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Weight estimation of superyachts

by

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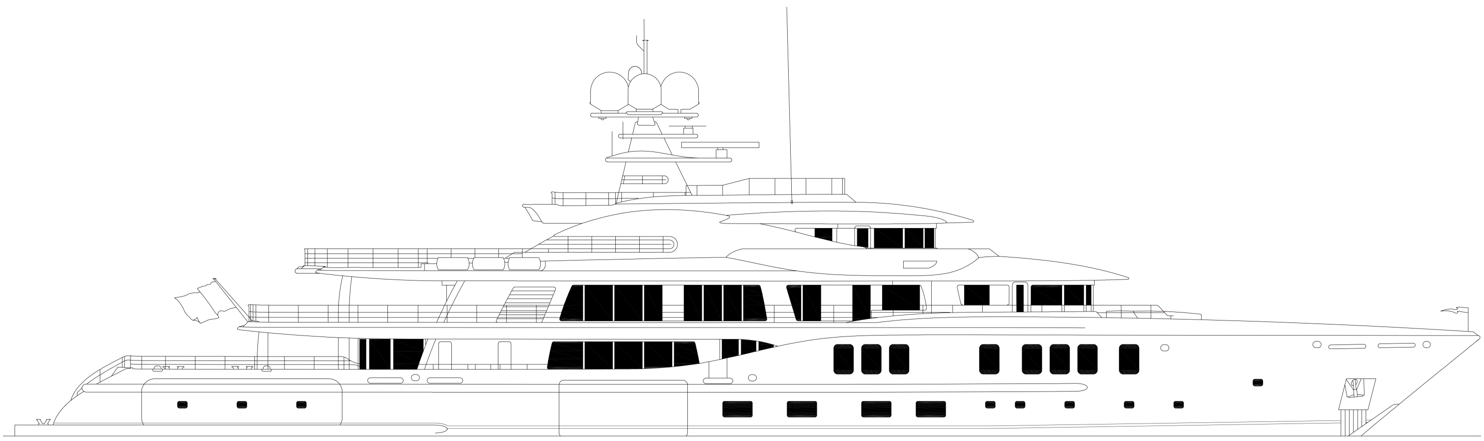

Thesis for the degree of MSc in Marine Technology in the specialization of Maritime Operations and Management

Weight estimation of superyachts

By

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Performed at

Damen Yachting

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Abstract

Superyachts are expected to be perfect since the owner pays millions for them, and the worst that could happen is tilting the ship once it floats. The lightweight, including the center of gravity, is essential to know with a high degree of certainty to prevent this. However, the lightweight is already expected in an early design phase, when still a lot is uncertain.
When the weight deviates from the initial estimations, it would predominantly lead to unwanted changes in speed and stability. At Damen Yachting, multiple methods are used to estimate the weight of the separate weight groups and items. The estimation method used depends on the available information at that stage and the preference of the designer or engineer. It is not always clear what method is used or why, so it would be helpful to use a single tool to update and keep track of the yacht's lightweight.
The objective is to research a standardized way of estimating the weight of a superyacht in different stages of the project, including validating the current, improved, and new methods and combining this in a single tool. The main question of the research is: How to accurately predict the weights and centers of mass of a superyacht, considering the level of detail in the design and engineering phase?

In the design phase, at the beginning of the project, most weight items or groups are based on comparisons with another yacht. Currently, this is done based on a single ship similar to the new design. Still, a significant improvement will be to compare the new design with multiple yachts, with the possibility for the designer to choose the comparison vessels.
The hull construction is the most significant part of the total lightweight. Therefore it is interesting to research a new estimation method for the structure in an early design stage. An estimation using a 3D model of the structure will be replacing this new method as soon as the information is available, so this method should expect a low level of detail.
The margins can also be improved. Currently, only the starting margin and the production margin at the end are set, but not in between. The tool should provide a guideline to tell what margin is expected during each project stage. Also, the complexity level can influence the expected margin, which can all be placed in a table for a clear overview.
The center of gravity estimation of the items is done similarly to the weights. The weight distribution of the yacht is currently not included in the weight estimations, but it will be included in the new weight estimation tool. To achieve this, besides the CoG, the length of the items also needs to be noted for the longitudinal weight distribution. With this information, distribution along the ship in the length direction can be calculated per meter.
The tool used for weight estimation should be able to handle formulas and graphs. Comparing the pros and cons of different available software, Microsoft Excel is the best software for the tool, which is also currently used at Damen Yachting.
To check if the newfound estimation methods improve the weight estimation, the accuracy of both the current and new methods is considered. The model can be validated by comparing these early design stage estimation methods with the more detailed estimates at the end of the engineering stage.

Finally, the research question can be answered, concluding the research.
The weights and centers of mass of a superyacht can be predicted in the design phase by comparing the new ship to a database of existing yachts. These estimations can be used to indicate the calculations' completeness and accuracy at the engineering phase.
The weight list includes margins based on the project's stage and complexity. This way, the estimations and calculation accuracy are transparent and explainable. Also, the longitudinal weight distribution is added to complete and track the center of gravity estimations. Both the design and engineering department can present their findings and estimations next to each other, resulting in a clear overview of development during the project.

Some aspects of the process of weight estimation can be discussed. When engineering the yacht, it is expected that no unnecessary weights are added, but sometimes an engineer wants to be on the safe side and adds more structure to a part of the hull. This could result in significantly more weight than estimated. Also, for the production, a margin is taken into account for deviations, but when adding more weight than expected, it could result in a heavier ship than estimated. This research assumes that this will not occur, but it would be interesting to know if it does. When it happens very often, the estimation or margins should be adjusted to take this into account. This subject is interesting to consider and investigate further but excluded from the scope of this research.
The designers and engineers working on the weight estimations should be familiar with the tool. The tool should be helpful to them, and they need to understand how the calculations are done. Otherwise, there is no trust in the tool, and it will not be used. Therefore it is essential to include them in the process of creating the tool and collect feedback to make it a team product.

Nomenclature

ATAS A web application of Damen Yachting for suppliers and subcontractors to view articles, items, documents, and standards used for the yachts

Azure An independent office for a broad range of yacht related services, like design, technical development, and yacht services

Center of Gravity (CoG) The center through which all weights of the ship may be assumed to act

Contract Design Consists of the preparation and formalization of the drawings, specifications, and other technical data

Detail Design The preparation of detailed working drawings for ship construction, procurement specifications for the purchase of materials, and planning for the ship construction

Equipment Number (EN) A non-dimensional parameter that can be used to select the right sized anchoring and chain cables for a new ship

General Arrangement (GA), General Arrangement Plan (GAP) A drawing to represent: volumes, spaces, compartments, bulkheads, hull forms, decks, and main equipment

Gross Tonnage (GT) A nonlinear measure of a ship's overall internal volume. It is used to determine things such as a ship's manning regulations, safety rules, registration fees, and port dues

Inclining test A test performed on a ship to determine its stability, lightship weight, and the coordinates of its center of gravity

Lightship The weight of the ship's structure, propulsion machinery, hull engineering, and outfit, without variable weights like fuel, passengers, cargo, and water on board

Nupas – Cadmatic A specialized software for shipyards and design bureaus, it is intended for design, support of projects and production

Preliminary Design Development of the final ship proportions, arrangements, power plant type, and structural layout that will satisfy the mission requirements

Siemens – NX (NX) An advanced high-end CAD/CAM/CAE software, for example, used for parametric design and direct solid/surface modeling and also Engineering analysis, using the finite element method

Work Breakdown Structure (WBS) A decomposition of the work to be performed by the project team. Also commonly used is an Extended Ship WBS (ESWBS). This is a system-based WBS for ships

Contents

1 Introduction

Superyachts are expected to be perfect since the owner pays millions for them. The worst that could happen is tilting the ship once it floats. The lightweight, including the center of gravity, is essential to know with a high degree of certainty to prevent this. However, the lightweight is already expected in an early design phase, when still a lot is uncertain.
The total weight needs to match the calculated displacement so that the vessel lies in the water as designed with the correct depth and trim. If this is not the case, this can lead to unwanted changes in speed, range, stability, maneuverability, and load capacity.
For a superyacht, an unforeseen extra weight would predominantly lead to unwanted changes in speed and stability. When discovered in a later engineering stage, this even could lead to changes of the hull to compensate for the extra weight with more displacement.

It is a complicated process to predict the weight of a ship at the beginning of a project. When designing the ship, a lot of information is still unknown, or items are sensitive to changes. After designing the vessel, the engineering department uses these first weight estimations to base their calculations and add more details. It is interesting to research an improved weight estimation method. When a ship deviates from the estimations, especially when heavier than expected, the company has to cope with the problem. This leads to extra production costs on the yacht and a delay in the project. In the worst case, even a redesign is needed to find out how to compensate the deviating weight.

1.1 Damen Yachting

At Damen Yachting (DY), there is currently no uniform, regulated method to calculate the weights of the superyachts. There is a chosen division in items for the weight calculations, but the method used per weight group or item is up to the designer/engineer to calculate it. There are multiple methods to estimate the weights. Based on the available information, the preferred method is chosen. It is not always clear what method is used or why. When more information is available, for example, when the estimations shift from design to engineering stage, other methods are often used to improve the estimation. Therefore it would be helpful to investigate what weight estimation method is best to use during the different design stages.

Ideally, both the design and engineering departments use a single tool to update and keep track of the ship's lightweight. If this tool, with the best estimation method included, is used and understood by all the engineers, it can result in a faster and more streamlined way of working since the work does not need to be checked extensively.
Better estimations also decrease the weight of the vessels in a later stage, which also reduces the material costs. Also, the costs to make changes later in the project will decrease, resulting in an interesting research topic for Damen Yachting.

1.2 Literature

Multiple existing methods are found to estimate weights and centers of mass on a ship. A method of Schneekluth and Bertram (1998) first divides the vessel into big groups and handles each group with a different approach. This is a great base to start with and look into the groups and how they are estimated to get an accurate result. This method is sometimes mentioned as a base for other, more item or group-specific methods.
Another method for preliminary designs of a ship uses a simple division of the lightweight. It estimates the weights of those groups based on tables with information on different kinds of ships. (Papanikolaou, 2014) These tables are based on known weights of existing ships. This can also be done for superyachts, especially when building in series.

Weight estimation is not only done for ships. For multiple industries, the weight estimation at the design stage can be critical, for example (in the case of a ship), to determine if it corresponds with the displacement. Therefore before looking into the weight estimation of a superyacht, it is essential to look into weight estimations in general first. In the offshore industry, weights and distribution are also crucial for the design. But also cost estimating and time schedule, for example in building/construction industries, are related to estimating in general.
Also in aircraft design is weight a key element and has a major influence on its performance. Multiple weight estimation methods are used like scaling of items and a physics-based method for the construction.(Reis, 2020) For the weight estimation of superyachts, it is interesting to look into those industries as well, to explore other methods that may be applicable.

A method to determine the weights of an offshore structure has a similar approach but, for example, uses utterly different weight groups. (El-Reedy, 2019) Comparing these methods to methods mainly used at ships results possibly in a new, improved method.

1.3 Research objective

The objective is to research a standardized way of estimating the weight of a superyacht in different stages of the project. This includes validating the current, improved, and new methods and combining this in a single tool.

1.3.1 Main question

Now the problem is clearly stated. The solution can be found by answering the following question:

How to accurately predict the weights and centers of mass of a superyacht, considering the date accuracy in design and engineering phase?

1.3.2 Subquestions

With the main question stated, it is hard to find an answer directly. Dividing the problem into multiple sub-questions results in finding the solution.
Each sub-question should be researched individually, and with the solutions of all the parts, it can be combined into the complete research of the main problem.

The questions are as followed:

1. How accurate are the current methods used for superyachts, and are there systematic errors in these methods?

First of all, it is essential to look into the currently used methods for weight and the Center of gravity (CoG) of the weight items on a superyacht. This will be a starting point to look at how accurate the current methods are. These results are also essential to compare to other and new methods found to see if it would result in a more precise estimation.

To check how good these current methods are, calculations in different stages of an already built ship are compared to see how accurate it is. Since DY currently uses different weight groups, it can also show which groups are especially interesting to look into further when it is more deviating than other groups.

2. Are there other methods that can complement the currently used methods?

With the currently used methods known, it is interesting to research other methods for weight calculation. This is done for different methods for yachts, ships in general, and other sectors like offshore engineering. This is important for the weight itself but also for the weight distribution of the items, so how the weight is presented. For example, this can be as a single point or as a distributed load.

3. Are the methods useful in both the design and engineering phases?

Finding different methods, determining their usefulness is essential. If a method can be considered valuable, it depends on how much information is needed as input for the calculations. More accurate methods could not be helpful because it requires a lot of information that is not (yet) available.
The amount of available data depends on the phase of the project. When the project is in the engineering phase, more details are known, calculating more precise weights. On the contrary, in the design phase, a rough estimation of weight is expected with only a few details known.

To get a good overview of the methods, they need to be linked to the project phase where it is functional and also determine how accurate or useful the method is if used in another phase. it needs to be determined how accurate or useful the method is if used in another phase. With this information, the quality of the methods in both the design and engineering phase, the best methods can be selected.

4. What new method can be developed to have a more accurate estimation of the superyacht's weight?

The most promising methods are most likely not developed primarily for superyachts. Therefore these methods are still not optimal for superyachts and need improvement.
A new method should be developed to get the best weight estimation of a superyacht possible with the knowledge of the found methods. For both the lightweight and the distribution of the weight items, this new method will be more accurate than the standard and currently used methods.
Testing this newly developed method with information and known weights from existing superyachts of DY results in accuracy compared with the currently used methods.

5. Can the new method be used in a single tool for both the design and engineering phases, resulting in a more accurate total weight estimation?

This new tool must be helpful in both the design and engineering phases and result in a more accurate lightship weight estimation than the current estimation methods. It is interesting what information/input needs to be added or changed to make it completely useful and accurate in both stages.

In the end, people from different departments have to use this method. Therefore it should be available in a clear and straightforward tool. This tool should give the best estimation with the available input at that moment. When having more input for the tool, it ideally should adapt the calculations to the available information to give the most accurate result.

With the research objective known and divided into multiple research questions, a problem analysis can be done. In the following chapters, the current situation in Damen Yachting is mapped to discover problems regarding the weight estimations. This is followed by literature research to investigate what the possibilities are for solving the problem.

2 Problem Analysis

This chapter investigates the current way of working in Damen Yachting, resulting in the problem analysis. The first sub-question, "How accurate are the current methods used for superyachts, and are there systematic errors in these methods?" is researched to focus on the lightship weight estimation parts that need improvement.
First, the weight estimation itself is discussed, followed by the margin and the center of gravity. The way of working is explained, discussing the estimation results.
Finally, the problem is described. Regarding the results and methods described, some interesting aspects are mentioned to be further investigated in the literature research.

2.1 Weight

Damen Yachting divides the weight of a superyacht into multiple groups. The main groups are given in table 1 below. This weights approach is well known, as described in the method of Schneekluth and Bertram (1998). This was shortly mentioned in the introduction and will also be discussed further in chapter 3.

1 Hull, superstructure and paint	**2 Outfitting**	**3 Remaining equipment**	**4 Joinery & outfitting**	**5 Electrical & Nautical**	**6 ER-installation**	**7 Inclining test correction**	**9 Change orders / Options**
Hull	Doors and hatches	Stearing gear	Luxury & crew accommodation	Electrical systems	Main engines		
Superstructure	Windows and portholes	Stabilizers	Teak decks	Navigation	Gearboxes		
Rudders		Anchoring & mooring equipment	Galley, panty & laundry	Communication	Shafting & propellers		
Ballast		Elevators	Insulation		Transverse thrusters		
Paint & cathodic		Cranes	Floors		Generators		
		Airconditioning & ventilation	Sanitary (incl. jacuzzi/sauna)		Tanks & fillings		
					Exhaust gas systems		
					Piping		

Table 1: Weight groups used at Damen Yachting

There are six main groups with weight items. Per group, some essential items are given in the table to provide a clear impression of what is included in a group. In group 7, a correction after the inclining test can be added. This could also be a negative number since the inclining weight of the ship can be lower than the estimated weight. In group 9, extra weight can be added for changes during the project or additional options for the client to add to the ship. These options and/or changes are sometimes estimated beforehand but can also be added later when necessary. Group 8 is not used on purpose in case a different group is needed in the future. In such a case, the group can be added without changing the numbers of other groups and items.

The items are not equal in weight and size, so some groups have a more significant portion of the weight than others. This is shown in figure 1. The percentage of the weight in a group to the total weight is taken for a range of yachts, and the average is displayed. Groups 7 and 9 are not considered here since they are almost always zero during the project. The diagram shows that the items in the first group include half of the total weight. This means a change in this group, for example, caused by using a different estimation, has a significant influence on the ship's total weight.

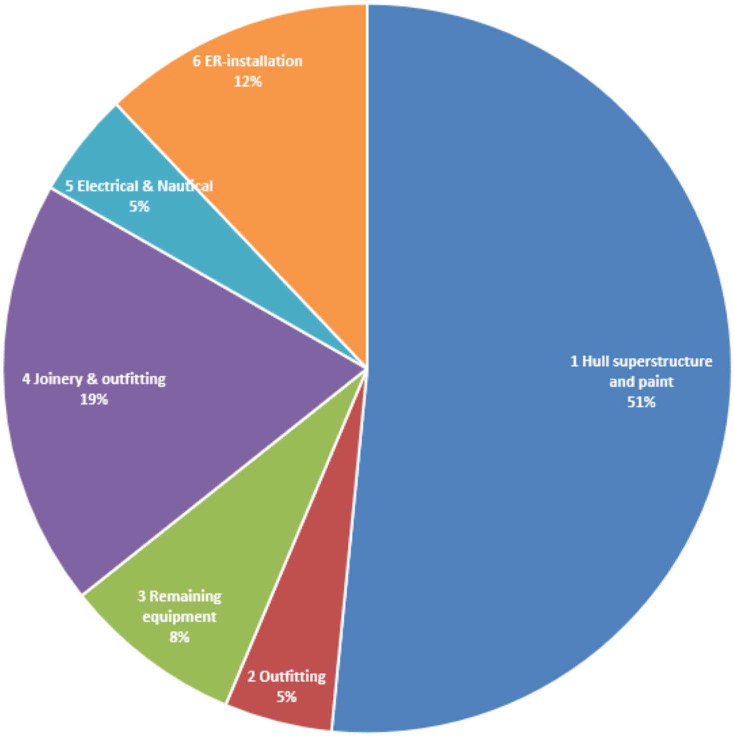


Figure 1: The average division of weights in a DY yacht

2.1.1 The design phase

The design department does the first estimation of the yacht's weight. At this point, only basic information is available. Take as an example the construction weight of the hull. The hull's shape is available at the design phase, but the structure with the beams and stiffeners is not yet. This results in a more global estimation per item than the detailed calculations and models used at the engineering phase, discussed in the next section.
Designers usually start looking for the weight of the different items in the list per group. As discussed, the bigger/heavier items, like the hull construction, are done first because this has the most considerable influence on the total weight. Different options to create a good estimation for an item are possible. In figure 2 below, the various sources of information are shown. The bigger the pie part, the more often it is used for an item to estimate the weight.

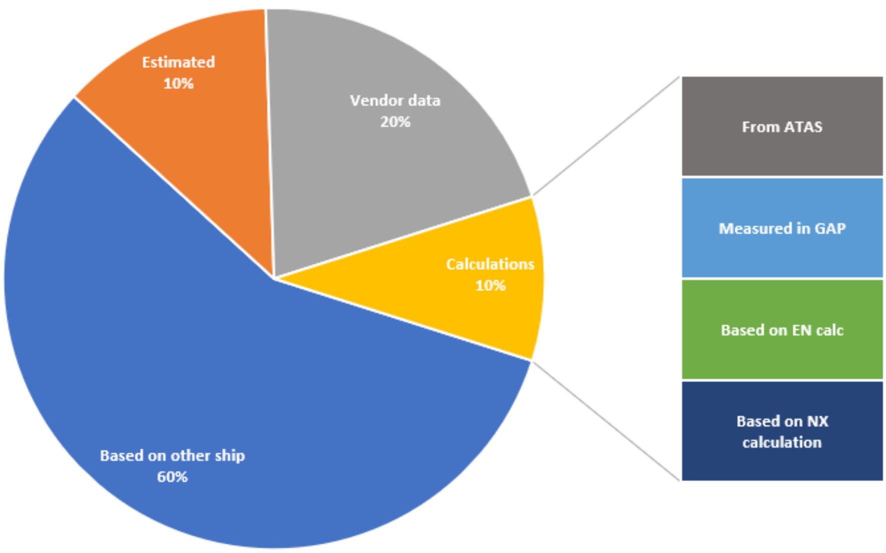


Figure 2: Information sources for weights in the design phase

This pie diagram clearly shows that most of the weights are based on another ship. This is most of the time a single ship that has the most similarities to the current project. Comparing the vessel's Gross Tonnage (GT) and converting the weight accordingly results in the estimated weight of an item.
The estimations are done mainly with a known weight per squared meter (kg/m^2) for a particular surface, like the floors. In this phase, the designer takes a single value for a combination of multiple layers and/or items. For example, they take a total kg/m^2 from another project for the complete floor, including all the separate layers.
A supplier gives a part of the weights. The designer can only check if an item's delivered weight is logical and likely to change later. Communication with the supplier is essential to estimate how certain a weight is and what margin is needed to take possible future changes into account, which will be further discussed in section 2.2.
The calculated items come from multiple sources. These are almost always programs that can calculate the weight of certain items. These calculations are precise, but the project is still sensitive to (significant) changes, and the calculation also needs to be reconsidered. The different programs are listed on the right side of figure 2.
Atas is a web application with articles, items, documents, and standards, and Siemens-NX is a CAD software program. These are, along with the Equipment Number (EN) parameter and the general arrangement plan (GAP), the most significant sources for calculating weights of items or groups.

2.1.2 The engineering phase

In the engineering phase, a lot more information and details of the project are known. The estimations done globally by a designer are replaced for more detailed item weights, given mainly by vendors. Looking back at the example of the hull's construction. Now with complete models of the ship, a better estimation of the weight of the steel can be made because a lot of beams and stiffeners are drawn in a model. This will result in a more accurate estimation, although some details (for example, brackets) are unknown or not drawn in the models.
In figure 3 below, the same pie diagram is made as in figure 2 but now for the engineering phase. Not only the sources of weights have changed, but also the number of items has increased. In the design phase, between one and two hundred items are listed, while in the engineering stage, lists are made of more than three thousand items.

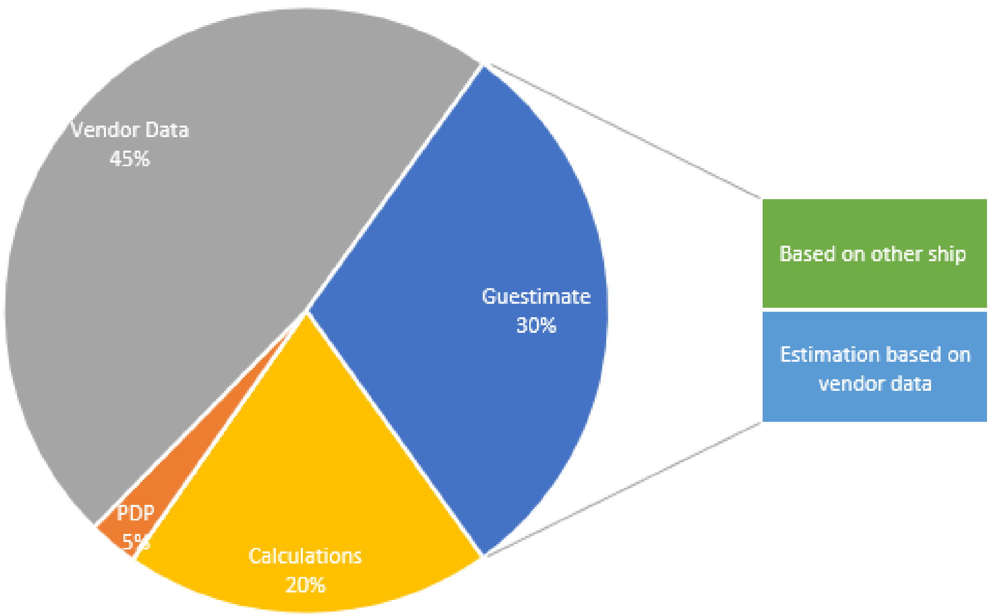


Figure 3: Information sources for weights in the engineering phase

As seen in figure 3, most weight items come from suppliers, which information is available and unlikely to change. A small amount is coming from the Design department, which can be in-house or from another design company like Azure. The rest of the items are either calculated or estimated. The calculated items are mostly coming from models like Nupas. These programs give precise weights according to the models made of the yacht. The "guesstimated" items can still be based on another ship or are provided by a supplier but are still likely to change.

2.1.3 comparison of weights

It is interesting to compare the weight estimation in the design phase and the engineering phase. Also, the inclining test is interesting to see what the result is after building the ship.

The current way of estimating the weight is done "Bottom-Up". At the start there is an empty sheet, and the items and weights are filled in once estimated. The downside is that all the other items still remain zero until it is investigated. Resulting in an incomplete LSW.

In appendix E, multiple examples of a ship's weight is shown. Multiple ships are showing the same trends. The graphs shows the weight in the three different phases. It also shows the weight with the extra margin included, discussed in section 2.2.
The CoG in length, transverse and vertical direction are also shown. This will be further discussed in section 2.3.

Looking at the weight estimation of this ship, it is clear that the estimation at the end of the design phase is much lower than at the end of the engineering phase.
As discussed before, in the design phase are much fewer details known. Therefore, the margins added to the estimation are more extensive, but almost in every case, this is still not enough to get close to the result of the inclining weight. The estimation including an extra margin at the design phase is still lower than the estimation of engineering without any margin. This shows that the estimation method in the design phase needs some improvement to get closer to the actual weight of the yacht. The margins are always additional to the weight estimation. If a margin is available for an item, this is seen as available extra weight so often used in a later stage.
Compared to time planning, the margin is a buffer and kept low to keep pressure on the schedule to make sure not to delay the schedule. When a ship is too heavy, exceeding the margin, this could be due to a too low estimation in the first place.

Looking at the estimation of the engineering phase, the estimation is already much closer to the actual weight of the ship. Also the engineering estimations are often too low. Because the estimation is mainly based on information from suppliers and models, it is hard to improve these methods. It is interesting to look into the margins if they can be improved by adjusting the margins.

To further investigate the differences in the weight estimation between the design and engineering phase, it is interesting to look at the group division of the weights and compare these. The difference between the design and engineering phases can be seen for multiple vessels in appendix F. The graph shows the increase of weight between the design and engineering phases. Also the increase of LCG, TCG, and VCG per group are shown, discussed later in section 2.3. The first group seems to have the most significant deviation between the two stages. It looks like the estimation of this group is done the least accurately, but this group also has the most weight in it. So it would be more accurate to compare the difference in weight in percentage of the total weight to compare how much has changed for each group between the phases.
It is also essential to keep in mind that there could always be some significant changes in the design during the engineering phase, resulting in big increases or decreases in weight in a specific group.

Looking at the increase of weight per group in percentages. No single group has the most deviation in estimating the weight in this case. Also, when looking at a whole range of yachts, there are always some groups that deviate but every time different groups. This shows that there is no single group to pay more attention to when just looking at the most significant deviation in weight from design to engineering phase.

When combining this information with the weight division in figure 1. The bigger groups have the most impact on the total weight when changed. For example, when not accurately estimating the hull structure is in the design phase, the change of weight (when checked in more detail during the engineering phase) in the group of the hull structure directly changes the total lightweight of the ship significantly.
It is interesting to look at the more significant weight groups because they can influence the total weight the most. In other words, it is not efficient to try to get a very accurate estimation for some items if it is barely affecting the total lightweight anyway. The focus then should be on the bigger/heavier groups and items.

2.2 Margin

The weights cannot be predicted precisely. Especially during the design phase, as explained before, a lot can still change or is not very accurate. A margin is added to the estimated weight to get some confidence in the estimations to have some room for changes. This is shown in the graphs in appendix E.
With the estimated weight and the weight including the extra margin, a range is made where the actual lightweight of the yacht should be.
There is more uncertainty in the estimations in the design phase, resulting in a more significant margin on top of the calculation. The engineering phase has more specific information on many items, so a smaller margin is possible in this phase. This is visible by the gap between the blue and green lines in the graph. Of course, the weight of the inclining test has no margin anymore since this is the actual weight.

In Damen Yachting, there are some guidelines for adding margins to weight items. For the yachts, it is usual to start with a 5% extra margin when beginning with the estimations. At Damen, a starting margin of 10% is used most of the time, and since DY is now more integrated with Damen, this is also used often. This already shows no fixed rule on choosing the margin at the beginning of the estimations. When getting more details, the designer or engineer can choose smaller margins. The margin can be reduced to 2%, which is always kept to include some unexpected extra weight added during the production. So the margin at the end of the engineering phase should be at least 2% on top of the estimated weight. The margin does not change directly from 5 to 2% but continuously changes during the project when updating the weight because of new information. Since there are no strict rules about the margins, these are changed a lot during the project. When handing over the weight calculation from design to engineering, The engineer can choose different margins for themselves when not confident with the global estimations of a designer. It is not unusual that the margin is changed back to a higher percentage at this point.

Finally, when estimating the total weight of the yacht, a margin for extra's, like adding more toys, is added and a margin for future changes like a refit. This way, it is known how much weight can be added to the ship after building. This is done separately from the lightweight estimation itself, so this will not be further discussed.

2.3 Center of gravity

Next to the lightweight itself, it is also important to know upfront what the center of gravity is on a yacht. The center of gravity (CoG) can tell if a ship is balanced and not inclining to the side or front/aft. Especially the height of the CoG, the VCG, is essential. This is used to determine the stability of the ship.

The LCG, TCG, and VCG are estimated the same way as the lightweight itself. These are estimated for each weight item separately to get the total CoG for the ship. Because stability is essential, a margin of 30 cm is always added to the total VCG of the yacht to make sure it is still stable enough.
The graphs in appendix E shows that the total LCG, TCG, and VCG are almost equal, and this is also the case for most of the other yachts. This indicates that these values are estimated accurately, but the graphs in appendix F shows that this is not the case for the separate groups. The graph shows the increase in LCG, TCG, and VCG from the design to the engineering phase per group. As seen in the graph, some groups do have differences while the total results in the same CoG. Again this is the same case for multiple yachts. Similar to the weights themselves, the bigger/heavier groups have a more significant impact on the total CoG, and therefore it is more interesting to look into these groups and items first.
For separate items, like a tender on board, it is easy to get the location of the CoG. But for items that are divided on the ship, like the hull construction or the piping through the whole ship, it is hard to put down a single location. This is still done by calculating the CoG of the item and taking this as the location, but it is essential to keep in mind that it is not a single weight in that location.
The distribution of the weight is, for example, necessary when determining the longitudinal strength. Although this is not a part of the weight calculation, it has a strong link since it needs the weight calculation for its analysis. Therefore the weight distribution is also essential to discuss. Currently, the weight distribution is not noted in the weight calculation, so the engineer has to find out separately how the weights are acting on the ship, as a single point load or divided over a certain length. This could be included in the weight calculation, but this will be discussed in the next section.

2.4 problem description

With the current situation at Damen Yachting known, it is interesting to look at problems they currently encounter, as seen in section 2.1.3. The estimation of the lightweight of a yacht is not always accurate. This section introduces multiple aspects, with the following research discussed in chapter 3.

2.4.1 Weight

Regarding the estimation methods for the weights. The information in both the design and engineering phase based on suppliers is not very interesting to look into because this information is almost entirely dependent on other parties. It is interesting to have a guideline on how much margin these items should have, based on the current phase of the project. This will be discussed in the next section.
The information that is calculated by the designer/engineer themselves is, on the other hand, interesting to look into. The most interesting idea is to research a new method for specific groups. It can be a method already used for other types of ships or even in other sectors. But also a completely new approach could be helpful. For example, a new method that is based on existing methods but specialized for superyachts.
In general, there should also be done some research into the group division. Some other divisions of groups, used in other sectors or types of ships, could result in a better estimation and especially a better overview of the different items. If this is the case, it could technically be easy to adapt to this change. However, this would make it harder to compare the information in the groups with previous vessels, making previous data based estimations less useful. Also, next to weight calculations, these groups are used for other purposes like cost estimations/indications, making it more work to use the weight estimations for those purposes.

At the design phase, multiple aspects are interesting to look into. When the estimation of the design phase is already more accurate, there will be fewer surprises later in the project since the estimation in the engineering phase would better match.
First, since most of the items are based on another yacht, it is interesting to research how this is done. When looking at a range of yachts, it will give a better estimation than only based on a single previous yacht.
Also, the source of these comparison vessels is essential. The used information is not always up to date and comes from the most recent calculated weights. This way, possible errors are taken over to the new design, although it was corrected later in the project of the comparing ship.
Suppose the estimation of an item from the design phase is more accurate than the engineering phase. In that case, the engineers could continue their more detailed estimations and keep the previously found estimation if there is no more detailed information of an item (yet). Currently, the engineer often recalculates the designer's work, which takes more time and could create disagreement between the designer and engineer. Therefore the estimation or calculation must be clearly explained to prevent such disputes.

2.4.2 Margin

Looking into the margins. It is interesting to create guidelines that give the designer or engineer a handheld what margin to take for an estimation. These margins could depend on the experience of the newly designed yacht, for example, giving a custom yacht more margins than a series yacht. Also, the margins should differ based on the level of detail and based on a guideline instead of every designer or engineer using their personal preferences. This way, the margins start the same and decrease with the level of detail increasing, leaving an agreed margin for production.
Introducing a new system of margins should not completely take away a designer's or engineer's input. Fixed percentages are not desired since the people estimating the weights should use their knowledge and experience of the items and make exceptions when they think it is needed.
A selection or range of margins within a certain level of detail could be a possible solution to combine a guideline with the input of a designer/engineer.

2.4.3 Center of gravity

One of the byproducts of the weight estimate is longitudinal weight distribution. For the location of the CoG of the weight items, it is interesting to look at the possibilities to include the distribution of the weight on the ship. As discussed before, on the weight calculation, it is not clear if the weight is a point load on that location or if the weight is initially distributed. Adding a dedicated place to indicate if the weight should be distributed along certain ordinates could make the following steps, for example, for the longitudinal strength, much easier.

Further, is it also for this part of the weight calculation interesting to research if other methods are used at ships or in other sectors estimate the locations more precisely since there are some differences between the estimations in the design and engineering phases.

2.5 Conclusion

The current weight group division is interesting to investigate. Some other divisions of groups, used in other sectors or types of ships, could result in a better estimation, especially an overview of the different items.
The most interesting idea is to research a new method for specific groups for the weight estimations themselves. It can be a method already used for other types of ships or even in other sectors. But also a completely new approach could be helpful. One of the methods is to compare the new design with the current fleet. Since most of the items are based on another yacht, it is interesting to research how a range of yachts can be used to improve the estimations.
For the margins, guidelines could be helpful to give the designer or engineer a handheld what margin to take for an estimation. Also, the longitudinal weight distribution can be added.

This answers the first sub-question, forming the scope of the solution approach, which will research the mentioned parts of the lightweight estimation. In general, this shows that the current way of estimating the weights is mainly bottom-up. The different parts are added and summarized to a total lightship weight.
By adding a top-down estimation, by estimation the total LSW and for the different weight groups first. An initial estimation can be made without the uncertainty of missing items. This could also lead to better margin settings since it is already known where the total weights approximately should end up.
The next chapter will look more into dept how these problems can be addressed and improved.

3 Solution approach

When looking into the total weight estimation of a superyacht. There is no single method but multiple approaches for different kinds of items and different stages of the project. The various used methods are inspected and researched for an improved or replacement method. Establishing a total improved weight estimation.
The second and fourth sub-questions, "Are there other methods that can complement the currently used methods?", and "What new method can be developed to have a more accurate estimation of the superyacht's weight?", are researched in this chapter using the problem analysis in the previous chapter. Multiple solutions are researched to improve the current weight estimations. Also the third sub-question, "Are the methods useful in both the design and engineering phases?" is directly investigated when researching the new or adjusted methods. The weight groups, margins, center of gravity, and tool used for the weight estimation are discussed in this chapter using literature on these essential aspects of the weight estimation and if an improvement can be found or created.
Considering the weight estimations themselves, the hull estimation is interesting to look into. Also comparisons with other yachts, used on many items at the beginning of the project, can be improved.

3.1 Weight groups

Starting with the division of the groups, it is important to research other systems that could improve the current item division. In general, a division of items into groups is recommended for shipbuilding, but there are some differences. (Cheirdaris, 2020) (Lamb, 2003) (Committee, 2002)
Three well-known item systems are the expanded ship work breakdown structure (ESWBS), used by the US navy, the Maritime Administration (MARAD) system, used for US commercial ships, and the SFI system, developed by the Norge Skips Forsknings Institute.
These three group systems are given in Appendix A. The system of MARAD is minimal since it uses only three main groups. (Lamb, 2003) (Committee, 2002) The ESWBS system looks like the current group division of Damen Yachting. Still, some groups are different because the focus on specific items is different for naval ships, and the armament group is not used at the yachts. (Straubinger, 1963) (Lamb, 2003) (Committee, 2002) The SFI system is also similar to the DY system, but the equipment is more divided into multiple different groups. (Cheirdaris, 2020). Looking at these different systems, changing the currently used group system does not look interesting because it already looks like these systems but only then adapted for yachts.
In the offshore industry, weight is also essential and estimated early in the project, as discussed in the introduction. Therefore it is also interesting to look into the used division there.
For offshore structures, the following primary division is used: (El-Reedy, 2019)
1. Structural steel 2. Architectural 3. Main equipment 4. Bulk material

The first group is the complete structure, which can be compared to the hull and superstructure of a yacht. It has an interesting detail because the offshore structure is further divided into a primary-, secondary-, and temporary steel part. The second group is comparable with the joinery and outfitting group, such as floors, windows, furniture.
The main equipment group contains all the mechanical-, electrical-, and instrument equipment. The last group contains all the bulk items like piping, HVAC, and cables.
The current first item group, the 'Hull, superstructure & paint' group, is extensive, as discussed in chapter 2. It is interesting to apply the method used in the offshore industry and divide the hull and superstructure into primary, secondary, and maybe even tertiary steel (or aluminium for the superstructure). This way, there is better control on this significant part of the total lightweight, and it can also help assign the correct margins. For example, the primary structure can have a smaller margin at the design stage since this is available very soon in the project. The tertiary structure is a smaller portion and can be an estimation with a significant margin because this part is only known at the very end of the project. This makes a better estimation than taking it together with a substantial margin for all the structures added later in the project.

The paint and other items that can be seen as "bulk" items like in the last group of the offshore system are spread over multiple groups now. They are all estimated the same way in the design phase, namely based on other yachts, and also the weight of all the items is divided over the whole ship instead of a single point. This does make sense how it is divided now, but it is helpful to have these items together. It is possible to leave these items how it is now, keeping in mind that they have a significant influence and can be handled similarly.

3.2 Weight estimations

For the weight estimations themselves, the hull is interesting to research. This has a significant impact on the total weight. Also, making a new method for the hull might be helpful for other items like the superstructure and paint weight. The database comparison estimation method is also interesting to improve, as discussed in chapter 2, because this method is often used at the beginning of the design stage.

3.2.1 Hull estimation

Looking at the current group division discussed in chapter 2, the Hull, Superstructure & Paint, Joinery/Outfitting, and ER-installation are the best groups to improve the weight estimation. As discussed, these groups are not specifically the worst predicted, but they have the most significant impact on the total weight because these are the most prominent groups.
Many items are "bulk" items in these groups, as it is called in the offshore industry. These items are hard to predict early, so they are mainly based on other yachts.

It makes sense to make estimations based on other vessels when almost no project information is available yet. Still, the General Arrangement (GA) is already known most of the time when starting the weight estimations. A lot of helpful information, like the location and sizes of bulkheads, walls, and floors, which can easily be measured using the GAs.
It is interesting to construct a method using the known surfaces for weight estimations. For developing such a method, an approach is made:
Starting with the hull, it is helpful to split this into primary, secondary, and tertiary steel construction, as done in the offshore industry, as discussed previously.
For different kinds of surfaces, a standard weight can be calculated. To achieve this, per surface, a standard layout needs to be made. For example, when looking at the primary construction of an average bulkhead, the number and shape of primary stiffeners and the thickness of the plates can be taken on average to get a weight per (squared) meter of bulkhead. Next to the bulkheads, this can also be done for surfaces like decks and the shell.
To get a systematic overview of the different surfaces in the hull, a three-level work breakdown structure is used. The first level contains the various surfaces of the hull that will be investigated, like bulkheads. The second level includes the major elements for each part of level one, like the plate, primary-, and secondary beams. Level three contains the sub-elements of level two, like the webs and flanges, including the thicknesses and shapes of the beams. (Gregory K. Mislick, 2015)
The more details this method takes into account, the more accurate the method is. But as soon as a 3D model of the complete hull is made, this new method will not be as precise as the model. Therefore, it is unnecessary to be very precise, and taking an average of certain surfaces is sufficient to estimate in the early design stage.

Research in production cost estimations is helpful for this method because weight estimations are used to estimate material costs.
The material quantity depends on the geometry of the structures. This includes the shape of the beams, the dimensions, and the material type. The WBS is followed backward to inspect the minor elements separately first and then combine them into a bigger assembly.
First, for each level-three sub-element, the features like thickness and materials are investigated. Then at a component level, the geometry and dimensions are essential. Now the shape of the beams and their lengths are inspected. These two steps are done for the primary and secondary structures.
Finally, the assembly level combines these components. The global dimensions and relations, like the beam spacing and the measures of the surfaces, are inspected. (Weustink, 2000)

When this method gives an estimation of the hull structure, which will be checked by comparing the results with the known hull weight in the engineering stage, the same can be done for the superstructure. This expansion of the method can even be done for other items that are related to surfaces. For example, with the information of the structure, other items like paint and insulation can also be estimated. However, it is essential to focus first on the hull and expand it to other items afterward.

3.2.2 Comparison with other yachts

In the design phase, it is essential to compare with other yachts to estimate the weight of items. As discussed before, some items are unknown or complex to calculate at the beginning of a project, so a previous ship is checked to get an initial estimation.
When a designer is looking at the estimation and calculations of a previous ship, it is done with only the recent information they have for themselves. But when this estimation is corrected or changed later in the project, the designer does not always know it, copying the errors to the new yacht. Therefore it is essential always to use the most up-to-date information of a comparing vessel. To achieve this, a database should be made of previous yachts with the weight information at the end of the engineering phase, or even better, a corrected weight list after building the ship.
Also, looking at a single comparing vessel increases the chance to copy an unknown mistake. The estimation would become much better when making a trend line of multiple superyachts previously built by DY.

According to the designers and engineers of Damen Yachting, when comparing a yacht, the GT is used to convert the weight to the new yacht. This is also mentioned, for example, for the weight of the hull construction, in the book Ship Design and Construction. (Lamb, 2003)
Using a database will only be successful when the database has sufficient and reliable information that is kept up to date. (Tas and Yaman, 2005) The downside of using a database is that this method is hard to use when a new project deviates from the current fleet. But using this method to estimate similar projects will increase the accuracy of the estimation. (Han, 2008)

A graph can be made with a trendline with the GTs and the most up-to-date weights of an item. The shape of this trendline (linear or polynomial) can be chosen by looking at its accuracy in comparing yachts. Also, it should be possible to select what ships need to in- or excluded in the comparison. For example, when designing a yacht, it should be considered if the Yacht Supports or SeaXplorers need to be used as comparison vessels or not. This way, the designer can adapt the database to get a good estimation from other yachts similar to the new design.

In figure 4, multiple yachts are plotted with their GT on the x-axis and lightweight on the y-axis. With the trendline formula, shown linear in blue and polynomial in red, the lightweight of a new project can be estimated based on the GT. The trendlines must cross (0.0), since there is no weight at zero GT.
This can be done for any item that is usually also estimated based on another yacht. The R^2 indicates how accurate the trendline is, with R^2 of 1.0 being perfectly aligned with the database. In this example, both trendlines are very accurate.
Checking the boxes in a list of the fleet include the desired yachts in the graph. The trendline will be adapted automatically and shows the new results based on the selection.

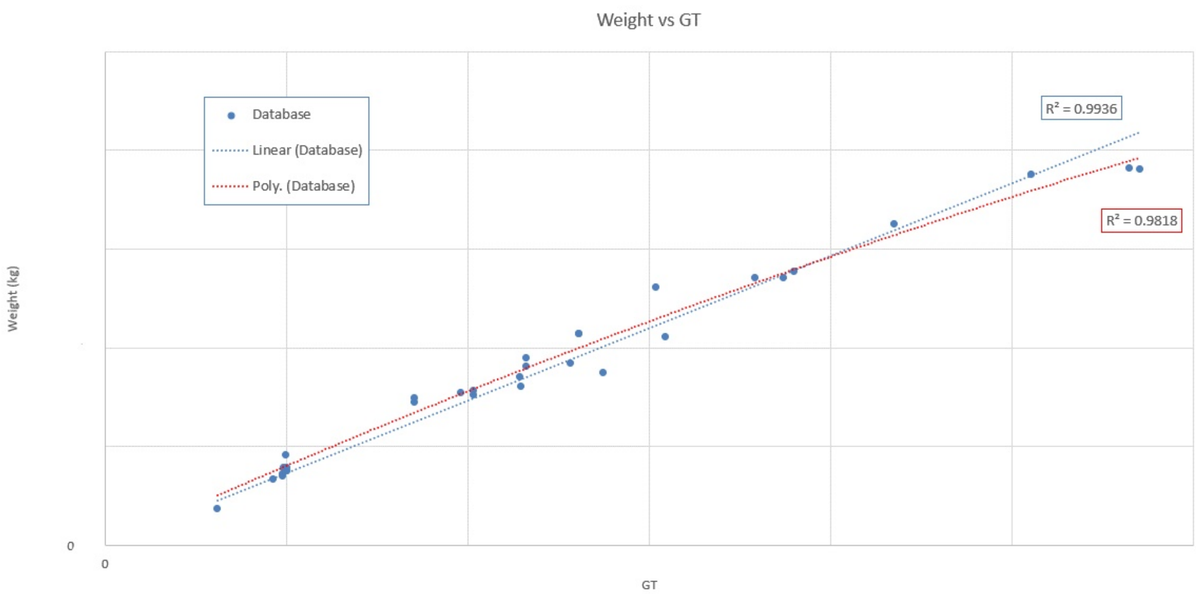


Figure 4: Example of a chart to estimate the weight converted from the GT based on a database of yachts

3.3 Adding margins

"Margins are included to cover the inherent limits on the precision of initial weight estimates." (Straubinger, 1963)
This is in one sentence the reason why margins should be included in a weight estimation. This paper explains that margin values, in any phase of design, depends on the experience and knowledge gained in the previous similar ships, the nature and status of the design (is it firm or still developmental), the extent of historical data available, and the result of studies of previous weight growth trends.
This shows it is hard to establish rules to use fixed margins because the vital information for the margins differs a lot. It is good to keep this in mind and maybe use this to establish guidelines for the margins.
In the preliminary design phase, a baseline is established, and during the project, the weight estimations are expected to improve. The cause is improved design information such as a refined baseline definition, structural drawings, release of the top-level requirements, and better definition and weights of machinery and equipment. This results in an improved quality of estimations for the weight and also the VCG. When such information is presented, margins can be reduced because of the enhanced estimations.

The book Ship Design mentions some recommendations for margins, based on Schneekluth and Bertram (1998). (Papanikolaou, 2014)
In the preliminary design stage 2-6% margin on top of the estimated weight is used, converging to construction tolerance during the project. During the final phase of the design, this tolerance is 1-2%. This guideline is similar to the current way Damen Yachting uses margins.

Also, the impact of the center of gravity of the added weight from the margin is mentioned. To take this into account, the vertical position of the weight center of the extra weight is located 20% higher than the estimated VCG of the vessel. The longitudinal position is assumed the same as the estimated LCG of the vessel. This way also a margin for the VCG is included. This method is different than DY is currently using and can be inspected and compared. The margins that are added on the VCG are much lower than the currently used 30 cm, but the impact of the margin depends on the size of the weight margin for the new VCG. So when the project is still very uncertain and significant weight margins are used, the total VCG is also higher than in a more detailed stage.

Looking for entirely different methods for using margins, the Bonen scale is fascinating. (Pedatzur, 2016)
This method is a standard in the Israeli defense industry, including air, land, naval, and space systems.
This Bonen scale gives the desired margin, depending on the complexity and risk level and the project stage. In table 2 below, the margin values for a (naval) ship are listed as recommended by the paper's author.

Complexity and risk level	**Stage of the project**			
	Feasibility study	**Contract design**	**Detailed design**	**Construction**
Level 1	5%	4%	2%	1%
Level 2	10%	8%	5%	2%
Level 3	15%	12%	8%	4%
Level 4	25%	15%	10%	5%

Table 2: The weight design margins according to the ship's features. (Pedatzur, 2016)

The levels in the left column indicate the complexity and risk of the (sub)system:
Level 1, Duplicating an existing system. This design presents a common engineering problem that has been successfully dealt with before. The tools and methods are well known and practiced, for example, the design of a new regular-size container vessel.
Level 2, Upgrading an existing system. There is a need to change, upgrade or add new features to a previously designed system. For example, adding a helicopter landing pad to an existing ship without changing other systems.
Level 3, Development of a new system. A brand new design with no previous versions, but other projects have demonstrated that the project is feasible. More investment is needed to enter a new design arena to deal with unfamiliar subjects.
Level 4, Technological breakthrough. Nothing like this has ever been done before. The design requires learning new disciplines, developing new theories, designing tools, etc. For example, designing a hull and superstructure made of composite materials.

It is suggested that the levels and stages should not be chosen for the whole initial weight estimate but rather for each different weight group. For example, a ship with a breakthrough hull design but a standard propulsion system could use 25% for the first group since it is a feasibility study with risk level 4, but for that same ship, the other groups can be 5-10%.

The methods of the US navy to use margins are conceptually like table 2. The US Navy margin range starts at 18% and can decrease to 6%. Most of their new ship projects can be considered Level 3. Looking at the table, this is comparable to the margins in this level. (Pedatzur, 2016)

For Damen Yachting, such a way of using a table like table 2 can be interesting. The projects for the superyachts are experiencing the same stages, so this would be interesting also to use. The margin values can be inspected by DY designers and engineers to adjust them to make the table specifically for Damen Yachting.
For the original table, it was suggested to use this for every weight group separately. This should also be the case for the superyachts, and maybe even the possibility to change this for certain items specifically. For example, the first group has different big-weight items. These should be considered separately as the level of details available may differ.

3.4 Center of gravity

The CoG is estimated for every item together with the weight. During the project, the arrangement gets more certain, and the location of the items gets more confirmed.

When compared to other yachts, also the CoG can be converted to the new yacht. The research done for the weight estimation when compared to other yachts can also be used for the CoG. When looking at the VCG, a similar graph as graph 4 can be made. In this case, VCG should be compared to the height of the ship.(Lamb, 2003) (Watson, 1998) So the x-axis should be the ship's height, and the y-axis the VCG. With the heights and VCGs of other vessels known. Similarly, a trendline can be made to estimate the VCG of the new project based on the already known height. This also works for LCG with the length and the TCG with the beam of the ship. For many items, this method is quickly surpassed by more accurate location information from the General Arrangements (GA). But this "comparison method" can primarily be used for items that do not have a specific location in the ship but are spread out, like cables and pipes.
With modern technology gaining information is faster and available earlier in the project. 3D models can easily be made based on the GA of the ship, and with these tools, it is simple to check the CoG of a specific item. Of course, this does not take away the risk of an item being moved or changed, so it still needs to be updated during the project.

3.5 Weight distribution

It is helpful to implement the longitudinal weight distribution into the tool because all the CoGs of the items are already estimated. The weight distribution can be estimated in an early stage by using an approximation method. Here, for example, for the hull weight, the total weight is distributed over the ship using a rectangle midships and trapezoids forward and aft, like in figure 5 below. The weight (W) and the LCG of the weight from amidships (d) are needed for this estimation method. Following the formulas in figure 5, quick weight distribution can be made in an early stage. (Hansch, 2008) (TheNavalArch, 2017)

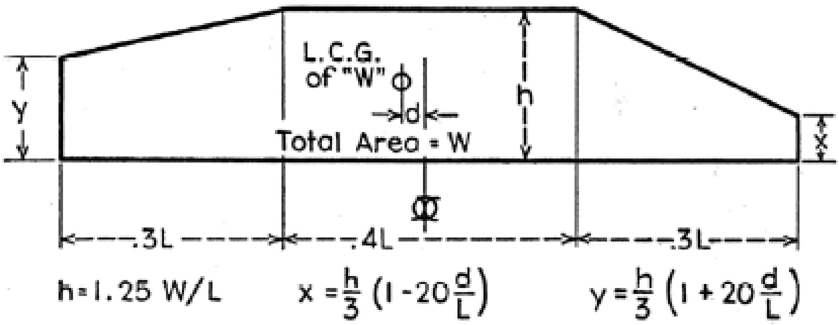


Figure 5: An approximation method for longitudinal weight distribution (Hansch, 2008)

When the weight items are estimated and listed, a grouping method can be used. The "bucket" method divides the ship into a certain amount of groups (or buckets) along the ship's length. Grouping the items located in that bucket results in a rough distribution of the weight. The use of more and smaller buckets result in a more precise distribution estimation.
The biggest downside of this method is that it only looks at the CoG of an item, even if the item itself is very long or spread out over the whole ship. Therefore it is often manually corrected for the items distributed on the entire ship, such as paint. Still, many items remain uncorrected. Therefore the accuracy of this method remains limited until this flaw is solved. (Hansch, 2008) (Straubinger, 1963)

It is interesting to look into improving this bucket method. It takes a bit more work, but when noting from/till what length (in ordinates or meters from the aft) the items are located in the ship, a better estimation of the distribution can be made. When using this improved method, the weight for an item can be calculated per meter or ordinate. This way, the total weight per meter can be estimated for the whole ship.
To improve the method even more, the distribution of an item can also be investigated. Is an item linear distributed, like an engine, or does the item need another distribution, like parabolic or as in figure 5.
If this level of detail is desired, these distribution formulas can be put in the tool beforehand. Then only the desired distribution of an item needs to be selected. This creates a new level of detail for the tot weight distribution of the ship, and it changes in real-time along with adjusting and adding more weights and CoGs.
The same bucket method can be used for the VCG and the TCG. For example, the weights can be grouped into decks to estimate the vertical weight distribution, which is useful when the weight of a particular deck is needed.

3.6 Tool selection

For all the different methods mentioned, a spreadsheet is suggested to keep track of all the weights and CoGs of the items. The information can be sorted per group and used for further calculations. With almost every spreadsheet software it is possible to implement formulas to automatically calculate total weights en CoGs of groups or the complete ship.
Currently, Damen Yachting is using Microsoft Excel to put the weight estimations in spreadsheets. Formulas and graphs can easily be created with Excel, but not with multiple people simultaneously. Also, Excel does not provide functions to make a report or analyze the information.
Google Sheets is similar to Microsoft Excel but with fewer functions. For example, making graphs is not as extensive as Excel. The most significant advantage is the ability to work online with multiple people simultaneously on a sheet. The downside, this software only works online. It can be downloaded as an excel file, but then you are working with two different software, losing the "real-time working together" function.
Another software program is Intellimas. This program has spreadsheet functions but replaces them with straightforward text, numeric, and checkbox fields with the calculations in the background. (Capterra, 2021)

This way, errors are not made in the calculations. The downside is that designers and engineers cannot check the calculation or make easy adjustments when needed.
For the purpose of the weight calculation, Excel is the best option. Suppose one person is looking into the weight estimations or gathering the information from others and putting it in the tool themselves. In that case, Google Sheets is not needed for online working with others. Also, there is a bigger change for errors when multiple people are making changes simultaneously. It is also possible to make parts of the sheets locked to prevent changing the formulas by accident. With features like drop-down lists in Excel, the same simple interaction can be achieved like with Intellimas without hiding the calculations. Also, the tool can be made more accessible and adjusted in Excel when it is desired to expand the tool with other functions than estimation the weights. With Intellimas, it is hard to make changes once the tool is made.

3.7 Accuracy

For the estimation improvements suggested in the previous sections, it is essential to measure if the improvement or new method works better than the currently used method. To do this, the accuracy of both ways needs to be considered and compared to check which method is better to use.
To measure accuracy, the following formulas can be used:

$$Accuracy = 100\% - ErrorRate \tag{1}$$

$$ErrorRate = \frac{|ObservedValue - ActualValue|}{ActualValue} \times 100 \tag{2}$$

Since the proposed new methods are used in the early design phase, it is possible to compare these estimations with the most up-to-date estimation/calculation at the end of the engineering stage. For the observed value, the weight according to the method is used. For the actual value, the most recent calculation at the end of the engineering stage is used. With these formulas, the accuracy of both the current and new methods can be calculated, and this can be done for multiple ships to ensure which method is more accurate and not just by coincidence.

3.8 Conclusion

The current group division is more extensive than the presented one, which will not improve the current estimations. The division of the hull into primary-, secondary-, and tertiary construction is very useful for the bottom-up estimations DY is currently using but does not achieve more accurate estimations with a top-down approach. It gives a better overview of the weights included in the hull construction estimation, and it can link different margins to these parts, which improves the accuracy of the estimation.
The weight estimation itself can be improved by adding a database comparison to estimate the weights of the groups top-down. This can be done by estimating the total LSW based on the database and dividing the groups in the same percentage as the current fleet shows. Also, the database can directly be used to compare the group or item weight, resulting in an estimation without missing items. This helps estimate weights during the design stage, but also for comparing new estimations during the engineering stage.
For the hull, another method is introduced to achieve more insight into the hull construction weight since this is the most significant component of the total LSW. An accurate steel weight estimation is made by dividing the hull into forward, mid, and aft parts.
Margins are already used to include uncertainties and missing items in the estimations. Still, with a new method, the margins are based on complexity and stage of the project the selection of margins are justified in all phases of the project.

This answers sub-questions 2, 3, and 4 partly because both new methods and complements on the current methods are introduced, useful for the design and engineering phases. It is not complete yet, since it is not verified and validated. The next chapter will describe the new methods and verify the tool which combines the different methods. Next, the model is validated to check if the LSW estimations are improved using the newly created tool.

4 Model description and verification

The different approaches discussed in the previous chapter are created and put in a single tool. In this chapter, the models are described, and these parts are computed with simple examples to verify the tool.
This is needed to answer sub-question 2, 3, and 4 again since the new methods need verification before validation is possible. It also starts answering sub-question 5, "Can the new method be used in a single tool for both the design and engineering phases, resulting in a more accurate total weight estimation?", by combining the different parts in a single tool and verifying it.

4.1 Weight groups

The current group division, shown in table 1 in chapter 2 used by DY, has groups that are split into a lower level to add more detail to the weight estimation. These groups and items are coded to find and add items to the total list easily. Also, for the comparison between ships, the codes and structure are helpful, but the main concern is the use of the codes. It is clearly stated what items are expected per code, although sometimes they are not estimated or calculated separately. Instead, the weight is included in another item/code. This makes the comparison for both codes inaccurate because it does not contain that specific item. When occurring, this should be explicitly mentioned by highlighting and remarking the weight in the tool.
The standard group division for the weight sheet is shown in appendix B.

The weight sheet made in the tool shows the groups and items with their code and shows different stages of the project. There is a separation between the design and engineering departments, so it is helpful to show these results next to each other. This is shown in figure 6 and appendix C. The design department uses the right list for their estimations, and the engineering department uses the left list for their calculations instead of overwriting the design estimations. During the engineering stage, the weight can be checked if the calculations are getting close to the estimation in the design stage, showing if parts of items or groups are still to be done. On the other hand, the design department can check whether the estimations are accurate once the engineering department fills the final weight. This leads to both departments easily using each other's results.

LIGHTSHIP WEIGHT	Engineering				D&P			
CODE	Weight (t)	X (m)	Y (m)	Z (m)	Weight (t)	X (m)	Y (m)	Z (m)
1000 Group 1 - Hull, superstructure, appendages, painting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000 Group 2 - Equipment for closing hull/superstructure and main fire integrity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3000 Group 3 - Remaining equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4000 Group 4 - Joinery and outfitting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5000 Group 5 - Electrical, nautical and communication installation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6000 Group 6 - Engine room installation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7000 Group 7 - Special equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9000 Group 9 - Other (potential CO's)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0 Group 0 - General Items	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOT LIGHTSHIP (weight margins included)	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**

Figure 6: Weight sheet overview

4.2 Database comparison

With the data of multiple vessels in the standard weight sheet, the weights can be put in a graph against the gross tonnage. This can be done by selecting the desired weight, like the total Lightship weight, weight of a group, or even the weight of a single item, shown in appendix D. The database should be kept up-to-date to take the modern fleet into account, therefore periodic database maintenance, including validation, needs to be scheduled to safeguard the accuracy.

On the overview page of the tool, shown in appendix D, a table shows the database with the desired weight item or group. An example of a ship in the database is shown in appendix B.
This table shows all the ships in the database, the main characteristics of the vessel, and the weight and CoG of the selected item. Also, a column for the source and date of the last data update is available to check whether the results are up to date.
In this table, the ships can be filtered to adjust the estimation. This could be needed if a weight deviated like discussed before, or to adjust the database to the desired ship group to increase the relevance of the used database. Yachts, Yacht Supports, and SeaXplorers are different types that should be compared separately.

Below the table, the graphs are shown. The graphs show the weight, LCG, and VCG against the GT, Length, and main-deck height respectively. The TCG is not used because this is not dependent on the ship's width, and this is always assumed to be on the centerline of a yacht. All the charts are shown in appendix D. Also other comparisons, for example weight against ship volume, are reviewed. Still, the weight against GT gives the clearest results because a straight trendline can be used and also because this is known at the beginning of the project and mostly used as a reference to the ships.

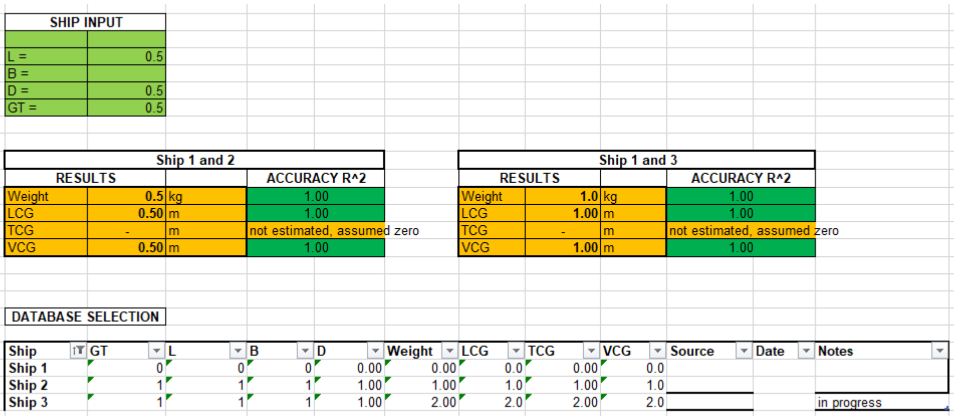
The graphs show the superyachts from the database as the points. With the points, a trendline is drawn. This is done linear, a second-order polynomial, and a power formula. Also, the formula and accuracy are shown for the trendlines. The formula is needed to estimate the weight of the new ship, also shown in the graph with the green vertical line. In simple terms, the R^2 is the accuracy of how well the trendline fits on the data points. A R^2 of 1 fits perfectly, and the lower the R^2, the less correlation between the points. A R^2 higher than 0.9 is considered very accurate and therefore sufficient to use the database. (Wyoming, 2016) (Frost, 2018) In this case, the R^2 is helpful to compare the different types of trendlines. As seen in the graph, all sorts of trendlines are sufficient, but when using polynomial trendlines overfitting the data needs to be considered, therefore the linear trendline is used. This is also the case when looking at the CoG's or selecting other vessels or weights for the graph.

Comparing the weights with the GT is not realistic for every item because not all items scale directly with the size of the ship. Therefore other references criteria for the remaining groups or items, like the m^2 of a room for the interior or the installed power for machinery, are recommended to use. It would expand the database estimations to as many items as possible, but the current tool focuses only on the weight against GT comparison. Also, adding more vessels to the database will improve this estimation method. When using more vessels the trendline will represent better the complete fleet, resulting in a better estimation when building a new ship the same way as the ships before. To ensure this, someone must be responsible for the database, adding and checking the data as their task.

Finally, in the overview sheet, the result of the calculated weight and CoG is shown clearly, including the accuracy of the trendline formula. This way, if the trendline has low accuracy, so the data has a low correlation, this is directly visible for the user.
The calculations are also shown in the tool but in a separate sheet to make the tool clear and more user-friendly.

4.2.1 Verification

Verification is done by making a simple database with simple input. When choosing a "ship" with a GT and weight of zero and a ship with a GT and weight of 1, the graph should now only show those two points, and a trendline of y = x is expected. A R^2 of 1 is expected since the trendline only goes through two data points. The graph in figure 8 shows this result.
The estimation of the LSW is also easily checked with these points. A GT of 0.5 should give a weight of 0.5 kg, since y=x. This result is shown in figure 7 together with the input and database. In the graph, this is shown as a green line. As an extra check, the second ship is doubled in weight. A trendline of y = 2x is expected, shown in the graph 8 with still a R^2 of 1. For the calculations with the new trendline, a weight of 1 kg is anticipated at a GT of 0.5, which is also the case, as shown in the results in the figure.
The same comparisons were done for the L versus LCG and D versus VCG and showed the same results.



SHIP INPUT	
L =	0.5
B =	
D =	0.5
GT =	0.5

Ship 1 and 2			
RESULTS			ACCURACY R^2
Weight	0.5	kg	1.00
LCG	0.50	m	1.00
TCG	-	m	not estimated, assumed zero
VCG	0.50	m	1.00

Ship 1 and 3			
RESULTS			ACCURACY R^2
Weight	1.0	kg	1.00
LCG	1.00	m	1.00
TCG	-	m	not estimated, assumed zero
VCG	1.00	m	1.00

DATABASE SELECTION

Ship	GT	L	B	D	Weight	LCG	TCG	VCG	Source	Date	Notes
Ship 1	0	0	0	0.00	0.00	0.0	0.00	0.0			
Ship 2	1	1	1	1.00	1.00	1.0	1.00	1.0			
Ship 3	1	1	1	1.00	2.00	2.0	2.00	2.0			in progress

Figure 7: Database estimation method example

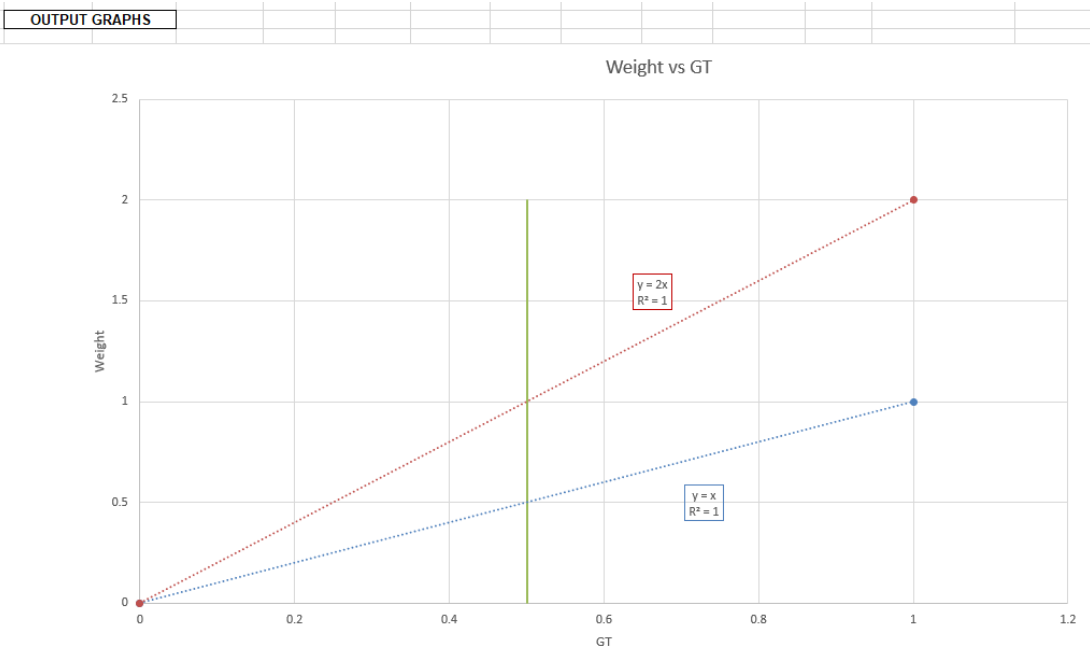


Figure 8: Database estimation method example

4.3 Top-down estimation

As already discussed, not all items can be estimated by comparing the database to the GT. But with a top-down method, these groups can still be estimated for an initial estimation.
Using the database to estimate the total lightship weight, this value can be split into the different weight groups. The percentage of every group's total weight needs to be known to do this. This can be calculated using the same database and averaged. This is already done at the beginning of the research in figure 1 in chapter 2. The estimated total LSW times the percentages of each group result in initial estimation per group. This can be done again in a lower level for each group into separate items, but this is very sensitive and is expected to have a lower accuracy. The group weights can be used at the design stage to check whether the estimations are getting close or some items are missing when deviating a lot. This is shown in the weight sheet of the tool, shown in figure 9 and appendix C.

LIGHTSHIP WEIGHT		Top-Down estimation
CODE		Weight (t)
1000	Group 1 - Hull, superstructure, appendages, painting	0.00
2000	Group 2 - Equipment for closing hull/superstructure and main fire integrity	0.00
3000	Group 3 - Remaining equipment	0.00
4000	Group 4 - Joinery and outfitting	0.00
5000	Group 5 - Electrical, nautical and communication installation	0.00
6000	Group 6 - Engine room installation	0.00
7000	Group 7 - Special equipment	0.00
9000	Group 9 - Other (potential CO's)	0.00
0	Group 0 - General Items	0.00
	TOT LIGHTSHIP (weight margins included)	0.00

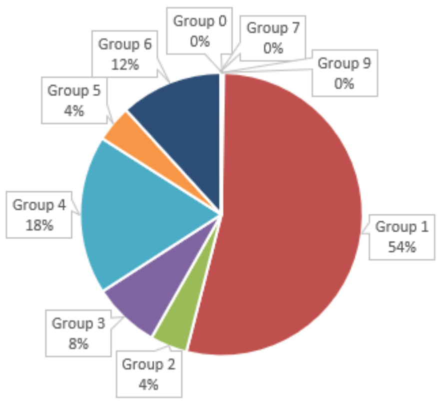


Figure 9: Top-down estimation in the weight sheet with the corresponding percentages of LSW per group

4.3.1 Verification

Quick verification of the tool is done by selecting a single ship in the database. The "average" percentages should now be exactly the same as the single selected ship, which is the case. Also, the estimation of the total LSW, and therefore the weight division into the group, should be the same as the ship. This is again the case, so this shows the calculations working. When adding another ship to the database, the average percentages per group can easily manually be calculated to check if there are no errors in this part as well.

4.4 Hull estimation

The hull estimation should be fast and straightforward. The database comparison can be used as a start, but a separate method for the hull is added to be sure and get a more accurate estimation. Visualizing the complete surfaces like bulkheads, decks, and shell structure take a lot of information about the new ship, which is not available yet. To limit the input, an analysis of existing structures should be made to accurately present a standard division of the number of parts in the structure. Looking at commercial vessels, when a part of the structure is built, the plate has the most significant weight, 82% of the total weight of the structure. The other 18% is consisting the beams and brackets. (Vlaar, 2010)
The surfaces of the structure are known much earlier during the project. With these dimensions and an estimation of the thickness of the surface, the weight of the construction can be estimated by combining the volume of the plate and the specific weight of the materials.
This research is done on multiple ships, and also a division in the location of the vessel is made, as shown in table 3 below. To make sure these values also comply with the yachts, a breakdown of the hull structure of several yachts is done. The percentage of plates of the total weight is shown in table 4. The results are similar to the results in the literature, confirming these are accurate.

	Average	Standard deviation
Aft	87%	6%
Mid	81%	4%
Fwd	84%	8%
Superstr.	76%	5%

Table 3: The average percentage of plate mass per section mass

	A6001	A476	A188
Aft	88%	86%	86%
Mid	84%	82%	82%
Fwd	84%	84%	84%
Superstr.	80%	76%	76%

Table 4: The average percentage of plate mass per section mass of the yachts

Table 3 is used in the hull estimation tool. When a first general arrangement is made, the length, height, and thickness of the plates of the sections can be filled in as input. This is shown in figure 10. The location of the section can be selected according to the table. The tool calculates the weight of the plates using a list of the steel weights and uses the selected percentage to estimate the total weight. The total hull weight is calculated when all parts are added to the tool. Because there is also a percentage given for the superstructure, this can also be estimated.

HULL

Name	Length (mm)	Height/Width (mm)	Thickness (mm)	Ship location	Material	Density (kg/m3)	plate volume (m3)	Plate weight (kg)	% plate	Total weight (kg)
Bulkhead 1	20,000	5,000	10	Mid	Steel A36	7849.128	1	7849.128	81%	9690.28
Bulkhead 2	40,000	5,000	10	Mid	Steel A36	7849.128	2	15698.256	81%	19380.56
Bulkhead 3	20,000	5,000	10	Fore	Steel A36	7849.128	1	7849.128	84%	9344.20
Bulkhead 4	20,000	5,000	10	Mid	Aluminum	2698.819	1	7849.128	81%	9690.28
						0	0	0	0%	0.00
						0	0	0	0%	0.00
Total										48105.33

Figure 10: Hull weight estimation sheet

This method is not very precise, and it is hard to estimate the weight of separate parts like beams, but when there is no 3D model available yet, it estimates the hull and superstructure weight sufficiently.

4.4.1 Verification

To verify if the tool works like intended, some values are filled in the sheet, shown in figure 10 in the first row, and in every row the input is changed to check if the result varies as expected. In the first row, the volume is 1 m^3, which is correct compared to the dimensions. Doubling the length in the second row doubles the volume, which is also correct.
Selecting the ship location gives the corresponding plate percentage, and selecting the material provides the correct density. Changing the location in the third and the material in the fourth row changes the plate percentages and density accordingly.
Calculating the density times the volume gives the correct plate weight, and dividing this by the plate percentage gives the correct tot weight.

4.5 Margins

Using the margin table 2 in chapter 3 as a base. Together with ISO standards (ECSA, 2021) and input of the DY naval architects, an adapted table specifically for DY is created.
Although the layout of the margin division in the ISO standard differs from the base margin table. The structure is similar: Margins vary based on the complexity and project stage criteria. The table presented in chapter 3 is more straightforward and compact, so better suitable to implement into the tool.
When rewriting the ISO standard to the same layout, the margin values are very similar to the table. Only some margins differ a single percent, and the level 4 risk level (technological breakthrough) is missing in the ISO standard. This confirms that the standard table contains justifiable values. After discussion with a team of naval architects of DY, only the construction values are adapted, and the stages' names make it suitable for DY. Also, a clear explanation for the risk/complexity levels is discussed to ensure this has a clear division and no room for misinterpretation.

Complexity and risk level	Stage of the project			
	D&P	Basic Engineering	Detailed Engineering	Production
Level 1	5%	4%	2%	2%
Level 2	10%	8%	5%	2%
Level 3	15%	12%	8%	4%
Level 4	25%	15%	10%	5%

Table 5: Final margin table for weight estimations

In table 5, the final margin table for the tool is presented. The stages in the table are similar to the stages used at DY, which is linked to the weight estimation level of detail. This level can still deviate per group or item. For example, the Design department can select an item as basic engineering when a lot of information is already available, and unlikely to change. The other way around is also possible if an item is still uncertain or sensitive to changes later in the project. Only the value of Level 1 at the production stage margin is changes compared to the standard table. DY wants to keep a minimum of 2% margin for production. The other values, defended by the Bonen-scale and ISO standard, are chosen to use as final values.
Finally, the complexity and risk levels need to be stated. As already discussed. The levels should leave no room for misinterpretation, and therefore the team of naval architects agreed with the following short description:

Level 1: Duplicating a part of the yacht from the previous version in a series build.
Level 2: Adjusting a part of the yacht from the previous version in a series build, OR a part of a similar vessel for a custom yacht.
Level 3: Developing a new custom yacht, OR specific owner requests with limited experience.
Level 4: Technological breakthrough with no examples of other yachts available and requires research.

The stages of a project are also stated. Here the D&P stage starts with global information like reserved space and descriptions, the basic engineering stage includes dimensions of items and custom orders from suppliers, and the detailed stage includes blueprints or standard orders from a supplier catalog. This division is already know and used both at the design and engineering department.

This table is used in the input weight sheet. The correct margin is automatically presented and used in the sheet by selecting the desired level and stage. The table itself, including the description, is presented in a separate sheet to be consulted when needed.

The margin of the CoG is also considered. Instead of a fixed margin of 0.3 meters on top of the VCG, a formula is used, like discussed in section 3.3:

Total estimated	W est.	VCG est.
Total added margin	W margin	VCG margin = VCG est. * 1.2
New total	W tot. (= W est. + W margin)	VCG tot. = (W est. * VCG est. + W margin * VCG margin) / W tot.

Table 6: Overview of estimated, added, and total weight and VCG

The estimated total weight and VCG are used as input in the formulas in table 6 above. The margin on the VCG is used on the total VCG and not on every separate item. In the second row, 20% is added to the estimated VCG and connected with the added margin weight. The new total VCG is calculated with these values, which is higher than the original VCG.
The advantage of this calculation method is the influence of the margin VCG depending on the margin weight and the margins used. So if a large total margin is used in the estimation, a larger margin is used on the VCG. A comparison is shown in table 7:

Total estimated	1000 kg	10.00 m	1000 kg	10.00 m
Total added margin	**50.00 kg (5%)**	12.00 m	**10.00 kg (1%)**	12.00 m
New total	1050 kg	**10.10 m**	1010 kg	**10.02 m**

Table 7: VCG margin example

A total margin of 5% results in a larger VCG as a margin of 1%, and this gives a better VCG estimation than a fixed value for the complete project.

4.5.1 Verification

The same approach for the hull estimation is made to verify the margins part of the weight sheet. In the first row in figure 11 below. Some values are filled in as a weight. Risk level 1 and DP stage are selected, and the tool automatically shows a margin of 5%, which is correct. In the second row, the level and in the third row, the stage are changed accordingly. The margin and total weight are shown in the blue columns, so this part of the tool works perfectly.
Using the same input for the VCG margin as used in table 7, the tool gives the same results, which is also correct.

Weight	Number	Risk Level	Stage	Margin	Option	TOTAL	
(density)					[1=NO]	Margin	Weight
[kg] or [kg/m2]	[-] or [m2]			[%]	[0=YES]	[kg]	
				6.75%		0	4
							4
1,000.0	1	Level 1	D&P	5%	1	50	1,050
1,000.0	1	Level 3	D&P	15%	1	150	1,150
1,000.0	1	Level 1	Detailed eng	2%	1	20	1,020

Figure 11: Example data for margin calculation

4.6 Weight distribution

The weight distribution calculation can be added to the weight sheet to give insight into the longitudinal weight distribution. The weight and their location, including the length of the items, are put into a model in an early stage of the project, so it is not helpful when a lot of effort is needed for the longitudinal weight distribution. Therefore a parabolic distribution of an item is not desired because this requires a lot of insight into the items to create the desired parabolic shape.
Placing the items in a graph as a single point weight takes no extra information since the CoG is known already. The downside is that all weight items are considered a point weight, which is inaccurate.
A linear distribution of the items requires a length of an item, which can be used to calculate the beginning and end point of the item, assuming the COG is in the middle of the item. This does take some extra effort, but it increases the estimation significantly. The different methods are shown in figure 12 The red line shows the actual longitudinal distribution of an example ship, the blue line the point distribution, and the yellow and green lines the linear distribution.

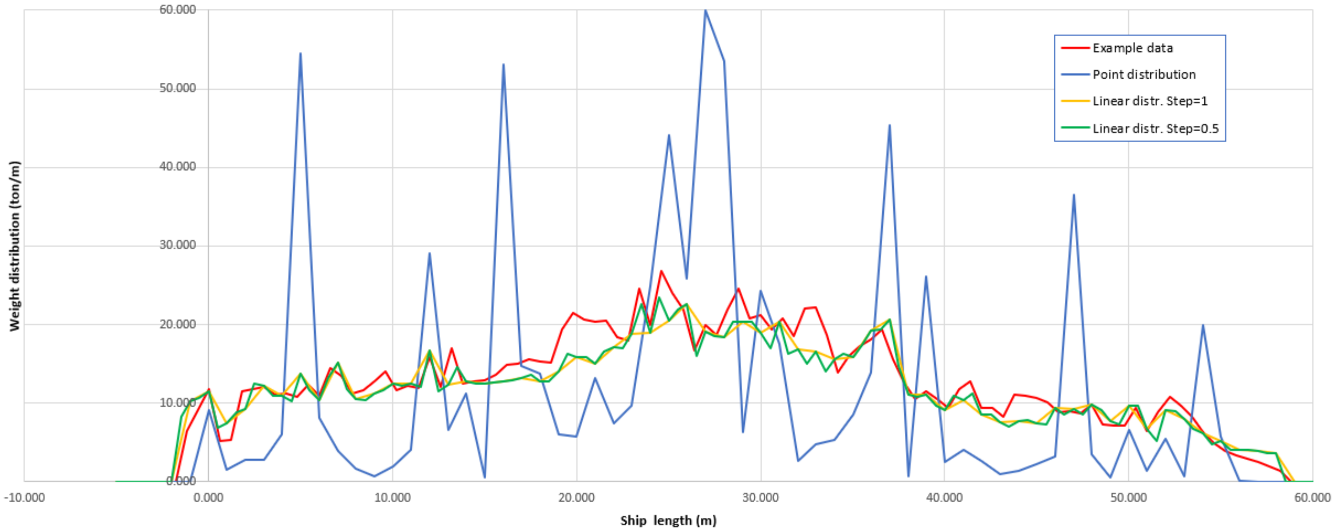


Figure 12: The weight distribution of a yacht

Another aspect that influences the estimation is the step size of the graph and calculation. The data can be slightly differently distributed when using a smaller step size. Usually smaller step size results in more accurate results, but when the location input is not so detailed, the small step size does not help. Figure 12 shows the linear distribution in yellow with a step size of 1 meter and green with a step size of 0.5. This means that with a step size of 0.5, the beginning and end points of the items are rounded to 0.5 meters.
Compared to the example data, the linear distribution with a step size of 0.5 m is slightly better. Decreasing the step size even more does not improve the graph, so the step size setting of the graph and calculation in the tool can be set to 0.5.

4.6.1 Verification

To verify if the weight distribution tool works correctly, a weight of 6 tons with a length of 10 meters is put into the tool, the red line in graph 13. When changing the weight to 3 tons, the green line is made. This is also half the weight per meter, which is correct. The blue line shows 3 tons, but with a length of 5 meters. This is also shown in the graph correctly. This indicates that the weight calculations into the distribution are done correctly in the tool.

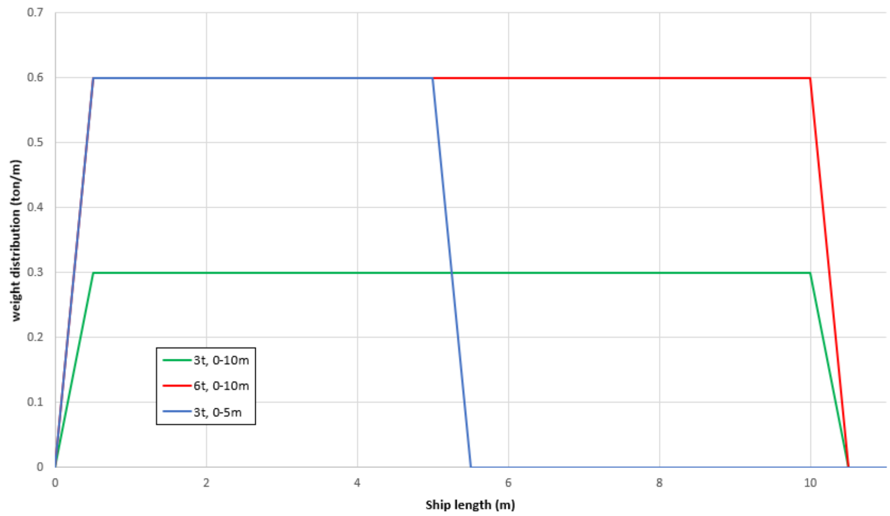


Figure 13: Weight distribution example

4.7 Conclusion

Sub-question 2 and 4 are now almost answered with the multiple aspects of the tool, and it is verified that the tool works. The weight distribution and the margins enhance the current weight sheets, and the newly developed fleet database comparison and hull estimation are an addition to estimating the LSW. Only the tool's accuracy is not researched yet, which is essential to prove the advantage of the new tool compared to the current methods. Sub-question 3 is also answered by showing the usefulness of the methods in both design and engineering stage, but this also depends on the validation of the tool.
The complete tool is discussed and verified and is now ready to use. Looking at the last sub-question, "Can the new method be used in a single tool for both the design and engineering phases, resulting in a more accurate total weight estimation?", the tool needs to be validated to be useful and proven to improve the current methods. This is researched in the next chapter.

5 Validation

With the tool described and verified, the last step is to validate it. When using the tool, it is essential to estimate the weight accurately. The different parts of the model are validated by using existing yachts as input and comparing the results with the actual weights and results of the yacht itself. This indicates the accuracy of the tool.

5.1 Database comparison

The ship's data is filled in when estimating a new yacht, which is the tool's first step, as seen in appendix D. With the trendline formula, the weight of the selected item is calculated. When filling in known ships and comparing the estimation with the known results, a form of out-of-data validation is done. (Hunton, 2019) By comparing multiple yachts, this estimation method is proven to be accurate.
Looking weight estimation of the ships in appenix E. The new LSW estimation method can be added to this graph to compare the results. This is shown in appendix G, including the accuracy of the new method calculated as discussed in section 3.7.

The new estimation is a bit lower than the final weight, but already better than the estimation in the design phase. A margin of 5% is added on top of this value, using the new margin table (table 5 in chapter 4) for Level 1 at the D&P stage. This is now a reasonable estimation of the total LSW of the ship. A margin of 4% would even be better, which is used in the next project stage of the margin table.

The database estimation method is also tested on the different weight groups, also shown in appendix G. Again, it is clear that the design estimation mostly deviates from engineering in the first group. The database estimation significantly improves the estimation of the first group and is also accurate for the other groups. To improve the accuracy for some groups, it is recommended to add more options for the database to compare the fleet, like installed power or squared meters of interior, instead of the GT only.

5.2 Top-down estimation

To validate the top-down estimation, the same method is used. With the total estimated LSW, the weight per group is calculated and compared to the actual results. The results for multiple ships are shown in G. It indicates that the method accurately estimates the weight per group based on the percentage per group of the total LSW. Some of the differences between estimation and the actual result are a bit large. Still, as a first starting point for the estimations, which will slowly be replaced with more information, this is a valuable estimation method.

5.3 Hull estimation

Multiple sections are checked and compared with the actual weights retrieved from the Nupas software to validate the hull estimation method. The results are listed in table 8. A different yacht is completely estimated using this method, shown in appendix H.

Section	**1111**	**1122**	**1152**	**1321**
Location	**Aft**	**Mid**	**Fore**	**Sup.**
Weight (kg)	46080	17360	10651	6892
Estimation (kg)	34450	13754	7143	6455
Accuracy	75%	79%	67%	94%

Table 8: Hull estimation comparison

The results show that the estimations are lower than the actual weights, and only the superstructure has a close estimation. The accuracy indicates that this estimation method is not highly accurate. According to the margin table, an accuracy above 90% is accepted since a margin of maximal 10% will be used in this case. The surfaces are measured by hand, and the thicknesses are not sure yet, but the primary cause is the definition of plates in the structure. When calculating the percentage of the plate in the structure, everything defined as a plate is taken into account, such as the web of a large beam in the bottom structure. When estimating the surfaces, these parts are unknown and not estimated as plates. This results in a different division of the structure. The percentage of the plate in the structure can be adjusted to get a better estimation, but since the database estimation already gives high accuracy, this method is more efficient to use. The graphs of the estimation of the hull are also shown in appendix H.

Only the yachts are selected for the database, excluding Yacht Supports and SeaXplorers, and the hull is selected as the desired output. This already gives high accuracy, but the type of yacht can also be adjusted when estimating a specific vessel in practice.
It is recommended to investigate the division of the hull in the future. When using the primary-, secondary-, tertiary- construction division as mentioned in chapter 3, these parts can better be estimated. If this is investigated in the current fleet, the parts of the hull can be calculated separately, or the secondary- and tertiary construction can be estimated as a percentage of the primary construction, which is available earlier in the project. These parts can also have different margins since the primary structure is much more certain and unlikely to change.

5.4 Weight distribution

Graph 12 in chapter 4 can be used to validate this part of the tool. The red line shows the actual weight distribution of a ship, and looking at the linear distribution with a step size of 0.5, the yellow line indicates that the weights' linear distribution is accurate. It is still not perfect, but when a complete model of the ship is made, a more accurate weight distribution can be made and will replace the distribution of this tool.

5.5 Conclusion

With the different parts of the tool validated, the tool is now complete, and the last sub-question can now be answered. The database comparison improves the estimations in the design stage. It confirms the estimations in the engineering stage, while the margin table adjusts and displays the estimations' accuracy. This estimation already improves the current estimations at the design phase for the total LSW and the weights per group.
The hull estimation method is not accurate enough, and the database comparison is more effective in estimating the hull weight. The weight distribution does not necessarily improve the LSW estimation but makes the tool more complete, and it can be used to check if the CoG's of the items are as expected.
This is all, except for the hull estimation method, combined and used in the tool, which is helpful for both the design and engineering stages and proven to be accurate.

The main question is only left to be answered, which is naturally concluded with answering all the sub-questions. The main question is: "How to accurately predict the weights and centers of mass of a superyacht, considering the date accuracy in the design and engineering phase?"

The weights and centers of mass of a superyacht can be predicted in the design phase by comparing the new ship to a database of existing yachts. These estimations can be used to indicate the calculations' completeness and accuracy at the engineering phase.
The weight list includes margins based on the project's stage and complexity. This way, the estimations and calculation accuracy are transparent and explainable.
Also, the longitudinal weight distribution is added to complete and track the center of gravity estimations. Both the design and engineering department can present their findings and estimations next to each other, resulting in a clear overview of development during the project.

6 Conclusion

The lightship weight is an essential factor in an early design phase. For a superyacht, an unforeseen extra weight would predominantly lead to unwanted changes in speed and stability. At Damen Yachting (DY), there is currently no uniform method to estimate the weights of the superyachts. Ideally, the design and engineering department uses a single tool to update and keep track of the ship's lightweight. Resulting in the following research objective.
The objective is to research a standardized way of estimating the weight of a superyacht in different stages of the project. This includes validating the current, improved, and new methods and combining this in a single tool. The following main question is stated:

How to accurately predict the weights and centers of mass of a superyacht, considering the level of detail in design and engineering phase?

The research is done by answering multiple sub-questions, finally answering the main question.
The first question is: How accurate are the current methods used for superyachts, and are there systematic errors in these methods?
The current weight estimations are split into the design and engineering stages. Comparing these estimations to the final ship weight displays that the design phase estimation is systematically too low. In both stages, a single method of weight documentation is missing, complicating comparing results. There is also no structure in using extra margins to include uncertainties on top of the estimations.

The second question is: Are there other methods that can complement the currently used methods?
Margins are already used to include some uncertainty when estimating the weights of items, but the rules of what margin should be used are lacking. Margins are used in all kinds of other building projects and not only for weights, so researching these cases results in a better method for Damen Yachting. A table with fixed margins, based on the risk/complexity level of the ship and the stage of the project, present the values to use with the estimations. This gives a better hold on the used margins in both project phases.
The longitudinal weight distribution is currently made later in the project using a model, but a faster distribution can already be made with the weight sheet. Only the length of the items is needed as an extra input. Dividing the weight linearly over the length gives an accurate distribution from the beginning of the project. A naval architect sometimes does this for convenience, but adding this to the standard weight sheet makes it available for anyone using the weights.

The third question is: Are the methods useful in both the design and engineering phases? The added methods to the weight estimation are helpful for both phases. Although the weight distribution will be replaced with a model in the engineering phase, a naval architect can still compare his results with the model to check the accuracy of the weight estimations.
The new methods presented in the next question are mainly helpful to improve the weight estimations in the design phase. Still, also in the engineering phase, the results can be compared to these methods to check if the more detailed estimations are still in line with the database. When deviating, the naval architect can investigate for errors or if something is left out.

The fourth question is: What new method can be developed to have a more accurate estimation of the superyacht's weight? Estimating weights using a database is not done yet. With a created fleet database, a formula is generated to scale the Gross Tonnage of an item, group, or total lightship weight.
To estimate the hull and superstructure more accurately, a method is created using the layout of the yacht and using the dimensions of the plates to scale to the total construction. This method is less accurate as the database method. On top of that it also takes more effort and information to obtain results, so this method is not implemented in the tool. The database method comparing the hull weight with GT is more effective.

The last question is: Can the new method be used in a single tool for both the design and engineering phases, resulting in a more accurate total weight estimation? In the design and engineering phase, the information is presented differently and on another level of detail. Therefore it makes more sense to use separate sheets for both phases and show them next to each other. This way, the design stage data is not overwritten by engineering but can be compared.
The estimation methods are not placed in the same file as the weight sheet but in the same folder. Dividing these parts of the tool results in a clear division in estimation methods and the new yacht's weight sheets.

Finally, with the answers to the sub-questions, the research question can be answered, concluding the research. The weights and centers of mass of a superyacht can be predicted in the design phase by comparing the new ship to a database of existing yachts. These estimations can be used to indicate the calculations' completeness and accuracy at the engineering phase.
The weight list includes margins based on the project's stage and complexity. This way, the estimations and calculation accuracy are transparent and explainable. Also, the longitudinal weight distribution is added to complete and track the center of gravity estimations. Both the design and engineering department can present their findings and estimations next to each other, resulting in a clear overview of development during the project.

7 Discussion

During the engineering stage, some deviation can take place. If there are some changes in the design during the engineering phase, this will be considered in the weight estimations of engineering. Still, it directly results in a more inaccurate estimation of the design phase. This makes sense and does not necessarily need to be a problem, but it is helpful to make a notation in the weight estimations. Therefore some space should be added in the tool to make such changes in the weight estimation clear. Then anyone looking at the estimations will know if the weight change is caused by a different and more accurate estimate or a complete change in design.

Some assumptions are made to get the weight estimation as accurate as possible. For example, for the production, a margin of 2% is used for the unforeseen extra weight added at this stage. But there may be some last-minute changes during the production process resulting in an additional weight that is not considered.
Also, in the engineering stage, there can be some deviations. When engineering a part of the ship, for example, the hull structure, it is possible that some changes are needed to make the structure stronger. For the weight estimation, it is assumed that only the minimum amount of structure is added to make it strong enough. But in reality, the engineer may want to take less risk and add more (possibly unnecessary) structure and weight.
If this is done often, the weights exceed the margins, and the ship will be heavier than estimated. It is possible to control this by keeping the weights into account during the engineering process. When detecting too much weight, it is possible to investigate if this could be prevented or (in the next project) the estimation needs to be changed. However, this is interesting when looking into how the departments are working, and it is not included in the scope of this thesis. It is recommended to inspect the company's workflow when the estimation deviates from the improved weight estimation method.

When making the tool for the improved weight estimation, both the design and engineering departments must use it. To achieve this, the designers/engineers who will use it have to believe that this method is the best way for the estimations. This can only be done by explaining the theory behind the tool and involving them during the creation of the tool. Otherwise, people will still think their own methods are better to use, so the tool would not be used as intended.

It is recommended to assign a person in the company to maintain the tool. The database can be updated with every new ship that is finished. With the latest data, the prediction is more in line with the company's current way of building yachts. Especially the Yacht supports and SeaXplorers are relatively new at Damen Yachting, so more data will give better results.
Also, the comparison method itself can be expanded. Now the weights are compared to GT only, but for some items, like interior or machinery, other comparisons, like square meters or installed power, are desired. This can be added to the tool but requires more fleet data. When this data is available, the graphs, trendlines, and formulas can easily be added in the same way it is done for the GT comparison. This is highly recommended for the company to make the estimations more complete and be able to use this tool for even more weight items.
Finally, it is recommended to investigate the division of the hull in the future. When using the primary-, secondary-, tertiary- construction division as mentioned in chapter 3, these parts can better be estimated. If this is investigated in the current fleet, the parts of the hull can be calculated separately, or the secondary- and tertiary construction can be estimated as a percentage of the primary construction, which is available earlier in the project. These parts can also have different margins since the primary structure is much more certain and unlikely to change.

Appendix

A Group systems

A.1 ESWBS

The US Navy uses the expanded ship work breakdown structure (ESWBS), which has the following groups: (Lamb, 2003)

1. Hull structure
2. Propulsion plant
3. Electric plant
4. Command & surveillance
5. Auxiliary systems
6. Outfitting systems
7. Armament

A.2 MARAD

For US commercial ships, the Maritime Administration (MARAD) is used: (Lamb, 2003)

- 0–0 to 9–9 Hull Structure
- 10–0 to 19–9 Outfitting
- 20–0 to 29–9 Machinery

A.3 SFI

The SFI item groups are as followed: (Cheirdaris, 2020)

- Group 1 : General costs and details that cannot be assigned to any of the following groups such as general arrangement, launching, and drydocking.
- Group 2 : Hull, superstructure and material protection of the vessel.
- Group 3 : Cargo equipment and machinery including the loading and unloading equipment.
- Group 4 : Ship specific equipment and machinery (navigational equipment, maneuvering machinery, anchoring equipment and communication equipment).
- Group 5 : Equipment serving crew and passengers such as the lifesaving appliances, furniture, catering equipment, and sanitary systems.
- Group 6 : Machinery main components including main engines, auxiliary systems, propellers, boilers, and generators.
- Group 7 : Equipment serving main machinery such as fuel and oil lubrication systems, starting air systems, exhaust systems, and automation systems.
- Group 8 : Ship Common Systems such as ballast and bilge systems, firefighting and electrical distribution systems.

B Database example

Ship		SHIP1					
JDOC	Group	Weight (input)	Accuracy	Weight	LCG	TCG	VCG
T	**Total Lightship Weight and COG**						
0	**Group 0 - General Items**						
1000	*Hull*						
1200	*Superstructures*						
1500	*Mill products*						
1600	*Fastenings*						
1800	*Rudders*						
1810	*Ballast*						
1900	*Surface treatment, paintwork and corrosion protection*						
1	**Group 1 - Hull, superstructure, appendages, painting**	**0.0**	#DIV/0!	**0.0**	**#DIV/0!**	**#DIV/0!**	**#DIV/0!**
2100	Hatches hull/superstructure						
2130	Manholes for tanks						
2135	Drain plugs for tanks						
2150	Special hatch covers						
2210	Watertight doors inside hull						
2240	Transom door						
2250	Watertight doors in the hull sides						
2310	Weathertight sliding doors inside hull						
2350	Weathertight sliding doors in the superstructure						
2360	Weathertight hinged doors in the superstructure						
2361	Non weathertight doors in the superstructure						
2369	Sliding exterior wall panels						
2370	Bulwark doors						
2390	Folding bulwark						
2400	Fire doors						
2700	Windows and portholes						
2710	Window, sliding sunroof system						
2	**Group 2 - Equipment for closing hull/superstructure and main fire integrity**	**0.0**	#DIV/0!	**0.0**	**#DIV/0!**	**#DIV/0!**	**#DIV/0!**

C Weight sheet overview

C.1 Weight summary sheet

LIGHTSHIP WEIGHT		Engineering				D&P				Top-Down estimation
CODE		Weight (t)	X (m)	Y (m)	Z (m)	Weight (t)	X (m)	Y (m)	Z (m)	Weight (t)
1000	Group 1 - Hull, superstructure, appendages, painting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000	Group 2 - Equipment for closing hull/superstructure and main fire integrity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3000	Group 3 - Remaining equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4000	Group 4 - Joinery and outfitting	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5000	Group 5 - Electrical, nautical and communication installation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6000	Group 6 - Engine room installation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7000	Group 7 - Special equipment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9000	Group 9 - Other (potential CO's)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	Group 0 - General Items	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	TOT LIGHTSHIP (weight margins included)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	FIXED BALLAST	0.0	0.00	0.00	0.00	0.0	0.00	0.00	0.00	0.0
	LIGHTHIP WITH BALLAST and weight margins	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	COG margins				see calc				see calc	
	LIGHTHIP WITH BALLAST and margins	0.000	0	0	0.00	0.000	0	0	0	0.000
	Options	0.0	0.00	0.00	0.00	0.0	0.00	0.00	0.00	0.0
	Ice accretion	0.0	0.00	0.00	0.00	0.0	0.00	0.00	0.00	0.0
	TOT. LIGHTHIP + Options	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

C.2 Weight input sheet

DAMEN yachting

Yard Number xxxxx
Author xxxxx
Checked xxxxx

Date: xxxxx
Document: xxxxx
Revision: xxxxx

xxxxx Input value
xxxxx Calculated value
xxxxx Value taken from other sheet
xxxxx Changed Cell

Row	JDOC	Item	Weight	Number	Risk Level	Stage	Margin	Option	TOTAL			+=SB		LONG DISTR			IDK	Revision	REMARKS
7			(density)					[1=NO]	Margin	Weight	LCG	TCG	VCG	Length	Xmin	Xmax		Revision	REMARKS
8	[-]	[-]	[kg] or [kg/m2]	[-] or [m2]			[%]	[0=YES]	[kg]		[m]	[m]	[m]	[m]	[m]	[m]	[-]	- A B C	[-]
10	Lightship weight incl. margins						0.00%		0	0	0.000	0.000	0.000						
11	Design margin on COG										0.000	0.000	see calc						
12	Total lightship									0	0.000	0.000	0.000						
14	Group 1 - Hull, superstructure, appendages, painting																		
15	1000	Hull																	
17	1001	General Contruction Hull																	
18		example			Level 1	D&P	5%		0	0					0.000	0.000			example
19					Level 1	D&P	5%		0	0					0.000	0.000			
20					Level 1	D&P	5%		0	0					0.000	0.000			
21	1004	Welding and Rolling																	
22					Level 1	D&P	5%		0	0					0.000	0.000			
23		Rolling margin	0	2.5%	Level 1	D&P	5%		0	0					0.000	0.000			
24		Welding addition	0	2.5%	Level 1	D&P	5%		0	0					0.000	0.000			
25					Level 1	D&P	5%		0	0					0.000	0.000			
27	1005	Double bottom tanks																	
28					Level 1	D&P	5%		0	0					0.000	0.000			
29					Level 1	D&P	5%		0	0					0.000	0.000			
30					Level 1	D&P	5%		0	0					0.000	0.000			
32	1007	Bulkheads hull																	
33					Level 1	D&P	5%		0	0					0.000	0.000			
34					Level 1	D&P	5%		0	0					0.000	0.000			
35					Level 1	D&P	5%		0	0					0.000	0.000			

D Database comparison estimation method

CONFIDENTIAL

The following section contains classified information. Therefore, it is removed from the report to maintain confidentiality.

E Weight comparison per stage

CONFIDENTIAL
The following section contains classified information. Therefore, it is removed from the report to maintain confidentiality.

F Weight comparison per weight group

CONFIDENTIAL
The following section contains classified information. Therefore, it is removed from the report to maintain confidentiality.

G Results of database comparison and top-down methods

CONFIDENTIAL
The following section contains classified information. Therefore, it is removed from the report to maintain confidentiality.

H Hull estimation

CONFIDENTIAL
The following section contains classified information. Therefore, it is removed from the report to maintain confidentiality.

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