draft ratio of 2.5)
- $\Delta C_{R,LCB}$: Location of the center of buoyancy, LCB (C_R diagrams correspond to ships with LCB near the best possible position)
- $\Delta C_{R,Hullform}$: Hullform variation (C_R diagrams are based on ships having a "standard" form [i.e. neither distinctively U nor V shaped])
- $\Delta C_{R,Bulb}$: Bulbous bow (C_R diagrams are based on ships not having a bulbous bow)

Considering these corrections, C_R is now estimated as follows:

$$C_{R,Corrected} = C_{R,Diagram} + \Delta C_{R,B/T\neq 2.5} + \Delta C_{R,LCB} + \Delta C_{R,Hullform} + \Delta C_{R,Bulb} \quad (24)$$

$C_{R,Diagram}$ given in equation (24) corresponds to the C_R estimated via the diagrams (see Appendix B).

The correction regarding $\Delta C_{R,B/T\neq 2.5}$ is applied when the beam/draft is not 2.5. This correction is considered in the CSAT as follows:

$$\Delta C_{R,B/T\neq 2.5} = 0.16\left(\frac{B}{T} - 2.5\right) * 10^{-3} \quad (25)$$

The correction for $\Delta C_{R,B/T\neq 2.5}$, equation (25), is limited to B/T $\leq$ 3 since greater values than this mean the correction will dominants the total wave-making resistance.

LCB is the longitudinal position of center of buoyancy and is described as the distance from this point to the midship section. In the CSAT, it is assumed a cruise ship design has LCB near the best possible position, and thus, $\Delta C_{R,LCB}$ is assumed to be zero.

The C_R diagrams are applicable for ships having a "standard" form. That is, not being distinctively U or V shaped. In regards to this, the following corrections are recommended for the given conditions:

If Fore Body is: (26a)

- Extreme U: $\Delta C_{R,Hullform} = -0.1 * 10^{-3}$
- Extreme V: $\Delta C_{R,Hullform} = +0.1 * 10^{-3}$

If After Body is: (26b)

- Extreme U: $\Delta C_{R,Hullform} = +0.1 * 10^{-3}$
- Extreme V: $\Delta C_{R,Hullform} = -0.1 * 10^{-3}$

Guldhammer and Harvald (1974) note when estimating the effective power of a preliminary ship design, it is not normally necessary to make the correction for $\Delta C_{R,Hullform}$ (i.e. equations [26a] and [26b]). Thus, $\Delta C_{R,Hullform}$ is assumed to be zero in this thesis.

The C_R diagrams are based on ships not having a bulbous bow. When a ship has a bulbous bow, the corrections for $\Delta C_{R,Bulb}$ listed in Table 4 are recommended. The correction values are applicable for the F_n and C_P combinations listed in the table. Note that this table is applicable for $A_{BT}/A_M \geq 0.10$. Some cell boxes in the table are empty which indicate data is not readily available for these particular F_n and C_P combinations.

Table 4

Recommended Corrections for $\Delta C_{R,Bulb} \cdot 10^3$

$\mathbf{C_P}$	$\mathbf{F_n = 0.15}$	$\mathbf{0.18}$	$\mathbf{0.21}$	$\mathbf{0.24}$	$\mathbf{0.27}$	$\mathbf{0.30}$	$\mathbf{0.33}$	$\mathbf{0.36}$
$\mathbf{0.50}$			$+0.2$	0	-0.2	-0.4	-0.4	-0.4
$\mathbf{0.60}$			$+0.2$	0	-0.2	-0.3	-0.3	
$\mathbf{0.70}$		$+0.2$	0	-0.2	-0.3	-0.3		
$\mathbf{0.80}$	$+0.1$	0	-0.2					

Note. These corrections are valid for $A_{BT}/A_M \geq 0.10$. Adapted from *Resistance and Propulsion of Ships* (p. 129), by Sv. Aa. Harvald, 1983, Malabar, FL: Krieger Publishing Company. Copyright 1983 by John Wiley and Sons, Inc.

Since a cruise ship design can have a F_n and C_P combination corresponding to one of the empty cell boxes in Table 4 that indicates $\Delta C_{R,Bulb}$ is unknown, the method proposed by Kristensen and Lützen (2012) is used to estimate $\Delta C_{R,Bulb}$. This method is an extension of the Guldhammer and Harvald (1974) method and considers the correction due to the influence of the bulbous bow as a percent of the residual resistance based on a regression analysis of 229 model test values for 21 different ships. In their analysis the total resistance coefficient was estimated for each individual ship using the Guldhammer and Harvald (1974) method without any correction in regards to the influence of a bulbous bow. Then, each value was subtracted from a ship's respective total resistance coefficient that was determined by model tests (i.e. with the influence of a bulbous bow) in order to estimate the bulbous bow correction. From their analysis the following equation is derived to estimate $\Delta C_{R,Bulb}$ as a function of F_n and $C_{R,Diagram}$:

$$\Delta C_{R,Bulb} = (250F_n - 90)\frac{C_{R,Diagram}}{100} \tag{27}$$

The roughness of the surface of a ship will affect C_T. Due to this, the incremental resistance coefficient is considered when calculating C_T in this thesis. Guldhammer and Harvald (1974) recommend using the C_A values as a function of Δ listed in Table 5.

Table 5

C_A as a Function of Δ

Δ	$\mathbf{C_A}$
1,000 T	$0.6 * 10^{-3}$
10,000 T	$0.4 * 10^{-3}$
100,000 T	0
1,000,000 T	$-0.6 * 10^{-3}$

Note. Adapted from *Resistance and Propulsion of Ships* (p. 130), by Sv. Aa. Harvald, 1983, Malabar, FL: Krieger Publishing Company. Copyright 1983 by John Wiley and Sons, Inc.

The relationship of the data in Table 5 can be expressed by the following formula:

$$C_A = [0.5\log(\Delta) - 0.1(\log(\Delta))^2] * 10^{-3} \tag{28}$$

In regards to the air resistance and steering resistance coefficients, C_{AA} and C_{AS} are assumed to be very small and in the preliminary design stage are assumed to be included in the incremental resistance coefficient.

Using the techniques provided in this section to estimate the S and the coefficients of C_T, R_T can now be estimated for a cruise ship design.

Propulsion Power

The power needed to move a ship through water (or tow the ship at some speed) is defined as effective power (P_E). P_E is estimated by the following equation that relates total ship resistance to speed:

$$P_E = R_T * v \tag{29}$$

The brake power needed to propel a ship ($P_{B,P}$) is relatable to effective power by the following equation:

$$P_{B,P} = \frac{P_E}{\eta_H \eta_B \eta_S \eta_M} = \frac{P_E}{\eta_{Tot}} \tag{30}$$

In equation (30), $\eta_{H,}$ η_B, η_S, and η_M are the hull, propeller, shafting, and mechanical efficiencies of the ship propulsion system respectively. η_{Tot} in the equation is the total efficiency of the ship propulsion system that is the combination of all the sub-efficiency components (i.e. $\eta_{H,}$ η_B, η_S, and η_M). It is deemed unnecessary in this thesis to estimate each sub-efficiency component since the parent cruise ship's (see Table 1) propulsion powers can be related to their effective powers in order to estimate η_{Tot}. More specifically, all parent cruise ships have electric machinery; however, the major distinguishing feature among the parent cruise ships is the type of propulsion and maneuvering system. That is, 12 ships have a traditional propulsion and maneuvering system (i.e. shafts and rudders) while 9 ships have a pod propulsion and maneuvering system. Therefore, to estimate η_{Tot}, ships with the same propulsion and maneuvering system are plotted for P_E as a function of $P_{B,P}$ multiplied by η_{Tot}, as shown in Figure 9. By linear-fitting each data series, an equation is made in the linear-form of y = m∗x. Slope, m, in this equation is equivalent to η_{Tot} while x is $P_{B,P}$. The values of η_{Tot} are 0.516 and 0.578 for traditional and pod propulsion and maneuvering systems respectively. These values are assumed in this thesis.

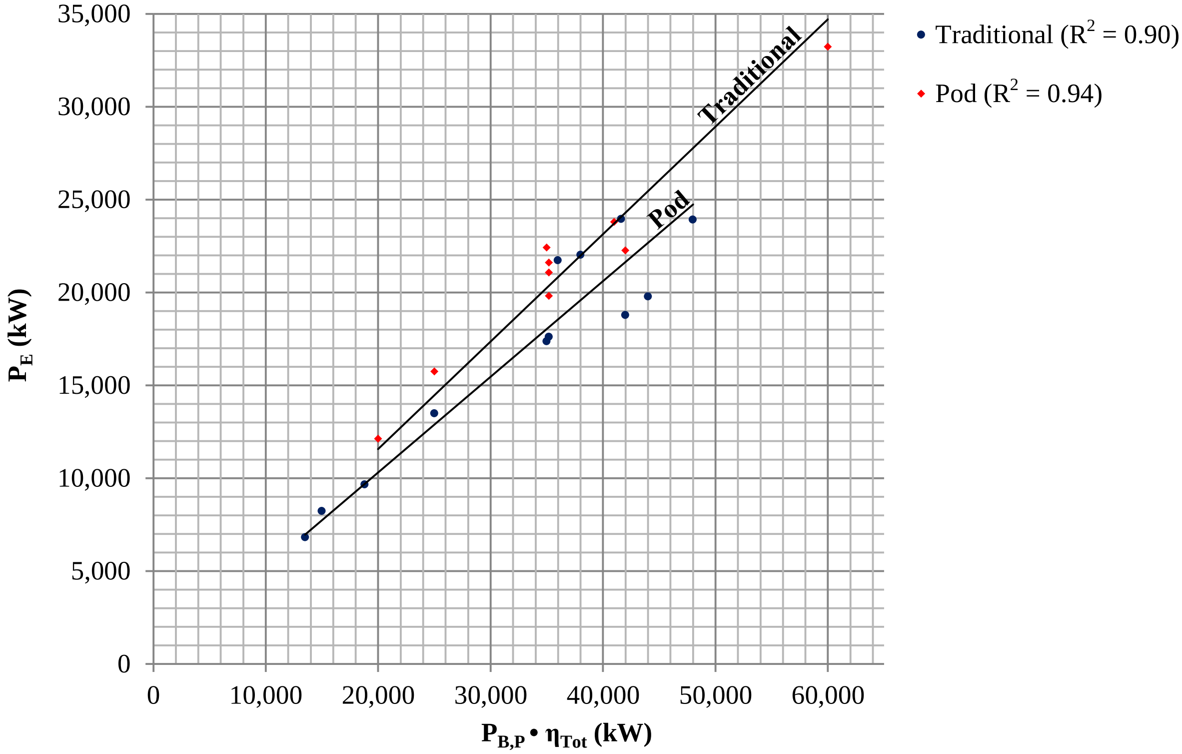

Figure 9. P_E as a function of $P_{B,P} \bullet \eta_{Tot}$ for traditional and pod propulsion and maneuvering systems. These correlations are exhibited among the parent cruise ships.

Estimated Total Power

$P_{B,P}$ is just the power needed for propulsion of a cruise ship. Clearly, there will be other ship components (e.g. for habitability and ship support) that will require power. Typically, an electric load analysis would be performed in the later design stages to predict the power needed for the different power consuming components of a ship. However, since much is unknown at the preliminary design stage, $P_{B,P}$ is used to estimate the total ship brake power ($P_{B,Tot}$) since a strong correlation is exhibited between these variables among the parent cruise ships, as shown in Figure 10. The following equation of the linear-fit (R^2 = 0.93) of the data points is used to estimate $P_{B,Tot}$ in units of kW:

$$P_{B,Tot} = 1.696(P_{B,P}) \tag{31}$$

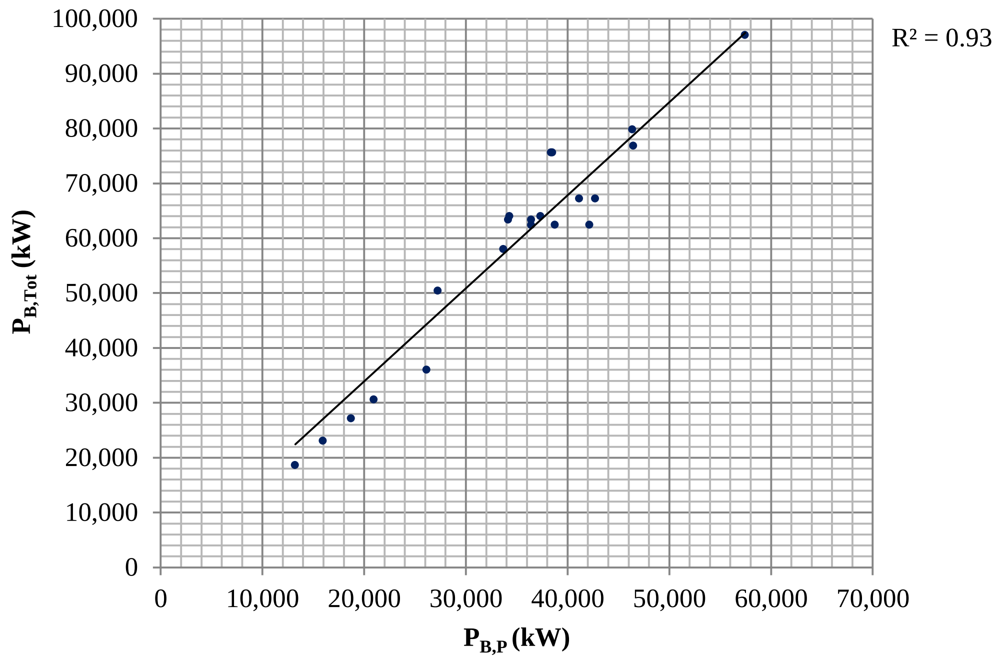

Figure 10. $P_{B,Tot}$ as a function of $P_{B,P}$. This correlation is exhibited among the parent cruise ships.

Engine Based Total Brake Power

The total ship brake power estimated via equation (31) represents the estimated minimum brake power required by the ships engine(s) to power all the ship's needs. A ship engine(s)'s maximum continuous rating (MCR) will likely differ from the $P_{B,Tot}$ estimation since engine models come in a finite number of different power outputs. Nevertheless, the MCR of all ship engine(s), MCR_{Tot}, should equal or exceed $P_{B,Tot}$ in order to ensure a ship's power requirements are fulfilled. That is,

$$MCR_{Tot} \geq P_{B,Tot} \tag{32}$$

In this thesis, the engine types considered are diesel and gas turbine engines. The MCR of a diesel engine is assumed to be either 6,000 kW or 12,600 kW. On the other hand, the MCR of a gas turbine is assumed to be either 4,600 kW or 25,000 kW. A cruise ship design's engine MCR in this thesis is predicated on its GT as follows:

For Diesel Engine(s):

$$\text{If} \quad GT < 40{,}000 \;\rightarrow\; \#\text{ of Diesels Engines} = \frac{P_{B,Tot}}{6{,}000\text{ kW}} \tag{33a}$$

$$\text{If} \quad GT \geq 40{,}000 \;\rightarrow\; \#\text{ of Diesels Engines} = \frac{P_{B,Tot}}{12{,}600\text{ kW}} \tag{33b}$$

For Gas Turbine Engine(s):

$$\text{If}\quad \mathrm{GT} < 40{,}000 \;\rightarrow\; \text{\# of Gas Turbines Engines} = \frac{\mathrm{P_{B,Tot}}}{4{,}600\ \mathrm{kW}} \qquad (33c)$$

$$\text{If}\quad \mathrm{GT} \geq 40{,}000 \;\rightarrow\; \text{\# of Gas Turbines Engines} = \frac{\mathrm{P_{B,Tot}}}{25{,}000\ \mathrm{kW}} \qquad (33d)$$

Most likely the calculations via equations (33a-d) will not produce a whole number. Therefore, the outputs of these equations are rounded up to the next whole number (e.g. 2.2 → 3). With this consideration in mind, the total MCR of a cruise ship design's engine(s) in this thesis is estimated by the following equation:

$$\mathrm{MCR_{Tot}} = (\text{\# of Engines}) * (\text{Each Engine MCR}) \qquad (34)$$

Manning

The International Maritime Organization's (IMO) *Resolution A.890* (1999) specifies the principles of safe manning. In this resolution it is stated the minimum safe manning level of a ship should be estimated taking into account all relevant factors that include the following:

1. Size and type of ship
2. Number, size, and type of main propulsion units and auxiliaries
3. Construction and equipment of the ship
4. Method of maintenance used
5. Cargo to be carried
6. Frequency of port calls, length and nature of voyages to be undertaken
7. Trading area(s), waters, and operations in which the ship is involved
8. Extent to which training activities are conducted on board
9. Applicable working hour limits and/or rest requirements

In the preliminary ship design stage, it is often difficult to quantify the exact number of manning needed on a ship since the design is incomplete at that point. Nonetheless, the total number of crew members ($\mathrm{N_{Crew}}$) for each parent cruise ship is known. Furthermore, since the parent cruise ships are operational, they obviously abide to the minimum safe manning levels. Therefore, by using a correlation among the parent cruise ships, $\mathrm{N_{Crew}}$ can be estimated.

A correlation is exhibited among the parent cruise ships between $\mathrm{N_{Crew}}$ and GT, as shown in Figure 11. As the figure suggests, $\mathrm{N_{Crew}}$ is linearly proportional to a cruise ship's GT. Linear-fitting the data points exhibits a $\mathrm{R^2}$ value of 0.98. Due to this strong correlation, the following equation of this fit is used to estimate $\mathrm{N_{Crew}}$ as a function of GT:

$$\mathrm{N_{Crew}} = 0.0107(\mathrm{GT}) \qquad (35)$$

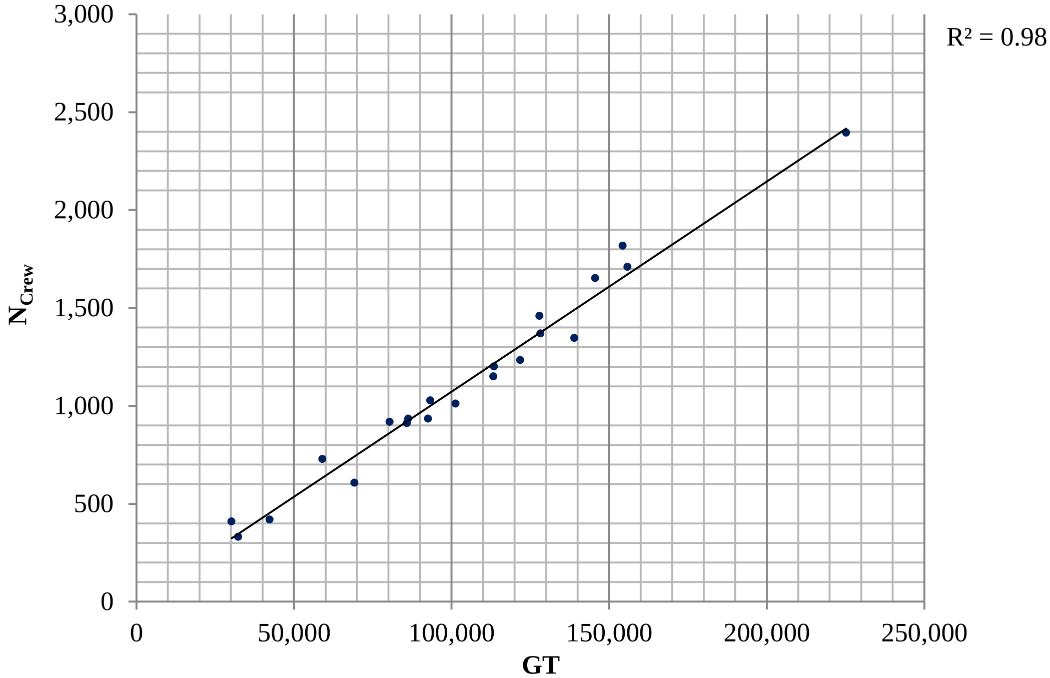

Figure 11. N_{Crew} as a function of GT. This correlation is exhibited among the parent cruise ships.

Ship Weight Breakdown – Displacement, Lightship Weight, and Deadweight

Overview

Although, the displacement of a cruise ship design is already estimated via equation (5), it is also feasible to estimate a cruise ship's displacement ($\Delta_{LSW+DWT}$) based on its lightship weight (LSW) and deadweight (DWT) as follows:

$$\Delta_{LSW+DWT} = LSW + DWT \tag{36}$$

$\Delta_{LSW+DWT}$ is estimated in this thesis since the weight group estimates of LSW and DWT are later used to analyze initial stability.

Lightship Weight

LSW of a cruise ship is primarily comprised of the structural hull (W_H), superstructure (W_{SS}), interior outfitting (W_{IO}), ship outfitting (W_{SO}), and machinery (W_M) weight groups. This includes all passenger staterooms, public spaces, galleys (i.e. dining rooms), storerooms, offices, and all crew spaces (Lamb, 2004). LSW is estimated as follows via the summation of these weight group components:

$$LSW = W_H + W_{SS} + W_{IO} + W_{SO} + W_M \tag{37}$$

LSW weight groups W_H, W_{SS}, W_{IO}, and W_{SO} are estimated in this thesis via a compact form of the table provided in *Ship Design and Construction* (Lamb, 2004) that pertains to a cruise ship design (i.e. Table 6).

Table 6
LSW Estimations for a Cruise Ship

Weight Group	Unit	Coefficient tonne/unit
Hull (W_H)	Hull Volume	0.080
Superstructure (W_{SS})	Superstructure Volume	0.040
Interior Outfitting (W_{IO})	Furnished Area	0.170
Ship Outfitting (W_{SO})	Total Volume	0.007
Machinery (W_M)	Installed Power	0.065

Note. Adapted from *Ship Design and Construction* (p. 37-9), by T. Lamb, 2004, Jersey City, NJ: The Society of Naval Architects and Marine Engineers. Copyright 2004 by the Society of Naval Architects and Marine Engineers.

As Table 6 indicates, to estimate W_{IO}, the furnished area (A_{Furn}) of a cruise ship design needs to be known. *Ship Design and Construction* (Lamb, 2004) provides a means to estimate A_{Furn} by correlating A_{Furn} to GT, as shown in Figure 12. The linear-fit of the data points in this figure corresponds to the following equation:

$$A_{Furn} = 0.7375(GT) \tag{38}$$

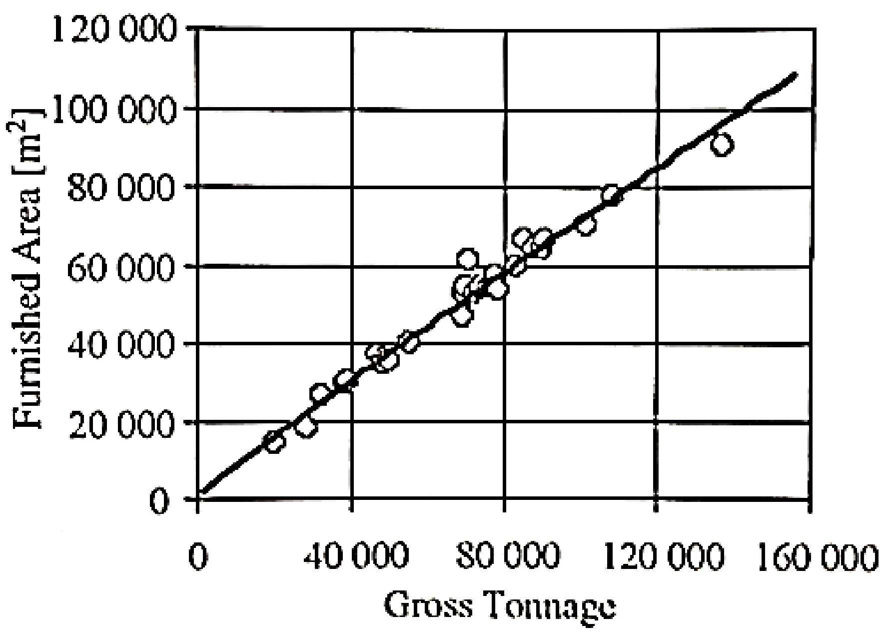

Figure 12. A_{Furn} as a function of GT. Adapted from *Ship Design and Construction* (p. 37-10), by T. Lamb, 2004, Jersey City, NJ: The Society of Naval Architects and Marine Engineers. Copyright 2004 by the Society of Naval Architects and Marine Engineers.

Although, Lamb (2003) provides a relationship to estimate the machinery weight group of a cruise ship design's LSW (see Table 6), this relationship is not deemed suitable since it is only applicable for diesel engines (i.e. this thesis considers diesel engines as well as gas turbine engines). Thus, Watson and Gilfillan's (1977) equation is used to estimate W_M instead. This equation separates the weight of the main engines (W_{ME}) from the remainder of the machinery weight (W_{Rem}) as follows:

$$W_M = \sum W_{ME} + W_{Rem} \tag{39}$$

In this thesis, a diesel engine's W_{ME} is assumed to be 59 t and 176 t for the 6,000 kW and 12,600 kW engines respectively. On the other hand, W_{ME} is assumed to be 2.8 t and 4.7 t for the 4,600 kW and 25,000 kW gas turbine engines respectively. These values are based on real engines.

As stated, a cruise ship design is assumed to have electric machinery (i.e. electric plants) in this thesis since all parent cruise ships do. The following equation proposed by Watson and Gilfillan (1977) is used to estimate W_{Rem} for an electric plant configuration:

$$W_{Rem} = 0.72(MCR_{Tot})^{0.78} \tag{40}$$

Deadweight

The DWT groups considered in this thesis are as follows: weight of passengers and crew and their belongings ($W_{P\&C}$), provisions and stores ($W_{P\&S}$), fuel oil (W_{FO}), lubrication oil (W_{LO}), freshwater (W_{FW}), black water in holding tanks (W_{BW}), gray water in holding tanks (W_{GW}), and water in swimming pools (W_{SP}). The following summation of these groups provides a means to estimate DWT:

$$DWT = W_{P\&S} + W_{SP} + W_{P\&C} + W_{FO} + W_{LO} + W_{FW} + W_{BW} + W_{GW} \tag{41}$$

To estimate $W_{P\&S}$ and W_{SP} in this thesis, the compact form of the table provided in *Ship Design and Construction* (Lamb, 2004) that pertains to a cruise ship design is used (i.e. Table 7).

Table 7
Methods to Estimate $W_{P\&S}$ and W_{SP}

Weight Group	**Unit**	**Coefficient tonne/unit**	**Estimated Weight (T)**
Provisions and Stores ($W_{P\&S}$)	Persons	0.20	
Water in Swimming Pools (W_{SP})			200

Note. Adapted from *Ship Design and Construction* (p. 37-9), by T. Lamb, 2004, Jersey City, NJ: The Society of Naval Architects and Marine Engineers. Copyright 2004 by The Society of Naval Architects and Marine Engineers.

$W_{P\&S}$ in Table 7 is estimated based on the number of persons (i.e. passengers and crew) on board a cruise ship. The value of W_{SP} in this table is applied to any cruise ship design analyzed in this thesis.

The deadweight component $W_{P\&C}$ considers the weight of all passengers and crew members as well as their personal objects (e.g. luggage). It is assumed that the average weight of a person is 100 kg. Additionally, it is assumed the weight of personal objects brought on board by a passenger is 50 kg and 100 kg for a crew member. This discrepancy in weight is because crew members are likely to have more personal objects since their stay is longer. With these considerations in mind, the following equation is used to estimate $W_{P\&C}$ in units of metric tons:

$$W_{P\&C} = (150 * N_{Passengers}) + (200 * N_{Crew}) \tag{42}$$

Lamb (2003) does provide methodology to estimate W_{FO} for a cruise ship design. However, this is only applicable for a cruise ship with diesel engine(s). Thus, this methodology is not used in this thesis. Instead, the following equation is used to estimate W_{FO} in metric tons:

$$W_{FO} = SFR * MCR\left(\frac{Range}{v_{Trial}}\right) * CF \tag{43}$$

SFR in equation (43) is the specific fuel rate of an engine. In this thesis, a diesel engine's SFR is assumed to be 185 g/kWh and 173 g/kWh for the 6,000 kW and 12,600 kW engines respectively. On the other hand, SFR is assumed to be 270 g/kWh and 227 g/kWh for the 4,600 kW and 25,000 kW gas turbine engines respectively. These values are based on real engines. The variable Range in the equation is based on v_{Trial} and the estimated fuel tank size of a cruise ship design. CF in the equation is a correction factor equal to 0.90 that accounts for the fact that a cruise ship will rarely require its engine(s) to operate at full MCR_{Tot}, unless under extreme circumstances.

Values of W_{LO} are provided in *Ship Design and Construction* (Lamb, 2003) and is 20 t for a diesel engine and 1% of that value for a gas turbine engine (i.e. 0.2 t).

Even though, modern cruise ships often produce freshwater by evaporating saltwater during a voyage, these cruise ships will also store freshwater in tanks due to unforeseen circumstances. To estimate the weight of the freshwater stored in these tanks, the following equation is used:

$$W_{FW} = 50 * 3.5\left(N_{Passengers} + N_{Crew}\right)(3.785 * 10^{-3}) \tag{44}$$

In regards to equation (44), the freshwater storage tank's capacity is predicated on the number of gallons used per person per day for a specific number of days. A person is assumed to use 50 gallons per day and a freshwater storage tank(s) is assumed to hold up to a cumulative 3.5

day period of persons' needs. The value of $3.785 * 10^{-3}$ in the equation is needed to convert the Imperial units of gallons to the Metric units of cubic meters. Note that the output units of this equation suggest units of volume not mass; however, since W_{FW} is represented in metric tons and the density of freshwater is assumed to be 1,000 kg/m^3, they are synonymous.

Black water consists of wastewater generated mostly from toilets (i.e. sewage). Currently, a cruise ship is allowed to discharge its black water when it is at least a certain distance from shore. However, when this is not the case (e.g. when the ship is at port), the ship must be able to store its black water. W_{BW} is estimated in this thesis based on the number of persons on the cruise ship and the amount of black water each person produces. According to Ocean Conservancy (2002), the average person produces 5-10 gallons of black water per day. Also, a cruise ship can hold up to three cumulative days of this production. Based on these notions, W_{BW} is estimated for a cruise ship design as follows:

$$W_{BW} = \left(N_{Passengers} + N_{Crew}\right) * (10 * 0.003785) * 3 * 1.025 * \text{Margin} \quad (45)$$

In regards to equation (45), it is assumed the average person on a cruise ship produces 10 gallons of black water per day and the ship's black water tank(s) has the capacity to hold up to 3 cumulative days of production. The value of 1.025 in this equation considers the density of black water and the conversion to the units of metric tons for W_{BW}. A margin of 10% (i.e. Margin is equal to 1.1) is added to the estimation to be conservative.

Gray water consists of non-sewage wastewater from dishwashers, showers, laundry, galleys, and etc. According to Ocean Conservancy (2002), the average person on a cruise ship produces 30-85 gallons of gray water per day. Also, a cruise ship can hold up to three cumulative days of this production. Based on these notions, the following equation is used to estimate the W_{GW} for a cruise ship design:

$$W_{GW} = \left(N_{Passengers} + N_{Crew}\right) * (40 * 0.003785) * 3 * 1.025 * \text{Margin} \quad (46)$$

In regards to equation (46), it is assumed the average person on a cruise ship produces 40 gallons of gray water per day and the ship's gray water tank(s) has the capacity to hold up to 3 cumulative days of production. The value of 1.025 in this equation considers the density of gray water and the conversion to the units of metric tons for W_{GW}. Again, a margin of 10% is added to the estimation to be conservative.

Notes

Note that this thesis presents two methods for computing Δ. One method is via a correlation among the parent cruise ships (i.e. equation [5]) and the other is by means of adding LSW to DWT (i.e. equation [36]). Nonetheless, this is not problematic since the difference in Δ values estimated via the two methods is small. Again, note that the weight groups of LSW and DWT are estimated in order analyze initial stability.

Initial Stability

Estimation Techniques

Stability is an important aspect to consider in preliminary ship design because an unstable ship would obviously not be a viable design even if it were considered to be potentially profitable. Although, profitability is the focus of this thesis, it is deemed worthwhile to analyze stability in some regard.

Initial stability of a cruise ship design is analyzed in this thesis. Initial stability is in regards to when a ship is upright, or very nearly (i.e. very small angle of inclination). The vertical center of buoyancy (KB), transverse and longitudinal metacenters ($KM_{T,L}$), transverse and longitudinal metacentric radiuses ($BM_{T,L}$), center of gravity (KG), and transverse and longitudinal metacentric heights ($GM_{T,L}$) are estimated for a cruise ship design. These vertical distances are in reference to the distance from a cruise ship's baseline.

KB is the point at which the buoyant forces acting on a ship's hull act through. Using formula provided in *Ship Design for Efficiency & Economy* (Schneekluth & Bertram, 1998), KB is estimated in units of meters as follows:

$$KB = T(0.9 - 0.3 * C_M - 0.1C_B) \tag{47}$$

$BM_{T,L}$ are the vertical distances between KB and $KM_{L,T}$ respectively. For shipshape vessels, $BM_{T,L}$ can be estimated as follows:

$$BM_T = \frac{\eta_T * B_{WL}^2}{T * C_B} \qquad \text{with:} \quad \eta_T = 0.084 * (C_{WP})^2 \tag{48a}$$

$$BM_L = \frac{\eta_L * L_{PP}^2}{T * C_B} \qquad \text{with:} \quad \eta_L = \frac{3}{40} * (C_{WP})^2 \tag{48b}$$

$\eta_{T,L}$ in equations (48a) and (48b) are coefficients estimated via the previous formulas that are provided in *Ship Design and Performance for Masters and Mates* (Barrass, 2004). These $\eta_{T,L}$ formulas are applicable for C_{WP} values between 0.692 and 0.893.

$KM_{T,L}$ are the distances from the keel to $GM_{T,L}$ respectively. The following equations are used to estimate $KM_{T,L}$:

$$KM_T = KB + BM_T \tag{49a}$$

$$KM_L = KB + BM_L \tag{49b}$$

KG is the point at which all ship weights act through. A cruise ship's KG at fully loaded conditions is estimated in this thesis using the weight group estimation techniques previously discussed and estimating the vertical center of gravity (VCG) of each weight group. This is mathematically as follows:

$$\mathrm{KG} = \frac{1}{\mathrm{LSW+DWT}}(\mathrm{W_H * VCG_H + W_{SS} * VCG_{SS} + W_O * VCG_O + W_M * VCG_M} \\ \mathrm{+ W_{P\&S} * VCG_{P\&S} + W_{SP} * VCG_{SP} + W_{P\&C} * VCG_{P\&C} + W_{Tanks} * VCG_{Tanks}}) \qquad (50)$$

In regards to equation (50), $\mathrm{W_{Tanks}}$ is the summation of a cruise ship design's fully loaded tank weights, as mathematically represented via equation (51). $\mathrm{W_O}$ is the summation of a cruise ship design's interior and ship outfitting weights, as mathematically represented via equation (52). It is assumed the VCG of each component in their respective group, occurs at the same height.

$$\mathrm{W_{Tanks} = W_{FO} + W_{LO} + W_{FW} + W_{BW} + W_{GW}} \qquad (51)$$

$$\mathrm{W_O = W_{IO} + W_{SO}} \qquad (52)$$

The VCG of a cruise ship's hull structure ($\mathrm{VCG_H}$) is based on the following formula provided by Kupras (1971):

$$\mathrm{VCG_H} = 0.01\mathrm{D}\left[46.6 + 0.135(0.81 - \mathrm{C_B})\left(\frac{\mathrm{L}}{\mathrm{D}}\right)^2\right] \qquad \mathrm{L} < 120\text{ m} \qquad (53a)$$

$$\mathrm{VCG_H} = 0.01\mathrm{D}\left[46.6 + 0.135(0.81 - \mathrm{C_B})\left(\frac{\mathrm{L}}{\mathrm{D}}\right)^2\right] + 0.008\mathrm{D}\left(\frac{\mathrm{L}}{\mathrm{B}} - 6.5\right) \qquad \mathrm{L} \geq 120\text{ m} \qquad (53b)$$

The outputted units of equations (53a) and (53b) is in meters and L is in regards to $\mathrm{L_{WL}}$.

The VCG of a cruise ship's superstructure material ($\mathrm{VCG_{SS}}$) is assumed to be located 40% of the distance from the main deck's surface to the ceiling surface of the upmost superstructure level. This is because the superstructure is assumed to have a rectangular prism form from the aft most edge of the superstructure to the longitudinal point at which the ship's pilothouse begins. From this point forward, the superstructure is assumed to be angled to allow for more favorable air resistance characteristics. Thus, $\mathrm{VCG_{SS}}$ is estimated in units of meters as follows:

$$\mathrm{VCG_{SS}} = \mathrm{D} + 0.4\left(\frac{\mathrm{V_{SS}}}{\mathrm{L_{PP} * B}}\right) \qquad (54)$$

The VCG of a cruise ship's outfitting ($\mathrm{VCG_O}$) is typically located above the main deck. To estimate $\mathrm{VCG_O}$ in units of meters, the following equation proposed by Kupras (1971) is used:

$$\mathrm{VCG_O} = \mathrm{D} + 1.25 \qquad \mathrm{L} \leq 125\ \mathrm{m} \qquad (55a)$$
$$\mathrm{VCG_O} = \mathrm{D} + 1.25 + 0.01(\mathrm{L} - 125) \qquad 125\ \mathrm{m} < \mathrm{L} \leq 250\ \mathrm{m} \qquad (55b)$$
$$\mathrm{VCG_O} = \mathrm{D} + 2.50 \qquad 250\ \mathrm{m} < \mathrm{L} \qquad (55c)$$

The outputted units of equations (55a-c) is in meters and L is in terms of $\mathrm{L_{WL}}$.

The VCG of a cruise ship's machinery ($\mathrm{VCG_M}$) depends on the innerbottom height ($\mathrm{h_{db}}$) and the height of the overhead of the engine room ($\mathrm{D'}$). Kupras (1971) suggests the following formula to estimate $\mathrm{VCG_M}$ in units of meters:

$$\mathrm{VCG_M} = \mathrm{h_{db}} + 0.35(\mathrm{D'} - \mathrm{h_{db}}) \qquad (56)$$

The value of 0.35 in equation (56) is in regards to $\mathrm{VCG_M}$ assumed to be at 35% of the height within the engine room space. For a cruise design analyzed in this thesis, an engine room is assumed to be two decks high due to the machinery the ship is most likely to have within this space. Also, the deck height is assumed to be 2.8 m. With these considerations in mind, $\mathrm{D'}$ is estimated as follows:

$$\mathrm{D'} = 5.6 + \mathrm{h_{db}} \qquad (57)$$

In regards to the variable $\mathrm{h_{db}}$ in equations (56) and (57), according to classification from ABS, the minimum value of $\mathrm{h_{db}}$ should be as follows:

$$\mathrm{h_{db}} \geq 32 * \mathrm{B} + 190\sqrt{\mathrm{T}} \qquad (58)$$

The units of equation (58) are millimeters. To be prudent, a margin of 10% is added to $\mathrm{h_{db}}$ in the CSAT.

The VCG of a cruise ship's provision and stores ($\mathrm{VCG_{P\&S}}$) is assumed to be located on the deck level at which they would be loaded. That is, the first deck that is completely above the waterline. The vertical location of $\mathrm{VCG_{P\&S}}$ within this deck is assumed to be at 40% the distance from the deck surface to the ceiling surface. Assuming this deck has a height of 2.8 m and its deck surface is 1 m above the waterline, $\mathrm{VCG_{P\&S}}$ is estimated as follows:

$$\mathrm{VCG_{P\&S}} = \mathrm{T} + 2.12 \qquad (59)$$

A cruise ship's swimming pool is assumed to be located on the superstructure level just below the upmost level. Assuming a swimming pool is 1.5 m in depth, the VCG in regards to the swimming pool water weight ($\mathrm{VCG_{PS}}$) is estimated as follows:

$$VCG_{SP} = D + \frac{V_{SS}}{L_{PP}*B} - 3.55 \tag{60}$$

To estimate the VCG regarding the weights of passengers and crew and their personal objects ($VCG_{P\&C}$), various assumptions are made. It is assumed the weights regarding passengers and their personal objects ($W_{Passengers}$) are evenly dispersed throughout the ship's superstructure levels. Thus, the VCG of these weights are assumed to be at 50% of the distance from the main deck's surface to the ceiling surface of the upmost superstructure level. In regards to the weights of crew members and their personal objects (W_{Crew}), it is assumed these weights are evenly dispersed throughout the ship decks. Thus, the VCG of these weights are assumed to be at 50% of the distance from the vertical position of h_{db} to the ceiling of the upmost superstructure level. With these considerations in mind, $VCG_{P\&C}$ is estimated as follows:

$$VCG_{P\&C} = \frac{1}{W_{P\&C}}\left\{W_{Passengers}\left(D + \frac{0.5*V_{SS}}{L_{PP}*B}\right) + W_{Crew}\left[h_{db} + 0.5\left(D + \frac{V_{SS}}{L_{PP}*B} - h_{db}\right)\right]\right\} \tag{61}$$

It is assumed all cruise ship tanks are comprised in the hull volume between the ship's baseline and innerbottom height. Additionally, it is assumed the VCG of all ship's tanks (VCG_{Tanks}) is positioned at 50% of this vertical distance. Thus, VCG_{Tanks} is estimated as follows:

$$VCG_{Tanks} = 0.5 * h_{db} \tag{62}$$

By inputting the values of VCG and W of each LSW and DWT group into equation (50), a ship's design KG can be estimated. Then, $GM_{T,L}$ can be estimated as follows since it is the distances between KG and $KM_{T,L}$:

$$GM_T = KM_T - KG \tag{63a}$$
$$GM_L = KM_L - KG \tag{63b}$$

Stability Criteria

At small angles of inclinations (i.e. <3º), for a given position of KG and KM considered to be fixed, GM will be constant for any particular waterline. Since KG can vary with the loading of a ship, even for a given displacement, BM will be constant for a given waterline (Tupper, 2004). With these considerations in mind, the following criteria acts as general rules in regards to a ship's initial stability:

1. If KM above KG, GM and GZ positive → Stable
2. If KM at KG, GM and GZ zero → Neutral
3. If KM below KG, GM and GZ negative → Unstable

Note that the variable GZ listed in the previous criteria is known as the righting lever (or simply lever) that is estimated as follows for small angles of inclination:

$$\mathrm{GZ} = \mathrm{GM}\sin(\varphi) \tag{64}$$

φ in equation (64) is some small angle of inclination.

IMO's *Resolution A.749* (1993) is the code on intact stability for all types of ships covered by IMO instruments. In this resolution it is stated the initial metacentric height should be no less than 0.15 m for passenger and cargo ships. This is the threshold at which a cruise ship design analyzed in this thesis is considered stable.

Chapter 4 – Net Present Value Model

Overview

In this thesis, the NPV model is used to analyze the implications of selecting a particular design feature in the preliminary design stage on a cruise ship's potential profitability.

NPV is the present value of the projected cash flow that includes the investments (Lamb, 2003). The particular form of the NPV model used in this thesis has the following components: estimated construction cost (C_C), total ship operating cost (C_{TO}), total ship revenue (B_{Total}), rate of return (r), and time period (t). The mathematical relationship to estimate a cruise ship design's NPV is as follows:

$$\mathrm{NPV} = C_C + \sum_{t=1}^{N} \frac{(B_{Total} - C_{TO})}{(1+r)^t} \qquad \text{where: } t = 1, 2, \ldots, N \tag{65}$$

N in equation (65) is the expected ship operating life. If the value of NPV for a cruise ship design is positive, the cruise ship is considered to be a profitable investment if implemented. On the other hand, a negative value indicates that the investment would not be profitable. The higher the NPV, the more profitable the cruise ship design would be.

Rate of Return and Ship Operating Life

The particular rate of return (i.e. r) utilized in equation (65) is the believed minimum acceptable rate of return (also known as the hurdle rate) that a cruise company would be willing to accept before implementing a preliminary cruise ship design. This is assumed to be 10% because S&P 500 companies typically yield returns somewhere between 8% and 11% annualized (Wikipedians, n.d.). Note that Carnival Corporation & plc is on the S&P 500 list. Thus, if a cruise ship design's NPV value in this thesis is positive at the 10% hurdle rate, this cruise ship design is likely to be a successful investment if implemented.

A ship operating life (i.e. N) of 30 years is assigned to a cruise ship design analyzed in this thesis. This estimation is based on *Royal Caribbean Cruises Ltd. 2013 Annual Report* (Royal Caribbean Cruises Ltd., 2013) that specifies a cruise ship typically has 30 years of useful life. Their assessment takes in consideration of the impact of anticipated technological changes, long-term cruise and vacation market conditions, and historical useful lives of similarly built ships.

Total Construction Cost

Estimation Technique

Often, when preparing a bid for a proposed ship, shipyards will estimate the construction cost of the ship based on the weights of its various components (e.g. hull, interior outfitting, and etc.). However, this approach of cost estimating requires proprietary data. Therefore, it would be very difficult to estimate construction cost in this thesis using this approach since such data is not readily available. Also, since a cruise ship design analyzed in this thesis is considered to be in the preliminary design stage, it is an incomplete definition of the design. Thus, a detailed construction cost estimation is not feasible. Nevertheless, a reasonably accurate construction cost estimation for a cruise ship design can be derived based on two defining features of the design that have major influences on its construction cost. These features are the ship's GT and the MCR of its engine(s). In regards to this, the following multi-linear equation relating GT and $\mathrm{MCR_{Tot}}$ to $\mathrm{C_C}$ is used in this thesis to estimate the construction cost of a cruise ship in \$ M:

$$\mathrm{C_C} = \alpha_1(\mathrm{GT}) + \alpha_2(\mathrm{MCR_{Tot}}) \tag{66}$$

To estimate the coefficients α_1 and α_2 in equation (66), a multi-linear regression of the responses in $\mathrm{C_C}$ on the predictors GT and $\mathrm{MCR_{Tot}}$ among the parent cruise ship data was performed. Based on this analysis, values of 4,563 and 3,036 are assigned to α_1 and α_2 respectively.

Accuracy of Estimation Technique

The accuracy of the estimated construction cost method (i.e. equation [66]) is evaluated by comparing $\mathrm{C_C}$ (note that $\mathrm{C_C}$ is the estimated construction cost) to the actual construction cost ($\mathrm{C_{C,Actual}}$) of each parent cruise ship, as shown in Table 8. The last column of this table indicates the percent (%) error when comparing $\mathrm{C_C}$ to $\mathrm{C_{C,Actual}}$ for each parent cruise ship. Note that in this analysis the actual GT and $\mathrm{MCR_{Tot}}$ of each parent cruise ship is used.

Table 8

Comparison of the Parent Cruise Ships' $C_{C,Actual}$ and C_C

Parent Cruise Ship	$C_{C,Actual}$ ($ M)	C_C ($ M)	% Error
AIDAaura	445	275	38.04
AIDAluna	425	425	0.01
Azamara Journey	204	195	4.60
Carnival Destiny	614	655	6.73
Carnival Dream	808	815	0.87
Carnival Miracle	465	582	25.06
Carnival Splendor	788	709	9.93
Celebrity Solstice	818	760	7.01
Costa Luminosa	579	617	6.57
Disney Dream	935	817	12.59
Nieuw Amsterdam	607	588	3.09
MSC Magnifica	586	602	2.66
MSC Opera	330	362	9.87
Norwegian Breakaway	840	854	1.67
Pride of America	540	520	3.69
Royal Princess	735	833	13.31
Ruby Princess	621	722	16.24
Freedom of the Seas	928	934	0.66
Oasis of the Seas	1,354	1,323	2.31
Seabourn Quest	260	218	16.33
		Average % Error	**9.06%**

Note. The last column of the table is the percent error between $C_{C,Actual}$ and C_C of each parent cruise ship. Also, each cost in the table is given in terms of U.S. dollars in the year 2014.

As Table 8 shows, the average percent error among the parent cruise ships is approximately 9%. Note that $C_{C,Actual}$ for each parent cruise ship is adjusted for inflation in terms of U.S. dollars in the year 2014. The inflation rate for each year between 1996 and 2013, as specified by the United States Department of Labor (2014), is listed in Table 33 in Appendix C. Also, note that $C_{C,Actual}$ for each parent cruise ship is based on the construction cost specified by a particular cruise company, dockyard, and/or other source in which these values could have been rounded and/or generalized by the respective source. Nevertheless, these values are deemed reasonable to the extent of providing a "ballpark" estimation of C_C in this thesis.

Figure 13 shows the correlation between $C_{C,Actual}$ and C_C for the parent cruise ships. The equation of the linear-fit of the data points has a slope approximately equal to 1 (i.e. 0.99) and a R^2 value of 0.93 which indicate: a) C_C is a linear function of GT and MCR_{Tot} and b) the C_C of each parent cruise ship is approximately equal to the $C_{C,Actual}$ of that ship. Therefore, equation (66) is considered a reasonable means to estimate C_C for a cruise ship design analyzed in this thesis.

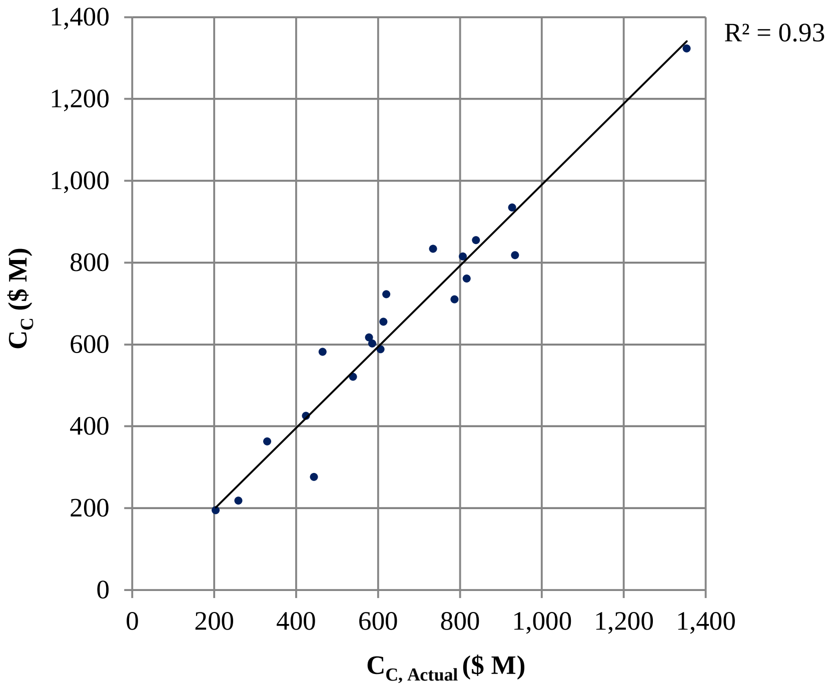

Figure 13. C_C plotted against $C_{C,Actual}$ for each parent cruise ship. The slope of the linear-fit is approximately 1.

Total Operating Cost

Overview

The total operating cost of a cruise ship can be broken down into the following components: commissions, transportation, and other (C_{CTO}); onboard and other ($C_{O\&O}$); fuel (C_{Fuel}); payroll and related ($C_{P\&R}$); food (C_{Food}); and other ship operating (C_{OSO}) costs. Summation of these components gives C_{TO} for a cruise ship design as follows:

$$C_{TO} = C_{CTO} + C_{O\&O} + C_{Fuel} + C_{P\&R} + C_{Food} + C_{OSO} \tag{67}$$

The specific techniques used to estimate each operating cost component in equation (67) is discussed in the following sub-sections.

Commissions, Transportation, and Other Costs

Commissions, transportation, and other costs consist of costs directly associated with passenger ticket revenues. This includes travel agent commissions, air and other transportation costs, port costs that vary with passenger head counts, and related credit card fares (Royal Caribbean Cruises Ltd., 2012). Thus, the estimation of C_{CTO} in this thesis is based on the number of passengers onboard a cruise ship during a voyage.

To estimate how C_{CTO} varies with $N_{Passengers}$, *Norwegian Cruise Line 2010-2013 Annual Reports* (Norwegian Cruise Line, 2010-2013) and *Royal Caribbean Cruises Ltd. 2010-2013 Annual Reports (*Royal Caribbean Cruises Ltd., 2010-2013) are evaluated. Each company's annual report for a given year, details the company's activities and financial performance of that year. Moreover, these annual reports are required at frequent intervals (quarterly in this case) by the stock exchange each company is involved with (e.g. New York Stock Exchange). In these reports, the annual values of C_{CTO} ($C_{CTO,Annual}$) and $N_{Passengers}$ ($N_{Passengers,Annual}$) are specified as well as the average cruise length ($T_{Voyage,Average}$) of a given year. Using this information C_{CTO} per passenger per day can be estimated by the following equation for a respective company and year:

$$\frac{C_{CTO}}{\text{Passenger}\cdot\text{Day}} = \frac{C_{CTO,Annual}}{(N_{Passengers,Annual})(T_{Voyage,Average})} \tag{68}$$

When inputting data into equation (68), it is assumed that all cruise ships of each cruise company that operated during a given year operated every day of that year. Once the values of C_{CTO} per passenger per day are obtained via this equation, each value is readjusted for inflation in terms of U.S. dollars in the year 2014. The results of this analysis are shown in Table 9.

Table 9

C_{CTO} per Passenger per Day

	Cruise Company	
Year	Norwegian Cruise Line $\left(\frac{\$}{\text{passenger}\cdot\text{day}}\right)$	Royal Caribbean Cruises Ltd. $\left(\frac{\$}{\text{passenger}\cdot\text{day}}\right)$
2010	42.48	39.00
2011	41.76	38.82
2012	40.53	37.36
2013	39.98	36.97
Average	**41.19**	**38.04**
Average Among Companies	**$39.61 per passenger per day**	

Note. These values are based on *Norwegian Cruise Line 2010-2013 Annual Reports* (Norwegian Cruise Line, 2010-2013) and *Royal Caribbean Cruises Ltd. 2010-2013 Annual Reports* (Royal Caribbean Cruises Ltd., 2010-2013).

The average value of C_{CTO} per passenger per day among both cruise companies (see last row of Table 9) is used to estimate C_{CTO} per voyage ($C_{CTO,Voyage}$) and annually ($C_{CTO,Annual}$) for a cruise ship design in this thesis as follows:

$$C_{CTO,Voyage} = \frac{C_{CTO}}{\text{Voyage}} = [39.61 * (N_{Passengers})] * T_{Voyage} \tag{69a}$$

$$C_{CTO,Annual} = \frac{C_{CTO}}{\text{Year}} = [39.61 * (N_{Passengers})]\left(\frac{365}{T_{Voyage}}\right) \tag{69b}$$

Onboard and Other Costs

Onboard and other costs consist of direct costs associated with onboard and other revenues. This includes the costs of products sold onboard a cruise ship, vacation protection insurance premiums, costs associated with pre- and post- cruise tours, and related credit card fees as well as the minimal costs associated with concession revenues (Royal Caribbean Cruises Ltd., 2012). Like the case with C_{CTO}, the value of $C_{O\&O}$ depends on the number of passengers for a cruise ship. Therefore, the estimation of $C_{O\&O}$ in this thesis is based on the number of passengers onboard a cruise ship during a voyage.

Again, using *Norwegian Cruise Line 2010-2013 Annual Reports* (Norwegian Cruise Line, 2010-2013) and *Royal Caribbean Cruises Ltd. 2010-2013 Annual Reports* (Royal Caribbean Cruises Ltd., 2010-2013), annual values of $C_{O\&O}(C_{O\&O,Annual})$ are given for each respective company and year. Using this information, $C_{O\&O}$ per passenger per day is estimated by the following equation for a respective company and year:

$$\frac{C_{O\&O}}{\text{Passenger}\cdot\text{Day}} = \frac{C_{O\&O,Annual}}{(N_{Passengers,Annual})\,(T_{Voyage,Average})} \tag{70}$$

When inputting data into equation (70), it is assumed that all cruise ships of each cruise company that operated during a given year operated every day of that year. Once the values of $C_{O\&O}$ per passenger per day are obtained via this equation, each value is readjusted for inflation in terms of U.S. dollars in the year 2014. The results of this analysis are shown in Table 10

Table 10

$C_{O\&O}$ per Passenger per Day

	Cruise Company	
Year	Norwegian Cruise Line $\left(\frac{\$}{\text{passenger}\cdot\text{day}}\right)$	Royal Caribbean Cruises Ltd. $\left(\frac{\$}{\text{passenger}\cdot\text{day}}\right)$
2010	17.14	15.94
2011	17.22	16.00
2012	17.17	15.34
2013	17.15	15.99
Average	**17.17**	**15.82**
Average Among Companies	**$16.49 per passenger per day**	

Note. These values are based on *Norwegian Cruise Line 2010-2013 Annual Reports* (Norwegian Cruise Line, 2010-2013) and *Royal Caribbean Cruises Ltd. 2010-2013 Annual Reports* (Royal Caribbean Cruises Ltd., 2010-2013).

The average value of $C_{O\&O}$ per passenger per day among both cruise companies (see last row of Table 10) is used to estimate $C_{O\&O}$ per voyage ($C_{O\&O,Voyage}$) and annually ($C_{O\&O,Annual}$) for a cruise ship design in this thesis as follows:

$$\mathrm{C_{O\&O,Voyage}} = \frac{\mathrm{C_{O\&O}}}{\mathrm{Voyage}} = \left[16.49 * \left(\mathrm{N_{Passengers}}\right)\right] * \mathrm{T_{Voyage}} \tag{71a}$$

$$\mathrm{C_{O\&O,Annual}} = \frac{\mathrm{C_{O\&O}}}{\mathrm{Year}} = \left[16.49 * \left(\mathrm{N_{Passengers}}\right)\right] \left(\frac{365}{\mathrm{T_{Voyage}}}\right) \tag{71b}$$

Fuel Costs

Fuel costs are those costs incurred with the purchase, delivery, and storage of fuel as well the financial impact of fuel swap agreements (Royal Caribbean Cruises Ltd., 2012). The factors that affect $\mathrm{C_{Fuel}}$ are considered to be the distance travelled by a ship, the average power used, and the cost per metric ton of fuel (Molland, 2008).

Fuel cost is regarded in terms of fuel cost per metric ton consumed. In this thesis, this cost is based on the historical cost specified in Carnival Corporation & plc 2013 Annual Report (Carnival Corporation & plc, 2013).

$\mathrm{C_{Fuel}}$ over the duration of a cruise voyage ($\mathrm{C_{Fuel,Voyage}}$) is estimated in this thesis by first estimating the ship's power consumption at sea ($\mathrm{P_{Sea}}$) and port ($\mathrm{P_{Port}}$) respectively. To estimate $\mathrm{P_{Sea}}$, the parameters $\mathrm{P_{B,Tot}}$ (via equation [31]) and $\mathrm{P_{B,P}}$ (via equation [30]) at service and trial speeds are used. It is assumed that when a cruise ship operates at sea, the ship is traveling at its service speed. Thus, $\mathrm{P_{Sea}}$ for a cruise ship design is estimated as follows in units of kW:

$$\mathrm{P_{Sea}} = (\mathrm{P_{B,P}})_{@\,\mathrm{v_{service}}} + \underbrace{\left[\mathrm{P_{B,Tot}} - (\mathrm{P_{B,P}})_{@\,\mathrm{v_{Trial}}}\right]}_{\mathrm{P_{Other}}} \tag{72}$$

The second term in equation (72) is the power dedicated to all other ship systems ($\mathrm{P_{Other}}$). $\mathrm{P_{Other}}$ is assumed to remain constant at all ship speeds during transit.

Since a cruise ship does not use propulsion when docked at port, $\mathrm{P_{B,P}}$ is assumed to be zero during this timeframe. Also, since many systems dedicated towards seagoing operations are not in use in port and many passengers are assumed to be on land, the power consumption of the cruise ship in port is assumed to be 85% of $\mathrm{P_{Other}}$. Therefore, $\mathrm{P_{Port}}$ is estimated in units of kW as follows:

$$\mathrm{P_{Port}} = 0.85 * \mathrm{P_{Other}} \tag{73}$$

For a specified $\mathrm{T_{Voyage}}$ and the number of ports a cruise ship will visit throughout a voyage ($\mathrm{N_{Ports}}$), the duration at sea ($\mathrm{T_{Sea}}$) can be estimated. Note that the average timeframe a cruise ship spends in port is assumed to be 6 hours. Using the outputs via equations (72) and (73), $\mathrm{C_{Fuel,Voyage}}$ can now be estimated via the following equation:

$$C_{Fuel,Voyage} = \frac{676}{1000} * SFR\left[P_{Sea}\underbrace{\left(24 * T_{Voyage} - 6 * N_{Ports}\right)}_{T_{Sea}} + P_{Port}\left(6 * N_{Ports}\right)\right] \tag{74}$$

In equation (74), the units of SFR are kg/kW-h.

Since, C_{Fuel} per year ($C_{Fuel,Annual}$) is needed to estimate annual C_{TO} ($C_{TO,Annual}$), the following equation is used to estimate $C_{Fuel,Annual}$:

$$C_{Fuel,Annual} = C_{Fuel,Voyage}\left(\frac{365}{T_{Voyage}}\right) \tag{75}$$

Payroll and Related Costs

Payroll and related costs are associated with onboard personnel (Royal Caribbean Cruises Ltd., 2012). Therefore, $C_{P\&R}$ can be estimated using a relationship involving it and N_{Crew}.

Again, using *Norwegian Cruise Line 2010-2013 Annual Reports* (Norwegian Cruise Line, 2010-2013) and *Royal Caribbean Cruises Ltd. 2010-2013 Annual Reports* (Royal Caribbean Cruises Ltd., 2010-2013), annual values of $C_{P\&R}$ ($C_{P\&R,Annual}$) for each respective company and year are provided. Using this data, $C_{P\&R}$ per crew member per day can be estimated by the following equation for a respective company and year:

$$\frac{C_{P\&R}}{(\text{Crew Member})\cdot\text{Day}} = \frac{C_{P\&R,Annual}}{(N_{Crew,Fleet}) * 365} \tag{76}$$

$N_{Crew,Fleet}$ in equation (76) is the number of crew members of all cruise ships (i.e. fleet) that operated during a given year for a respective company. Again, like the case with equations (68) and (70), when inputting data into the equation it is assumed all cruise ships of each cruise company that operated during a respective year operated every day of that year. Also, when inputting $C_{P\&R,Annual}$ values into the equation, inflation in terms of U.S. dollars in the year 2014 is considered. The results of this analysis are shown in Table 11.

Table 11

$C_{P\&R}$ per Crew Member per Day

	Cruise Company	
Year	Norwegian Cruise Line $\left(\frac{\$}{\text{crew member}\cdot\text{day}}\right)$	Royal Caribbean Cruises Ltd. $\left(\frac{\$}{\text{crew member}\cdot\text{day}}\right)$
2010	65.65	60.46
2011	68.89	61.15
2012	70.00	58.20
2013	68.26	57.99
Average	**41.19**	**38.04**
Average Among Companies	**$63.82 per crew member per day**	

Note. These values are based on *Norwegian Cruise Line 2010-2013 Annual Reports* (Norwegian Cruise Line, 2010-2013) and *Royal Caribbean Cruises Ltd. 2010-2013 Annual Reports* (Royal Caribbean Cruises Ltd., 2010-2013).

From this analysis, the average value of $C_{P\&R}$ per crew member per day among both cruise companies (see last row of Table 11) is used to estimate $C_{P\&R}$ per voyage ($C_{P\&R,Voyage}$) and annually ($C_{P\&R,Annual}$) for a cruise ship design in this thesis as follows:

$$C_{P\&R,Voyage} = (63.82 * N_{Crew}) * T_{Voyage} \tag{77a}$$

$$C_{P\&R,Annual} = (63.82 * N_{Crew}) * 365 \tag{77b}$$

Food Costs

Food costs are those costs associated with food for both passengers and crew of a particular duration. Since C_{Food} depends on $N_{Passengers}$ and N_{Crew}, a relationship involving these variables can be used to estimate C_{Food}.

C_{Food} per person will differ between $N_{Passengers}$ and N_{Crew}. Therefore, C_{Food} is estimated via the following multi-linear equation with coefficients β_1 and β_2 that correspond to $N_{Passengers}$ and N_{Crew} respectively:

$$C_{Food} = \beta_1(N_{Passengers}) + \beta_2(N_{Crew}) \tag{78}$$

To estimate the values of coefficients β_1 and β_2 in equation (78), a multi-linear regression analysis is performed using values of C_{Food} per year ($C_{Food,Annual}$), $N_{Passengers,Annual}$, and N_{Crew} specified in *Norwegian Cruise Line 2010-2013 Annual Reports* (Norwegian Cruise Line, 2010-2013) and *Royal Caribbean Cruises Ltd. 2010-2013 Annual Reports* (Royal Caribbean Cruises Ltd., 2010-2013). From this analysis, β_1 and β_2 are estimated to be 33.89 and 7,227 respectively. By using equation (78) with these coefficient values and the variable

$N_{Passengers}$ in the form of $N_{Passengers,Annual}$, $C_{Food,Annual}$ for a cruise ship design can be estimated. To estimate C_{Food} per cruise voyage, ($C_{Food,Voyage}$) the following equation is used:

$$C_{Food,Voyage} = \beta_1(N_{Passengers,Voyage}) + \beta_2\left(\frac{N_{Crew} * T_{Voyage}}{365}\right) \quad (79)$$

Other Ship Operating Costs

Other ship operating costs consist of operating costs such as repairs and maintenance, port costs (which do not vary with passenger numbers), ship operating lease costs, and ship related insurance and entertainment costs (Royal Caribbean Cruises Ltd., 2012). Since GT serves as the basis for assessment of taxes and fees, it is assumed C_{OSO} will vary linearly with GT.

To estimate the rate at which C_{OSO} varies with GT, annual values of C_{OSO} ($C_{OSO,Annual}$) obtained via *Norwegian Cruise Line 2010-2013 Annual Reports* (Norwegian Cruise Line, 2010-2013) and *Royal Caribbean Cruises Ltd. 2010-2013 Annual Reports* (Royal Caribbean Cruises Ltd., 2010-2013) are analyzed. In each report, $C_{OSO,Annual}$ corresponds to the value obtained via all cruise ships that operated during that year for a respective company. Due to this, the total GT of all cruise ships (GT_{Total}) in each cruise company's fleet that operated during each of these years needs to be estimated. This is accomplished by summing the GT of all cruise ships in a cruise company that operated in a given year. Using this information, C_{OSO} per GT per day for each cruise company can be estimated by the following equation for a respective year:

$$\frac{C_{OSO}}{GT \cdot Day} = \frac{C_{OSO,Annual}}{(GT_{Total}) * 365} \quad (80)$$

Once the values of C_{OSO} per GT per day are obtained via equation (80) for the cruise companies, each value is then readjusted for inflation in terms of U.S. dollars in the year 2014. The results of this analysis are shown in Table 12.

Table 12
C_{OSO} per GT per Day

	Cruise Company	
Year	Norwegian Cruise Line $\left(\frac{\$}{GT \cdot day}\right)$	Royal Caribbean Cruises Ltd. $\left(\frac{\$}{GT \cdot day}\right)$
2010	0.65	0.81
2011	0.64	0.79
2012	0.52	0.79
2013	0.53	0.80
Average	**0.58**	**0.80**
Average Among Companies	**$0.69 per GT per day**	

Note. These values are based on *Norwegian Cruise Line 2010-2013 Annual Reports* (Norwegian Cruise Line, 2010-2013) and *Royal Caribbean Cruises Ltd. 2010-2013 Annual Reports* (Royal Caribbean Cruises Ltd., 2010-2013).

The average value of $\mathrm{C_{OSO}}$ per GT per day (see last row of Table 12) is used to estimate $\mathrm{C_{OSO}}$ per voyage ($\mathrm{C_{OSO,Voyage}}$) and annually ($\mathrm{C_{OSO,Annual}}$) for a cruise ship design as follows:

$$\mathrm{C_{OSO,Voyage}} = \frac{\mathrm{C_{OSO}}}{\mathrm{Voyage}} = (0.69 * \mathrm{GT}) * \mathrm{T_{Voyage}} \tag{81a}$$

$$\mathrm{C_{OSO,Annual}} = \frac{\mathrm{C_{OSO}}}{\mathrm{Year}} = (0.69 * \mathrm{GT}) * 365 \tag{81b}$$

By inputting the variables estimated in this sub-section and the previous sub-sections, $\mathrm{C_{TO}}$ can now be estimated via equation (67).

Total Revenue

Overview

The total revenue (or benefit) generated by a cruise ship mainly consists of passenger ticket revenues ($\mathrm{B_{Ticket}}$) and onboard and other revenues ($\mathrm{B_{O\&O}}$). Therefore, $\mathrm{B_{Total}}$ can be estimated as follows:

$$\mathrm{B_{Total}} = \mathrm{B_{Ticket}} + \mathrm{B_{O\&O}} \tag{82}$$

The specific techniques used to estimate each revenue component in equation (82) is discussed in the following sub-sections.

Passenger Ticket Revenues

Passenger ticket revenues consist of revenues generated by the sale of passenger tickets. As discussed in Chapter 3, a cruise ship design analyzed in the CSAT can have the stateroom types LLS, MLS, and/or HLS. The $\mathrm{B_{Ticket}}$ per passenger per day of each of these stateroom types is based on research by Cruise Market Watch (2012), as given in Table 13. Note that these values pertain to the year 2012 and have been adjusted for inflation in terms of U.S. dollars in the year 2014. The values of $\mathrm{B_{Ticket}}$ per passenger per day given in the table are assumed for a cruise ship design analyzed in this thesis as well.

Table 13
B_{Ticket} per Passenger per Day for the Stateroom Types (Cruise Market Watch, 2012)

Stateroom Type	$\mathbf{B_{Ticket}}$
LLS	\$142.29 $\frac{\mathrm{passenger}}{\mathrm{day}}$
MLS	\$198.90 $\frac{\mathrm{passenger}}{\mathrm{day}}$
HLS	\$303.96 $\frac{\mathrm{passenger}}{\mathrm{day}}$

Onboard and Other Revenues

Onboard and other revenues consist of revenues generated by the sale of goods and/or services onboard a cruise ship that is not included in the passenger tickets prices, cancellation fees, sales of vacation protection insurance, pre- and post- cruise tours, and air packages (Royal Caribbean Cruises Ltd., 2012).

$B_{O\&O}$ for a cruise ship can be influenced by numerous factors such as cruise line type (e.g. contemporary, premium, or luxury), passenger age, passenger income, and many other factors. Since cruise line type is not quantified in this thesis and since passenger age and passenger income are similarly relatable to onboard and other passenger spending habits, the parameter used in this thesis to estimate $B_{O\&O}$ is the average passenger income.

Cruise Lines International Association (CLIA) is a cruise industry trade association with representation in North and South America, Europe, Asia, and Australasia. In their *Cruise Lines International Association 2011 Cruise Market Profile Study* (2011), $B_{O\&O}$ per day is related to passenger income, as listed in Table 14. Their analysis is based on polling of over 1,000 cruise passengers. Note that in their analysis, passengers who make less than $40 K are not considered. The values of $B_{O\&O}$ per passenger per day given in the table are assumed for a cruise ship design analyzed in this thesis as well.

Table 14
$B_{O\&O}$ per Passenger per Day (Cruise Lines International Association, 2011)

Income	$\mathbf{B_{O\&O}}$
$40 K - $59 K	$\$53.12\ \frac{\text{passenger}}{\text{day}}$
$60 K - $79 K	$65.13\ \frac{\text{passenger}}{\text{day}}$
$80 K +	$66.13\ \frac{\text{passenger}}{\text{day}}$

Chapter 5 – Cruise Ship Analysis Tool

In order to proficiently analyze the implications of selecting a particular design feature in the preliminary design stage on a cruise ship's potential profitability, the Cruise Ship Analysis Tool is constructed in Excel. In more detail, the CSAT provides a means to analyze the physical and performance characteristics of a preliminary cruise ship design in a clear, concise, and user-friendly interface. The CSAT consists of three Excel spreadsheets.

The first Excel spreadsheet is entitled *CSAT (Parameter Estimations)*. As the title suggests, this spreadsheet pertains to parameter estimations of a cruise ship design. A user inputs the data listed in Table 15 to obtain several parameters of a cruise ship design that include those listed in the table. A depiction of this spreadsheet is shown in Figure 14. As the figure shows, depictions of a cruise ship design's general dimensions and power curves are provided in this spreadsheet. Although, Figure 14 does not show the estimated parameter outputs of this spreadsheet, a user can see them by simply scrolling down on the actual spreadsheet.

Table 15

Inputs and Outputs of the CSAT (Parameter Estimations) Excel Spreadsheet

Inputs	**Outputs**		
v_{Trial}	GT	Δ	KB
$v_{Service}$	L_{OA}	LSW	KG
$N_{Passengers}$	L_{WL}	DWT	BM_T
Travel Duration	B_{WL}	N_{Crew}	GM_T
% of LLS	T	C_T	C_B
% of MLS	D	S	C_{WP}
% of HLS	∇	R_T	C_M
Engine Type	V_H	P_E	C_P
Propulsion and Maneuvering System	V_{SS}	$P_{B,Tot}$	R_n
Bulbous Bow Criterion	V_{St}	MCR_{Tot}	F_n

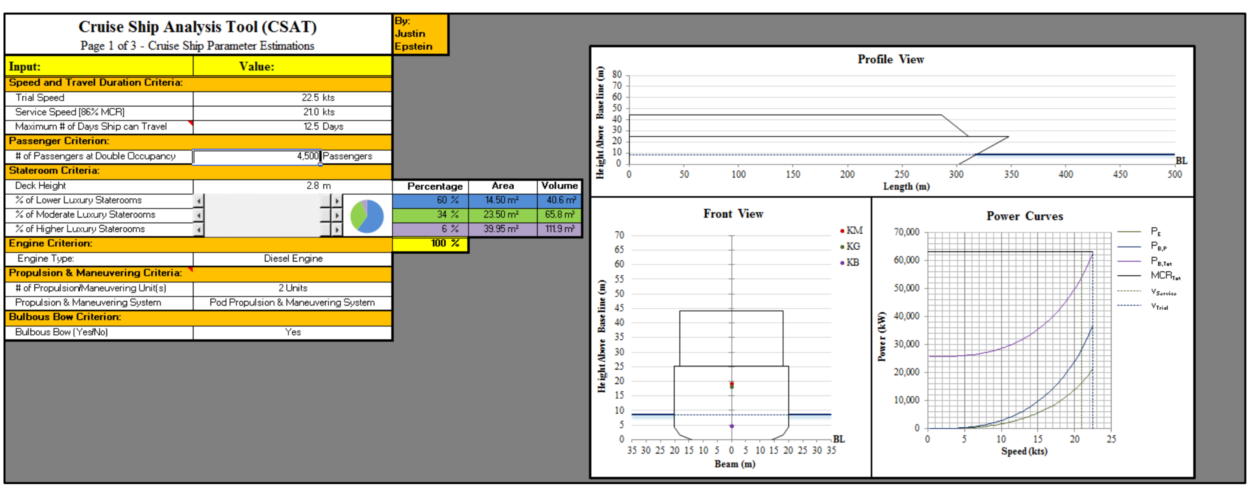

Figure 14. Snapshot of the *CSAT (Parameter Estimations)* Excel spreadsheet.

The second Excel spreadsheet is entitled *CSAT (Cost Analysis)*. As the title suggests, this spreadsheet pertains to cost estimations of a cruise ship design. A user inputs data into the *CSAT (Parameter Estimations)* spreadsheet and the data listed in Table 16 into this spreadsheet to obtain several cost parameters of a cruise ship design that include those listed in the table. A depiction of this spreadsheet is shown in Figure 15. As the figure shows, pie charts of the components C_{TO} and B_{Total} are provided in this spreadsheet. The lower left figure in this spreadsheet showcases the cash flow report of the cruise ship design over its operating life. This figure can be used to analyze the time at which the ship becomes profitable (if ever). The figure on the far right side of this spreadsheet showcases a specified variable as a function of stateroom arrangement (i.e. the percentage of all staterooms that is composed by a particular type). This variable can be specified as being NPV, BCR, GT, or etc. by varying the list box and/or clicking the button above the figure. One use of this figure can be to evaluate the particular stateroom arrangement (e.g. 100% LLS, 0% MLS, and 0% HLS) that exhibits the greatest NPV given the inputs specified in the *CSAT (Parameter Estimations)* and *CSAT (Cost Analysis)* spreadsheets. Although, Figure 15 does not show the estimated cost outputs of this spreadsheet, a user can see them by simply scrolling down on the actual spreadsheet.

Table 16
Inputs and Outputs of the CSAT (Cost Analysis) Excel Spreadsheet

Inputs	**Outputs**	
r	NPV	$B_{O\&O,MLS}$
$\mathbf{T_{Life}}$	BCR	$B_{O\&O,HLS}$
$\mathbf{T_{Voyage}}$	IRR	C_{CTO}
$\mathbf{N_{Ports}}$	C_C	$C_{O\&O}$
$\mathbf{T_{Port}}$	C_{TO}	C_{Fuel}
$\mathbf{C_{Fuel}}$ **per metric ton**	B_{Total}	$C_{P\&R}$
$\mathbf{B_{Ticket}}$ **of LLS per day**	$B_{Ticket,LLS}$	C_{Food}
$\mathbf{B_{Ticket}}$ **of MLS per day**	$B_{Ticket,MLS}$	C_{OSO}
$\mathbf{B_{Ticket}}$ **of HLS per day**	$B_{Ticket,HLS}$	
Average Passenger Income	$B_{O\&O,LLS}$	

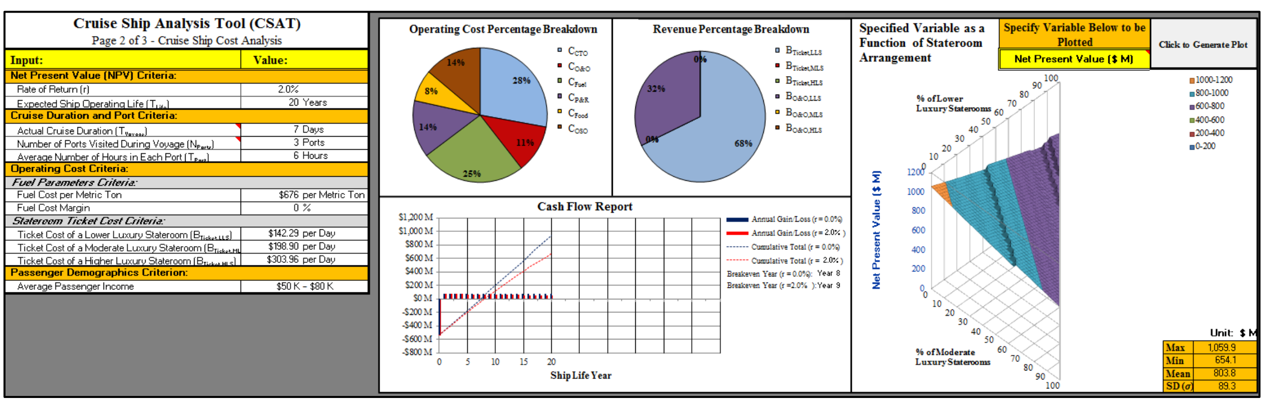

Figure 15. Snapshot of the *CSAT (Cost Analysis)* Excel spreadsheet.

In regards to the third Excel spreadsheet, entitled *CSAT (Miscellaneous Data)*, this spreadsheet pertains to miscellaneous data needed to support the algorithms of the other two spreadsheets. In this spreadsheet, a user can also see the data point values of the variable surfaced plotted in the far right figure of the *CSAT (Cost Analysis)* spreadsheet as a function of stateroom arrangement.

Chapter 6 – Results and Analysis

Net Present Value Analysis Approach

NPV is estimated for cruise ship designs to estimate the most favorable cruise ship design and assemblage of each design. A cruise ship design is defined by its passenger carrying capacity at double occupancy. Cruise ships designs with $N_{Passengers}$ equal to 750, 1500, 3000, and 4500 are analyzed, as listed in Table 17. These cruise ship designs are referred to as Cruise Ship Design, A, B, C, or D in this thesis. The range of $N_{Passengers}$ is chosen such that to encompass most built cruise ships that operate currently.

Table 17
Cruise Ship Designs

Cruise Ship Design	$N_{Passengers}$
A	750 Passengers
B	1,500 Passengers
C	3,000 Passengers
D	4,500 Passengers

Note. Each cruise ship is defined by its $N_{Passengers}$.

For the cruise ship designs analyzed (see Table 17), the variables listed in Tables 3, 13, and 18 are considered fixed. One reason trial and service speeds are fixed at 22.5 kts and 21.0 kts respectively is because these values are prototypical of a cruise ship. The speed criteria are also attributed to the methodology used to predict residual resistance in which predictions are valid for F_n values between 0.15 and 0.45 (see Appendix B). Each cruise ship design is specified to have two propulsion units since this is prototypical of a cruise ship. Note that all parent cruise ships have at least two propulsion units in which 19 of 21 ships have two units. The cruise duration, number of ports per voyage, and number of hours per port are fixed at 7 days, 3 ports, and 6 hours respectively since these are the average values as of the year 2014. The reasons the rate of return and ship life are 10% and 30 years respectively were discussed in Chapter 4.

Table 18
Fixed Variables of the Cruise Ship Designs

Fixed Variables	Value
v_{Trial}	22.5 kts
$v_{Service}$	21.0 kts
# of Propulsion Units	2 units
T_{Voyage}	7 days
N_{Ports}	3 ports
T_{Port}	6 hours
r	10%
N	30 years

For the cruise ship designs analyzed (see Table 17), NPV is estimated for the design feature assemblages of each design. A design feature assemblage is defined as the specific synthesis of stateroom arrangement, engine type, type of propulsion and maneuvering system, and bulbous bow criterion (see Table 19) a cruise ship is designed to have.

Table 19
Some of the Components that Characterize a Design Feature Assemblage

Engine Type		**Type of Propulsion and Maneuvering System**		**Bulbous Bow Criterion**	
Diesel	Gas Turbine	Traditional	Pod	Applicable	N/A

A cruise ship design's stateroom arrangement is defined as the percentage of each type of stateroom relative to all staterooms that a cruise ship design has. The stateroom types analyzed are LLS, MLS, and HLS in which their characteristics are listed in Tables 3 and 13. An example of a specific stateroom arrangement is 82% LLS, 14% MLS, and 4% HLS. A cruise ship design's stateroom arrangement is analyzed in increments of 2% of each stateroom type. This indicates a total number of 1,326 possible stateroom arrangements.

For each one of the 1,326 stateroom arrangements, variation of the other design feature assemblage components are analyzed (i.e. engine type, type of propulsion and maneuvering system, and bulbous bow criterion). There are eight possible combinations of the design feature assemblage components listed in Table 19. Each specific combination is defined as an EP&B design feature combination in this thesis from this point on. An EP&B design feature combination pertaining to a cruise ship is referenced to a specific code, as listed in Table 20. Each code consists of one letter and three numbers. The letter in each code represents the corresponding cruise ship design (see Table 17). The first number in each code represents if the ship has a diesel engine (1) or a gas turbine engine (2). The second number in each code represents if the ship has a traditional (1) or pod (2) propulsion and maneuvering system. The third number in each code represents if the ship has a bulbous bow (1) or not (2). The possible number of EP&B design feature combinations and stateroom type arrangements indicate each cruise ship design is analyzed for a total number of 10,608 (i.e. 8∗1,326) different design feature assemblages.

Table 20
EP&B Design Feature Combinations

Cruise Ship Design	**EP&B Design Feature Combinations**							
A	A.1.1.1	A.1.2.1	A.1.1.2	A.1.2.2	A.2.1.1	A.2.1.2	A.2.2.1	A.2.2.2
B	B.1.1.1	B.1.2.1	B.1.1.2	B.1.2.2	B.2.1.1	B.2.1.2	B.2.2.1	B.2.2.2
C	C.1.1.1	C.1.2.1	C.1.1.2	C.1.2.2	C.2.1.1	C.2.1.2	C.2.2.1	C.2.2.2
D	D.1.1.1	D.1.2.1	D.1.1.2	D.1.2.2	D.2.1.1	D.2.1.2	D.2.2.1	D.2.2.2

Note. There are eight possible EP&B design feature combinations for each cruise ship design analyzed.

Net Present Value Results and Analysis of Cruise Ship Designs

Given that the variables in Tables 3, 13, and 18 are fixed, surface plots are constructed for Cruise Ship Designs A, B, C, and D to showcase the design feature assemblage of each cruise ship design that exhibits the greatest NPV (i.e. the most profitable), as shown in Figures 16-19 respectively. The x-axis of each figure located at the lower right side represents the percentage of moderate luxury staterooms (i.e. MLSs) the cruise ship design has. The y-axis of each figure located at the lower left side represents the percentage of lower luxury staterooms (i.e. LLSs) the cruise ship design has. The z-axis located left of each figure represents NPV. The percentage of higher luxury staterooms (i.e. HLSs) is not represented by an axis, however, it is implicit. For example, the coordinates pertaining to a design feature assemblage being 10% LLS and 20% MLS indicate this assemblage has 70% HLS. Each of the eight EP&B design feature combinations for a respective cruise ship design is surface plotted individually. Thus, the EP&B design feature combination for a given stateroom arrangement that exhibits the greatest NPV is considered the most profitable EP&B design feature combination at this stateroom arrangement. Moreover, the stateroom arrangement and EP&B design feature combination (i.e. design feature assemblage) that exhibits the greatest NPV of a cruise ship design is considered the most profitable design feature assemblage of that cruise ship design.

The stateroom arrangement that exhibits the highest and lowest NPV for each EP&B design feature combination of a cruise ship design is listed in Table 21. The values in parenthesis in a cell box correspond to the percentage of each type of stateroom the cruise ship design with that NPV has (i.e. LLS%, MLS%, HLS%).

Table 21
Minimum and Maximum NPV for Each EP&B Design Feature Combination

	Cruise Ship Design							
	A		**B**		**C**		**D**	
EP&B	**Min NPV**	**Max NPV**	**Min NPV**	**Max NPV**	**Min NPV**	**Max NPV**	**Min NPV**	**Max NPV**
1.1.1	-$316.9M (0,0,100)	-$215.1M (82,16,2)	-$325.3M (0,0,100)	-$139.4M (100,0,0)	-$88.8M (0,4,96)	$49.4M (100,0,0)	$162.0M (0,60,40)	$267.6M (100,0,0)
1.2.1	-$261.6M (0,0,100)	-$177.5M (88,6,6)	-$205.6M (0,0,100)	-$53.7M (100,0,0)	$48.6M (0,64,36)	$155.5M (100,0,0)	$318.3M (2,46,52)	$388.7M (100,0,0)
1.1.2	-$394.4M (0,0,100)	-$252.2M (82,16,2)	-$430.4M (0,0,100)	-$168.7M (100,0,0)	-$205.4M (0,0,100)	-$37.9M (100,0,0)	$40.7M (50,0,50)	$166.3M (100,0,0)
1.2.2	-$294.1M (0,0,100)	-$194.1M (82,16,2)	-$300.3M (0,0,100)	-$117.1M (100,0,0)	-$49.1M (0,30,70)	$75.8M (100,0,0)	$215.8M (26,2,72)	$297.3M (100,0,0)
2.1.1	-$450.9M (12,60,28)	-$346.0M (82,16,2)	-$484.7M (0,0,100)	-$240.0M (100,0,0)	-$330.9M (0,0,100)	$155.5M (100,0,0)	-$67.5M (0,0,100)	$106.2M (100,0,0)
2.1.2	-$559.8M (0,0,100)	-$387.6M (82,16,2)	-$648.3M (0,0,100)	-$278.5M (100,0,0)	-$434.1M (0,0,100)	-$188.4M (100,0,0)	-$265.9M (0,0,100)	-$52.5M (100,0,0)
2.2.1	-$359.9M (0,0,100)	-$277.3M (82,16,2)	-$377.8M (0,0,100)	-$177.8M (100,0,0)	-$114.0M (0,0,100)	$40.9M (100,0,0)	$96.4M (50,0,50)	$214.9M (100,0,0)
2.2.2	-$403.5M (12,60,28)	-$315.4M (82,16,2)	-$451.8M (0,0,100)	-$210.8M (100,0,0)	-$276.4M (0,0,100)	-$89.5M (100,0,0)	-$1.36M (0,0,100)	$145.1M (100,0,0)

Note. The values in parenthesis in a cell box correspond to the percentage of each type of stateroom the cruise ship design with that NPV has (i.e. LLS%, MLS%, HLS%).

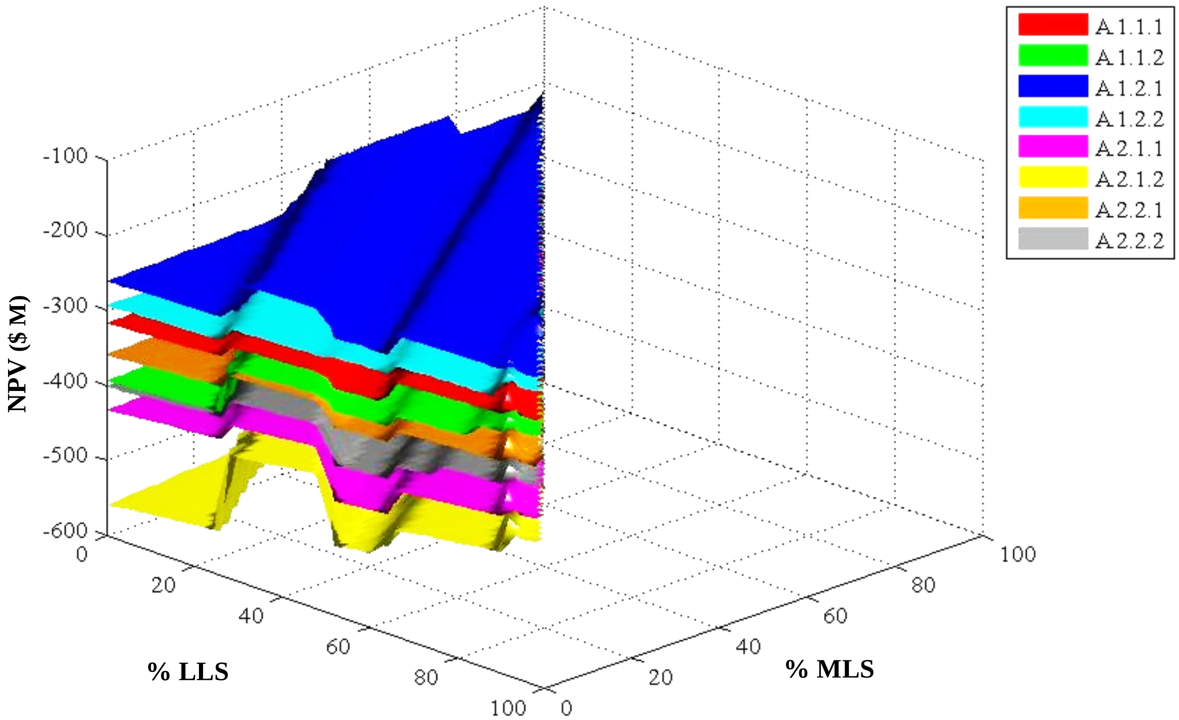

Figure 16. NPV for each design feature assemblage of Cruise Ship Design A. The legend right of the figure indicates a respective EP&B design feature combination.

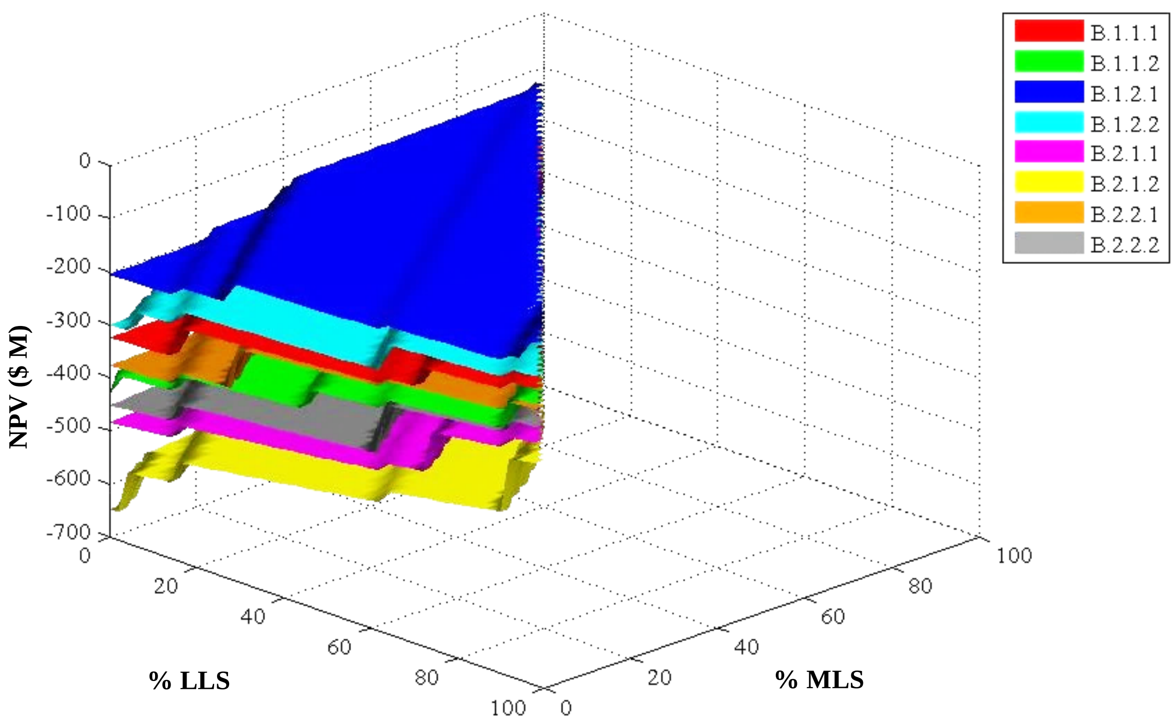

Figure 17. NPV for each design feature assemblage of Cruise Ship Design B. The legend right of the figure indicates a respective EP&B design feature combination.

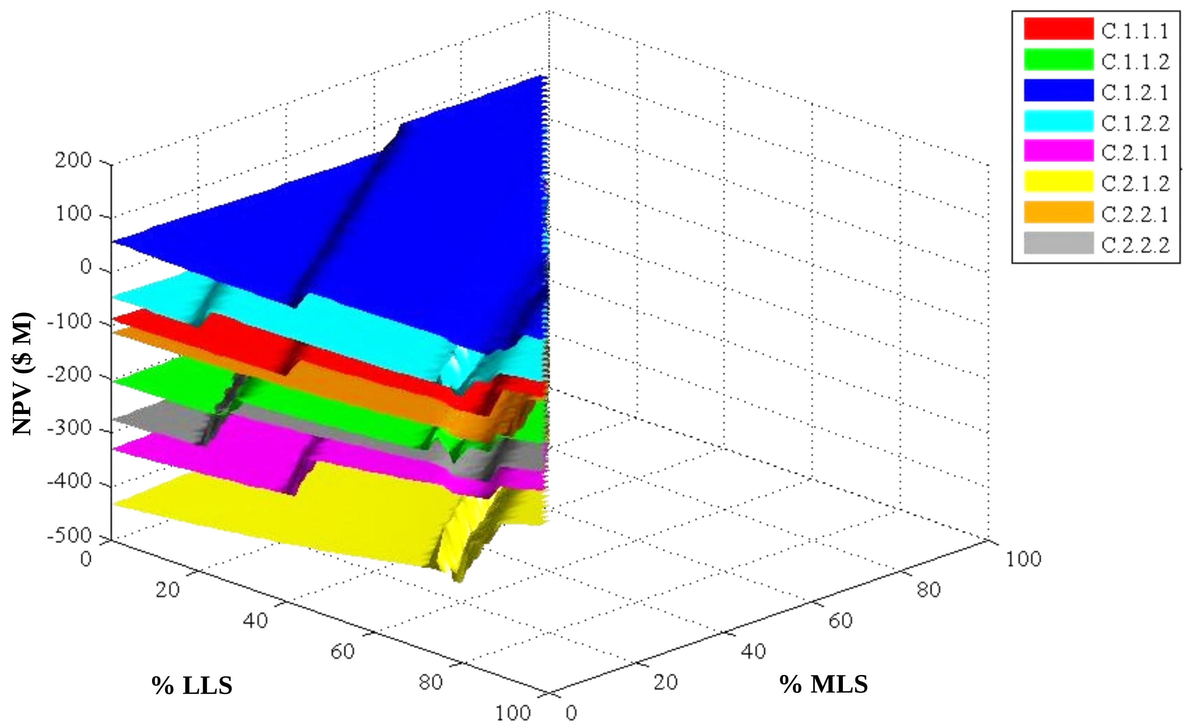

Figure 18. NPV for each design feature assemblage of Cruise Ship Design C. The legend right of the figure indicates a respective EP&B design feature combination.

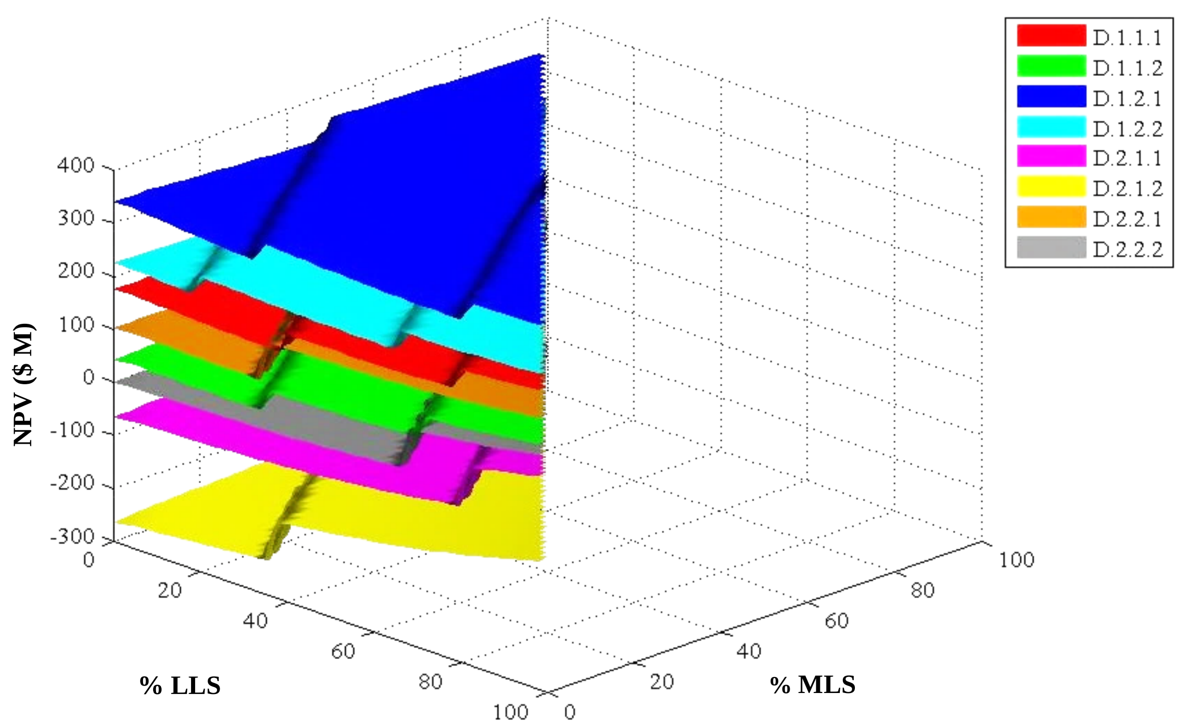

Figure 19. NPV for each design feature assemblage of Cruise Ship Design D. The legend right of the figure indicates a respective EP&B design feature combination.

Analysis of Figures 16-19 indicate a stateroom arrangement pertaining to EP&B design feature combination 1.2.1 (i.e. diesel engine, pod propulsion and maneuvering system, and bulbous bow criterion) produces a greater NPV than any other EP&B design feature combination with the same stateroom arrangement. EP&B design feature combination 1.2.2 (i.e. diesel engine, pod propulsion and maneuvering system, and no bulbous bow) and 1.1.1 (i.e. diesel engine, traditional propulsion and maneuvering system, and a bulbous bow) produce the second and third greatest NPV for a given stateroom arrangement when compared to the other EP&B design feature combinations. These results and notions are analyzed in more detail in the following section.

Analysis of the Most Profitable EP&B Design Feature Combination

Implications of Engine Type

As previously stated, for a given stateroom arrangement, EP&B design feature combinations 1.2.1, 1.2.2, and 1.1.1 produce a greater value of NPV (i.e. more profitable) in the order listed. The common design feature assemblage component among these EP&B design feature combinations is the engine type being a diesel engine.

One reason a diesel engine promotes a greater value of NPV than that of a gas turbine engine is because C_{Fuel} of a diesel engine is lower than that of a gas turbine. This is attributed to the specific fuel rate of each engine type in which SFR is the rate at which fuel is consumed per unit of power delivered. SFR values utilized in this thesis are based on the power outputs of actual engines and are between 0.173-0.185 kg/kW-hr for the diesel engines and between 0.227-0.270 kg/kW-hr for the gas turbine engines.

Surface plotting the total ship life fuel cost ($C_{\text{Fuel,Life}}$) for each design feature assemblage of a cruise ship design supports the SFR notion. $C_{\text{Fuel,Life}}$ is plotted for every design feature assemblage of Cruise Ship Design C as a function of stateroom arrangement, as shown in Figure 20. The figure illustrates, for a given stateroom arrangement, $C_{\text{Fuel,Life}}$ will be lower for EP&B design feature combination 1.2.1 than any other combination of Cruise Ship Design C. This indicates the consequences of selecting a gas turbine engine since $C_{\text{Fuel,Life}}$ for EP&B design feature combination C.2.2.1 is greater than that of C.1.2.1 for a given stateroom arrangement. Therefore, the higher SFR of the gas turbine engine compared to that of the diesel engine resulted in a higher $C_{\text{Fuel,Life}}$ for this cruise ship design.

Another interesting aspect of Figure 20 is that for a given stateroom arrangement, Cruise Ship Design C will exhibit a greater $C_{\text{Fuel,Life}}$ for EP&B design feature combination 2.2.1 (i.e. a gas turbine engine, pod propulsion and maneuvering system, and a bulbous bow) than that of 1.2.2 (i.e. a diesel engine, pod propulsion and maneuvering system, and no bulbous bow). This indicates the advantage in terms of reduction in $C_{\text{Fuel,Life}}$ of having a bulbous bow for a cruise ship design is offset by the disadvantage of the increase of $C_{\text{Fuel,Life}}$ as a result of having a gas turbine engine. Although, $C_{Fuel,Life}$ is only surface plotted for Cruise Ship Design C, these results are consistent among the cruise ship designs analyzed.

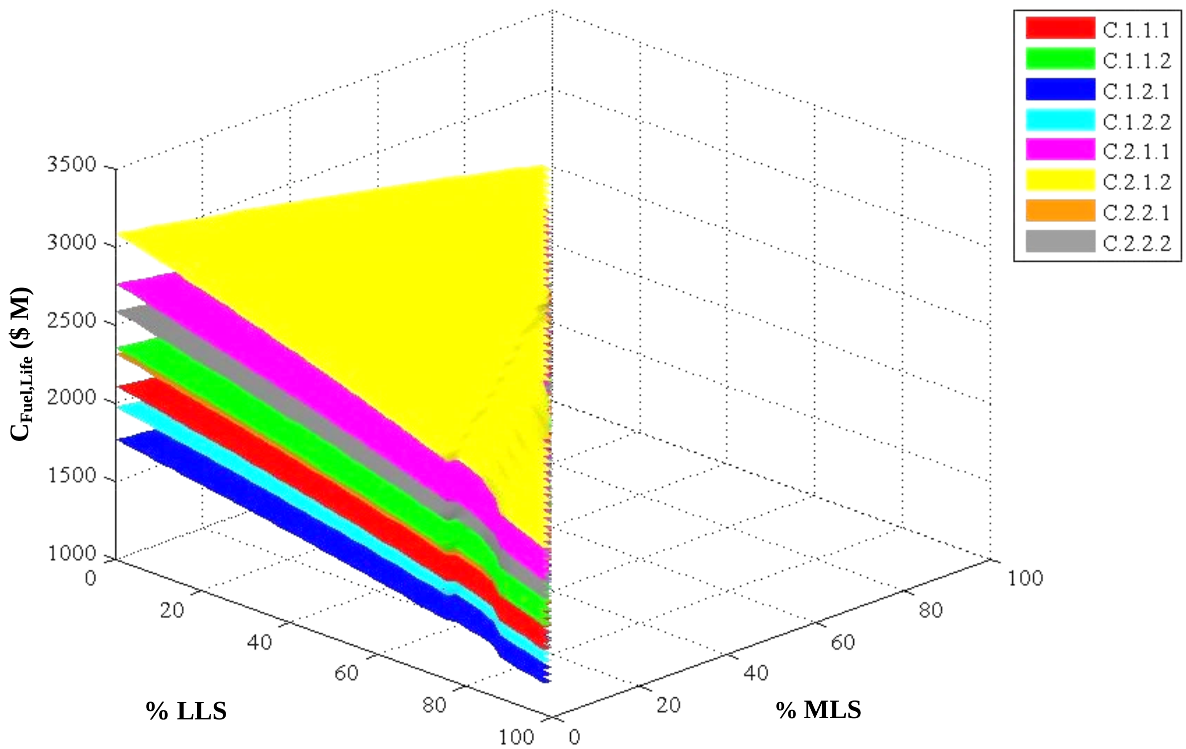

Figure 20. $C_{Fuel,Life}$ for each design feature assemblage of Cruise Ship Design C. The legend right of the figure indicates a respective EP&B design feature combination.

Figures 20 and 21 illustrate the significance of reducing $C_{Fuel,Life}$ on Cruise Ship Design C's total ship operating cost ($C_{TO,Life}$). Figure 21 illustrates the percentage of $C_{TO,Life}$ composed of $C_{Fuel,Life}$ for each possible design feature assemblage of Cruise Ship Design C. As the figure shows, $C_{Fuel,Life}$ is approximately 20-40% of $C_{TO,Life}$. To put this in perspective, this could mean a reduction of approximately \$550 M in $C_{TO,Life}$ if the ship's design feature assemblage is characterized as being 100% HLS and EP&B design feature combination C.1.2.1 compared to that of 100% HLS and EP&B design feature combination C.2.2.1. Moreover, in this scenario, NPV is -\$114.0 M and \$57.3 M for C.2.2.1 and C.1.2.1 respectively. Therefore, the engine type in this case determined if the ship were to be profitable or not if implemented. This notion exemplifies how the NPV analysis can be used to evaluate how a design feature decision in the preliminary design stage could ultimately alter a ship's ability to be profitable.

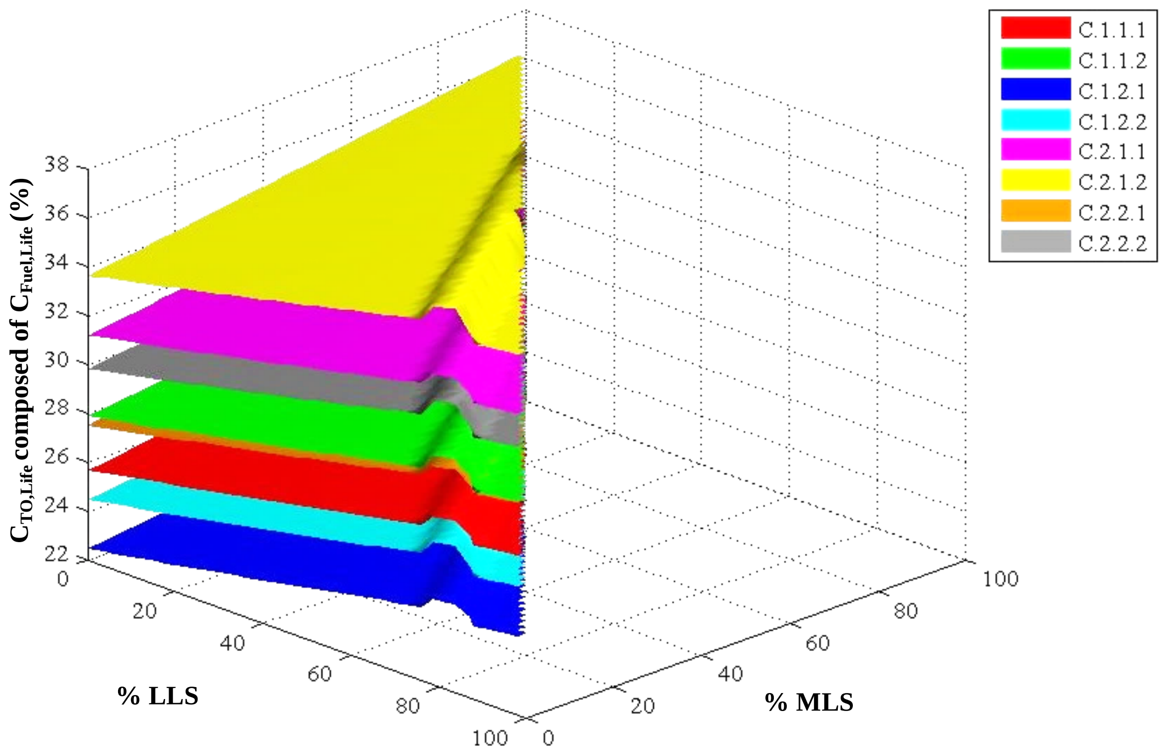

Figure 21. % of $C_{TO,Life}$ that is $C_{Fuel,Life}$ for design feature assemblages of Cruise Ship Design C. The legend right of the figure indicates a respective EP&B design feature combination.

Although, cost analysis is the focus of this thesis, it is important to note some of the advantages a gas turbine engine has over a diesel engine that can prompt a ship designer to consider it. Some favorable attributes of a gas turbine engine are that it has a greater power-to-weight ratio and is smaller in size compared to a diesel engine with similar power output. This can be beneficial for a cruise ship since the extra space exhumed via selecting a gas turbine engine instead of a diesel engine can be utilized for other ship functions. Also, the gas turbine engine's waste heat could be exploited for onboard services (Molland, 2008). Lastly, if speed is of the essence, it can be difficult to satisfy the ship's power requirements and/or meet emission regulations using diesel engines along.

Implications of Propulsion and Maneuvering System

Figures 16-19 indicate that for a given stateroom arrangement, EP&B design feature combination 1.2.1 of a cruise ship design will always exhibit a greater NPV than that of any other EP&B design feature combination. The reasons a diesel engine is more conducive to a profitable ship design (i.e. a greater NPV) than that of a gas turbine engine were discussed in the previous sub-section. In this sub-section, the focus is to analyze why a pod propulsion and maneuvering system promotes a more profitable cruise ship design than that of a traditional propulsion and maneuvering system. Again, note that all cruise ship designs analyzed in this thesis are assumed to have electric machinery.

Typically, a traditional propulsion and maneuvering system will consist of long shaft line(s) and rudder(s) that will result in a greater wetted surface of a ship. Since S is increased, the ship's R_T is also increased. On the other hand, a pod propulsion and maneuvering system does not have long shaft line(s) since the motor is inside the pod unit and the propeller is directly connected to the motor shaft. Also, a pod unit can rotate 360º, thus, a ship with this system is not likely to require rudders. For these reasons, a pod propulsion and maneuvering system typically has a lower S and R_T than that of traditional propulsion and maneuvering system. This notion is supported in Figure 22 in which the reduction of R_T (at v_{Trial}) that the ship would exhibit if EP&B design feature combination 1.2.1 was selected instead of 1.1.1 is surface plotted. As the figure shows, each cruise ship design exhibits a reduction in R_T if a pod propulsion and maneuvering system is selected instead of a traditional propulsion and maneuvering system, regardless of stateroom type. The reduction of R_T is approximately between 3-6% among the cruise ship designs. Since a reduction in R_T results in a reduction in $C_{Fuel,Life}$, this is one reason why a pod propulsion and maneuvering system is conducive to a more profitable cruise ship.

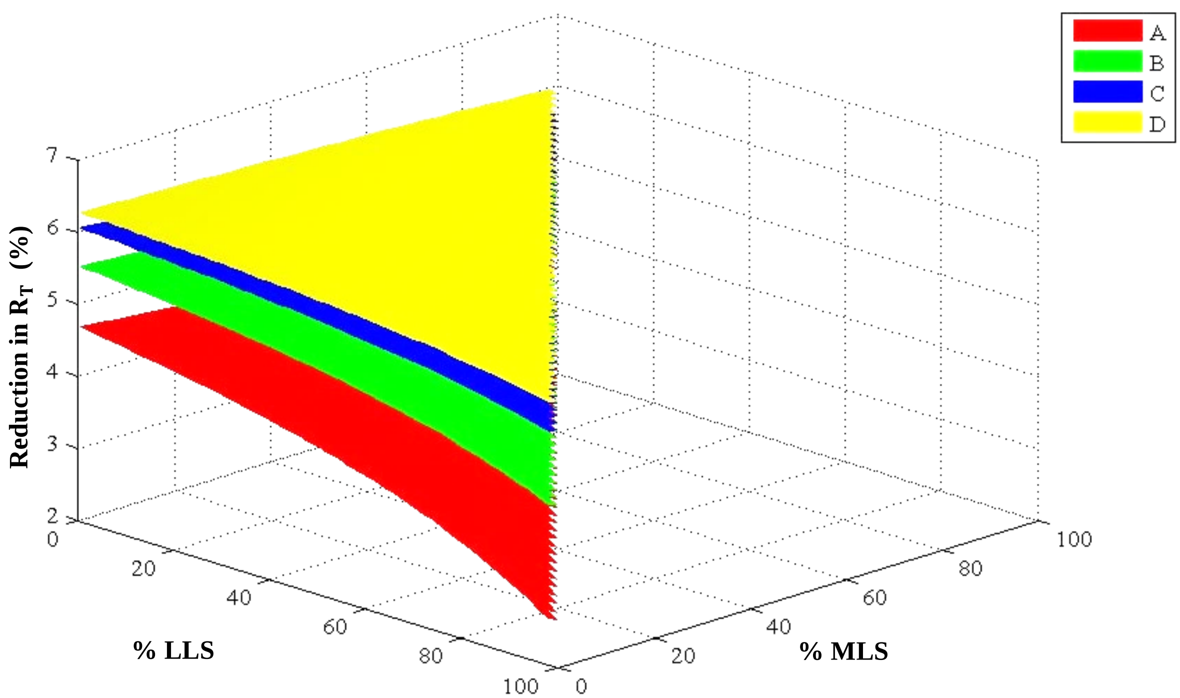

Figure 22. Reduction in R_T if EP&B design feature combination 1.2.1 is selected instead of 1.1.1. The legend right of the figure indicates the specific cruise ship design.

Another favorable attribute of a pod propulsion and maneuvering system is that the propeller(s) can be fixed lower below the stern than that of a traditional propulsion and maneuvering system. This increases mechanical and hydrodynamic efficiency. Also, since the motor is inside the pod unit, a ship's usable volume can be utilized for more purposes. An example of this is when the *Carnival Elation*'s traditional propulsion and maneuvering system was replaced by a pod propulsion and maneuvering system. By doing this, the ship now had the capability to have an incinerator. In fact, this was the first cruise ship to have a pod propulsion and maneuvering system.

Although, a pod propulsion and maneuvering system was stated to be conducive to a more profitable cruise ship, it is important to note a caveat of this notion. That is, pod units historically have had reliability issues that include electrical, bearing, shaft sealing, and lubricating oil contamination issues. If a cruise ship has any pod issues, the ship will likely need to be dry docked to be fixed. According to Stieghorst (2013), this is attributed to a pod unit being very compact and difficult to fix at sea. For example, a pod unit on the Celebrity Cruises cruise ship *Infinity* had bearing issues and the ship had to be emergency dry docked (Bearing Failure Sidelines Cruise Ship Again, 2005). Obviously, if a cruise ship is dry docked, it relinquishes its ability to generate revenue, thus, a very problematic issue for a cruise line whose profitability is contingent on its ships keeping to their strict schedules. In fact, reliability issues drove Carnival Cruise Lines away from pod systems entirely in which their cruise ships delivered after 2005 (as of 2014) did not have them. Nonetheless, reliability of pod propulsion and maneuvering systems have improved over time and perhaps the reason why Carnival Cruise Lines' new ship *Carnival Vista* will be built with a pod system.

Implications of Bulbous Bow

The reasons that a diesel engine and a pod propulsion and maneuvering system are conducive to a more profitable cruise ship have been discussed. This section focuses on the other design feature of EP&B design feature combination 1.2.1 that promotes a greater value of NPV. That is, the effect of a bulbous bow on a cruise ship's profitability.

A bulbous bow modifies the flow of water around a ship's hull to reduce R_T. In the case of finer faster ships, this typical means the reduction on wave-making resistance. In the case of slower fuller ships, this tends to mean the reduction of viscous resistance (Hudson, Molland, & Turnock, 2011). A bulbous bow is effective in terms of reducing R_T when the reduction of these resistances by the bulb outweighs the increase in skin friction resistance caused by the addition of the bulb's wetted surface. As a ship's speed decreases, wave-making resistance will subsequently decrease. Thus, a bulbous bow is typically more effective at higher speeds.

To evaluate the implications a bulbous bow has on a cruise ship's profitability, the reduction in R_T (at v_{Trial}) due to the addition of a bulbous bow is analyzed, as shown in Figure 23. In regards to this figure, the reduction in R_T that each cruise ship design exhibits if EP&B design feature combination 1.2.1 is selected instead of 1.2.2 is surface plotted. As the figure shows, the cruise ship designs would exhibit a reduction in R_T of approximately 6-12% if they had a bulbous bow rather than if they did not. A reduction in R_T results in a subsequent reduction of $C_{Fuel,Life}$. This is why a bulbous bow is conducive to a more profitable cruise ship design.

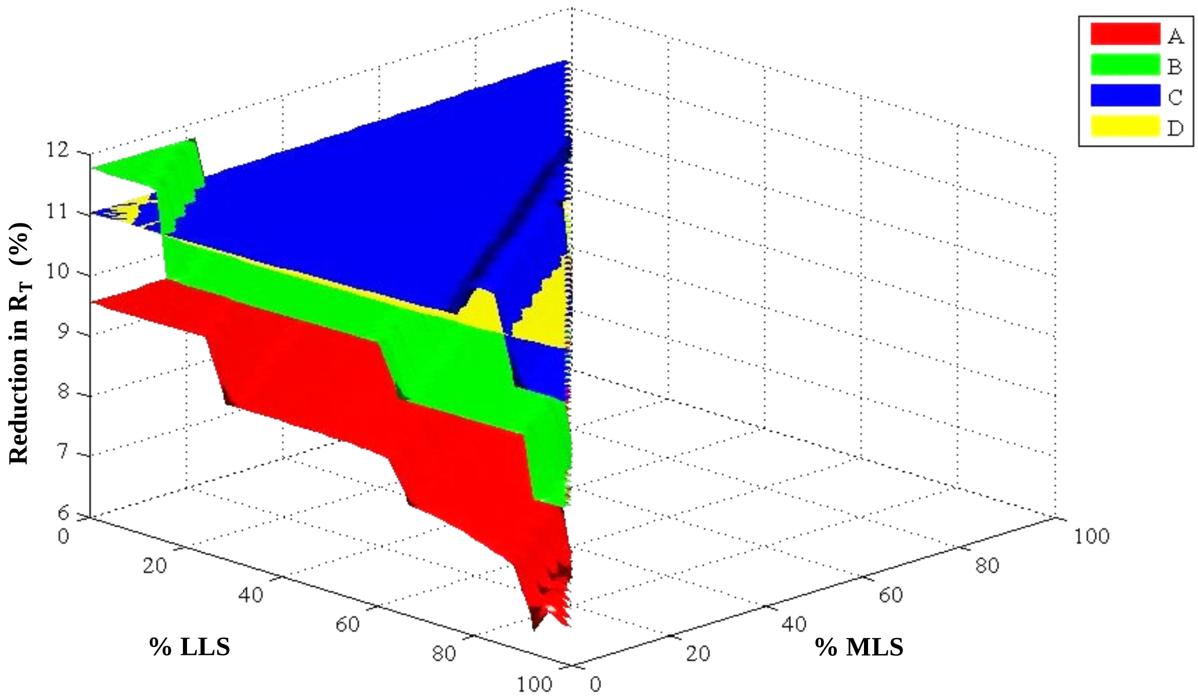

Figure 23. Reduction in R_T if EP&B design feature combination 1.2.1 is selected instead of 1.2.2. The legend right of the figure indicates the specific cruise ship design.

Implications of Passenger Carrying Capacity

Figures 16-19 illustrate NPV of a given stateroom arrangement increases as $N_{Passengers}$ increases. This is because as $N_{Passengers}$ increases, B_{Total} will increase more than that of the total ship cost (C_{Total}). Consider the case in which $N_{Passengers}$ for the cruise ship design feature assemblage corresponding to C.1.2.1 and 100% LLS is increased from 3,000 to 3,002 passengers. With this $N_{Passengers}$ increase, the ship's GT will also increase since it is a function of V_{St}. C_C and $C_{TO,Life}$ will also increase resulting in an average increase in C_{Total} of almost \$211 per day. However, by increasing $N_{Passengers}$ by 2 passengers, there is also an average increase in B_{Total} of almost \$420 per day. This results in a net gain of \$209 per day. This effect is also evident for the opposite design feature assemblage endpoint corresponding to C.1.2.1 and 100% HLS. That is, by increasing $N_{Passengers}$ by 2 passengers, the increase of B_{Total} (i.e. \$743 per day) is greater than that of the increase of C_{Total} (i.e. \$505 per day) resulting in a net gain of \$238 per day.

Since NPV increases as $N_{Passengers}$ increases, this seems to indicate a cruise ship design being infinitely large in terms of GT is most favorable in terms of NPV. Obviously, this is unrealistic. One limitation on ship size can be predicated on the requirement of a ship being able to transit through a particular waterway. For example, in order for a ship to be able to travel through the Panama Canal, the ship's B_{WL} has to be less than 32.3 m in order to fit through the canal's locks. Also, having a greater ship size could limit the ports at which it can dock at since its T can increase to the point at which the ship can be susceptible to running aground. Another aspect to consider is as $N_{Passengers}$ increases, it is more difficult to fill a ship at its double occupancy carrying capacity unless demand would increase as well. To this point, the percentage of Cruise Ship Design D's $N_{Passengers}$ for EP&B design feature combination 1.2.1 that needs to be filled in order for its NPV to equal that of Cruise Ship Design C at 100% of its $N_{Passengers}$ is analyzed, as shown in Table 22. For this analysis, NPV is analyzed at the stateroom arrangement endpoints.

Table 22

Consequences on NPV of Not Achieving the Specified $N_{Passengers}$ of a Cruise Ship Design

	100% LLS	**100% MLS**	**100% HLS**
Cruise Ship Design D	89.9% Full	92.1% Full	94.1% Full
Cruise Ship Design C NPV	$155.5 M	$87.2 M	$57.3 M

Note. This tables shows the percentage of Cruise Ship Design D's $N_{Passengers}$ that must be filled to Equal NPV of Cruise Ship Design C at its $N_{Passengers}$. This analysis is applicable for EP&B design feature combination 1.2.1.

As Table 22 indicates, Cruise Ship Design D has to be relatively full for it to be considered a more profitable investment than that of Cruise Ship Design C. That is 89.9% (i.e. at 100% LLS), 92.1% (i.e. at 100% MLS), or 94.1% (i.e. at 100% HLS) of Cruise Ship Design D's $N_{Passengers}$ must be fulfilled in for its NPV to at least match that of Cruise Ship Design C at its full $N_{Passengers}$.

As Table 21 shows, NPV is negative for every stateroom arrangement corresponding to A.1.2.1 and B.1.2.1. On the other hand, NPV is positive for every stateroom arrangement corresponding to C.1.2.1 and D.1.2.1. Therefore, at some $N_{Passengers}$ between that of Cruise Ship Designs B and D, NPV will become greater than zero. This is analyzed for EP&B design feature combination 1.2.1 since NPV is greater for this combination than any other for a given stateroom arrangement. Given the assumptions in Tables 3, 13, and 18, this particular $N_{Passengers}$ is estimated to be 2,086 passengers with a corresponding stateroom arrangement of 100% LLS, 0% MLS, and 0% HLS.

Implications of Stateroom Arrangement

As previously stated, at a given stateroom arrangement, EP&B design feature combination 1.2.1 of a cruise ship design will always exhibit a greater NPV than that of any other EP&B design feature combination. NPV corresponding to the stateroom arrangements of EP&B design feature combination 1.2.1 are surface plotted for each cruise ship design to estimate the design feature assemblage that is considered most profitable. The results are shown in Figures 24-27. The color bar located right of each figure corresponds to values of NPV.

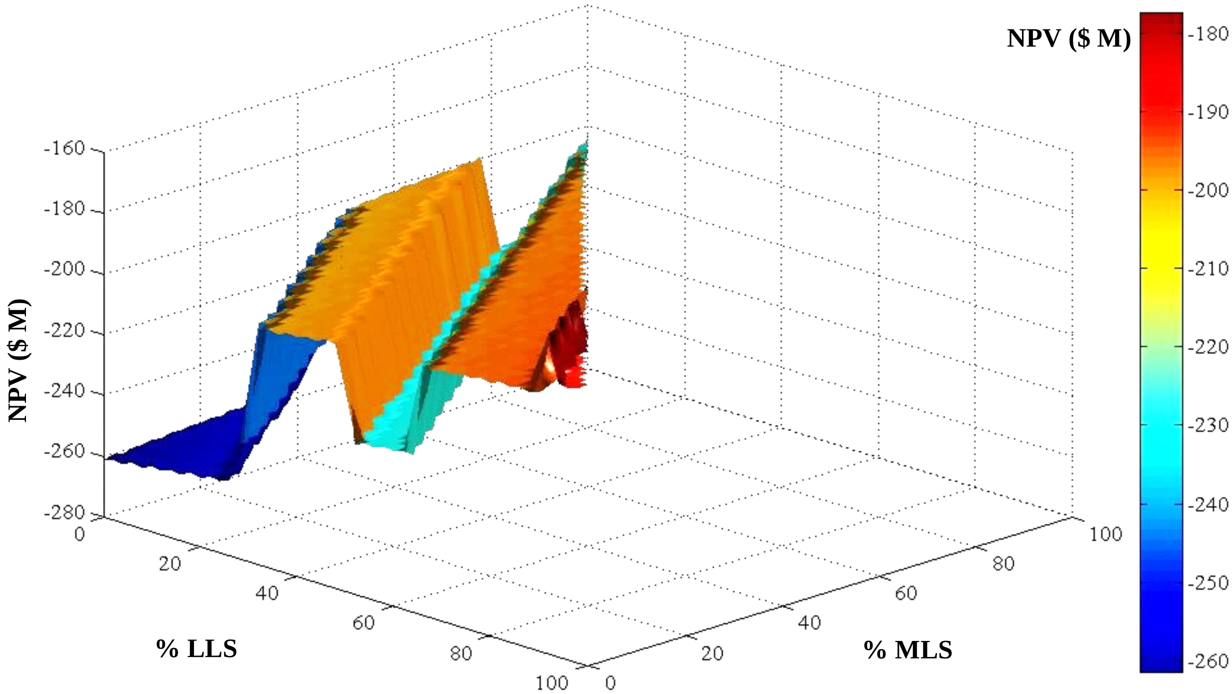

Figure 24. NPV for EP&B design feature combination 1.2.1 of Cruise Ship Design A. The color map located right of the figure represents values of NPV.

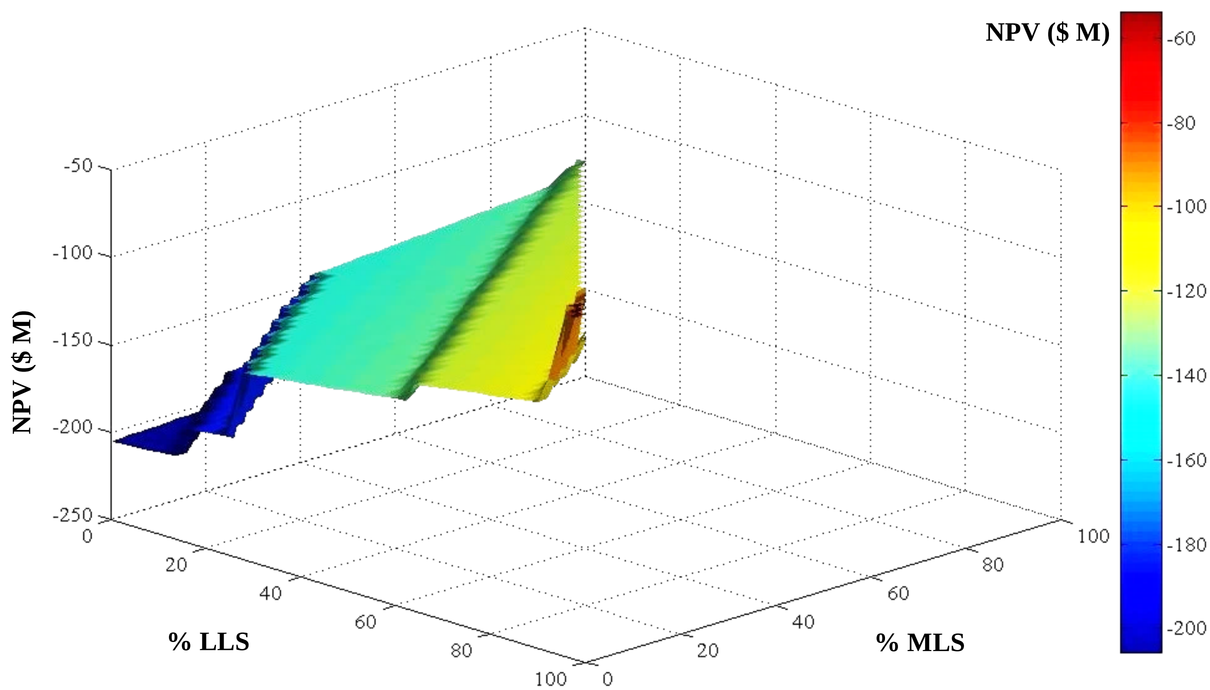

Figure 25. NPV for EP&B design feature combination 1.2.1 of Cruise Ship Design B. The color map located right of the figure represents values of NPV.

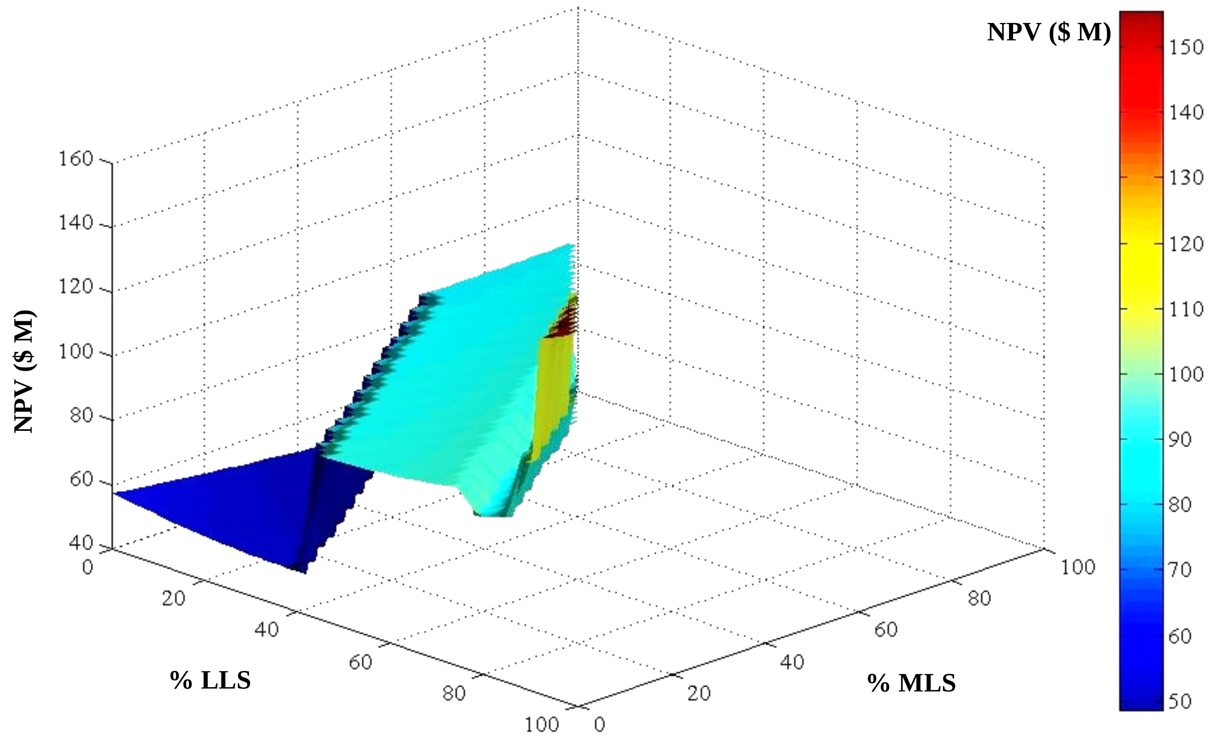

Figure 26. NPV for EP&B design feature combination 1.2.1 of Cruise Ship Design C. The color map located right of the figure represents values of NPV.

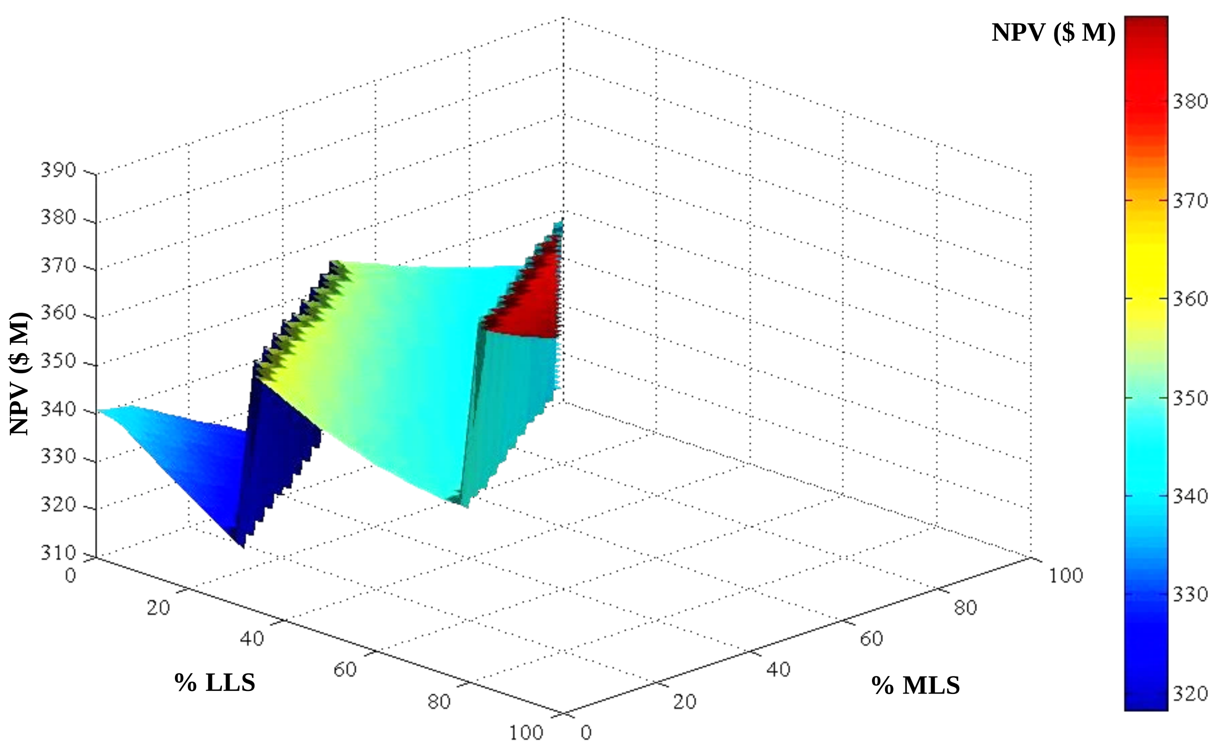

Figure 27. NPV for EP&B design feature combination 1.2.1 of Cruise Ship Design D. The color map located right of the figure represents values of NPV.

The design feature assemblage that exhibits the greatest NPV (i.e. the most profitable) of each cruise ship design is listed in Table 23. Also, the major physical and performance characteristics of these cruise ship designs regarding their most profitable design feature assemblage are listed in Table 24.

Table 23
Design Feature Assemblage that Exhibits the Greatest NPV for Each Cruise Ship Design

Cruise Ship Design	NPV	EP&B Design Feature Combination	Stateroom Arrangement LLS (%)	Stateroom Arrangement MLS (%)	Stateroom Arrangement HLS (%)
A	-$177.5 M	A.1.2.1	88%	6%	6%
B	-$53.7 M	B.1.2.1	100%	0%	0%
C	$155.5 M	C.1.2.1	100%	0%	0%
D	$388.7 M	D.1.2.1	100%	0%	0%

Table 24
Parameters of Cruise Ship Designs and their Most Profitable Design Feature Assemblage

	Cruise Ship Design			
Parameter	**A**	**B**	**C**	**D**
GT	24,621	48,993	97,986	146,978
$\mathbf{L_{OA}}$	177.5 m	225.6 m	287.2 m	330.8 m
$\mathbf{L_{PP}}$	158.7 m	201.7 m	256.9 m	295.9 m
$\mathbf{L_{WL}}$	161.9 m	205.8 m	262.0 m	301.8 m
$\mathbf{B_{WL}}$	23.3 m	28.3 m	34.5 m	38.7 m
T	6.2 m	6.9 m	7.75 m	8.4 m
D	14.9 m	18.0 m	21.7 m	24.3 m
∇	13,772 m^3	25,791 m^3	48,523 m^3	70,227 m^3
$\mathbf{V_{Tot}}$	78,050 m^3	155,307 m^3	310,614 m^3	465,921 m^3
$\mathbf{V_{H}}$	43,860 m^3	88,640 m^3	176,319 m^3	261,762 m^3
$\mathbf{V_{SS}}$	34,190 m^3	66,667 m^3	134,295 m^3	204,159 m^3
Δ	14,117 T	26,436 T	49,736 T	71,983 T
$\mathbf{MCR_{Tot}}$	36,000 kW	50,400 kW	50,400 kW	63,000 kW
$\mathbf{GM_{T}}$	1.30 m	1.36 m	1.01 m	1.35 m
$\mathbf{N_{Passengers}}$	750 passengers	1,500 passengers	3,000 passengers	4,500 passengers
$\mathbf{N_{Crew}}$	263 crew members	524 crew members	1,048 crew members	1,573 crew members
$\mathbf{V_{St}}$	17,484 m^3	34,791 m^3	69,581 m^3	104,372 m^3
% of LLS	88%	100%	100%	100%
% of MLS	6%	0%	0%	0%
% of HLS	6%	0%	0%	0%

In regards to Cruise Ship Design A, NPV is analyzed to be greatest (i.e. -$177.5 M) at EP&B design feature combination 1.2.1 and a stateroom arrangement of 88% LLS, 6% MLS, and 6% HLS. On the other hand, NPV is greatest for Cruise Ship Designs B, C, and D at EP&B design feature combination 1.2.1 and a stateroom arrangement of 100% LLS, 0% MLS, and 0%

HLS having values of -\$53.7 M, \$155.5 M, and \$388.7 M respectively. The relatively great increases in NPV for minor variations in stateroom arrangement, as seen in Figures 24-27, are attributed to C_C being estimated via a multi-linear regression of the predictors GT and MCR_{Tot}. Moreover, it is assumed MCR_{Tot} must equal or exceed $P_{B,Tot}$ in order to ensure the ship's power needs will be fulfilled. For example, consider the case in which $P_{B,Tot}$ is estimated to be 51,000 kW for a cruise ship design that is characterized as being greater than 40,000 GT and corresponding to EP&B design feature combination 1.2.1. The ship is assumed to need some number of 12,600 kW diesel engines to produce the ship's power. Four of these diesel engines are not enough since this would indicate a MCR_{Tot} of 50,400 kW which is slightly less than $P_{B,Tot}$. Thus, five engines are used instead, indicating a MCR_{Tot} of 63,000 kW.

Cruise Ship Design A has a different stateroom arrangement (being 88% LLS, 6% MLS, and 6% HLS) that exhibits the greatest NPV (-\$177.5 M) than that of the other cruise ship designs for EP&B Design Feature Combination 1.2.1. This is a byproduct of the R_T and B_{Ticket} characteristics of this particular design feature assemblage of Cruise Ship Design A.

Figure 28 shows R_T and NPV (i.e. via color map) for EP&B design feature combination 1.2.1 of Cruise Ship Design A (i.e. A.1.2.1). Analyzing the data points in this figure shows the design feature assemblage that has the greatest NPV (i.e. 88% LLS, 6% MLS, and 6% HLS) has the second lowest R_T, being 904.5 kN. The design feature assemblage corresponding to 82% LLS, 16% MLS, and 2% HLS has the lowest R_T and the second greatest NPV being 903.6 kN and -\$177.6 M respectively. These design feature assemblages have the two lowest R_T values since their $C_{R,Diagram}$ and S values are relatively favorable among the A.1.2.1 design feature assemblages. In more detail, these design feature assemblages either pertain to the $L/\nabla^{1/3}$ is equal to 6.5 or 7.0 Guldhammer and Havarld (1974) residual resistance diagrams (see Appendix B). As these diagrams show, $C_{R,Diagram}$ is greater for a given F_n and C_P as $L/\nabla^{1/3}$ decreases. The design feature assemblages that exhibit the two greatest values of NPV have values of $L/\nabla^{1/3}$ rounded to 7.0, thus, their relatively favorable $C_{R,Diagram}$ values. For a given F_n and $L/\nabla^{1/3}$, $C_{R,Diagram}$ decreases as C_P decreases. The design feature assemblages pertaining to the two greatest values of NPV for A.1.2.1 have the lowest rounded C_P value (i.e. 0.625) among the design feature assemblages measured. Also, since these design feature assemblages are less luxurious in terms of stateroom arrangement than most of their counterparts, their GT and V_H are lower resulting in a relatively low wetted surface. As Figure 29 illustrates, the multiplication of $C_{R,Diagram}$ times S is very low for these two design feature assemblages, thus, their favorability towards relatively low values of R_T. The color map located right of the figure represents values of NPV (\$ M).

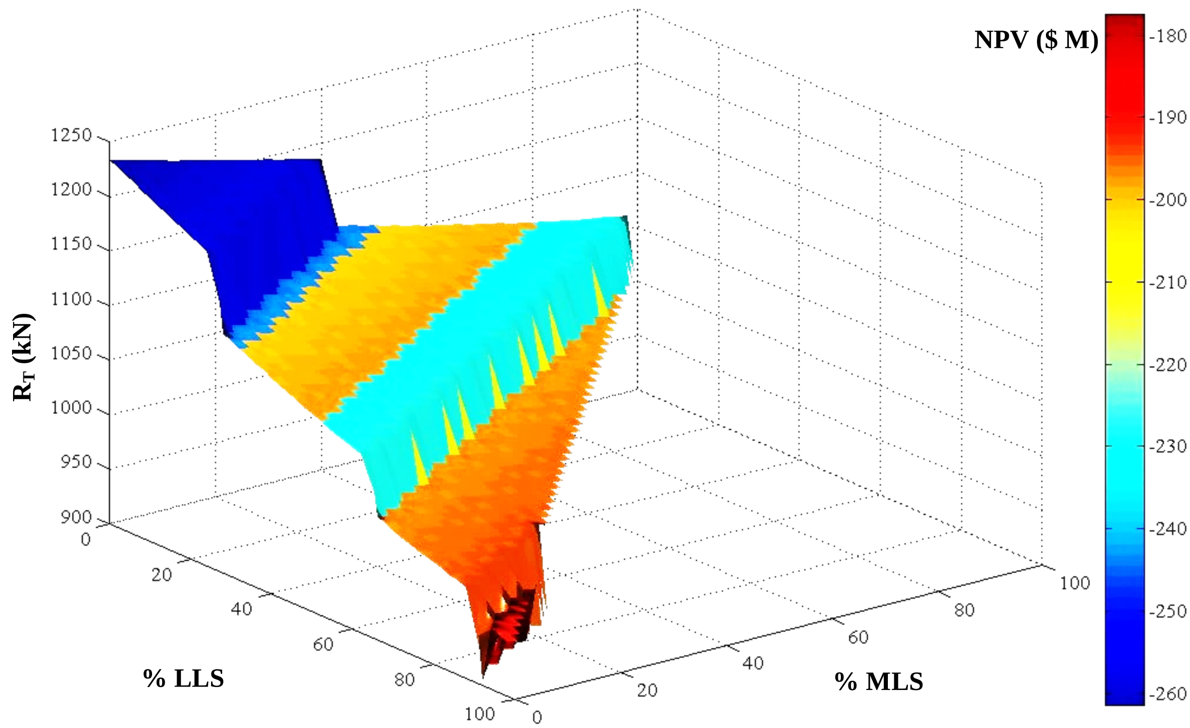

Figure 28. R_T for EP&B design feature combination 1.2.1 of Cruise Ship Design A. The color map right of the figure represents values of NPV.

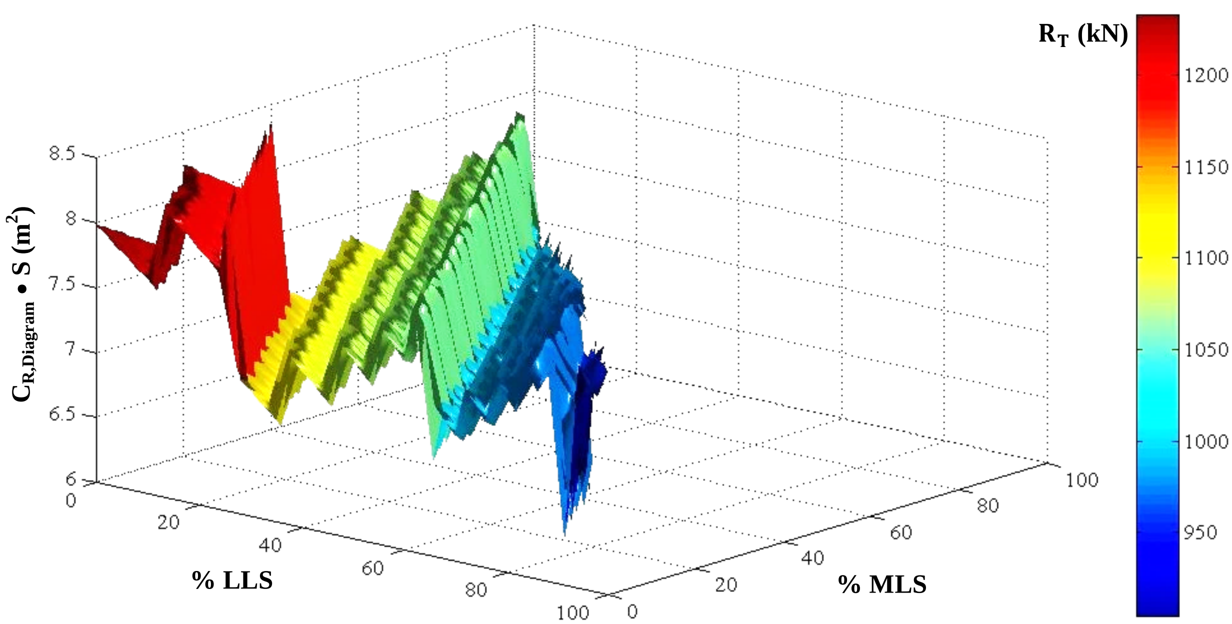

Figure 29. $C_{R,Diagram} \cdot S$ for EP&B design feature combination 1.2.1 of Cruise Ship Design A. The color map right of the figure represents values of R_T.

C_{Fuel} is directly related to R_T. At lower $N_{Passengers}$, C_{Fuel} is a larger component of C_{TO}, as shown in Figure 30 regarding EP&B design feature combination A.1.2.1. Since C_{Fuel} is directly related to R_T, a relatively low R_T is conducive to a relatively low NPV, especially at lower $N_{Passengers}$. Nonetheless, the stateroom arrangement of A.1.2.1 that has the lowest R_T does not also have the greatest NPV for Cruise Ship Design A since a particular stateroom of more luxuriousness is considered to be more advantageous in terms of NPV. The design feature assemblage pertaining to 88% LLS, 6% MLS, and 6% HLS has a $B_{Ticket,Life}$ of $1,282 M while the design feature assemblage pertaining to 82% LLS, 16% MLS, and 2% HLS has a $B_{Ticket,Life}$ of $1,274 M. Since their $C_{Fuel,Life}$ values are relatively close in value (i.e. $771 M), the greater $B_{Ticket,Life}$ of the design feature assemblage pertaining to 88% LLS, 6% MLS, and 6% HLS results in a greater NPV than that of the design feature assemblage pertaining to 82% LLS, 16% MLS, and 2% HLS.

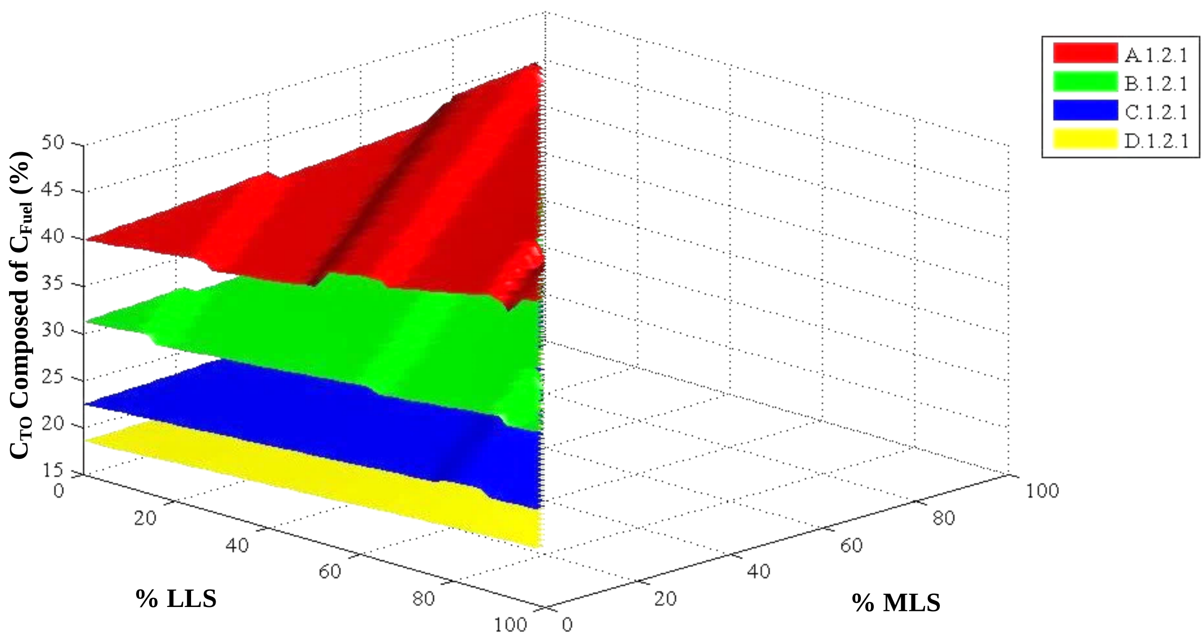

Figure 30. C_{TO} composed of C_{Fuel} for EP&B design feature combination 1.2.1. The legend right of the figure indicates the specific cruise ship design and EP&B combination.

The most profitable design feature assemblage of Cruise Ship Designs B, C, and D in terms of NPV is at EP&B design combination 1.2.1 and a stateroom arrangement of 100% LLS, 0% MLS, and 0% HLS. Their NPVs are -$53.7 M, $155.5 M, and $388.7 M respectively. As discussed, this was not the case for Cruise Ship Design A. This seems to indicate, for cruise ship designs with greater values of $N_{Passengers}$, the advantage in terms of revenue that would be generated by selecting more luxuriousness stateroom arrangements is offset by the disadvantage from the subsequent increase of GT that results in greater construction and operating costs. This is because as the luxuriousness of the stateroom arrangement increases, the ratio of B_{Ticket}-to-GT dependent costs (i.e. C_C, C_{Fuel}, $C_{P\&R}$, C_{Food}, and C_{OSO}) will decrease.

The ratio of B_{Ticket}-to-GT dependent costs is plotted in Figure 31 for the EP&B design feature combination 1.2.1 of each cruise ship design. As the figure illustrates, the ratio of B_{Ticket}-to-GT dependent costs is greatest at the least luxurious stateroom arrangement (i.e. 100% LLS, 0% MLS, and 0% HLS) for Cruise Ship Designs B, C, and, D. On the other hand, the ratio of B_{Ticket}-to-GT dependent costs is lowest at the most luxurious stateroom arrangement (i.e. 0% LLS, 0% MLS, and 100% HLS) for Cruise Ship Designs B, C, and, D. This notion is not supported in the figure regarding Cruise Ship Design A for the reasons previously stated.

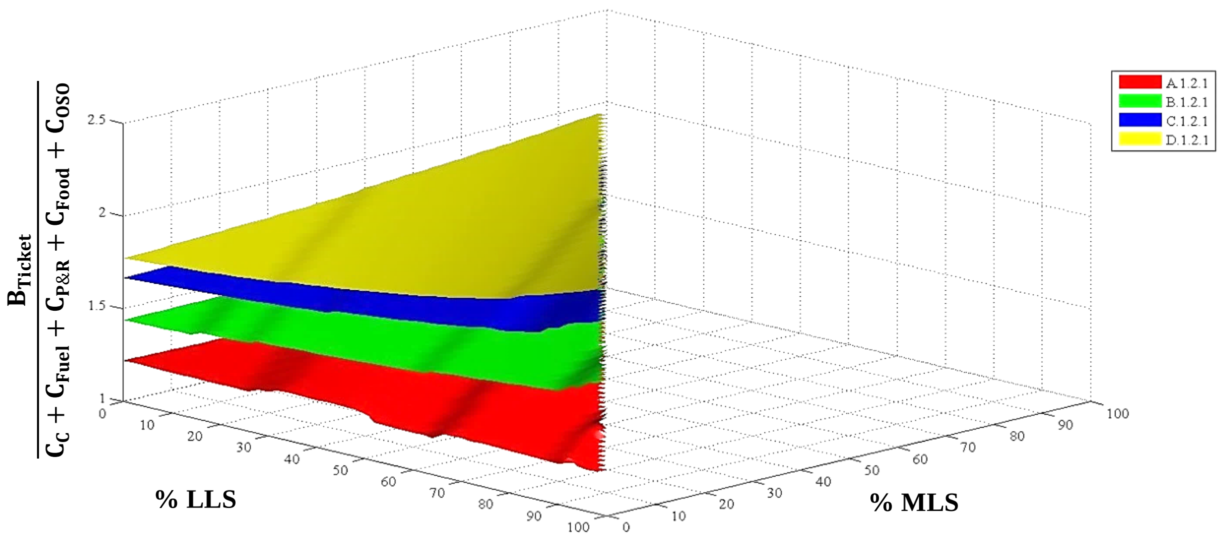

Figure 31. B_{Ticket}-to-GT dependent costs for EP&B design feature combination 1.2.1. The legend right of the figure indicates the specific cruise ship design and EP&B combination.

C_C, $C_{P\&R}$, C_{Food}, C_{OSO}, and B_{Ticket} increase linearly as GT increases; however, C_{Fuel} does not follow this trend. This is because $C_{R,Diagram}$, as estimated via Guldhammer and Harvald diagrams (1974), is not a linear function of F_n given a C_P and $L/\nabla^{1/3}$ combination. Moreover, these diagrams show (see Appendix B), as F_n increases between the approximate range of 0.15 and 0.30, the rate of change of $C_{R,Diagram}$ also increases. Assuming the prototypical ship speeds given in Table 18 are fixed among cruise ship designs, by reducing $N_{Passengers}$ or specifying a less luxurious stateroom arrangement, the size of the cruise ship design will resultantly decrease. This means L_{PP} will also decrease resulting in a greater value of F_n. As F_n increases, the rate of change of C_{Fuel} will increase as well. This is the reason C_{Fuel} is a greater percentage of C_{TO} as $N_{Passengers}$ and/or stateroom luxuriousness decreases, therefore, the reason NPV increases as $N_{Passengers}$ increases.

Cruise Ship Designs B, C, and D had their greatest NPV at the design feature assemblage corresponding to EP&B design feature combination 1.2.1 and a stateroom arrangement of 100% LLS, 0% MLS, and 0% HLS. On the other hand, Cruise Ship Design A had its greatest NPV at the design feature assemblage corresponding to EP&B design feature combination 1.2.1 and a stateroom arrangement of 88% LLS, 6% MLS, and 6% HLS. This notion suggests, at some value greater than a particular $N_{Passengers}$, the design feature assemblage corresponding to EP&B design feature combination 1.2.1 and a stateroom arrangement of 100% LLS, 0% MLS, and 0% HLS will always result in the greatest NPV. Given the assumptions listed in Tables 3, 13, and 18, this $N_{Passengers}$ is estimated to be 854 passengers.

Implications of Speed

Figures 16 and 17 show NPV is negative for any design feature assemblage of either Cruise Ship Design A or B. Moreover, given the assumptions in Table 18, it is unlikely a cruise ship design will be profitable at $N_{Passengers}$ less than 2,086 passengers. However, built cruise ships having $N_{Passengers}$ similar to that of Cruise Ship Designs A and B exist and are profitable. For example, the profitable ship *Azamara Journey* has slightly less $N_{Passengers}$ (i.e. 710 passengers) than that of Cruise Ship Design A. Thus, at least one of the fixed variables in Table 18 must be varied in order for a cruise ship design with $N_{Passengers}$ lower than 2,086 passengers to be deemed profitable (i.e. + NPV).

As stated, NPV is negative for any design feature assemblage of either Cruise Ship Design A or B. One way for these cruise ship designs to exhibit a positive NPV is by lowering their speeds. To this point, the $v_{Service}$ and v_{Trial} needed for Cruise Ship Designs A and B to be considered neutral investments is analyzed, as shown in Table 25. This was analyzed for EP&B design feature combination 1.2.1 since it is the most profitable. Also, it is assumed v_{Trial} is 106% of $v_{Service}$.

Table 25
Variation in Ship Speeds Needed for A.1.2.1 or B.1.2.1 to Have a Zero NPV

	Speeds		**Stateroom Arrangement**		
Cruise Ship Design	$\mathbf{v_{Service}}$	$\mathbf{v_{Trial}}$	**LLS (%)**	**MLS (%)**	**HLS (%)**
A	17.5 kts	18.5 kts	98%	2%	0%
B	19.9 kts	21.1 kts	100%	0%	0%

The results from Table 25 indicate a cruise ship's speed plays a vital role in determining a cruise ship's ability to be profitable, especially at lower $N_{Passengers}$. For example, reductions of about 17% in $v_{Service}$ and 18% in v_{Trial} indicate Cruise Ship Design A would be considered a neutral investment. Reductions of about 5% in $v_{Service}$ and 6% in v_{Trial} indicate Cruise Ship Design B would also be considered a neutral investment. This notion suggests the lower the $v_{Service}$ and v_{Trial}, the higher the NPV. The caveat of this notion is that a cruse ship's itinerary will influence the lowest possible $v_{Service}$ since the ship likely abides by a very strict schedule.

Implications of Stateroom Ticket Prices

When evaluating NPV, values of B_{Ticket} per passenger per day were assumed based on historical data (see Table 13). This assumption could have an impact on the stateroom arrangement that exhibits the greatest NPV for a cruise ship design defined by its $N_{Passengers}$.

If B_{Ticket} per passenger per day was varied for one of the stateroom types while the others remained constant, at some B_{Ticket} per passenger per day of that stateroom arrangement, the stateroom arrangement that exhibits the greatest NPV would change. This is analyzed for

EP&B design feature combination 1.2.1 of each cruise ship design, as shown in Table 26. In this analysis, only the B_{Ticket} per passenger per day of one stateroom type is varied at a time. Note that it was originally assumed B_{Ticket} per passenger per day of LLS, MLS, and HLS were $142.29, $198.90, and $303.96 respectively. Since the stateroom arrangement corresponding to 100% LLS, 0% MLS, and 0% HLS is the greatest NPV for B.1.2.1, C.1.2.1, and D.1.2.1, only an increase in the B_{Ticket} of MLS or HLS, or a decrease in the B_{Ticket} of LLS, would result in a different stateroom arrangement that exhibits the greatest NPV. On the other hand, a decrease or increase in A.1.2.1's B_{Ticket} of LLS, MLS, or HLS would result in a different stateroom arrangement that exhibits the greatest NPV.

Table 26

Sensitivity of the Most Profitable Stateroom Arrangement to B_{Ticket} Changes

		B_{Ticket} per Passenger per Day for each Stateroom Type			Stateroom Arrangement		
Cruise Ship Design	**NPV**	**LLS B_{Ticket} ($\frac{\$M}{passenger \cdot day}$)**	**MLS B_{Ticket} ($\frac{\$M}{passenger \cdot day}$)**	**HLS B_{Ticket} ($\frac{\$M}{passenger \cdot day}$)**	**LLS (%)**	**MLS (%)**	**HLS (%)**
A (LLS ↑)	-$173.3 M	144.14	198.90	303.96	90%	2%	8%
A (MLS ↑)	-$177.5 M	142.29	199.05	303.96	82%	16%	2%
A (HLS ↑)	-$177.2 M	142.29	198.90	306.05	90%	2%	8%
A (LLS ↓)	-$178.2 M	141.98	198.90	303.96	82%	16%	2%
A (MLS ↓)	-$177.7 M	142.29	197.92	303.96	90%	2%	8%
A (HLS ↓)	-$177.6 M	142.29	198.9	303.58	82%	16%	2%
B (MLS ↑)	-$53.7 M	142.29	201.80	303.96	96%	4%	0%
B (HLS ↑)	-$53.7 M	142.29	198.90	311.87	98%	0%	2%
B (LLS ↓)	-$68.7 M	139.39	198.90	303.96	96%	4%	0%
C (MLS ↑)	$155.5 M	142.29	201.27	303.96	96%	4%	0%
C (HLS ↑)	$155.5 M	142.29	198.90	310.01	92%	0%	8%
C (LLS ↓)	$131.1 M	139.92	198.90	303.96	96%	4%	0%
D (MLS ↑)	$388.7 M	142.29	199.96	303.96	46%	54%	0%
D (HLS ↑)	$388.7 M	142.29	198.90	305.37	82%	0%	18%
D (LLS ↓)	$372.3 M	141.23	198.90	303.96	46%	54%	0%

Note. This analysis pertains to EP&B design feature combination 1.2.1 and the ↓ or ↑ symbol next to LLS, MLS, or HLS in parenthesis indicates which stateroom type's B_{Ticket} is being varied.

As Table 26 indicates, the stateroom arrangement that is considered the most profitable is sensitive to variations in B_{Ticket} per passenger per day. For example, only an increase of 0.7% in HLS's B_{Ticket} per passenger per day for A.1.2.1 results in the stateroom arrangement that exhibits the greatest NPV changing from 88% LLS, 6% MLS, and 6% HLS to 90% LLS, 2% MLS, and 8% HLS. Also, an increase of only 0.5% in HLS's B_{Ticket} per passenger per day for D.1.2.1 results in the stateroom arrangement that exhibits the greatest NPV changing from 100% LLS, 0% MLS, and 0% HLS to 82% LLS, 0% MLS, and 18% HLS.

Cruise Ship Designs A and B have negative NPVs for every design feature assemblage, given the assumptions in Tables 3, 13, and 18. Nonetheless, built cruise ships having similar $N_{Passengers}$ to that of these cruise ship designs are known to be profitable. The increase in

B_{Ticket} per passenger per day of a stateroom type needed for Cruise Ship Designs A and B to be considered neutral investments are analyzed, as shown in Table 27. In this analysis, only the B_{Ticket} per passenger per day of one stateroom type is increased at a time. Also, if the B_{Ticket} per passenger per day of a LLS or MLS has to be increased such that its B_{Ticket} per passenger per day is greater than that of a more luxurious stateroom type, it is not considered viable.

Table 27

Variations in B_{Ticket} Needed for A.1.2.1 or B.1.2.1 to Have a Zero NPV

	B_{Ticket} per Passenger per Day for each Stateroom Type			Stateroom Arrangement			
Cruise Ship Design	**LLS B_{Ticket} ($\frac{\$ M}{passenger \cdot day}$)**	**LLS B_{Ticket} ($\frac{\$ M}{passenger \cdot day}$)**	**LLS B_{Ticket} ($\frac{\$ M}{passenger \cdot day}$)**	**LLS (%)**	**MLS (%)**	**HLS (%)**	**EP&B Design Feature Combination**
A (↑MLS)	142.29	277.90	303.96	2%	98%	0%	1.2.1
A (↑ HLS)	142.29	198.90	405.32	0%	0%	100%	1.2.1
B (↑ LLS)	152.70	198.90	303.96	100%	0%	0%	1.2.1
B (↑ MLS)	142.29	222.86	303.96	0%	100%	0%	1.2.1
B (↑ HLS)	142.29	198.90	342.57	28%	0%	72%	1.2.1

Note. ↑ next to LLS, MLS, or HLS in parenthesis indicates which stateroom type's B_{Ticket} per passenger per day is being increased.

Table 27 indicates the variation in a stateroom type's B_{Ticket} per passenger per day needed for Cruise Ship Designs A and B to be considered neutral investments. For example, Cruise Ship Design A's B_{Ticket} per passenger per day for a MLS or HLS would have to be increased by 40% or 33% respectively for the design to be considered a neutral investment. An increase in a LLS's B_{Ticket} per passenger per day for this design is deemed unreasonable since an increase resulting in a B_{Ticket} per passenger per day greater than that of MLS's B_{Ticket} per passenger per day is required. Cruise Ship Design B's B_{Ticket} per passenger per day for a LLS, MLS, or HLS would have to be increased by 7%, 12%, or 13% respectively for the design to be considered a neutral investment. This notion suggests as $N_{Passengers}$ increases, the stateroom arrangement that is considered the most profitable of a cruise ship design is more likely to change due to a specific stateroom type's B_{Ticket} increase.

Implications of Stateroom Volume

When evaluating NPV, stateroom type volumes were based on historical data. This basis could have an impact on which particular stateroom arrangement is considered the most profitable for a cruise ship design defined by its $N_{Passengers}$. Since the stateroom arrangement corresponding to 100% LLS, 0% MLS, and 0% HLS exhibits the greatest NPV for B.1.2.1, C.1.2.1, and D.1.2.1, if the LLS's volume is increased, or if the MLS's or HLS's volume is decreased, the stateroom arrangement that exhibits the greatest NPV of each design would change at some variation in volume. On the other hand, if the LLS's, MLS's, or HLS's volume is increased or decreased, the stateroom arrangement of A.1.2.1 that exhibits the greatest NPV would change at some variation in volume. Table 28 shows the results of these changes in volume. In this analysis, only the volume of one stateroom type is varied at a time. Also, each stateroom type's B_{Ticket} per passenger per day is constant with values listed in Table 13. Note that it was originally assumed LLS, MLS, and HLS had volumes of 40.60 m^3, 65.80 m^3, and 111.86 m^3 respectively.

Table 28

Sensitivity of the Most Profitable Stateroom Arrangement to Stateroom Volume Changes

		Volume of Each Stateroom Type			Stateroom Arrangement		
Cruise Ship Design	**NPV**	**LLS Volume (m^3)**	**MLS Volume (m^3)**	**MLS Volume (m^3)**	**LLS (%)**	**MLS (%)**	**HLS (%)**
A (↑ LLS)	-\$177.6 M	40.611	65.800	111.860	82%	16%	2%
A (↑ MLS)	-\$177.7 M	40.600	66.968	111.860	90%	2%	8%
A (↑ HLS)	-\$177.6 M	40.600	65.800	112.028	82%	16%	2%
A (↓ LLS)	-\$174.9 M	40.068	65.800	111.860	90%	2%	8%
A (↓ MLS)	-\$177.5 M	40.600	65.688	111.860	82%	16%	2%
A (↓ HLS)	-\$177.2 M	40.600	65.800	110.656	90%	2%	8%
B (↑ LLS)	-\$68.6 M	41.812	65.800	111.860	96%	4%	0%
B (↓ MLS)	-\$53.7 M	40.600	64.932	111.860	98%	2%	0%
B (↓ HLS)	-\$53.7 M	40.600	65.800	108.920	98%	0%	2%
C (↑ LLS)	\$126.5 M	41.804	65.800	111.860	82%	18%	0%
C (↓ MLS)	\$155.6 M	40.600	64.764	111.860	96%	4%	0%
C (↓ HLS)	\$155.5 M	40.600	65.800	109.144	92%	0%	8%
D (↑ LLS)	\$373.6 M	41.020	65.800	111.860	98%	2%	0%
D (↓ MLS)	\$389.1 M	40.600	65.324	111.860	44%	56%	0%
D (↓ HLS)	\$388.9 M	40.600	65.800	111.213	82%	0%	18%

Note. This analysis pertains to EP&B design feature combination 1.2.1 and the ↓ or ↑ symbol next to LLS, MLS, or HLS in parenthesis indicates which stateroom type's volume is being varied.

Table 28 indicates the stateroom arrangement that is considered the most profitable is sensitive to variations in stateroom volume. For example, only an increase of 0.011 m^3 in LLS's volume is needed to change the most profitable stateroom arrangement of A.1.2.1 from 88% LLS, 6% MLS, and 6% HLS to 82% LLS, 16% MLS, and 2% HLS. Also, only an increase of 0.42 m^3 in LLS's volume is needed to change the most profitable stateroom arrangement of D.1.2.1 from 100% LLS, 0% MLS, and 0% HLS to 98% LLS, 2% MLS, and 0% HLS.

Cruise Ship Designs A and B have negative NPVs for every design feature assemblage, given the assumptions in Tables 3, 13, and 18. Nonetheless, built cruise ships having similar $N_{Passengers}$ to that of these cruise ship designs are known to be profitable. The reduction in volume of a stateroom type needed for Cruise Ship Designs A and B to be considered neutral investments are analyzed, as shown in Table 29. In this analysis, only the volume of one stateroom type is reduced at a time. Also, if the volume of a MLS or HLS has to be reduced such that its volume is lower than that of a less luxurious stateroom, it is not considered viable.

Table 29
Variations in Stateroom Volume Needed for A.1.2.1 or B.1.2.1 to Have a Zero NPV

	Volume of Each Stateroom Type			Stateroom Arrangement			
Cruise Ship Design	**LLS Volume (m^3)**	**MLS Volume (m^3)**	**MLS Volume (m^3)**	**LLS (%)**	**MLS (%)**	**HLS (%)**	**EP&B Design Feature Combination**
A (↓ LLS)	23.044	65.800	111.860	100%	0%	0%	1.2.1
A (↓ HLS)	40.600	65.800	75.576	0%	0%	100%	1.2.1
B (↓ LLS)	35.924	65.800	111.860	96%	2%	2%	1.2.1
B (↓ MLS)	40.600	55.776	111.860	0%	100%	0%	1.2.1
B (↓ HLS)	40.600	65.800	98.224	10%	0%	90%	1.2.1

Note. ↓ next to LLS, MLS, or HLS in parenthesis indicates which stateroom type's volume is being decreased.

Table 29 indicates the variation in a stateroom type's volume needed for Cruise Ship Designs A and B to be considered neutral investments. For example, Cruise Ship Design A's stateroom volume for a LLS or HLS would have to be decreased by 43% or 32% respectively for the design to be considered a neutral investment. A decrease in MLS's volume for this design is deemed unreasonable since a decrease resulting in a volume less than that of HLS's volume is required. Cruise Ship Design B's stateroom volume for a LLS, MLS, or HLS would have to be decreased by 12%, 15%, or 12% respectively for the design to be considered a neutral investment. This notion suggests as $N_{Passengers}$ increases, the stateroom arrangement that is considered the most profitable of a cruise ship design is more likely to change due to a specific stateroom type's volume decrease.

Analysis of Initial Stability

As mentioned, the focus of thesis was to evaluate the implications of selecting particular design features in the preliminary design stage on a cruise ship's potential profitability. Nonetheless, a ship designer should not solely rely on profitability as the only indicator of a preliminary cruise ship design's viability.

Stability is another important aspect to consider in the preliminary design stage. To this point, GM_T is estimated for EP&B design feature combination 1.2.1 of each cruise ship design. The results are surface plotted in Figure 32. As the figure shows, GM_T of each stateroom arrangement regarding EP&B design feature combination 1.2.1 of each cruise ship design is between values of 0.4 m and 1.4 m. These results indicate each cruise ship design is considered stable in general terms of initial stability. Additionally, these values of GM_T exceed the GM_T requirement of 0.15 m specified in IMO's *Resolution A.749* (1993) regarding passenger and cargo ships.

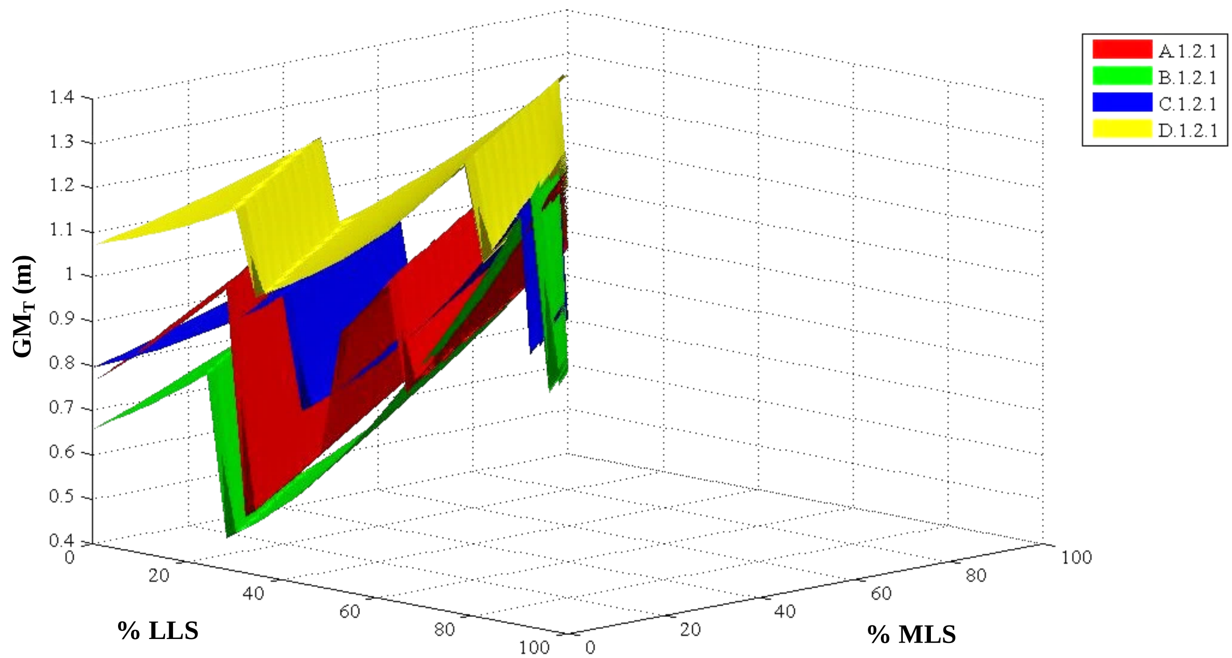

Figure 32. GM$_T$ for EP&B design feature combination 1.2.1 of each cruise ship design. The legend right of the figure indicates the specific cruise ship design and EP&B combination.

It is acknowledged, there are many other aspects of stability analysis that are not performed in this thesis that could influence a preliminary cruise ship design's viability. Thus, as the case of the comprehensive profitability analysis performed, in industry a comprehensive stability analysis would be performed as well.

Results Comparison to Parent Cruise Ships

The validity of the techniques used to estimate the physical and performance characteristics of a cruise ship design are assessed by comparing the actual parameter values of a parent cruise ship with their estimated values. This is accomplished for the cruise ships *Carnival Dream*, *Oasis of the Seas*, and *Norwegian Breakaway*, as shown in Table 30.

Table 30

Comparison of Estimated and Actual Parameters of Parent Cruise Ships

	Parent Cruise Ship								
	Carnival Dream			***Oasis of the Seas***			***Norwegian Breakaway***		
Par.	**Estimated**	**Actual**	**% Error**	**Estimated**	**Actual**	**% Error**	**Estimated**	**Actual**	**% Error**
L_{OA}	323.5 m	305.6 m	5.9%	391.9 m	361.6 m	8.4%	327.5 m	324.0 m	1.1%
L_{WL}	295.1 m	274.6 m	7.5%	357.4 m	336.6 m	6.2%	298.7 m	306.1 m	2.4%
L_{PP}	289.4 m	269.2 m	7.5%	350.4 m	330.0 m	6.2%	292.8 m	300.1 m	2.4%
B_{WL}	38.0 m	37.2 m	2.2%	44.5 m	47.0 m	5.3%	38.4 m	39.7 m	3.3%
T	8.35 m	8.20 m	1.8%	9.55 m	9.10 m	4.9%	8.37 m	8.30 m	0.8%
GT	137,872	128,251	7.5%	238,815	225,282	6.0%	142,694	145,645	2.0%
$P_{B,P}$	44.4 MW	44.0 MW	0.9%	56.3 MW	60.0 MW	6.3%	36.5 MW	35 MW	4.3%
MCR	75.6 MW	75.6 MW	0.0%	100.8 MW	97.0 MW	3.8%	63.0 MW	62.4 M	1.0%
N_{Crew}	1,475	1,369	7.7%	2,706	2,394	13%	1,527	1,651	7.5%
C_C	$859 M	$808 M	6.3%	$1,395 M	$1,354M	3.0%	$842 M	$840 M	0.2%

Note. This Analysis is performed for the *Carnival Dream*, *Oasis of the Seas*, and *Norwegian Breakaway* Parent Cruise Ships. The highlighted columns in the table indicate the percent error between actual and estimated values.

As Table 30 indicates, the estimated and the actual values regarding the parent cruise ships listed in the table are relatively close in value (i.e. < 9% error). For example, the percent error between the estimated and the actual MCR of each parent cruise ship analyzed is no greater than 4% error. Also, the comparison of the estimated and actual values of C_C indicates an error no greater than 7% error.

Table 31 shows the actual and the ideal stateroom arrangements with their associated NPVs for the parent cruise ships listed in Table 30. The actual stateroom is the one the ship actually has. On the other hand, the ideal stateroom arrangement is the one that is estimated to exhibit the greatest NPV (i.e. the most profitable). When estimating NPV regarding these stateroom arrangements, the actual speed characteristics, $N_{Passengers}$, EP&B design feature combination, B_{Ticket} values, and stateroom volumes of each parent cruise ship are used.

Table 31

Comparison of the Actual and Ideal Stateroom Arrangements of Parent Cruise Ships

		% LLS	**% MLS**	**% HLS**	**NPV**
Cruise Ship: *Carnival Dream*	**Actual**	51%	46%	3%	-$361 M
	Ideal	0%	100%	0%	-$264 M
Cruise Ship: *Oasis of the Seas*	**Actual**	28%	65%	7%	$1,911 M
	Ideal	0%	100%	0%	$2,136 M
Cruise Ship: *Norwegian Breakaway*	**Actual**	32%	51%	17%	$844 M
	Ideal	2%	98%	0%	$869 M

Note. This analysis pertains to the parent cruise ships listed in Table 30. In this analysis r and N are still assumed to be 10% and 30 years respectively.

As Table 31 indicates, the ideal stateroom arrangement is 0% LLS, 100% MLS, and 0% HLS for *Carnival Dream* and *Oasis of the Seas* in which their respective NPVs are -$264 M and $ 2,136 M. *Norwegian Breakaway* has a slightly different ideal stateroom arrangement of 2% LLS, 98% MLS, and 0% HLS with a NPV of $869 M. These parent cruise ships have a different stateroom arrangement that exhibits the greatest NPV than that of Cruise Ship Designs, A, B, C, and D. This is mostly attributed to the differences in stateroom volumes and tickets prices between these parent cruise ships and the cruise ship designs. Nonetheless, stateroom volumes and ticket prices of the cruise ship designs are based on statistical data.

The stateroom arrangement comprised of all (or mostly) MLSs is deemed to be the most profitable stateroom arrangement of the parent cruise ships listed in Table 30. As stated, a MLS is considered to have an accompany balcony (e.g. normal-sized balcony stateroom); thus, a MLS cannot be an interior stateroom. This notion could lead one to wonder if it is practical for a cruise ship to have all (or mostly) MLSs.

Typically, a cruise ship will have certain decks allocated mostly towards passenger accommodations due to noise, logistical, and other reasons. For a typical cruise ship of greater GT, its beam is wide enough such that to have four rows (i.e. in the longitudinal direction) of staterooms along two passageways. That is, two rows of exterior staterooms (e.g. balcony staterooms) are located on the outsides of the passageways while two rows of interior staterooms are located on the insides of the passageways. Thus, if a traditional cruise ship design did not have interior staterooms, it would have usable volume on these decks that would go unused and be ill-suited for other functions. Nonetheless, there is a revolutionary cruise ship superstructure design concept that can be utilized in order to have a greater percentage of balcony staterooms (i.e. MLS and/or HLS).

By splitting a cruise ship's superstructure into two halves (i.e. port and starboard superstructures), four rows of balcony staterooms along two passageways can be achieved. Since this design concept is utilized in hopes of increasing passenger ticket revenue, the inner balcony staterooms (i.e. courtyard balcony staterooms) would need to be transversely spaced enough such that to have an aesthetically pleasing view that warrants the increased ticket price over that of a LLS. This design concept will result in a cruise ship with a relatively wide beam (i.e. known as a super-wide cruise ship). The built cruise ship *Oasis of the Seas* is a real life example of this design concept, as shown in Figure 33. This cruise ship has an astonishing large beam of 47 m which is at least 5 m greater than that of any of the other parent cruise ships (see Table 1).

Figure 33. *Oasis of the Seas*' split superstructure. Adapted from Royal Caribbean International, 2014, Retrieved from www.royalcaribbean.com/findacruise/ships/class/ship/home.do?shipCode=OA.

One consideration that might limit the number of balcony staterooms (i.e. MLSs or HLSs) a cruise ship could have is that a cruise ship can only have balcony staterooms in its superstructure; however, usually all passenger staterooms are in the superstructure. Also, a cruise ship's hull must be watertight up to a 40º angle of heel. Obviously, balcony staterooms are not watertight.

Carnival Dream has negative NPVs in Table 31 for both the actual and the ideal stateroom arrangements. This notion does not suggest this cruise ship's revenue will not exceed its costs after its life (assumed 30 years), but rather this ship is not considered profitable at a 10% rate of return. However, at a rate of return of 6.5% this ship is analyzed to be a neutral investment and at 0%, a profitable investment with a NPV of $1,207 M.

Chapter 7 – Conclusion

Overview

The implications of selecting a particular design feature in the preliminary design stage on a cruise ship's potential profitability were evaluated in this thesis. Also, the specific design feature assemblage that promotes the most profitable cruise ship design was analyzed. Profitability was analyzed in terms of net present value.

Research Approach and Utilization

The potential profitability of a preliminary cruise ship design with varying design feature assemblages was analyzed using the NPV model. A cruise ship design was considered to be a profitable investment if its NPV was greater than zero for a rate of return and ship operating life of 10% and 30 years respectively. The greater the NPV, the more profitable the cruise ship design was considered to be.

A cruise ship design was defined by its passenger carrying capacity at double occupancy. A design feature assemblage was defined as the specific synthesis of design features. A design feature was considered to be a finite design decision that would influence the cruise ship's physicality and/or performance in some facet. The major design features considered were stateroom arrangement, engine type, propulsion and maneuvering system, and bulbous bow criterion. Stateroom arrangement was defined as the percentage of each type of stateroom relative to all cruise ship staterooms. The stateroom types considered were LLS, MLS, and HLS, having increasingly greater luxuriousness (i.e. more amenities and greater volume) in that order. The engine types considered in this thesis were diesel and gas turbine engines of varying power output. Also, the propulsion and maneuvering systems considered were traditional and pod.

To estimate the NPV of a cruise ship design in this thesis, the physical and performance characteristics of that cruise ship design were estimated using the techniques discussed in Chapters 3 and 4. Some techniques involved utilizing statistics from built cruise ships. These built cruise ships were referred to as parent cruise ships and consisted of 21 different classed cruise ships from 12 different cruise lines. The statistical data via these parent cruise ships was not the only means utilized in this thesis to estimate the physical and performance characteristics of a cruise ship design. For example, residual resistance of a cruise ship design was estimated using model data provided in the publication *Ship Resistance – Effect of Form and Principal Dimensions* (Guldhammer & Harvald, 1974). All of the physical and performance estimation techniques discussed in this thesis were utilized and showcased in the Cruise Ship Analysis Tool which was then used to analyze the profitability of a preliminary cruise ship design.

The CSAT is a clear, concise, and user-friendly interface constructed in Microsoft Excel. The Excel workbook consists of three Excel spreadsheets. The *CSAT (Parameter Estimations)* spreadsheet pertains to parameter estimations of a cruise ship design. The *CSAT (Cost Analysis)* spreadsheet pertains to cost estimations of a cruise ship design. The *CSAT (Miscellaneous Data)* spreadsheet pertains to miscellaneous data needed to support the algorithms of the other two spreadsheets.

Using the CSAT, NPV as a function of a cruise ship's design feature assemblages were surface plotted and the design feature assemblage that exhibits the greatest NPV was estimated. This design feature assemblage was considered the most favorable and likely to be the most profitable design feature assemblage if the cruise ship design was implemented. The NPV of the most profitable design feature assemblage of each cruise ship design analyzed was compared to each other in order to analyze the implications a cruise ship's $N_{Passengers}$ has on NPV.

Major Findings and Caveats

NPV characteristics were analyzed for cruise ship designs of varying design feature assemblages. Each cruise ship design was distinguished by its $N_{Passengers}$ in which Cruise Designs A, B, C, and D had 750, 1500, 3000, and 4500 passengers respectively. This range of $N_{Passengers}$ was chosen such that to encompass most built cruise ships. When analyzing NPV for the cruise ship designs, the variables listed in Tables 3, 13, and 18 were assumed.

For each cruise ship design, the EP&B design feature combination consisting of a diesel engine, pod propulsion and maneuvering system, and a bulbous bow (i.e. 1.2.1) exhibited the greatest NPV for a given stateroom arrangement. The greatest NPV of Cruise Ship Designs A, B, C, and D were -$177.5 M, -$53.7 M, $155.5 M, and $388.7 M respectively. This indicates, as $N_{Passengers}$ increases, NPV increases. This is because as $N_{Passengers}$ increases, B_{Total} will increase more than that of C_{Total}. This notion seems to suggest a cruise ship design being infinitely large in terms of GT would exhibit the greatest NPV, therefore, being the most profitable design. This notion is obviously unrealistic. As $N_{Passengers}$ increases, GT increases since it correlated to V_{St}. As GT increases so does B_{WL}, L_{PP}, T, ∇, and other ship physical parameters. By increasing these parameters a ship will be less able to transit through certain waterways.

Given the assumptions in Tables 3, 13, and 18, NPV was analyzed to be negative for any design feature assemblage of Cruise Ship Designs A and B. In fact, a cruise ship design was considered to need a $N_{Passengers}$ of 2,086 passengers for it to be deemed a neutral investment. Nonetheless, built cruise ships having similar $N_{Passengers}$ of that of Cruise Ship Designs A and B are known to be profitable. This notion suggests at least one of the assumed variables in these tables needed to be varied in order for those cruise ship designs to be considered profitable. The speeds $v_{Service}$ and v_{Trial} needed to be reduced at least 19% and 17% respectively for Cruise Ship Design A to be considered a neutral investment. On the other hand, reductions of at least 8% and 6% in $v_{Service}$ and v_{Trial} were needed for Cruise Ship Design B to be considered a neutral investment. B_{Ticket} per passenger per day needed to be increased at least 40% or 33% for a MLS or a HLS respectively for Cruise Ship Design A to be considered a neutral investment.

Moreover, B_{Ticket} per passenger per day of a LLS needed to be greater than that of a MLS for this design to be considered a neutral investment. This was deemed unreasonable. On the other hand, Cruise Ship Design B's B_{Ticket} per passenger per day for a LLS, MLS, or HLS needed to be increased at least 7%, 12%, or 13% respectively for this design to be considered a neutral investment. In regards to stateroom volume, the volume of a LLS or HLS needed to be decreased at least 43% or 32% respectively for Cruise Ship Design A to be considered a neutral investment. Since this LLS volume (i.e. 23.044 m^3) is less than that of any stateroom volume of a parent cruise ship, this reduction was deemed unreasonable. Cruise Ship Design B's LLS, MLS, or HLS volume had to be decreased at least 12%, 15%, or 12% respectively for this design to be considered a neutral investment.

The EP&B design feature combination of a diesel engine, pod propulsion and maneuvering system, and a bulbous bow was analyzed to be the most profitable combination for a given stateroom arrangement, regardless of $N_{Passengers}$. This was true for a diesel engine because of its lower SFR than that of a gas turbine engine. This was true for a pod propulsion and maneuvering system because of the reduction in R_T (i.e. a lower S) when compared to that of a traditional propulsion and maneuvering system. This was true for a bulbous bow since the bulb reduced R_R more than it increased R_F (i.e. due to the bulb increasing S) for any cruise ship design.

Although, the EP&B design feature combination of a diesel engine, pod propulsion and maneuvering system, and a bulbous bow was stipulated to be the most profitable combination for all cruise ship designs, there are caveats of this notion. In regards to engine types, a gas turbine engine can be deemed preferable if an engine of a greater power-to-weight ratio is needed. In regards to propulsion and maneuvering systems, some ship designers may prefer a traditional design because of historical reliability issues with pod designs. This notion is especially important in the cruising industry because these reliability issues can dry dock a cruise ship resulting in the ship being unable to generate revenue for some time. Nonetheless, reliability of pod designs has improved over time.

The stateroom arrangement that exhibited the greatest NPV (i.e. for EP&B design feature combination 1.2.1) was estimated to be 88% LLS, 6% MLS, and 6% HLS for Cruise Ship Design A. This was because of this design feature assemblage's R_T and B_{Ticket} characteristics in which a low R_T is conducive to a high NPV, especially at lower $N_{Passengers}$. This design feature assemblage had the second lowest R_T (904.5 kN) with a $C_{Fuel,Life}$ of $771 M. The reason this design feature assemblage exhibited the lowest NPV rather than the one with the lowest R_T (i.e. the stateroom arrangement of 82% LLS, 16% MLS, and 2% HLS had a R_T of 903.6 kN) was because the difference in $B_{Ticket,Life}$ ($8 M) was greater than that of the difference in $C_{Fuel,Life}$ (i.e. < $1 M). The stateroom arrangement that exhibited the greatest NPV for Cruise Ship Designs B, C, and, D was 100% LLS, 0% MLS, and 0% HLS. This indicated the least luxurious stateroom arrangement was most profitable for these cruise ship designs. In fact, at $N_{Passengers}$ greater than 854 passengers, this stateroom arrangement will always exhibit the greatest NPV. This trend occurs because the advantage of additional revenue generated via selecting a more luxurious stateroom arrangement is offset by the disadvantages of increases in construction and operating costs as $N_{Passengers}$ increases. In more detail, the ratio of B_{Ticket}-to-GT dependent costs (i.e. C_C, C_{Fuel}, $C_{P\&R}$, C_{Food}, and C_{OSO}) decreases as the luxuriousness of the stateroom arrangement increases.

As stated, when analyzing NPV, the variables listed in Tables 3, 13, and 18 were assumed to be fixed for the cruise ship designs analyzed. Fixing these variables can influence the stateroom arrangement that exhibits the greatest NPV of a cruise ship design. For example, an increase of only $1.85 in LLS's B_{ticket} per passenger per day indicated the most profitable stateroom arrangement of A.1.2.1 changed from 88% LLS, 6% MLS, and 6% HLS to 90% LLS, 2% MLS, and 8% HLS. Also, an increase of just 0.011 m^3 in LLS's stateroom volume indicated the most profitable stateroom arrangement of A.1.2.1 changed to 82% LLS, 16% MLS, and 2% HLS. Thus, the most profitable stateroom arrangement is clearly sensitive to fluctuations in ticket prices and volumes of the stateroom types. Nonetheless, the ticket prices and volumes of the stateroom types analyzed were based on statistical data.

Possible Future Research

This thesis analyzed the implications specific preliminary design feature decisions can have on a cruise ship design's potential profitability. This was primarily analyzed in regards to stateroom arrangement, engine type, propulsion and maneuvering system, and bulbous bow criterion. Possible future research can include consideration of even more design features. Perhaps, the implications of hullform decisions can be more thoroughly analyzed.

Cruise ship designs of $N_{Passengers}$ between 750 and 4,500 passengers were analyzed. This was partially due to the fact that most cruise ships have $N_{Passengers}$ within the range. Another reason was because of the limitations and caveats of the Guldhammer and Harvald method (1974) that was used to estimate C_R of a cruise ship design. For one, these C_R diagrams are applicable for F_n between 0.15 and 0.45. At a F_n greater than about 0.30, these diagrams are deemed somewhat unreliable for hullforms different than that of the models used in the towing tests since slight variations in hullform can greatly influence C_R values. Since speeds were constant at 22.5 kts and 21.0 kts for v_{Trial} and $v_{Service}$ respectively, analyzing cruise ship designs with even lower $N_{Passengers}$ than that of Cruise Ship Design A can result in inaccurate C_R estimations because of their higher F_n. Thus, one future recommendation would be to consider utilizing another method to predict C_R for cruise ship designs with lower $N_{Passengers}$ than the ones analyzed in this thesis.

It was assumed that passenger cruise related spending habits were predicated on their annual income. This was based on research by the Cruise Lines International Association (2011). Nonetheless, passenger $B_{O\&O}$ may be sensitive to the stateroom type at which a passenger stays in. This would be an interesting future study to analyze this notion.

The sensitivity of the most profitable stateroom arrangement to ticket price or volume fluctuations of different stateroom types was analyzed. An interesting future study would perhaps be to analyze the implications these fluctuations have on consumer demand.

Thesis Significance

This thesis provided a means to evaluate the implications that specific preliminary design feature decisions can have on a cruise ship's potential profitability. This was accomplished utilizing the net present value (NPV) model and the physical and performance estimations techniques discussed in this thesis. These techniques (and NPV model) were than showcased in the Cruise Ship Analysis Tool (CSAT) that provided a clear, concise, and user-friendly interface to analyze the profitability of preliminary cruise ship designs.

This thesis then analyzed the implications that various design features have on a cruise ship's profitability and determined the specific design feature assemblage of these design features that exhibited the greatest profitability for different cruise ship designs. Furthermore, this thesis analyzed the implications that varying speed, passenger carrying capacity, stateroom ticket price or volume, have on a cruise ship's potential profitability. This thesis was not just myopic towards cost analysis in which initial stability was analyzed as well for the cruise ship designs. This analysis suggested the cruise ship designs passed the initial metacentric height stability criteria set forth in IMO's *Resolution A.749* (1993).

It is the author's belief the techniques discussed in this thesis can be utilized by a ship designer in order to provide a more favorable design for his/her customer. This can be accomplished quickly and reasonably with the CSAT. It is also believed the utilization of these techniques and the CSAT provide a ship designer with a viable means to analyze the consequences that early ship design decisions can have over a ship's life. Furthermore, the CSAT can serve as a gauge of one's own estimation techniques.

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Appendix

Appendix A – Block Coefficient and Displacement Volume and Weight

Table 32

$C_{B,PP}$, ∇, and Δ Estimations of the Parent Cruise Ships

Parent Cruise Ship	$\mathbf{C_{B,PP}}$	$\mathbf{\nabla}$ **(m^3)**	$\mathbf{\Delta}$ **(T)**
AIDAaura	0.65	21,002	21,527
AIDAluna	0.68	36,832	37,753
Azamara Journey	0.64	15,975	16,374
Carnival Destiny	0.67	45,956	47,105
Carnival Dream	0.69	58,050	59,502
Carnival Miracle	0.67	45,756	46,899
Carnival Splendor	0.68	50,229	51,484
Celebrity Solstice	0.69	63,424	65,010
Costa Luminosa	0.68	47,493	48,681
Disney Dream	0.70	63,185	64,765
Nieuw Amsterdam	0.66	42,731	43,800
MSC Magnifica	0.69	48,206	49,411
MSC Opera	0.68	30,163	30,917
Norwegian Breakaway	0.71	71,975	73,774
Norwegian Epic	0.70	72,561	74,375
Pride of America	0.70	47,431	48,617
Royal Princess	0.72	71,592	73,382
Ruby Princess	0.66	50,223	51,478
Freedom of the Seas	0.72	72,592	74,406
Oasis of the Seas	0.71	102,106	104,659
Seabourn Quest	0.64	18,238	18,694

Appendix B – Guldhammer and Harvald Residual Resistance Diagrams

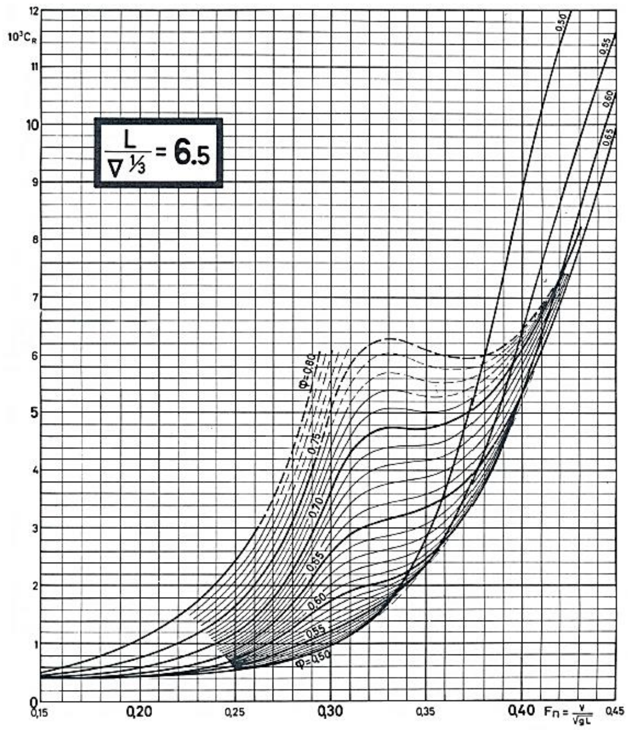

Figure 34. $C_{R,Diagram}$ diagram of $L/\nabla^{1/3}$ equal to 6.5. Reprinted from *Resistance and Propulsion of Ships* (p. 123), by Sv. Aa. Harvald, 1983, Malabar, FL: Krieger Publishing Company. Copyright 1983 by John Wiley and Sons, Inc.

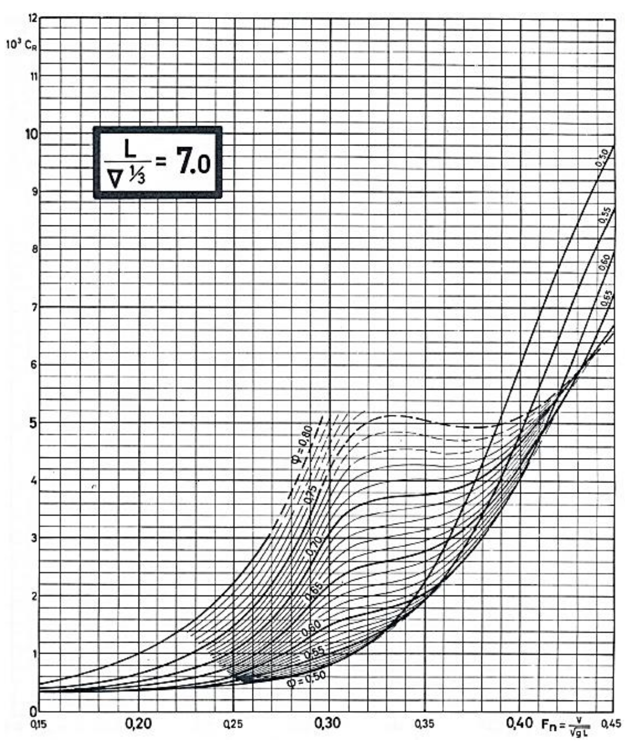

Figure 35. $C_{R,Diagram}$ diagram of $L/\nabla^{1/3}$ equal to 7.0. Reprinted from *Resistance and Propulsion of Ships* (p. 124), by Sv. Aa. Harvald, 1983, Malabar, FL: Krieger Publishing Company. Copyright 1983 by John Wiley and Sons, Inc.

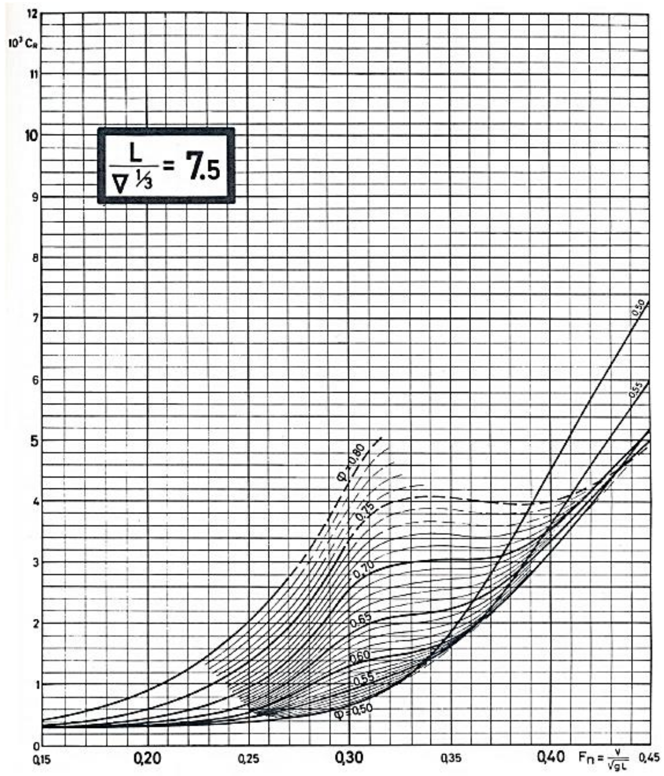

Figure 36. $C_{R,Diagram}$ diagram of $L/\nabla^{1/3}$ equal to 7.5. Reprinted from *Resistance and Propulsion of Ships* (p. 125), by Sv. Aa. Harvald, 1983, Malabar, FL: Krieger Publishing Company. Copyright 1983 by John Wiley and Sons, Inc.

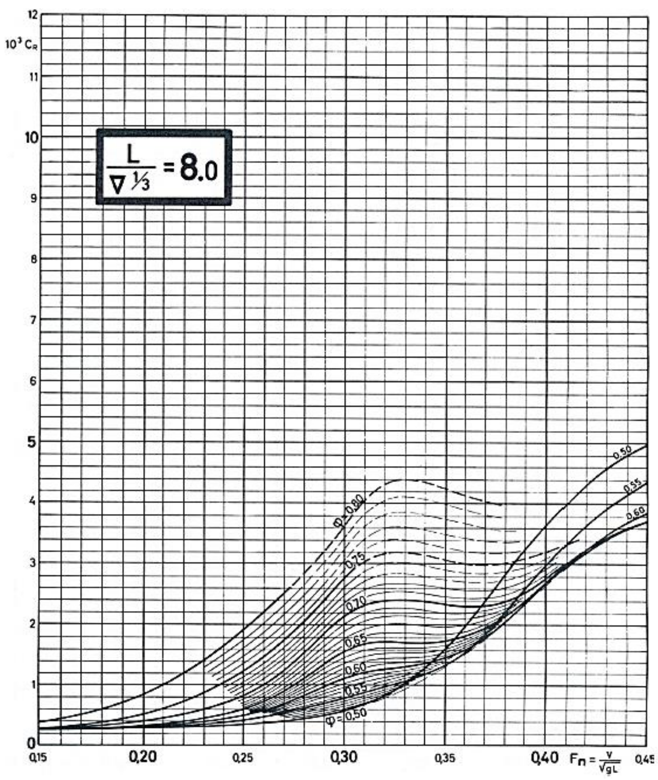

Figure 37. $C_{R,Diagram}$ diagram of $L/\nabla^{1/3}$ equal to 8.0. Reprinted from *Resistance and Propulsion of Ships* (p. 126), by Sv. Aa. Harvald, 1983, Malabar, FL: Krieger Publishing Company. Copyright 1983 by John Wiley and Sons, Inc.

Appendix C – Inflation Rates

Table 33

Consumer Price Index in Terms of 2014 U.S. Dollars

Year	**Price**
1996	1.5
1997	1.46
1998	1.44
1999	1.4
2000	1.36
2001	1.32
2002	1.3
2003	1.27
2004	1.24
2005	1.2
2006	1.16
2007	1.13
2008	1.09
2009	1.09
2010	1.07
2011	1.04
2012	1.02
2013	1

Note. Adapted from Bureau of Labor Statistics, 2014, Retrieved from http://www.bls.gov/cpi.

Vita

The author was born in Arlington, Virginia. He obtained his Bachelor's degree in Ocean Engineering at the University of Rhode Island in 2013. He joined the University of New Orleans Naval Architecture graduate program to pursue a Masters in Engineering with a concentration in Naval Architecture.