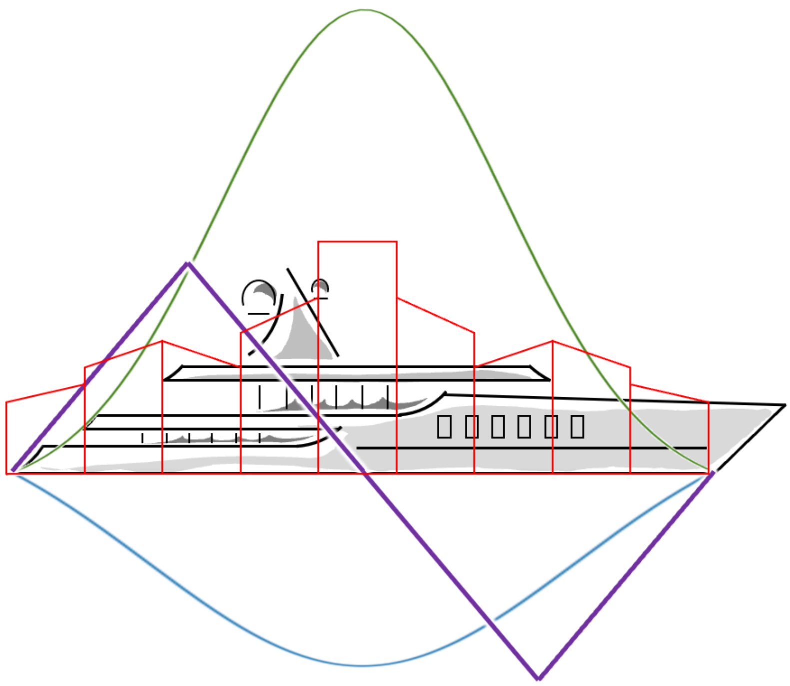
A time-savings sensitivity analysis of varying mass distribution techniques on ship longitudinal strength



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# Summary

Ship hulls are continuously subjected to various loads and may create extensive unbalanced loading on the structure if distributed unevenly. As such, the hull girder's longitudinal strength is one of the most crucial considerations in ship design. The lack of this characteristic may be a direct cause of catastrophic fracturing and sinking of a vessel. Calculating longitudinal strength involves collecting and inputting all individual weight items throughout the design and engineering stages. Unfortunately, near the end of the detailed engineering phases, upwards of $5000$ different weight items make-up the full vessel weight distributions. This tedious process requires a great deal of time and resources to complete.

The purpose of the investigation is to determine and apply a detailed methodology to save valuable time during the weight input steps of the engineering phases. This will be done through an in-depth sensitivity approach focusing on the influence of distributed loading versus point loading to the longitudinal strength parameters: still water shear force and bending moment.

First, a literature study related to understanding general longitudinal strength requirements, shear and bending moment calculation procedures, various weight distribution techniques, and sensitivity methods are considered to understand the academic objective. According to the assessment, the study's scope investigates the effects of three weight distribution techniques: approximate parabolic, point-wise grouping, and trapezoidal direct using a local one-at-a-time sensitivity approach. This analysis will adhere to a general longitudinal strength accuracy requirement of $\pm10$%, as determined from a series of interviews and internal studies. Next, a small-scale robustness and verification investigation of the three weight distribution numerical models were completed. From the initial results, it was concluded that the parabolic approximation method does not meet the general accuracy requirements.

Furthermore, a large-scale *Damen Yachting* case study is conducted. Each weight distribution model will be further analyzed using real input data and directly compared to one another. Evidently, both the grouping and trapezoidal distribution techniques handle the longitudinal strength calculations well. Unfortunately, when distributed loads are represented as individual point loads, associated results deviate drastically from the baseline metrics. For commercial purposes, the trapezoidal presents slightly increased accuracy of $0.22$% and $0.35$% for shear and bending moment, respectively. Whereas, the grouping has a lower accuracy of $0.38$% and $3.49$%; however, it is favoured for academic purposes due to improved weight input control. Next, the local sensitivity methodology is implemented. This approach addresses the key steps and comparisons metrics by investigating the effects of full input distributed loading versus partial input point-loading on longitudinal strength. Ultimately, the non-grouping of items provides the largest time-reduction of $29.88$% for the comparison threshold point.

Additionally, two different vessel verification studies were conducted to give further confidence in the overall procedure and findings. From the results, time reductions of $24.97$% and $27.00$% were additionally determined. Furthermore, in all cases, the elbow point metric only varied between $0.3\% - 2.3\%$ from the fully detailed cases (exact). Ultimately, the number of items requiring full input parameters is associated with $10\% - 25\%$ of the total item amounts, which directly corresponds to a relative time-savings order of magnitude of $30\% - 25\%$, respectively.

# List of Symbols

| | | |
|---|---|---|
| $\%Error$ | Relative Percent Error | [%] |
| $\alpha$ | Sensitivity Factor | [-] |
| $\bar{x}$ | Centroid Location | [meter] |
| $\theta$ | Angle of Inclination | [degree] |
| $A$ | Total Area | $[{}^{tonne}/_{meter}]$ |
| $C$ | Load Equilibrium Correction | $[{}^{tonne}/_{meter}]$ |
| $f$ | Resultant Load | $[{}^{tonne}/_{meter}]$ |
| $JDOC$ | *Damen Yachting* Item Grouping | [-] |
| $L$ | Vessel Length | [meter] |
| $L^2JDOC$ | *Damen Yachting* Double Lumped Item Grouping | [-] |
| $L_D$ | Distribution Length | [meter] |
| $LCB$ | Longitudinal Center of Buoyancy | [meter] |
| $LCG$ | Longitudinal Center of Gravity | [meter] |
| $LJDOC$ | *Damen Yachting* Lumped Item Grouping | [-] |
| $M$ | Bending Moment | [tonne·meter] |
| $n$ | Discretization Factor | [-] |
| $Q$ | Shear Force | [tonne] |
| $T_{total}$ | Total Time | [hour] |
| $TCG$ | Transverse Center of Gravity | [meter] |
| $VCG$ | Vertical Center of Gravity | [meter] |
| $W(w)$ | Applied Load | $[{}^{tonne}/_{meter}]$ |
| $w_a$ | Aft Distribution Magnitude | $[{}^{tonne}/_{meter}]$ |
| $W_b(b)$ | Buoyancy Load | $[{}^{tonne}/_{meter}]$ |
| $w_f$ | Fore Distribution Magnitude | $[{}^{tonne}/_{meter}]$ |
| $x$ | Position | [meter] |
| $x_L$ | Aft Distribution Bound | $[{}^{tonne}/_{meter}]$ |
| $x_R$ | Fore Distribution Bound | $[{}^{tonne}/_{meter}]$ |
| $x_{off}$ | Centroid Offset Location | [meter] |
| $x_{station}$ | Station Position | [meter] |

# Contents

# 1 Introduction

The hulls of ships are subjected to several loads and if distributed unevenly there may be large unequal loading on the structure. A ship with sufficient strength should be able to bear its self-weight, the weight of its cargo, and the forces which the sea exerts upon it [1]. Longitudinal strength (LS) pertains to assessing the global strength of the entire ship when it is floating in still water or waves. To determine whether the ship has sufficient strength to withstand loading conditions, forces and moments acting of the ship's structure need to be calculated and analyzed in various operational conditions. With the collaboration of *Damen Yachting's* naval architectural group, the influence of the point-loads contrary to distributed loads on still water shear and bending moments will be investigated using a literature-based sensitivity approach.

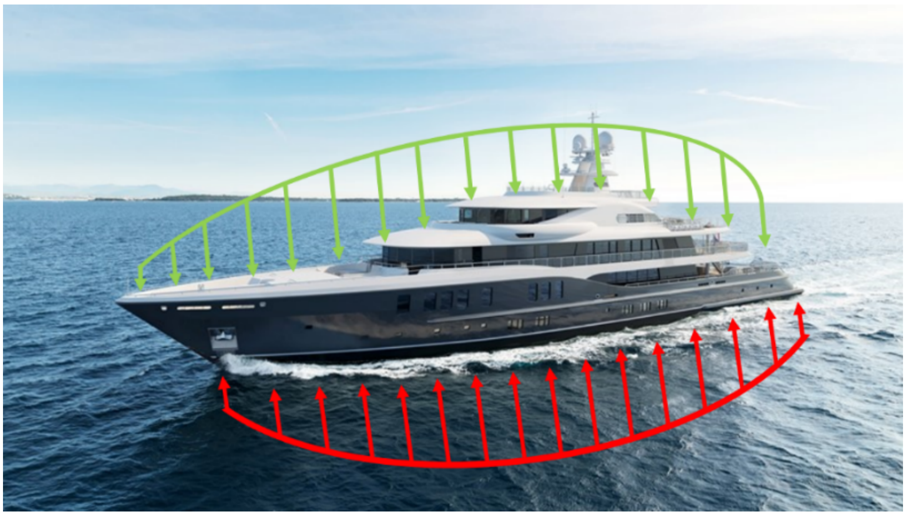


Figure 1: Loading and buoyancy distribution in the 74.00m *AMELS 242*

## 1.1 Motivation

The longitudinal strength of the hull girder is one of the most important strength considerations in a ship. The lack of this characteristic may be a direct cause of catastrophic fracturing and sinking of a vessel. As such, early-stage design requires rapidly exploring and iterating lightship weights and their corresponding locations for optimal bending and shear loads. However, these loads are generally very rough estimations based on previously built vessels and have the potential to change throughout the engineering process [13]. In later engineering stages, these strength parameters are much more accurate due to the increased number of weight items and improved location accuracy. This rise of detail directly corresponds to additional time spent inputting item information to correctly obtaining longitudinal strength information. Currently, the process consists of inputting all individual items throughout the design and engineering stages. Unfortunately, near the end of the detailed engineering phases upwards of 5000-6000 different weight items make-up the full vessel weight distributions. At this point, results are reviewed by structural specialists who either deem the structure sufficient or insufficient based on bending moment and shear force effects. If not sufficient, iteration requiring rearrangement and re-input of these loads must be completed. Therefore, correctly completing this process takes valuable time and resources from projects already constrained due to tight deliverable timelines.

## 1.2 Research Goal

The purpose of the investigation is to determine and apply a detailed methodology to save valuable time during the weight input stages of the engineering phases. This will be done through an in-depth sensitivity approach focusing on the influence of distributed loading versus point-loading to the maximum still water shear and bending moment results.

To reach this goal, a few key research questions will be addressed and answered throughout the course of the study. These include,

1. What is the *Damen Yachting* longitudinal strength minimum requirements and what literature methods regarding weight distribution techniques and sensitivity approaches can be applied to investigate these general guidelines?

2. How do the various weight distribution models behave under irregular loading conditions and how can these inconsistencies be overcome?

3. Can distributed loads be fully represented by concentrated point loads occurring at each weight's center of gravity?

4. How do various weight distribution techniques contribute to the accuracy of still water longitudinal strength output parameters?

5. At which point (if any), can the loads be mixed between distributed loads and concentrated point loads to obtain similar longitudinal strength output results?

### 1.2.1 General Investigation Outline

To answer these critical questions a series of steps and procedures will be followed. First, a literature review will be completed and outlined in section (2). This will be composed of critical information related to the understanding of general analysis requirements, longitudinal strength parameters, various weight distribution techniques, and common sensitivity procedures. Next, a detailed workflow of the study will be proposed in section (3). This section will highlight the overall process and main steps within the study. The developed numerical weight distribution models will then be discussed and compared while considering a small-scale evaluation in section (4). Once the numerical models are fully understood, a large-scale *Damen Yachting* case study will be conducted in section (5). Each weight distribution model will be further analyzed using real data and directly compared. At this point, section (5.2) will apply a detailed sensitivity methodology where results will be thoroughly discussed and analyzed based on inputs and still water error parameters. Additionally, section (5.3) will outline two verification case studies. These will be evaluated and compared to give further confidence in the overall procedure and findings. Based on the definitive results, section (6) will outline a recommended weight input strategy to successfully implement and utilize all learnings in future projects. Finally, section (6.2) will present general conclusions and potential future works to improve both the numerical models and sensitivity study.

# 2 Literature Study

This section aims to expand on key topics that will be beneficial in further understanding and advancement through the course of study by answering the first main research question,

*'What is the Damen Yachting longitudinal strength minimum requirements? And what literature methods regarding weight distribution techniques and sensitivity approaches can be applied to investigate these general guidelines?'*

First, an introduction and highlight of the current *Damen Yachting* design and engineering procedure will be presented. This section will also discuss the longitudinal strength level of detail associated with each design and engineering phase. Additionally, a breakdown of the current longitudinal strength input processes along with the main study focus will be outlined. This information will provide context into the requirements in the eventual longitudinal strength evaluations. Next, the technical aspects of still-water longitudinal strength will be addressed and a calculation procedure of shear and bending moments are discussed. Additionally, various loading distribution techniques are presented, along with the advantages and disadvantages of each. Finally, various sensitivity techniques will be discussed and elaborated.

## 2.1 *Damen Yachting* Build Process

Generally, in a new build program, engineering activities must be executed to support the main project activities of customer acceptance, class approval, procurement, construction, setting to work, testing and final delivery of the contracted product. The engineering packages must provide the required technical information, which increases in extent and detailing during the project's progress, from the conceptual design to completion and delivery. The standard process for a ship's new building program is seen in figure (2).

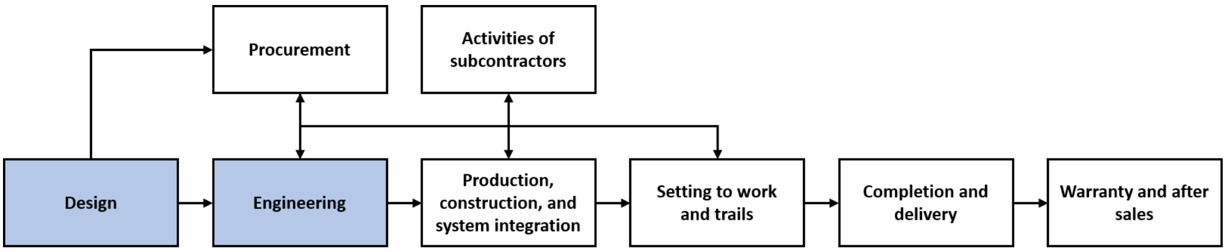



Figure 2: Standard main process for a ship's new building program [17]

The following sections will further elaborate on the design and engineering processes as this particular area is most relevant to the longitudinal strength investigation. Additionally, all acquired information about the internal *Damen Yachting* design processes and can be seen in the appendix (A.1).

### 2.1.1 Phases of Design and Engineering

The full design and engineering process can be further decomposed into six critical stages: Design, Design Check, Basic Engineering, Detailed Engineering, Production Support, and Warrant/After Sales Support. While engineering activities are continually applied throughout the building program, a general overview of the first-four most relevant stages will be outlined.

**Design** The design process generally follows a traditional spiral approach and can be broken into three main sections: idea phase, concept design, and basic design.

- The idea phase consists of evaluating the market needs/client needs. At this point, a brief composed of program requirements is created.

- The concept design phase looks into the preliminary vessel calculations, such as weight, stability, and general arrangements (layouts). Since information is highly lacking at this stage, it is usually accomplished through comparative studies.
- The basic design stage is essentially the same as concept design; however, more detail is added to each component. For the first vessel of a series or a 'one-off,' the Design Department will prepare a Product Definition Package (PDP). This package will additionally include 3D modelling, construction elements, and engine rooms items and layouts.

For follow-up ships within the same series, only a small part of the PDP is required. The PDP or part thereof forms the basis for the Engineering Department to execute their work. The longitudinal strength results in the design phase are generally of low accuracy. Since these parameters require exact weight and location information, this early in the design process, such criterion is impossible to determine. Therefore, the shear and bending moments are usually estimated using available information primarily composed of sister vessel weight information.

**Design Check** Upon completion and receipt of the full PDP, a design check with discrete activities and objectives is required. The primary goals of this stage are,

- Check if the design meets the requirements of Regulatory Bodies, as stated in the building specifications.
- Check to see if requirements, as stated in the building specification, can be accommodated (space-wise) in the design.
- Determine if functionality, as specified in PDP, is inline with *Damen Yachting's* standards and ways of working.

Ultimately, a final deliverable listing the findings of compliance and non-compliance is created in a report form. During the design check stage, more detailed weight information is added to the existing PDP document. These additional weight parameters are then used to evaluate the longitudinal strengths to verify that the results do not drastically vary. Unfortunately, due to the general lack of detailed weight information, such check benefits are likely not to occur in this development stage.

**Basic Engineering** Once the design has been checked, evaluated, and verified, the basic engineering stage begins where the primary goals are,

- Creation of formal engineering documentation consisting of general plans, lists, diagrams, etc.
- Creation of technical procurement specifications based on the specification/class requirements to purchase all the equipment and systems.
- Gain approval by Classification Society and Flag State for construction and systems, as well as the agreement with management about the implementation of the building specifications, is required during this phase of the build process.

It should be noted that actions could (and usually do) run parallel with the design check. This implies that changes within the design are possible throughout the basic engineering phase. The longitudinal strength parameter's level of detail dramatically increases during this stage. This is primarily due to the increase in general item amount, detail, and location accuracy. As such, a substantial time increase is a direct consequence. The expected shear and bending results are considered moderately accurate at this stage as generally, all-important items such as heavy machinery and hull/superstructures are included.

**Detailed Engineering** Detailed engineering is to begin upon completion of the basic engineering package. This phase's primary goals are a continuation of the previous stage. However, the level of detail associated is substantially increased.

- Creation of detailed drawings for the vessel building, which includes section models/drawings and description of parts, profiles, templates, etc.

- Creation of outfitting models/drawings containing technical foundations and descriptions of parts, profiles, templates, etc.
- Creation of coordination models/drawings containing all piping, cable trays, ducts, penetrations, and equipment and create spools, and isometrics is required.
- Acquiring and checking vendor data of all specified equipment/systems meet the requirements as outlined in the purchase order specifications.

When the full detailed engineering package is completed and delivered, the process's production support phase takes precedent. During the detailed engineering stage, the longitudinal strength parameters' level of detail is at a maximum. Unfortunately, during this stage, an apparent discrepancy between time-input and result-outputs can be seen. The main items are already included within the final weight sheets; however, individual elements such as light fixtures, ladders, windows, etc. are now included. These items do not have significant mass effects but are generally composed of many individual items. As such, the overall impact on the shear and bending moment curves vary slightly with respect to a substantial increase in item weight inputs.

### 2.1.2 Current Longitudinal Strength Evaluation Process

Currently, the longitudinal strength input approach is as follows,

1. Individual items are entered manually into an excel data list. Each item is composed of six critical inputs: Weight, LCG, Aft Limit, Fore Limit, TCG, and VCG. The items are then grouped and sorted within their *Damen Yachting* item specialization codes known as JDOCs.
2. Next, each input parameter is determined through the use of multiple resources. However, the item locations are typically found from a CADmatic 3D model. This model is periodically updated to include each item (nearly all). From this integrated 3D model, exact item locations can be found.
3. When all inputs are determined for each item, the list is transferred to commercial stability software MAXSURF. This program, depending on the loading conditions and assigned tank fluid levels, calculates the longitudinal strength shear and bending moment results.

Unfortunately, depending on the design stage, item amounts can vary drastically. A completed vessel after the detailed engineering is typically known to consist of $\sim 5000$ individual weight items. Therefore, the entire process of inputting all six parameters for each item can become extremely tedious and time-consuming.

### 2.1.3 Design Phase Focus

The *Basic Design* phase is identified as the phase where an initial longitudinal strength weight input simplification and study can add the most value to the engineering process of *Damen Yachting*. There are multiple reasons and benefits for focusing on this particular phase.

First, the ability to speed up the acquisition of problem knowledge early in the engineering process allows for mitigation of risk instead of costly redesigns later in the project. An essential aspect of this problem is accurately estimating the required maximum shear force, bending moments, and associated positions. Under-estimating this result can lead to trimming effects and unaccounted structural loading, which can cause such redesigns. Secondly, this phase in the design generally has the most considerable leap of total input parameters. Therefore, the ability to save time while reducing the required staff-hours of the experienced naval architects are seen as incredibly important. This can ultimately speed up the basic engineering process and allow for more time allocation to other critical areas of the engineering process.

**General Requirements** Therefore, a method to produce longitudinal strength results quickly and accurately is required without inputting every known parameter. As such, an evaluation margin is necessary for both maximum still water strength shear and bending moment. These criterion were selected based on conversations with both the *Damen Yachting* Naval Architectural and Structural departments (appendix (A.1)).

1. **The general still water shear and bending moment results must fall within a 10% accuracy margin**

   The first criteria will be the primary accuracy margin for the investigation. These estimations are results based on an internal review of past vessels ranging from 55-75 meters. It can be seen that first-of-series and customs have a maximum of $\sim 10\%$ $(6.4\% \pm 2.5\%)$ weight deviation from the final detailed engineering to the PDP weight estimate. As such longitudinal strength parameters should not be larger than this amount at any stage in the design. Therefore, the following evaluation criteria will be used,

   $10\%$ margin - Yachts < 80m
   $5\%$ margin - Yachts 80m - 100m
   $2\%$ margin - Yachts > 100m

   Essentially, the larger the vessel, the larger the applied weight onto the structure is. As such, a variation of shear force and bending moments can have a sizeable range depending on the margin allowance. Therefore, the minimization of the margins per vessel length increase was deemed appropriate. It should be noted that these discrete length criteria were chosen through past experiences and are mostly arbitrary. An additional investigation into various vessel lengths and sizing effects on shear and bending moments per design stage could play a crucial future role in longitudinal strength estimation and simplifications.

2. **The maximum vessel displacement must not be exceeded to maintain design speed**

   Additionally, while it may not directly impact the study, a maximum displacement for the attainable design speed is required. If the loading is exceeded and the general vessel displacement is too large, additional resistance will reduce the estimated design speed. As such, a strict weight limit is established for each vessel to ensure vessel displacement is conserved. It should be noted that since the study utilizes existing case weight distributions, it is expected that this criterion is sufficiently met in all cases.

3. **The general vessel trim must not exceed the allowable half-length rule of thumb limit**

   Finally, as a general rule of thumb, the maximum allowable trim of a vessel should be one-half of the vessel's length in centimetres. For example, if the ship is 60m, the maximum permissible trim should not exceed 30cm or 0.3m. Like the above criterion, the applied loading is based on existing weight item inputs. As such, expected trimming effects are assumed appropriate. However, to ensure the numerical models adequately captures such effects, sufficiently small discretization will be incorporated, so artificial trimming results are neglected.

## 2.2 Still Water Shear and Bending Moments

An essential aspect of ship design is the understanding of the ship's strength. This refers to the ability of the vessel to withstand the loads applied and imposed on the structure. One of the most crucial strength parameters is known as the longitudinal strength of the ship. The standard approach of determining this parameter is through the static longitudinal strength approach, otherwise known as the still water assumption. This case assumes the vessel is in a state of equilibrium where the buoyancy loading distribution is equally opposed by the loading of the ship itself [2].

However, the weight distribution along the length varies. The unevenness in the weight distribution acting downwards and the buoyancy force distribution acting upwards causes a resultant, "still water bending moment," which ultimately has the potential to cause the hull girder to bend or fracture [6]. If the weight loading is larger in the midships than the buoyancy loading, this causes "sagging". If the buoyancy in this area is larger, it causes what is known as "hogging". These conditions can be seen highlighted in figure (3).

### 2.2.1 Shear and Moment Calculation Procedure

When the loading condition is given, loads such as force and moment acting on the ship due to equipment loads, cargo loads, etc., can be calculated. Such loads will be used as one of the input data for hull structural design in the next design stage. First, the buoyancy curve $b(x)$ can be obtained by applying the Archimedes Principle and integrating transverse sectional areas, under the water plane in the longitudinal direction. Next, the weight

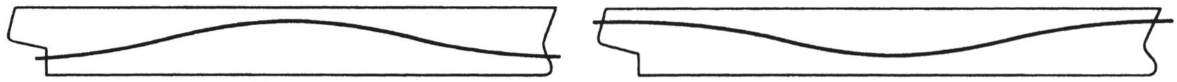



Figure 3: Hogging and sagging conditions [13]

curve $w(x)$ can be made by summing up the lightweight distribution and the dead-weight for each loading condition. Then, the load curve $f(x)$ can be generated by summing up the weight curve and the buoyancy curve while considering their signs,

$$f(x) = w(x) - b(x) \tag{2.1}$$

By having the resultant loading distribution, the shear force curve $Q(x)$ can be calculated by integrating the load curve in the longitudinal direction per unit interval of length.

$$Q(x) = \int (w(x) - b(x))dx \tag{2.2}$$

The bending moment curve $M(x)$ can then be calculated by integrating the shear force curve in the longitudinal direction using a similar process.

$$M(x) = \int Q(x)dx = \iint (w(x) - b(x))dxdx \tag{2.3}$$

From the relationships deduced above, when the net load is zero, the shear force will have a maximum or minimum value, and the moment curve will show a point of inflection. When the net load is a maximum, the shear force curve has a point of inflection. Where shear force is zero, the bending moment is a maximum or minimum, respectively. Figure (4), highlights the full general calculation procedure to determine both still water shear and bending moments.

Knowing the weight distribution, and finding the buoyancy distribution, gives the net load per unit length. However, certain approximations and criteria are needed to deal with distributed loads sufficiently. First, the shear force and bending moment must be zero at the ship's ends as represented in the free-free Euler-beam theory. If there is an additional residual force or moment after integration, this is usually corrected arbitrarily by assuming the difference can be spread uniformly along the ship length [13]. Finally, the center of buoyancy and the center of gravity of the loading must be aligned to ensure additional moments are not applied.

## 2.3 Weight Distribution Techniques

Determining the longitudinal weight distribution is vital to the proper calculation of the longitudinal strength of a ship. Before the advent of computers, the determination of a ship's weight distribution was a "rather laborious process" [8]. Due to the amount of effort involved, approximation methods were developed over the years. With the computational advancement, means of collecting all the weights with centers between given locations became less labour-intensive.

For longitudinal strength calculations, various levels of detail are acceptable and generally yield globally similar results. However, the higher the complexity, the more fidelity is imposed on the loading resulting in detailed shear and bending moment results. As such, three different loading classes will be analyzed: one approximate distribution, and two direct distributions.

### 2.3.1 Approximate Methods

Numerous approximation methods for distributing hull weight have been proposed in the past. Hull weight is traditionally defined as lightship minus the weight of the anchor, chain, anchor handling gear, steering gear,

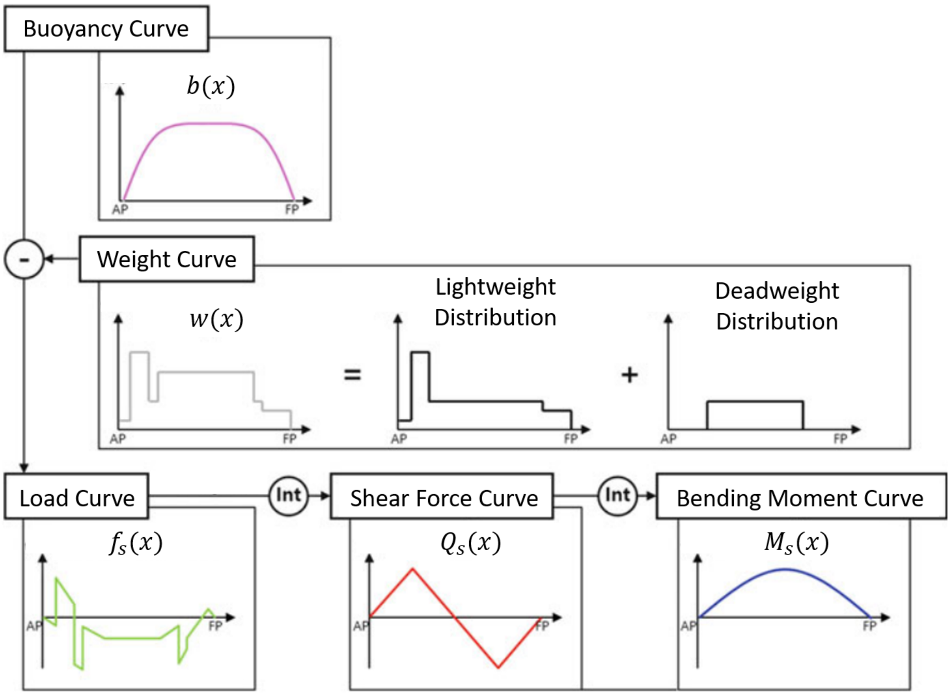



Figure 4: Still water bending moment general calculation process [9]

and main propulsion machinery. Items left out of hull weight are then independently distributed as rectangles or trapezoids and combined with the hull weight distribution to determine the total weight distribution for the ship [5]. The parabolic approximate distribution method is intended for vessels that don't have or have a relatively small parallel middle body. This approximation can be seen in figure (5).

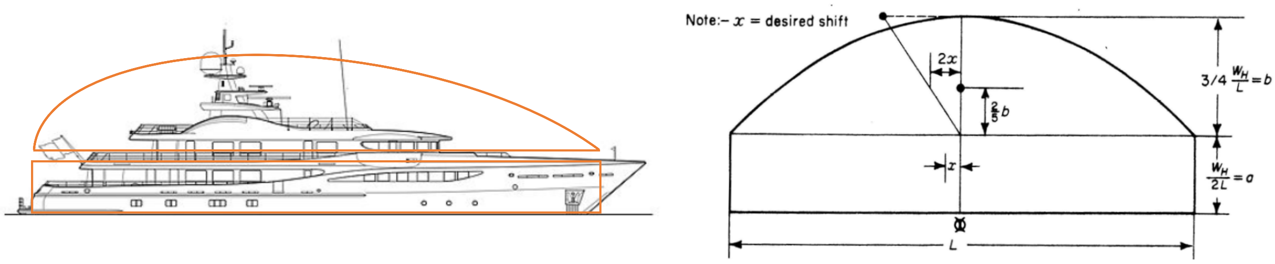



Figure 5: Illustration and formula representation of the parabolic approximate loading method [5]

Where $W_H$, is the weight of the hull, L is the length of the vessel, and x is the desired shift of the centroid to align with that of the corresponding buoyancy distribution. Principally a straight line is drawn through the center of the parabola approximation; the relevant relations then shift this line. A new parabolic path is then determined by using the newly translated points describing the modified parabola. Therefore, this method has the advantage that the centroid of the distribution can be shifted by "swinging the parabola" to alter the global center of weight.

Unfortunately, these approximations are general and appropriate only for initial stage design due to their low fidelity and lack of weight distribution control. Thus, these methods provide low accuracy estimation for extremely fast baseline results.

### 2.3.2 Grouping Methods

The original grouping method is also known as the ”Point-wise Bucket” method. This loading strategy derives its name from the fact that the weight details are placed within strictly bounded domains based on their longitudinal center of gravity. If an item’s longitudinal center of gravity falls in the extents of a ”bucket”, it is included in that region as a concentrated point load. This method is illustrated in Figure (6), where the center of each distribution is described as a combined loading.

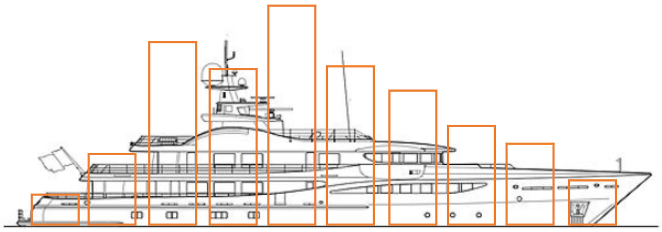


Figure 6: Illustration of the ”Bucket loading method”

The main consequence of this method is that weight details are lumped representations of distributed weights. One item can represent 1 or 100 meters longitudinally. It can be interpreted that the center of gravity of each distributed loading does not necessarily mean that all or even most of the reported weight falls within a specific bucket. Therefore, a degree of uncertainty in the loading is present as the lumped distributions can artificially skew shear and moment results as full weight lengths are not physically present.

### 2.3.3 Direct Methods

The approach that offers the most promise is distributing the individual weight items directly. The distribution of each weight can then be summed to determine the entire ship’s weight distribution at a high level of fidelity. This whole ship distribution can then be used to create any representation of the weight distribution [5]. The fundamental geometric shape for this distribution method is a trapezoid. Representing a weight as a trapezoid requires knowing the weights, $W$, the longitudinal aft and forward extents, and the longitudinal center of gravity, $LCG$, location. This method is commonly applied in commercial software tools such as MAXSURF, PIAS, etc. The loading distribution and corresponding trapezoidal representation can be seen in figure (7).

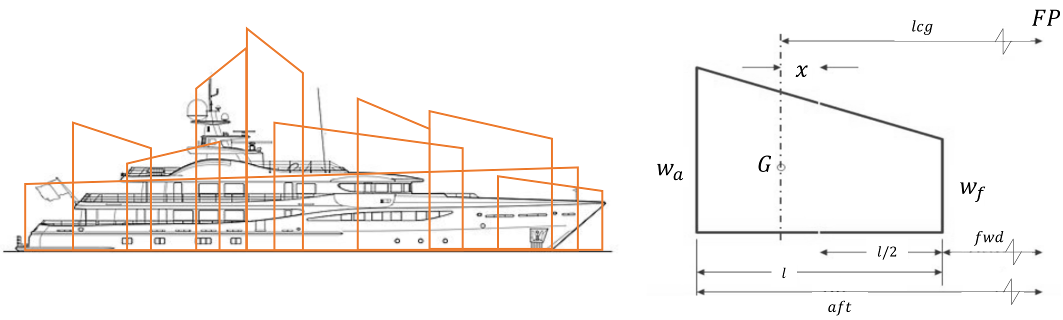



Figure 7: Illustration and trapezoidal representation of the direct loading method

The offset location of the centroid, $x_{off}$, and bounding weight distributions, $w_a$ and $w_f$ can be determined using the following relations,

$$x_{off} = LCG - (fwd + l/2) \tag{2.4}$$
$$w_a = {}^{W}\!/_{l} + 6\left({}^{Wx}\!/_{l^2}\right) \tag{2.5}$$
$$w_f = {}^{W}\!/_{l} - 6\left({}^{Wx}\!/_{l^2}\right) \tag{2.6}$$

The difficulty with trapezoidal representations is that they are limited to weights where the center resides in the middle one-third of the length. Attempts to represent weight whose center falls outside, using the equations for trapezoidal representations, results in part of the weight distributions being negative [5]. Such a description is flawed as it subtracts weight from a location that the item should be adding weight, as seen in figure (8).

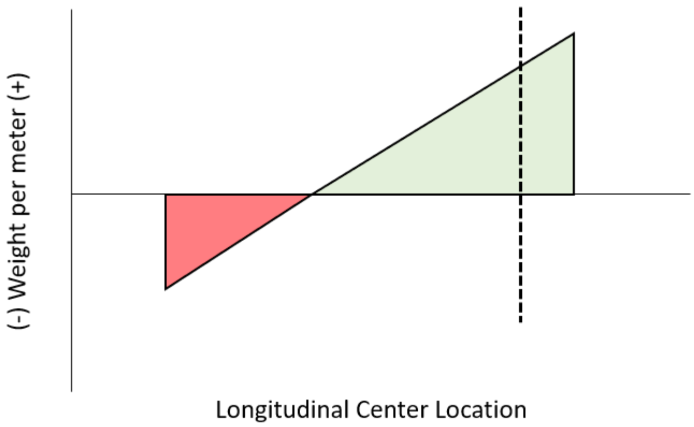



Figure 8: Negative trapezoidal loading representation due to extreme LCG placement

This error can be overcome by requiring that the user adjust the inputs so that the center falls in the middle one-third of the extents by merely changing the extents outward/inward until the center meets the criteria. Unfortunately, this option often reduces the overall accuracy of the resultant distribution.

## 2.4 Sensitivity Methods

Sensitivity analysis is an important aspect of design as it allows for an increased understanding of the relationships between input-output variables in a system or model. Therefore, this type of analysis can not only identify the variables that have important effects on the overall outputs but also indicate which of those variables that are not necessary to be considered, and which variables strongly influence other variables. This type of study essentially reduces the degree of uncertainty amongst the input-output responses. This general procedure consists of evaluating function derivatives with respect to the design variables. Traditionally, this derivative response is known as the sensitivity factor, $\alpha_i$, where $i$ is the random variable. This can be normally defined as,

$$\alpha_i = \frac{\partial f}{\partial x_i}|_{x^*} \tag{2.7}$$

Where $x^*$ is the specific design point in the standard normal design space. Currently, there are many techniques available to extract derivative information. However, in most cases, the ability to determine the exact derivative information is impossible to determine. As such, these sensitivity techniques are generally incorporated to provide close approximations. The overall method selection is based on a few key aspects; implementation effort, efficiency, and accuracy. In this study, two sensitivity approaches will be outlined, and one will be implemented: the localized one-at-a-time method and the global variance-based method.

### 2.4.1 Local One-at-a-time (OAT) Sensitivity

One of the easiest and most common approaches is changing one factor at a time, seeing what effect this produces on the output results. This approach is known as a local sensitivity method, as all evaluations are determined at a single point. The OAT analysis customarily involves; Moving one input variable while keeping others at their baseline (nominal) values and then returning the variable to its nominal value. This process is then repeated for each of the other inputs in the same way.

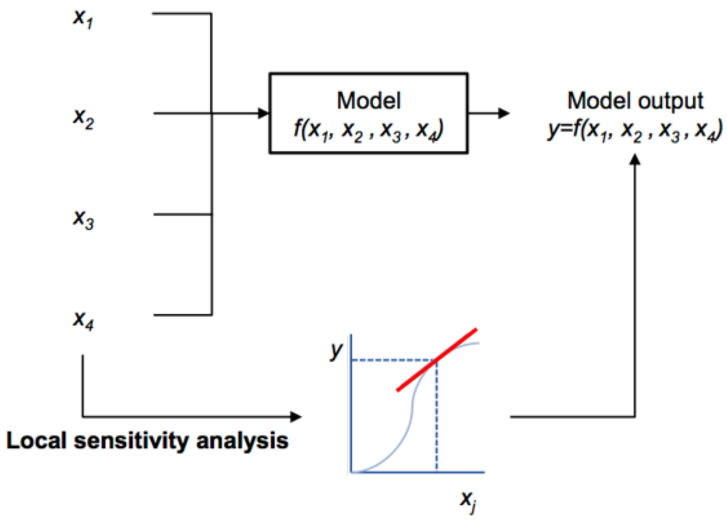



Figure 9: General local sensitivity analysis flowchart [4]

The sensitivity may then be measured by monitoring changes in the output. This approach appears a logical strategy as any change observed in the output will be due to the single variable changed. Furthermore, by changing one variable at a time, one can keep all other variables fixed to their baseline values. For example, if the expected outcome of the analysis is a sensitivity response of $\partial f/\partial x = 4$ when perturbing the distribution length at the evaluation point, for every input we can expect an output change corresponding to the same factor of span change. While this response is merely an approximation of the expected response, it does give valuable insight into the expected change. This general process can seen in figure (9). Typically, the technique used to complete this form of sensitivity analysis is the finite difference method.

#### 2.4.2 Global Variance-based Sobol Sensitivity

Variance-based sensitivity analysis, also known as the Sobol method, is a form of global sensitivity analysis. This means that parameter interactions within the whole domain can be considered. These types of methods generally work. These methods are usually considered a class of probabilistic approaches that quantify the input and output uncertainties as probability distributions and decompose the output variance into parts attributable to input variables and combinations of variables. For example, given a model with two inputs: mass and distribution length and one output: bending moment, one might find that the variance in the first input causes $70$% of the output variance, $20$% by the difference in the second, and $10$% due to interactions between the two. These percentages are directly interpreted as measures of sensitivity. The general flow process of this method can be seen in figure (10).

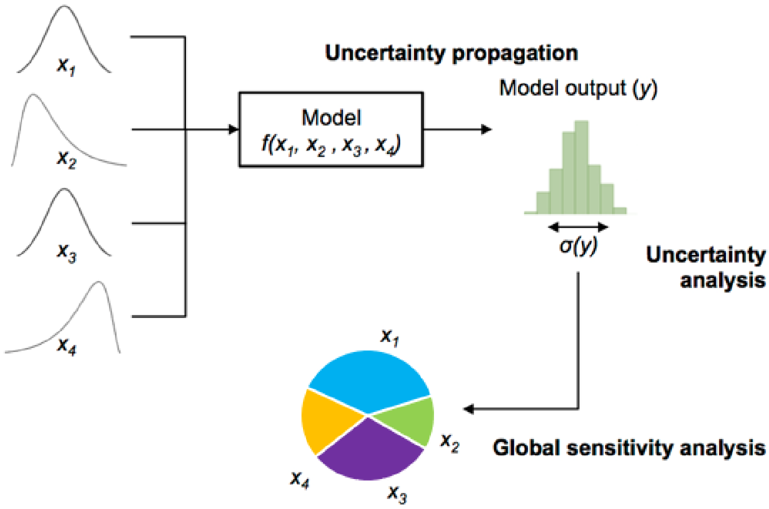



Figure 10: General global sensitivity analysis flowchart [4]

Therefore, the output's sensitivity to an input variable is measured by the amount of variance in the output caused by that input. These can be expressed as conditional expectations,

$$Var(E_{x_{\sim i}}(Y \,|\, x_i)) \tag{2.8}$$

$Var$ and $E$ denote the variance and expected value operators, respectively. $x_{\sim i}$ denotes the set of all input variables except $x_i$. This expression essentially measures the contribution $x_i$ alone to the variance in, $Y = f(x_i)$ and is known as the first-order sensitivity index [11]. Variance-based methods allow full exploration of the input space, accounting for interactions, and nonlinear responses. For these reasons, they are widely used when it is feasible to calculate them. Usually, this calculation involves using the Monte Carlo method due to the large data sets and stochastic nature of the analysis. Unfortunately, a limitation of the Monte Carlo method is that an extremely high number of model evaluations are required to get reliable statistics. If the model is computationally expensive, the Monte Carlo method may require insurmountable computer power [12].

## 2.5 Literature Review Summary

From the literature investigation, the first research question can successfully be addressed.

The *Damen Yachting* minimum requirements can be decomposed into three main criteria. Of these three, only the first criteria related to relative accuracy is crucial in the forthcoming investigation. The 10% relative error margins will be used as the deciding benchmark whether corresponding results are deemed acceptable or not.

Secondly, it was found that many weight distribution techniques exist. However, only the three most common methods were investigated and will be further implemented within the study. These include Parabolic Approximate, Point-wise Grouping, and Trapezoidal Direct. The parabolic is expected to have the least accuracy but the most straightforward implementation. The Grouping method may not have the highest accuracy, but the overall control over input parameters will be high and easy to implement. Finally, the Trapezoidal Direct method is expected to produce the highest level of accuracy at the cost of time due to individual weight item inputting.

Finally, two sensitivity approaches were analyzed: Local and Global sensitivity. These methods vary based on the overall information gain versus computational demand. Local methods focus on a singular operating point, whereas Global methods determine the design variable interactions across the whole domain. Ultimately, the study will be best served using a Local sensitivity approach as the investigation directly focuses on the influence of the distribution length design variable while keeping all other parameters fixed.

# 3 General Workflow Implementation

To successfully answer the outlined research questions, a general investigation workflow process is implemented to give a clear road map of the necessary steps and procedures. This flow chart can be seen in figure (11).

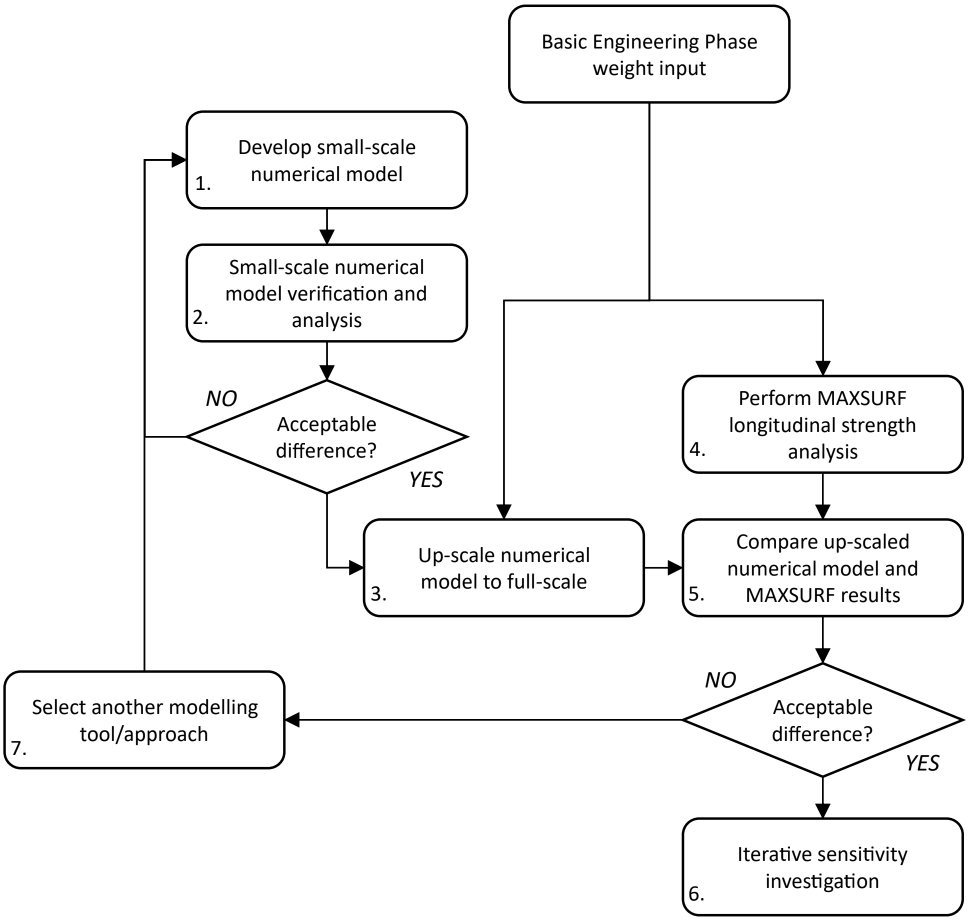



Figure 11: General framework and process flow chart for longitudinal strength assessment

Each critical step can be detailed as follows,

1. The procedure will begin with the development of three load distribution models: parabolic, point-wise grouping, and trapezoidal direct. The model development process and assumptions will be outlined in section (4.1).

2. Next, each model will undergo small-scale robustness and verification analysis. This analysis will pinpoint any underlining issues with the model through a general comparative study while incorporating the critical general requirements (section (4.3)).

3. If the models meet the general criteria, they are ready to be scaled-up and analyzed using a *Damen Yachting* case vessel. However, the associated weight inputs must first be organized and arranged so that the MATLAB models can input the weight items.

4. The determine the baseline comparison results, the corresponding engineering phase weight inputs are implemented within the commercial software MAXSURF. These results will then be imported within the MATLAB platform to provide a consistent comparative study (section (5.1)).

5. Once the comparative baselines are established, each weight distribution model is directly compared and analyzed.
6. If the differences are once again acceptable to the requirements, an iterative sensitivity study using various grouping schemes are conducted.
7. If at any critical point (diamond shapes), the models do not successfully meet the general requirements, a new model must be analyzed and evaluated.

The full procedure and comparative metrics are discussed in section (5.2). It should be noted that an additional, more detailed sensitivity procedural framework will be outlined in the forthcoming chapter.

# 4 Model Generation and Small-scale Analysis

This section aims to elaborate on model development. It also hopes to inform the reader of critical strengths and limitations which potentially exist. First, a brief introduction and overview of the model will be addressed. This elaboration will be followed with a highlight of any noticeable limitations that exist in the model space. Next, a general model robustness evaluation will be performed to understand the model's inner workings. Finally, a small-scale accuracy verification study will be done. This part hopes to verify the small-scale model through comparison means while keeping the general design requirements in mind.

## 4.1 Model Development Overview and Assumptions

The longitudinal strength model is formulated so that the three distribution techniques can seamlessly be applied to individual cases. This allows for a relatively quick and direct comparison to evaluate each technique's suitability under varying loading conditions. The model implements a few controlling parameters which influence the overall results and analysis for each distribution. The key parameters include,

- **Length,** $L$**:** The length parameter is used to establish the overall structural length of the structure. Varying this parameter greatly influences associated shear and bending moment locations and magnitudes depending on the applied load condition. However, this single parameter allows for any structure of any length to be analyzed. This parameter is expressed in meters.
- **Station Position,** $x_{station}$**:** The length of the vessel is decomposed into multiple stations. A station is a transverse cross-section along the ship's length, which is normal equally spaced. This modifiable parameter is intricately linked with the length of the vessel and provides discrete location references.
- **Discretization Factor,** $n$**:** The length of the beam can be discretely subdivided into multiple individual segments. This process is implemented in numerical methods to convert a complex continuous function evaluation into a more straightforward lumped area approximation. In particular, the grouping method uses these sections as point-load grouping edges. In contrast, the approximate and trapezoid methods use these factors as grid refinement for enhanced accuracy. Unfortunately, at a cost simplicity, a discretization error is introduced within the system.
- **Displacement Load,** $W_b$**:** The total displacement of the structure represents the buoyancy load applied as a counteracting force to maintain a state of equilibrium. Each vessel generally has a buoyancy distribution unique to the hull shape. As such, the associated loading and form must be determined before analysis. This parameter is expressed in the tonnes.
- **Applied Load,** $W$**:** The loading applied within each distribution technique varies slightly from case to case. The parabolic approximation method directly incorporates the additional loads as a single distribution along the structure's span. The grouping and direct processes, on the other hand, have more versatility and control. The grouping method application allows for user-defined center of gravity location, $x_{LCG}$, and load distribution lengths, $L_D$. If the weight has a range set as 0, the model defines the load as a single concentrated load applied at the LCG. The trapezoidal loading is similar; however, instead of determining an overall distribution length, the distribution end boundaries are defined as $x_L$ and $x_R$, respectively. If the distance between the longitudinal center of gravity is equal on both sides, the loading will be a rectangular distribution. If the LCG is slightly off-centred, then the distribution will be converted into a trapezoidal approximation. If the $LCG$ is outside the middle one-third of the distribution length, a critical negative error will be introduced.

When the model is correctly implemented, and all key parameters are applied, a figure highlighting all the crucial information is returned. This figure includes both station and discretization points, the buoyancy distributed loading, the applied loading, the resultant loading, the shear force, and the corresponding bending moment. Ultimately, this model is implemented as a tool to evaluate multiple distribution techniques at the expense of computational time. As such, model simplifications and assumptions were applied to ensure complexity and computational demand remained reasonable. The main assumptions made in the model are,

- **Integration Methods:** The determination of the shear force and bending moments require area integration to be successfully evaluated. However, the mathematical description and formulation of these curves are generally complex or impossible to determine. As such, a numerical tool to approximate the defined area of these complex curves is implemented. This numerical tool is known as the trapezoidal approximation method. Essentially it decomposes a curve with an unknown area into individual trapezoids. These trapezoids are much easier to evaluate and provide a remarkably close approximation in many cases. This approximation error can further be reduced by increasing the discretization factor. The general methodology is highlighted in figure (12). As the curve is further refined, more trapezoids can represent the curve and the corresponding error decreases. This method was applied in all situations where the area of a distribution needed to be determined.

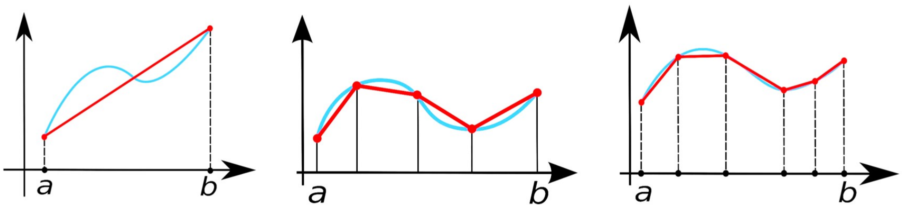



Figure 12: Trapezoidal approximation with increasing discretization

- **Linear Interpolation:** Particularly for the grouping technique, curve points must be interpolated such that the loading occurs in the middle portion of the discretized edges. This allows the loading to be applied in the exact center. Thus, a simple linear interpolating function is used to achieve this effect. However, as a consequence, the shear and moment curves do not begin at the outermost locations. Therefore, with a small discretization factor, effective area integration will yield slightly less. Fortunately, this effect is usually trivial as the resulting area in the fore and aft sections are generally quite small. Therefore, with a slight increase in the mesh refinement factor, the effect essentially becomes negligible.
- **Discretization Bounding:** The grouping technique does not incorporate a conventional discretization. Instead, the n-factor decomposes the equal spaced bin sizes into smaller domains. The MATLAB implementation requires that loads and locations to be placed within the bounding edges for the grouping effect to be activated. If the loading lies precisely on one of the edge points, depending on where it is on the left or right, bound the following relation is maintained, $A \leq x_g < B$. Therefore, the load may not always be grouped in the correct location.

## 4.2 Robustness Evaluation

With the models generated and the key influencing parameters and assumptions clearly outlined, a general robustness evaluation is done for each distribution technique. Robustness testing is any quality assurance methodology focused on testing and critically evaluating the model's effectiveness and operability. One such method is known as the Fault Injection technique. Fault injection is a testing method that can be used to check the robustness of systems where a fault is applied to the system. At this point, the system's resiliency is observed, and critical failures are evaluated [7]. Using this evaluation procedure, the second research question can be addressed.

*'How do the various weight distribution models behave under irregular loading conditions and how can these inconsistencies be overcome?'*

Two important conditions must be met to have a successful numerical longitudinal strength evaluation: Buoyancy and loading equilibrium, as well as an aligned LCB and LCG. These conditions are further elaborated in section (2.2.1). By applying the fault injection methodology, both these criteria are evaluated independently, and resulting effects are observed.

**Buoyancy and applied loading are in a state of equilibrium** For still water conditions, the applied loading and buoyancy force must be in a state of equilibrium. When this condition is met, the resulting load integration will allow for the shear force's zero end boundary conditions to be met. The general formulation of the resultant load can be seen from equation (2.1). To ensure this condition is always achieved, an additional term must be introduced to balance the load remainder.

$$f(x) = w(x) - b(x) \neq 0 \tag{4.1}$$
$$f(x) = w(x) - b(x) + C = 0 \tag{4.2}$$

Where $C$ is the associated correction load that must be distributed over the structure's span to ensure equilibrium. An example case where the loading is both unbalanced and balanced can be seen in figure (13), and (14), respectively. In this small-case, a buoyancy load of 500 tonnes and a corresponding weight of 50 tonnes is applied to a structure. Numerically, there are approximately 450 tonnes of unaccounted weight that needs to be added to ensure load balance. The loading is presented on a structure of six-unit length. A discretization factor within each station, $n = 1$, was applied as the robustness focus is functionality over accuracy.

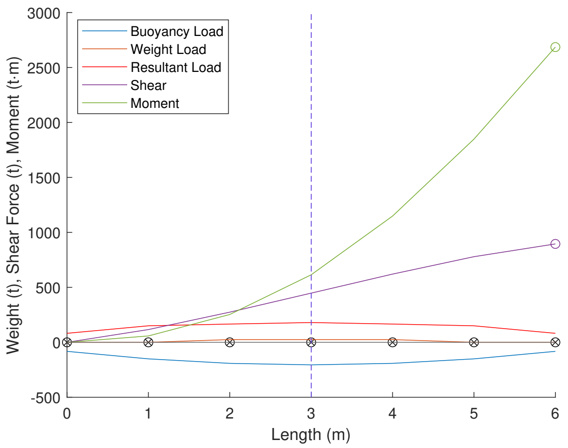



Figure 13: Non-equilibrium loading

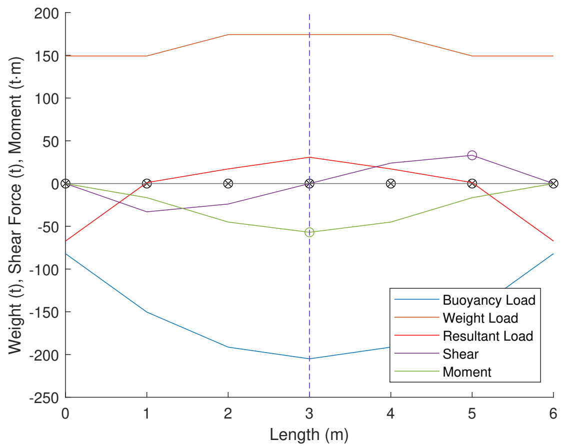



Figure 14: Equilibrium loading

From the results the output effects are quite clear. When the system is not balanced (figure (13)), the end boundary conditions for shear are not met. This causes a continual applied shearing effect through the length of the structure. This evidently, also effects the applied moment and greatly exaggerates the results. This case clearly does not meet the general Archimedes' principle, physical law of buoyancy. When the remaining load correct, the results become much more appropriate (figure (14)). When the condition is met, the boundary zero-end boundary conditions for shear are also correctly enforced. The added load can be seen directly in the corresponding weight load line within the figure. These examples are performed with the direct method; however, a robustness test was done for the approximate and grouping methods as well. This testing proved to have equally similar output effects and likeness.

**LCB and LCG alignment** In the previous study, the moment was balanced due to the equilibrium condition; however, this is not always guaranteed. The moment balance is a result of the corresponding longitudinal centers of buoyancy and gravity alignments. When the LCB of the buoyancy distribution matches the LCG of the applied load, no additional trimming moment will exist. Thus, the zero-end boundary conditions for the moment are retained. If they do not align, a trimming effect (i.e. a moment imbalance) will be expected. The LCB and LCG of each loading distribution shape can be numerically evaluated by determining the centroid via the first moment integral in the x-coordinate location.

$$\bar{x} = \frac{\int_A (x \cdot dA)}{A} \tag{4.3}$$

Where A is the total area of the distribution, dA is the area change along the continuous length, and $x$ is the evaluation point of the corresponding area location. Using this approach and applying a similar loading case, except with a location offset of one-unit length, an additional robustness investigation can be evaluated. The results for both a non-aligned and aligned LCB and LCG can be seen in figure (15), and (16) respectively.

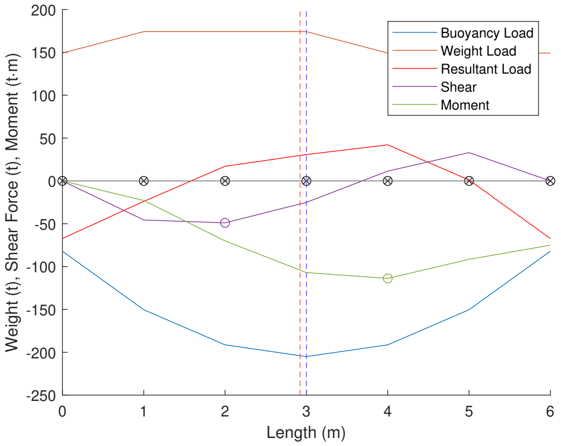



Figure 15: Non-aligned LCB & LCG

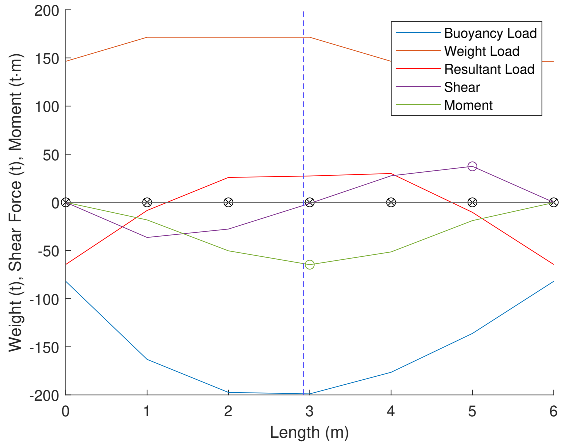



Figure 16: Aligned LCB & LCG

From the results, the output effects are once again quite transparent. When the load is off-centred, the LCG is slightly shifted (red dashed line). While the equilibrium conditions ensure the shear load meets the end conditions, the moment is not affected as an induced trimming effect is present. To achieve balance, the parabola defining the buoyancy distribution is shifted to align the LCB with the LCG. Once these parameters are aligned, the zero-end boundary conditions are satisfied for both shear loading and bending moments.

Due to the numerical method approximations, it should be noted that an exactly zero end moment and shear condition may not always be present. However, further mesh refinement can reduce this deviation error. Ultimately, it is up to the analyst to implement engineering sense when evaluating whether the differences are sufficiently small. These examples are once again performed with the direct method. However, a robustness test was done for the additional approximate and grouping method, which proved to have similar effects.

## 4.3 Small-scale Model Analysis and Comparison

From the robustness evaluation, it could be determined that the models are able to fulfill the necessary governing relations if the two criteria are satisfied. However, this test did not evaluate the accuracy of each model. To ensure the developed models accurately determines still water longitudinal strength components, an additional case study was completed. This analysis is completed as a means for model verification. Verification is the process of comparing analytical results with the simulation model to ensure its accuracy. Once the exact shear and bending outcomes for the case are established, a clear understanding of the model accuracy and capabilities will be further understood. This study will evaluate a basic barge with varying loading distributions applied on the main deck.

*'A box shaped barge, length 30m, breadth 8m and depth 6m, floats at an even keel draft to 4m in saltwater of relative density 1.025 kg/m$^3$, has 500 tonnes of ore spread over the midship half-length and two cases of machinery each weighing 20 tonnes, measuring 2m x 2m x 2m, stowed on the centre line 5m from each end. Construct a curve of loads for the still water condition assuming the weight of the barge to be evenly distributed over the full length and from it draw curves for Shear Force and Bending Moments.[3]'*

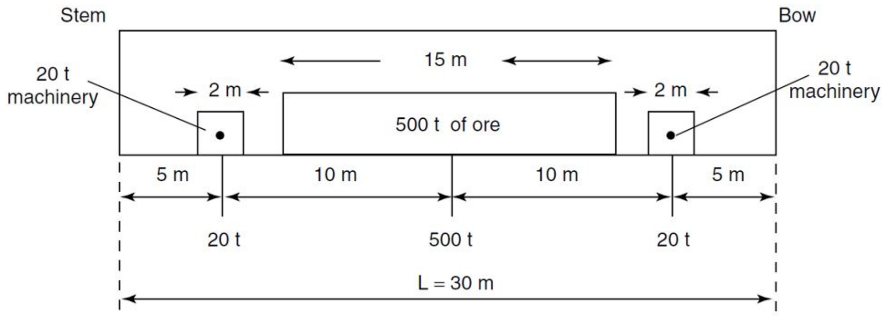



Figure 17: General barge schematic with loading and locations [3]

From the case study, the displacement of the barge can simply be calculated using Archimedes principle assuming a basic rectangular shape.

$$\text{Displacement of barge} = 30 \times 8 \times 4 \times 1.025 = 984 \text{ tonnes}$$

This total displacement can further be decomposed into both the weight of the barge and weight of the cargo respectively s. Since we know the total loading applied on the barge, the remaining portion is the influence of the structure itself.

$$\text{Weight of cargo} = 540 \text{ tonnes}$$
$$\text{Weight of barge} = 444 \text{ tonnes}$$

Having established the individual mass components, the loading distributions applied can be evaluated has the loading per length. Thus, the barge, buoyancy, ore, and machinery loading distributions can be simply determined as,

$$\begin{aligned} \text{Weight of barge per metre run} &= {}^{444}/_{30} = 14.8 \text{ tonnes/m} \\ \text{Buoyancy per metre run} &= {}^{984}/_{30} = 32.8 \text{ tonnes/m} \\ \text{Ore spread per metre run} &= {}^{500}/_{15} = 33.3 \text{ tonnes/m} \\ \text{Machinery spread run} &= {}^{20}/_{2} = 10.0 \text{ tonnes/m} \end{aligned}$$

Under these loading conditions, the corresponding shear and bending moments can be plotted in figure (18). From the figure, the shear force has a positive contribution up until the middle plane. In this section, the shear force then gives a corresponding equal negative contribution, which is due to the symmetric nature of the applied loading and structure. As such, the applied maximum bending moment will become a maximum in the middle section of the barge. It should be noted that the figure shows an inverted bending moment diagram for simplified visualization; however, it remains as a positive contribution. The analytical maximum resultant loading for shear force and bending moment are,

$$Q_{max,analytical} = 115.0 \text{ tonnes}$$
$$M_{max,analytical} = 887.5 \text{ tonnes·m}$$

Having determined the maximum resultant shear force and bending moment of the cases study, the same small-scale model loading techniques will be individually compared and evaluated in terms of accuracy using the requirements established in section (2.1.3). To evaluate these parameters, a percent error calculation is done using the analytical results as the correct values, and the numerical model results as the theoretical.

$$\%Error = \left| \frac{True - Theoretical}{True} \right| \cdot 100 \tag{4.4}$$

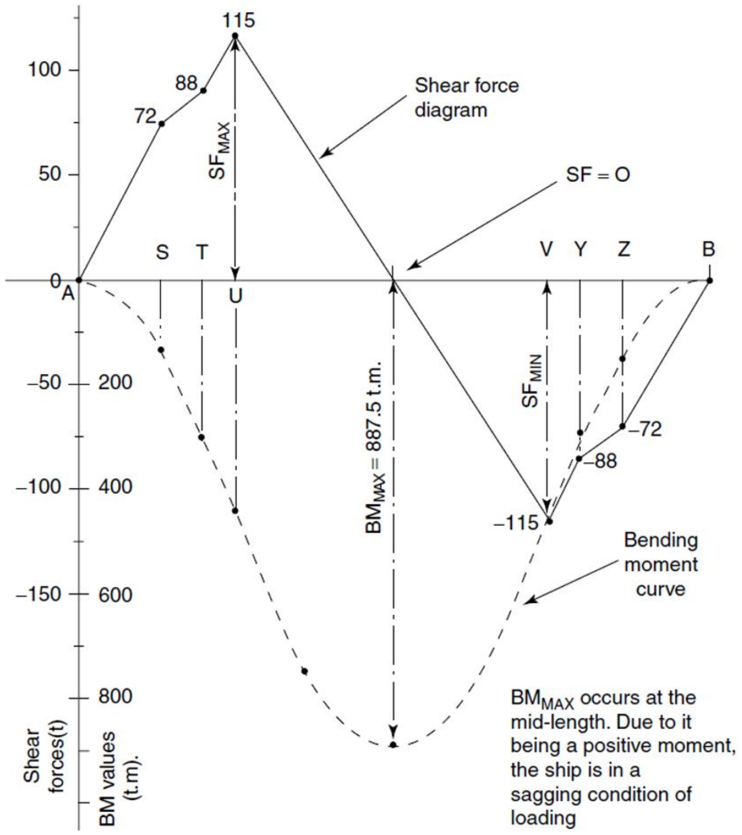



Figure 18: Shear force and bending moment analytical results [3]

### 4.3.1 Parabolic Approximation Method

The parabolic approximation method, as outline in section (2.3.1), relies on empirical formulations to determine both the shear force and bending moments. The corresponding case study results can be seen in figure (19), and a summary of the maximum shear and bending results can further be seen in the table (1).

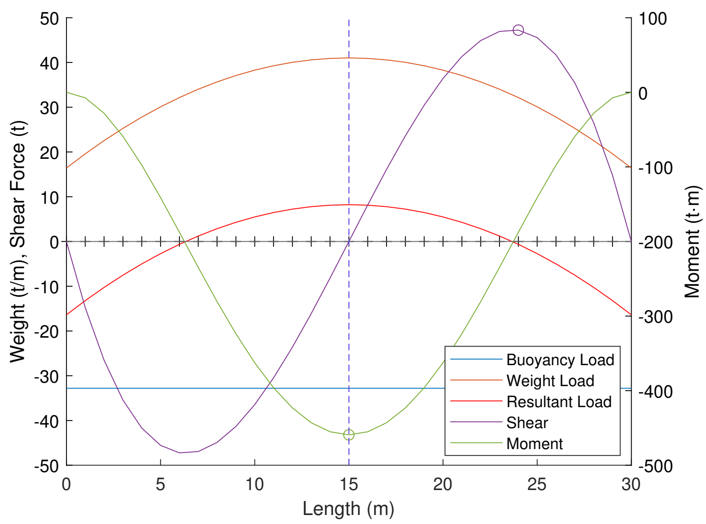



Table 1: Parabolic distributed shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 47.2 | 58.9 |
| $M_{max}$ (t.m) | 459.2 | 48.3 |

Figure 19: Parabolic distributed shear and bending moment results (n=10)

It can be seen that this approach produces a substantial deviation between the expected analytical results and the model results. While the general shape of both shear force and bending moment are similar, the results are significantly under predicted. As such, this method is only suitable for very early-stage design scenarios as it is easy to implement. However, for detailed evaluations, this method is clearly inadequate, as the loading cases are lumped within a parabolic distribution. Even with varying grid refinement, the corresponding fineness does not affect the shear force and bending moment results.

From the general still water shear and bending moment accuracy requirements, this method does not have the necessary precision to evaluate the case. The percent error for both shear and bending moment compared to the baseline results deviate 48.9% and 38.3% more than the established 10% limit.

### 4.3.2 Point-wise Grouping Method

The point-wise grouping method, as outlined in section (2.3.2), relies on combining load concentrations to form lumped representations of distributed weights within discretized regions. Additionally, these distributed loads can either be approximated as a single point load or multi-point load acting along the span of the distribution. Therefore, two small cases will be evaluated: a singular-point, and a multi-point load case.

**Single-point Grouping** First, the single-point load method will be analyzed. The corresponding case study results can be seen in figure (20), and a summary of the maximum shear and bending results can further be seen in the table (2). In this case, the shear and moments are significantly over predicted. The case's percent error is higher than even the parabolic approximation method, which is generally the first approach. The massive moment peak is due to the lack of load distribution in the analysis. Distributions help to reduce shear loading effects, but under point loading, buoyancy and hull loads continually act freely on the structure. This ultimately increases the local shear force area, which in turn increases the determined moment. As such, the percent error is consequently significant. Unfortunately, refining the discretized grouping regions does nothing to aid in the accuracy of single-point loading. Evidently, this causes an adverse effect as the applied loading's influence is further contracted. However, the discretization factor does aid in the alignment of the LCG and LCB. This allows for the end moment boundary condition to be also satisfied and produce a negligible end difference.

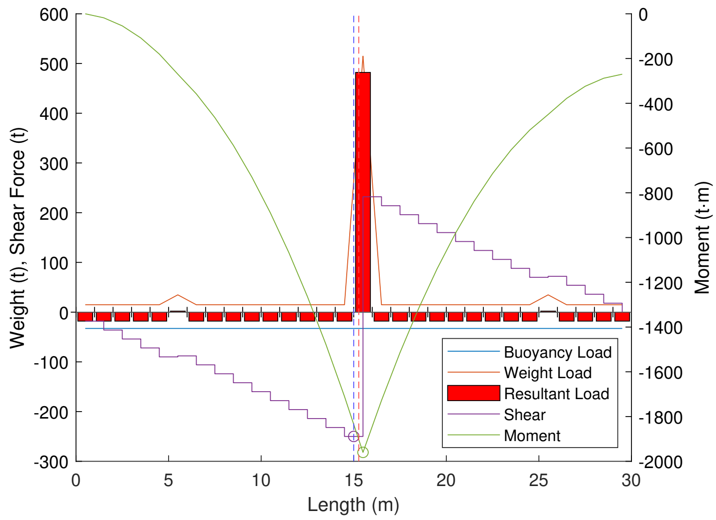



Figure 20: Single-point grouping shear and bending moment results (n=1)

Table 2: Single-point grouping shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 250.0 | 117.4 |
| $M_{max}$ (t.m) | 1960.0 | 120.8 |

**Multi-point Grouping** The multi-point group investigation analyzes the substitution of single-points with full distribution lengths. The corresponding case study results can be seen in figure (21), and a summary of the maximum shear and bending results can further be seen in the table (3). This loading application gives a much better representation of the shear and moment results. From the summary results, an error reduction of over 100% is obtained for maximum shear and bending moments. However, this can further be improved by refining the discretized grouping regions. Grid refinement naturally allows for a more accurate loading distribution, and subsequently reduces the percent error even further. Clearly, this technique meets the general 10% accuracy requirements established in section (2.1.3).

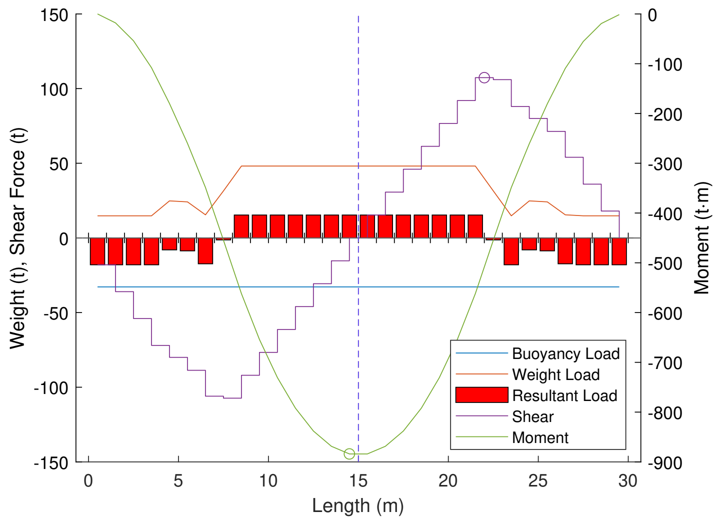



Figure 21: Multi-point grouping shear and bending moment results (n=1)

Table 3: Multi-point grouping shear and bending moment summary

| SWS&B | Results | Error (%) | $\Delta$ (%) |
|---|---|---|---|
| $S_{max}$ (t) | 107.3 | 6.7 | -110.7 |
| $M_{max}$ (t.m) | 883.7 | 0.4 | -120.4 |

### 4.3.3 Trapezoidal Direct Method

The trapezoidal direct method, as outlined in section (2.3.3), implements individual distributions as trapezoidal loads. This technique is generally considered the most accurate and most commonly performed; however, it requires the mass of every single item to be truly useful. Thus, this approach can take a considerable amount of time to implement it fully. The corresponding case study results can be seen in figure (22), and a summary of the maximum shear and bending results can further be seen in the table (4).

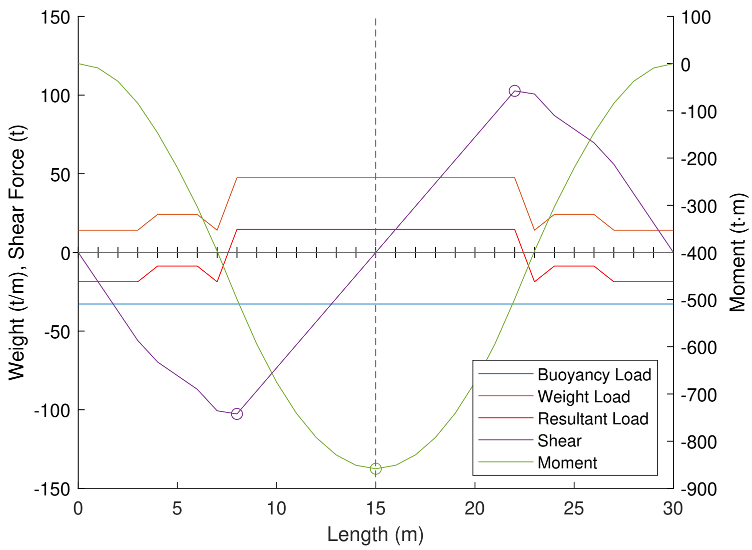



Figure 22: Trapezoidal distributed shear and bending moment results (n=5)

Table 4: Trapezoidal distributed shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 102.7 | 10.7 |
| $M_{max}$ (t.m) | 858.3 | 3.3 |

From the results, this technique does an excellent job of approximating the case study results. This technique can be even more accurate as the exact case can be replicated using a finer discretized grid. In general, this method's procedure is quite simple; however, care needs to be taken in the placement of the LCG. Too far from the midsection can result in a negative distribution, thus underestimating the applied loading. Based on the general requirements, this distribution technique replicates the weighs most closely. However, this is entirely dependent on the discretization factor, $n$, implemented. The smaller $n$, the longer the calculation but, the more accurate the results. It is known that this technique is applied in commercial naval architectural software such as MAXSURF; as such, the results were expected to be similar.

## 4.4 Small-scale Model Analysis Conclusions

Based on the results from the small-scale investigation, a few preliminary conclusions can be drawn. It can clearly be seen that the parabolic distribution technique does not meet the necessary accuracy requirements. While the ease of implementation, general output shape, and overall simplicity is a highly sought-after trait, the shear and bending moment results were not within the acceptable margins. As such, the parabolic method will not be further investigated. Both the grouping and trapezoidal methods performed very well. As expected, the trapezoidal direct method captured the necessary accuracy requirements as the error percentages proved negligible with higher levels of discretization. The grouping method also proved sufficient. However, it should be noted that this only applied to the case were the distribution lengths were correctly incorporated. When the loads were assumed as 100% point loads, the outputs were an extremely poor approximation of the case study results. Bearing this consequence in mind, the grouping method and trapezoidal methods are expected to obtain remarkably similar results if distribution lengths are considered. As such, both the trapezoidal and grouping methods will undergo up-scaling and will be further analyzed.

# 5 Large-scale Analysis

This section aims to thoroughly analyze a *Damen Yachting* vessel using the varying mass distribution techniques to provide a correct procedure to maximize time utilization in the basic engineering process. To achieve this objective, the study will provide an elaboration of the existing methods and the associated errors which may be present within the current study distribution techniques. Furthermore, using a modified local sensitivity approach, the overall research objective will be addressed with the mission of analytically comparing and evaluating the relative procedural time-savings per weight distribution. Finally, an additional case verification will be included to provide further insight into the study.

## 5.1 *Damen Yachting* YS7512 Case Study

*'With her quality hardware and perfect finish, the YS7512 is in the top class of luxury yachting. Within her beautiful exterior, this support yacht is packed with capability. Never run out of storage space with all the tenders, toys, submersibles, vehicles, surf, and dive gear you want – plus extensive below-deck stores for absolutely everything. With around 40 crew and staff, your team is capable of anything!'* [16]

The case investigation will primarily focus on the new Yacht Support, YS7512, issued by *Damen Yachting*. These vessels are purpose-built to support superyacht operations globally. The vessel exterior can be seen in figure (23).

Figure 23: Rendering of the *Damen Yachting, YS7512* yacht support vessel [16]

The general specifications of the YS7515 can be seen in table (5).

Table 5: YS7512 specifications

| | |
|---|---|
| Length overall | 75.00 metres (246 ft) |
| Beam overall (at hull) | 12.60 metres (41 ft) |
| Draught (full load) | 4.00 metres |
| Gross Tonnage | 1900 GT |
| Maximum speed | 18.0 knots |
| Range @ 15.0 knots | 5,000 nautical miles |
| Guests | 4 |
| Crew | 31 + Captain |
| Staff | 4 |

Since these vessels are primarily used for owner-support, the weight loading on such craft can vary drastically from conventional superyachts. Thus, this investigation will prove to provide an interesting and meaningful investigation.

### 5.1.1 MAXSURF Trapezoidal Direct

As stated in section (2.1.2), the general process consists of implementing commercial stability software MAXSURF to determine the longitudinal strengths in varying loading conditions. In this stage of the basic engineering, 1391 full weight inputs were used. The resulting still water shear and bending curves from the commercial software can be seen in figure (24). Seven different curves are ultimately given to the end-user, along with the maximum shear and bending moments (with locations). Overall, MAXSURF completes the longitudinal strength evaluations quickly; however, detailed output information such as individual item volumes, LCG's, and bounds are not externally provided as the solution is primarily a black-box solution.

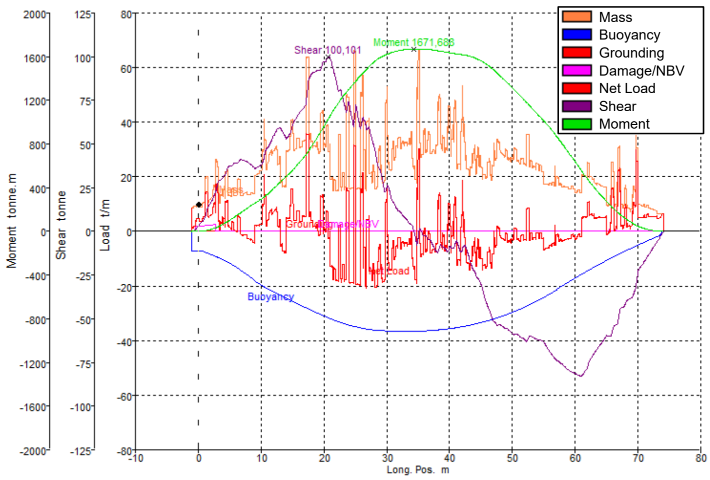



Figure 24: MAXSURF shear and bending moment output results

Since the investigation requires a detailed look into weight loading and weight locations, MATLAB was used to provide more control over the inputs. However, to provide a baseline comparison, MAXSURF weight, buoyancy, shear, and moment output data were extracted and imported within the working MATLAB file. The results of the MATLAB imported data can be seen summarized in figure (25). Based on the results, the data extraction/importing process's errors are negligible and can be used as a clear baseline comparison of the MATLAB trapezoidal direct and point-wise grouping distributions.

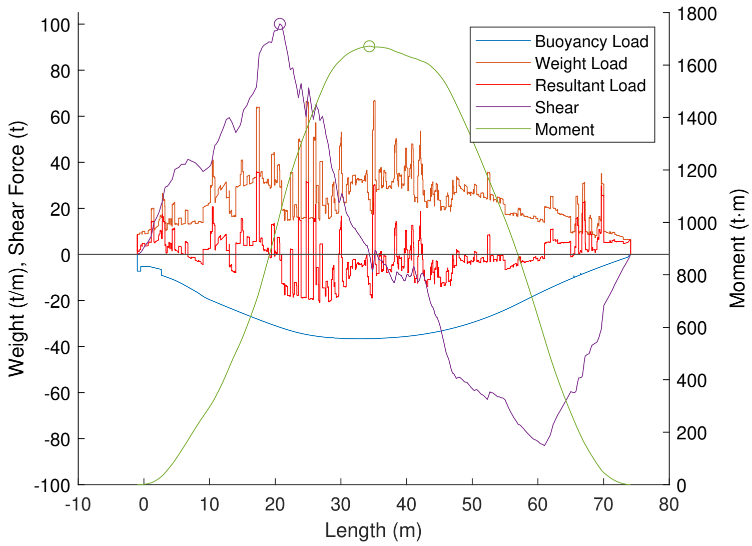



Table 6: MAXSURF to MATLAB shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 100.1 | 7.8e-5 |
| $M_{max}$ (t.m) | 1671.7 | 1.7e-4 |

Figure 25: MAXSURF to MATLAB imported shear and bending moment results

### 5.1.2 MATLAB Trapezoidal Direct

From section (2.3.3), the trapezoidal direct distribution technique was clearly outlined. This literature investigation shows that MAXSURF software incorporates the trapezoidal weight distribution technique within its longitudinal strength evaluations. As such, the MATLAB working model should prove to provide an extremely close representation of the output baseline results. Both the MAXSURF and MATLAB weight curve results can be seen in figures (26), and (27) respectively.

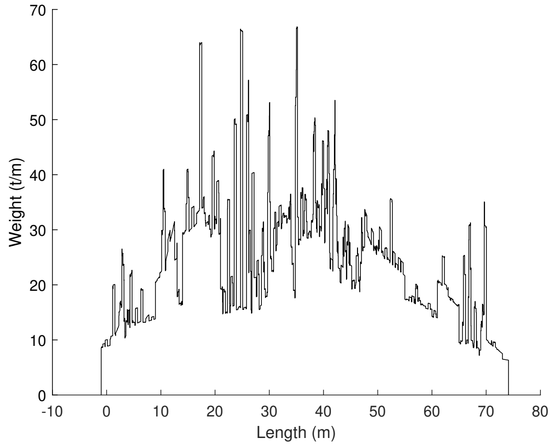



Figure 26: MAXSURF weight distribution

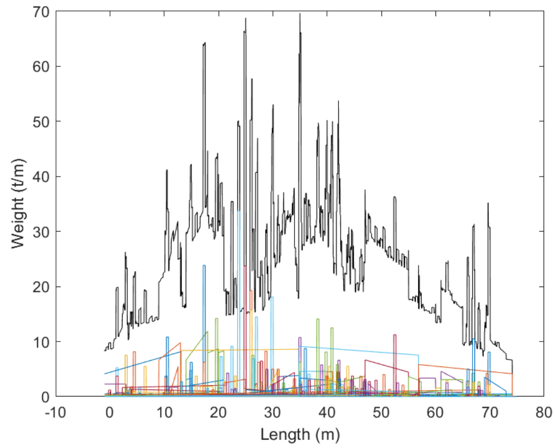



Figure 27: MATLAB trapezoidal weight distribution

As expected, both weight distributions follow an extremely similar shape. An added benefit to the MATLAB technique is a thorough understanding of why the shape of the curve is as it is. This can directly be seen in the figure, where each trapezoidal weight distribution is plotted. This representation proves that the influence of the weights varies greatly depending on the associated weight and the distributed lengths. While the approximations between the two are quite close, some errors do exist with the MATLAB model. The main errors, discretization and irregular geometries, can be seen in figures (28), and (29) respectively.

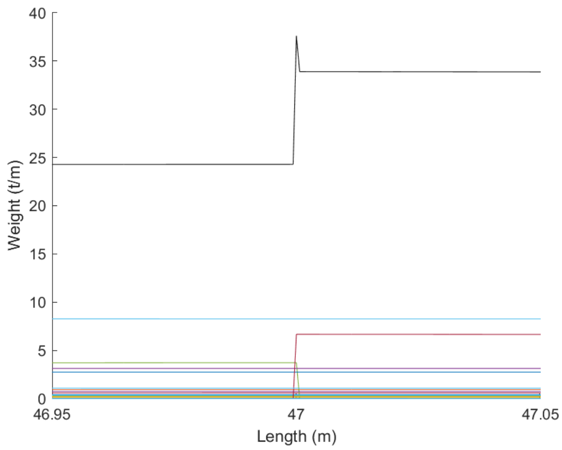



Figure 28: Trapezoidal discretization error

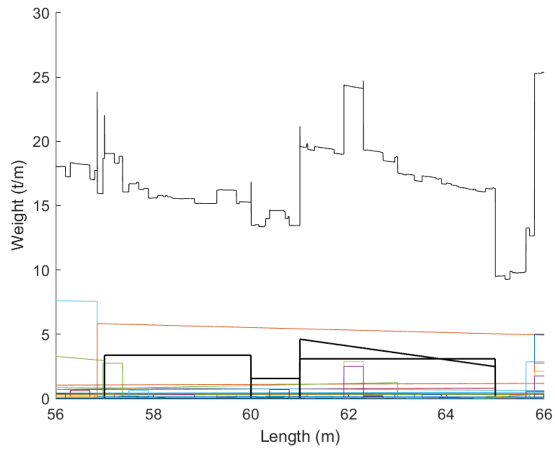



Figure 29: Trapezoidal irregular geometry error

Discretization errors are due to the process of decomposing the model into smaller segments. Unfortunately, this artificially creates added mass due to numerically overlapping weights. As such, slivers of added weight are introduced to the system. The smaller the discretization factor, the less the added effect; however, these added masses have the potential to add non-existent mass, which shifts the LCG of the loading. This combined effect ultimately adds an artificial trimming moment within the numerical model. The secondary error is linked directly to an internal MAXSURF process. When irregular geometries, such as tanks lined along a hull, are created within the software, these intricate shapes are decomposed into multiple linked geometries. If caution is not taken, a singular trapezoidal may be considered instead of small independent ones, which can significantly change the loading distribution's overall shape. The difficulty in this process is that MAXSURF does not explicitly give modified shape locations and size.

When considering a sufficiently small discretization factor, $n = 1500$, and each irregular object is carefully decomposed into the appropriate geometries and locations; the trapezoidal distributed results can be compared to that of the MAXSURF output results in figure (30). Ultimately, the MATLAB trapezoidal direct distribution method proves to replicate the baseline case accurately. However, discretization is a dominating characteristic in the technique.

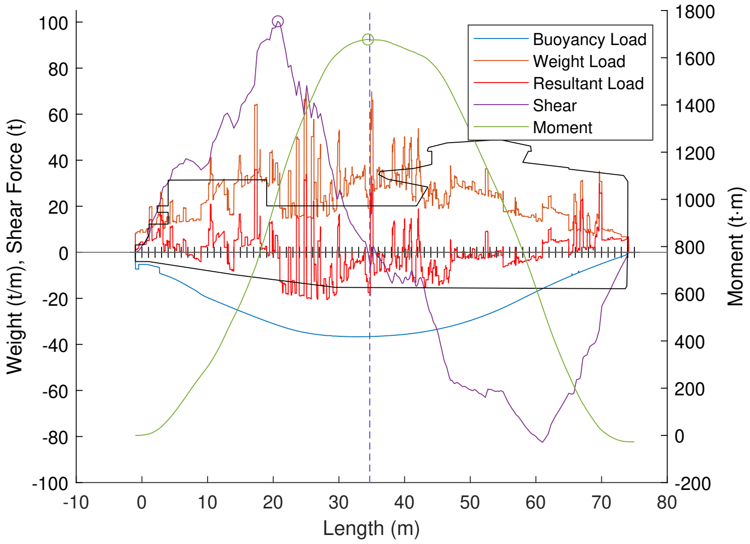



Figure 30: Trapezoidal distributed shear and bending moment results (n=1500)

Table 7: Trapezoidal distributed shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 100.32 | 0.22 |
| $M_{max}$ (t.m) | 1677.50 | 0.35 |

### 5.1.3 MATLAB Point-wise Grouping

The point-wise grouping distribution can transform distributive loads into individual point loads and group each within established edge boundaries. As seen in section (4.3), both single-point loading and distributive loading cases were analyzed. It was ultimately determined that the individual single-point groupings were not a good representative of the small-scale case study results. As such, it is expected that a similar situation will occur in the event of the large-scale assessment. Evidently, the results can be seen in figure (31) to confirm the expected results. The single-point grouping and shear results are extremely poor approximations of the baseline as weight influence is both a factor of the load amount and the distribution lengths. Therefore, a clear conclusion can be provided to the third research question,

*'Can distributed loads be fully represented by concentrated point loads occurring at each weight's center of gravity?'*

No. Based on a thorough small-scale and large-scale investigation, when single-point loads are applied, both shear and moment curves are no longer a valid approximation. However, when using the correct distributions lengths, the multi-point grouping becomes a substantially better approximation for both shear and moment results. The full multi-point grouping results can be seen in figure (32) for a bin discretization size of $n = 2$. Unfortunately, when this strategy is applied not much difference is introduced between the trapezoidal direct and multi-point grouping methods.

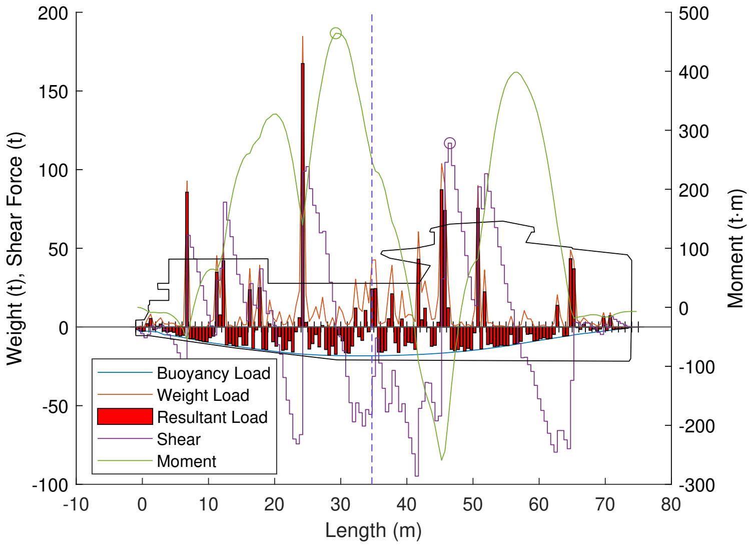



Figure 31: Single-point grouping shear and bending moment results (n=2)

Table 8: Single-point grouping shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 116.70 | 16.70 |
| $M_{max}$ (t.m) | 464.49 | 72.21 |

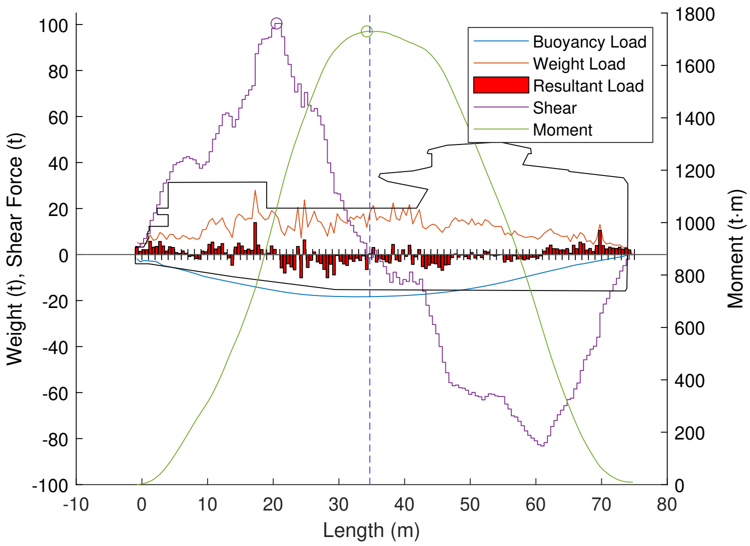



Figure 32: Multi-point grouping shear and bending moment results (n=2)

Table 9: Multi-point grouping shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 100.48 | 0.38 |
| $M_{max}$ (t.m) | 1730.0 | 3.49 |

While the grouping technique's results and the general procedure is highly comparable to the trapezoidal direct method, a few hidden advantages exist. This technique offers vast control over the loading parameters and how those loadings are implemented. The method can easily switch between distributed and non-distributed loadings without the need for significant discretization factors. This makes the script more efficient when applying concentrated loads. Another advantage of the grouping distribution is the capability to control the bounding edges of each bin. This control means that discretization is not required to incorporate each associated weight input fully. Ultimately, eliminating any discretization errors implemented within the system. This grouping capability also allows for further understanding of the effect of lengthwise weight grouping simplifications. As seen in figure (33), the load grouping bins can be reduced to a high degree while still retaining a reasonably high level of detail in the resulting shear and bending curves.

In general, the study approach relies on similar item weight groupings (JDOC) with each associated distribution

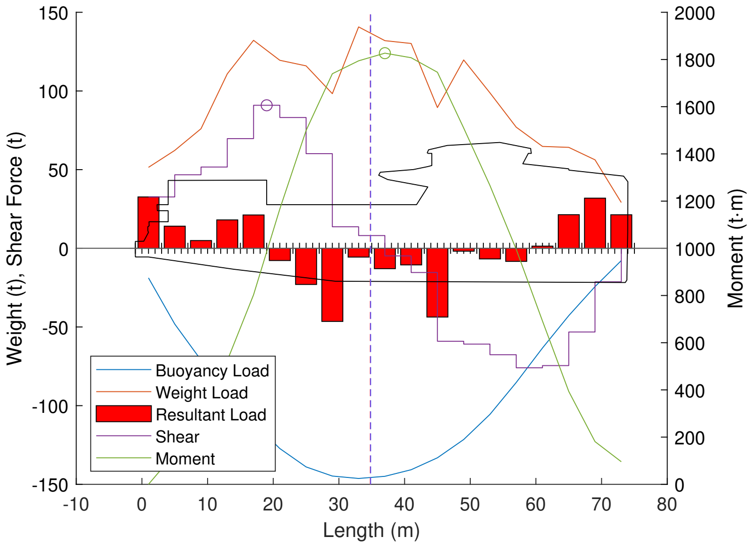



Figure 33: Multi-point grouping shear and bending moment results (n=1/4)

Table 10: Multi-point grouping shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 90.90 | 9.20 |
| $M_{max}$ (t.m) | 1826.8 | 9.28 |

length known. However, this does not mean it is the only way to analyze the loading. Another suggestion is through individual accommodation weight groupings. Accommodation lengths are known, and items within each room can easily be determined and sorted. Once understood, the general effects of accommodation mass can be categorized and grouped along with varying distributed lengths. With small script modifications, the point-wise grouping technique offers the versatility to apply non-equal bin edges, potentially allowing for a more controlled alternative study.

### 5.1.4 Direct Comparison

Upon detailed investigations for both the small-scale and large-scale results, each distribution technique can be directly compared. Based on this comparison a clear conclusion can be provided to the fourth research question,

*'How does various distribution techniques contribute to the accuracy of still-water longitudinal strength output parameters?'*

The direct comparison curves and results of each distribution technique can be seen in figure (34) and table (11 respectively. The trapezoidal distribution is the most accurate as each weight is independently applied with a distribution capable of shifting the location of it's LCG. It was expected that this technique is the most accurate as it incorporates no general simplifications.

Alternatively, the grouping technique decomposes each distribution into a series of concentrated loads. These loads are then accumulated and summed within segmented bins. Depending on the bin size, the results and accuracy vary. It can be seen that the moment distribution is slightly over predicted. This overestimation is a direct contribution of the shear curve. While the line generally follows a similar trend, the curve is composed of step intervals. These steps contain edges which continually add and subtract associated area. However, in this case, too much area is included. Thus, the related integration results in an over prediction of the bending moment curves. This amount attributes 3% error as compared to the trapezoidal distribution at 0.2% error.

It should be noted that the parabolic distribution is included in the direct comparison figure. This technique was previously dismissed as not sufficiently accurate, which is further proven in the following results. Ultimately, the trapezoidal method is the clear front runner. While the grouping technique offers potential for a higher degree of versatility and control, the accuracy of the resulting curves is lower. Therefore, for commercial applications, the trapezoidal is suggested. For research and investigative studies, the grouping distribution technique is the preferred option.

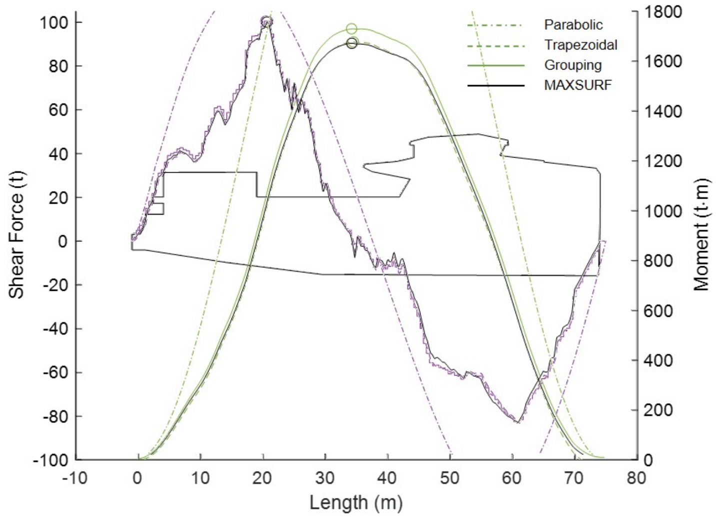



Figure 34: MAXSURF, Trapezoidal, Grouping, and Parabolic direct comparison

Table 11: Direct compare shear and bending moment summary

| SWS&B | $S_{error}$ (%) | $M_{error}$ (%) |
|---|---|---|
| MAXSURF | 7.8e-5 | 1.4e-4 |
| Parabolic | 16.38 | 67.37 |
| Grouping | 0.38 | 3.49 |
| Trapezoidal | 0.22 | 0.35 |

## 5.2 Sensitivity Investigation, Evaluation, and Comparison

To answer the fifth and final research question,

*'At which point (if any), can the loads be mixed between distributed loads and concentrated point loads to obtain similar longitudinal strength output parameters?'*

A sensitivity investigation is required. This investigation involves a modified local sensitivity approach. Section (2.4), outlines the general theoretical workflow processes involving both local and global studies. However, since the objective is of a discrete and finite nature, point-load or distribution, a local approach is more suitable. It should be noted that the global strategy would also answer this question; however, the additional information gain in proportion to the increased computational demand was deemed not suitable. The traditional local sensitivity approach generally relies on the determination of derivative influence metrics. However, since a clear output is sought, relative errors between baseline and current longitudinal strength parameters per associated weight input will be extracted with hopes in understanding the general influence of weight parameters on the shear and bending moment results. The overall sensitivity procedure can be seen as outlined in figure (35).

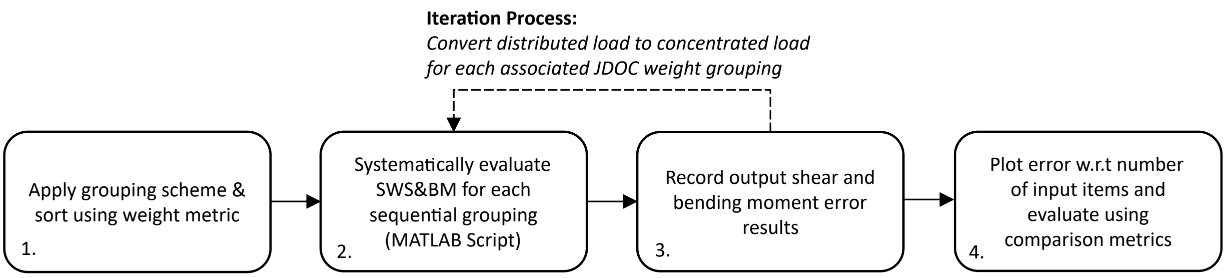



Figure 35: Sensitivity process breakdown

Each critical step can be detailed as follows,

1. First, four weight grouping schemes will be evaluated: Non-grouping, JDOC, Lumped JDOC (LJDOC), Double Lumped JDOC ($L^2$JDOC). These groupings are merely individual weights grouped (lumped) within

*Damen Yachting's* company breakdown structure. These groupings will provide additional insight into the influence of individual weights as compared with grouped ones.

2. Using a general MATLAB iterative approach, each grouping will be sequentially converted from full distributions to individual point loads. In other words, the total number of inputs per weight item will be reduced from a total of 6 inputs per item to 4 inputs per item. This reduction is due to the elimination of the fore and aft distribution length limits to produce single-point loads.

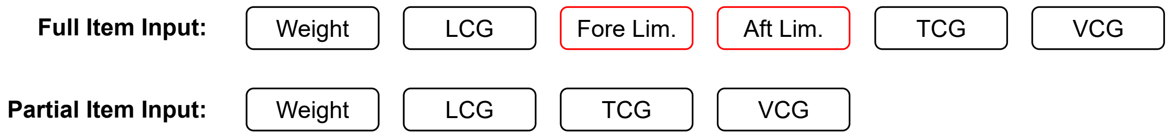



Figure 36: Full distribution to point-load input conversion

3. After each item conversion, the relative longitudinal strength shear and bending moment results are recorded. Once recorded, the next iteration of the procedure begins. This process sequentially follows from the heaviest to the lightest weight item group.

4. Once all results are obtained, a definite figure highlighting the error relations per weight item will be collected and evaluated with respect to the general margin requirements for this phase focus of basic engineering. Additionally, a critical 'elbow point' comparative study will be introduced to transfer learnings to future projects.

For each analysis case, both the trapezoidal and grouping distribution techniques will be implemented. The trapezoidal method will approximate concentrated loads with narrow weight distributions. The distribution lengths for this model will apply a scaling factor of $n = 5e^{-3}$. This factor was deemed sufficiently small since the total length contribution of 70m would be reduced to a mere 0.35m. Any smaller and the applied discretization factors would need to substantially increase to accurately capture the loading. The grouping model, due to the nature of the model, could simply introduced direct point loads without any consequence. This secondary evaluation comparison will provide an independent sensitivity verification of the corresponding output results. Since both techniques perform similarly, it can be expected that each result will show comparable trends. If this is not that case, a likely mistake within the models themselves exists.

### 5.2.1 Comparison Metrics

To ensure each grouping scheme is evaluated and compared consistently, additional study metrics are applied.

**Weight Ranking Metric** The investigation will organize each grouping based on a maximum weight metric, i.e. groups will be sorted from maximum to minimum. By incorporating this ranking metric, a consistent analysis can be accomplished throughout each sensitivity study. The weight groupings can thus be presented through a pie representation, as seen in figure (37).

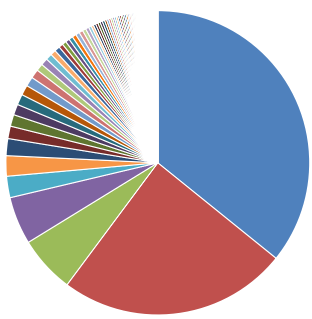


Figure 37: Sorted JDOC weight breakdown

This representation allows for a relatively straightforward and consistent iteration sensitivity procedure, where groups are sequentially converted from distributions to concentrated loads.

**Triangle Threshold Elbow Point** The study evaluates and compares the determined error with that of error margins established in the general requirements. However, to determine this relative difference, the baseline with all weight input results are required. Therefore, the relative errors between the error margins in new vessels can never be determined until all loads and lengths are incorporated. This poses difficulty as any key learnings are non-transferable. As such, an additional comparative metric will be implemented. This tool will allow for a definite point in the design space in which the accuracy margins and time-savings can be confidently achieved.

To determine this point, the only data information required is sorted item weights. By having the loads ranked, a clear cumulative weight distribution per number of input parameters can be determined. At one specific point, the associated differences between each mass input will provide negligible cumulative changes to the weight curve. Therefore, a kink, or elbow at a particular input region will exist. The more significant the disparity between item count and input weight, the more prominent this transition point becomes. This elbow does not require any additional information besides the associated weight inputs and thus is not dependent on the full longitudinal strength input parameter seen in figure (36).

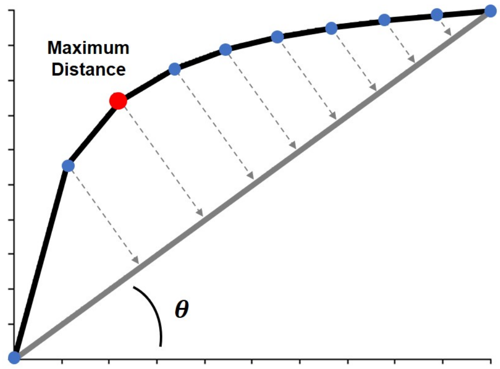



Figure 38: Triangle threshold general process [10]

This metric can be determined using a triangle threshold technique, which can be seen as outlined in figure (38). Theoretically, the elbow threshold point is the parameter which experiences the maximum distance perpendicular to a linear line connecting the first and last points. Using simple geometric relations associated with the angle of inclination, $\theta$, each perpendicular distance can be determined and evaluated for each associated point. Once all perpendicular distances are determined, the elbow point is associated with the largest absolute length.

**Time Baseline** The final research question's focus is the point at which mixed concentrated and distributed loading replicates a full distributed loading case. However, the main research objective is to evaluate the potential time-savings associated with decreased input amounts. For this to occur, a clear metric able to compare relative time-savings is required. To create this comparative baseline, an independent self-time study was conducted.

Over the course of 8 hours (1 working day), individual weight items were fully inputted using the current *Damen Yachting* procedure. As previously outlined in section (2.1.2) and seen in figure (36), there are a total of six inputs per item that are necessary to successfully evaluate the complete longitudinal strength; Weight, LCG, Fore Limit, Aft Limit, TCG, and VCG. Over the course of the day, 267 items were successfully inputted. It should be noted that the 8-hour period included slack time such as coffee, bathroom, lunch (30 min) breaks, and any additional time delays. Based on this time evaluation it can be determined,

$$\frac{8 \text{ hours}}{267 \text{ items} \cdot \frac{6 \text{ inputs}}{1 \text{ items}}} = \frac{0.005 \text{ hours}}{1 \text{ input}} = \frac{0.3 \text{ minutes}}{1 \text{ input}}$$

Therefore, using this time evaluation metric, and the number of items associated to the basic engineering phase (1391 items), the total time baseline can be determined as,

$$T_{total} = 1391 \text{ items} \cdot \frac{6 \text{ inputs}}{1 \text{ items}} \cdot \frac{0.3 \text{ minutes}}{1 \text{ input}} = 2504 \text{ minutes } (41.73 \text{ hours})$$

Therefore, the total time required to enter the 1391 items is slightly longer than one standard 40-hour working week. It should be noted that this time metric provides a general comparative basis for relative change. Thus, even though this parameter can be subject to change, the corresponding relative time change remains consistent.

### 5.2.2 Sensitivity Analysis

Using the outlined sensitivity procedure and established comparative metrics, the full sensitivity analysis can be conducted. The full case results for L$^2$JDOC, LJDOC, JDOC, and non-grouping (Individual) can be seen in sections (5.2.3), (5.2.4), (5.2.5), and (5.2.6) respectively. Additionally, all sensitivity output results for each case can be seen summarized in the table (12). Since the vessel is below 80 meters, the general accuracy requirements of 10% error margins will be implemented.

Table 12: YS7512 sensitivity results summary

| Method [1] | % Mass | %E Shear | %E Mom. | Full Input [2] | Time (hrs) | Partial Input [3] | Time (hrs) | Total (hrs) | % Time Reduction |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **L$^2$JDOC** | | | | |
| G - Exact | 98.93 | 5.0 | 4.9 | 1384 | 41.52 | 7 | 0.14 | 41.66 | 0.17 |
| T - Exact | 98.93 | 4.8 | 7.8 | 1384 | 41.52 | 7 | 0.14 | 41.66 | 0.17 |
| G - Elbow | 76.74 | 9.0 | 14.3 | 221 | 6.63 | 1170 | 23.40 | 30.03 | 28.04 |
| T - Elbow | 76.74 | 9.1 | 17.5 | 221 | 6.63 | 1170 | 23.40 | 30.03 | 28.04 |
| | | | | | **LJDOC** | | | | |
| G - Exact | 84.56 | 4.7 | 6.0 | 821 | 24.63 | 570 | 11.40 | 36.03 | 13.66 |
| T - Exact | 84.56 | 5.7 | 9.2 | 821 | 24.63 | 570 | 11.40 | 36.03 | 13.66 |
| G - Elbow | 76.5 | 19.8 | 27.6 | 116 | 3.48 | 1275 | 25.50 | 28.98 | 30.55 |
| T - Elbow | 76.5 | 19.8 | 30.9 | 116 | 3.48 | 1275 | 25.50 | 28.98 | 30.55 |
| | | | | | **JDOC** | | | | |
| G - Exact | 77.55 | 6.8 | 9.5 | 101 | 3.03 | 1290 | 25.80 | 28.83 | 30.91 |
| T - Exact | 78.88 | 4 | 8.2 | 103 | 3.09 | 1288 | 25.76 | 28.85 | 30.87 |
| G - Elbow | 89.65 | 0.3 | 3.2 | 167 | 5.01 | 1224 | 24.48 | 29.49 | 29.33 |
| T - Elbow | 89.65 | 0.02 | 0.1 | 167 | 5.01 | 1224 | 24.48 | 29.49 | 29.33 |
| | | | | | **Individual** | | | | |
| G - Exact | 64.98 | 7.3 | 7.4 | 27 | 0.81 | 1364 | 27.28 | 28.09 | 32.69 |
| T - Exact | 76.68 | 5.1 | 7.7 | 48 | 1.44 | 1343 | 26.86 | 28.30 | 32.18 |
| G - Elbow | 93.07 | 0.03 | 2.7 | 144 | 4.32 | 1247 | 24.94 | 29.26 | 29.88 |
| T - Elbow | 93.07 | 0.8 | 1.2 | 144 | 4.32 | 1247 | 24.94 | 29.26 | 29.88 |

From the results a few clear observations and conclusions can be drawn to ultimately answer the third and final research question driving the study,

1. **Weight vs. Items**

   From each analysis, a figure presenting item count per weight grouping is presented. From this additional pie representation, it can be concluded that the associated number of input items does not correlate to the weight contributions. In other words, the most substantial objects usually only make up a small portion of the inputs. This effect can be seen highlighted in section (5.2.3), where the largest weight grouping makes up 67% of the total weight. However, the number of inputs only makes up 14% of the total number of items (195/1391). Based on this observation, the disproportionality between the significant influencing weights versus the total number of items is highly skewed. As such, it is expected that at least a small portion of

[1] G & T are short for Grouping and Trapezoidal respectively
[2] Full Input relates to the amount of items leading up to the threshold point requiring all input parameters
[3] Partial Input relates to the amount of items after the threshold point requiring only the partial input parameters

items will bear negligible influence as compared to the associated weight distributions.

From table (12), this effect is quite clear. The *full inputs* column relates to the number of items that must be fully implemented. In comparison, the *partial inputs* relate to the items with reduced inputs, which essentially determines the associated time-savings. The summation of full and partial input items makes up the total number of items. Each sensitivity study case allows for a relative time-reduction. However, the magnitude of this time reduction varies quite drastically depending on the grouping scheme applied. Evidently, the full number of inputs reduces as the mass groupings become less collected. It should be noted that the degree of reduction varies throughout the process. Ultimately, this factor is highly dependent on which distribution model is implemented, what accuracy requirements are applied, and which comparison metric is used.

2. **Point-wise Grouping vs. Trapezoidal Direct**

   Both the grouping and trapezoidal distribution models were implemented in the sensitivity study. It was previously determined that both models, when considering the full distributions, behave very similarly in terms of overall shear and bending moment curve shapes and accuracy. As such, using both models allow for an additional model verification study in each case.

   From the results, each distribution technique had nearly identical shapes and outputs. The primary deviations are a direct consequence of the shear and bending moment error calculations. While both are generally close to one another, in the preliminary case study comparison, the grouping technique caused a slight overprediction of the bending moment results due to the shear force curve's step-like nature. While these deviations do occur, they are quite small, and the overall shape and trends of each resultant error plot show close similarities. Additionally, depending on the item grouping, the associated error concerning the number of full inputs is highly dependent on the general requirements criteria of 10%. In the coarsest item grouping scheme, the error margins are well above the margin limit throughout most weight groupings for both distribution techniques. This result ultimately leads to a small reduction in time-savings. However, when applying no item groupings, both distributions consist of results well below the accuracy margin. As such, it can be further verified that both models capture the shear and bending sufficiently.

   It should be noted that the degree of discretization for each model was selected, such that the concentrated load conversions were fully captured in each model. This high degree of discretization for each case required substantial computational resources. This effect resulted in long simulation times, particularly for the individual non-grouped case (section (5.2.6)). A complete sensitivity for both trapezoidal and grouping had an associated simulation time of 5 hours, 19 minutes and 34 hours, 15 minutes. The grouping simulation time was substantially higher than the trapezoidal and thus extremely inefficient. For future simulations, it might be beneficial to implement an additional model study to evaluate the effects of discretization on each technique to understand each method's computational capabilities and limitations.

3. **JDOC Item Groupings vs Individual Items**

   Previous observations clearly outlined that a disparity between the number of items and the weight influence varies throughout each case. Ultimately, this effect is entirely due to the implementation of groupings. The coarser the cluster, the least relative time reduction is present. Whereas, when no grouping is implemented, the largest time-savings can be found. This result is due to the nature of the group. Since the comparison metric is entirely weight-based, it would make sense that item grouping is not the correct approach. Within each of these weight collections are individual items, each with their own influence. As such, assuming groups of items behave the same as a single item is clearly not possible. The larger the group, the more likely items with significant influence will be lumped together. As such, when analyzing the individual item influence, the potential of finding the true resultant time-savings becomes likely.

   From the results, while adhering to the general 10% accuracy requirements, a maximum of 32.69% time-savings can potentially be acquired. This is a substantial portion of time that can now be utilized freely in other engineering areas. Due to the slight error changes between models, full item cut-offs vary slightly. In the grouping method distribution, only 27 full inputs, as opposed to the trapezoidal direct 48 inputs, are required to meet the accuracy limits. While this does vary, both cases produce equally high relative time savings, and the deviation is a mere 0.51%.

Additionally, the deviation between the JDOC grouping and the individual groupings are 1.78%. While this relative savings are small, the adverse effects of the grouping methodology are quite clear. As such, item grouping should not be used as a metric to simplify weight item inputs.

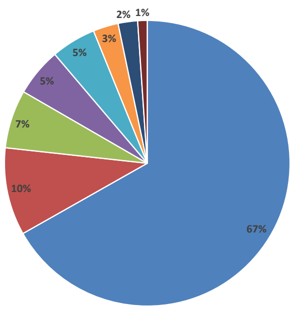
4. **Elbow Point vs Margin Point**

   The results clearly show that a substantial time reduction can be achieved as only a few items are influential when evaluating longitudinal strength. However, this study evaluates weight information already obtained; therefore, all results are in hindsight. This revelation means that the learnings are only useful for what *could* have been done, not what *should* be done. As such, a tool/technique capable of determining the approximate number of influential weight items is highly sought after. As outlined in section (5.2.1), the triangle threshold elbow point is considered. As previously described, this metric will allow for clear indication when the influencing weight has successfully been inputted without the reliance of complete item inputs.

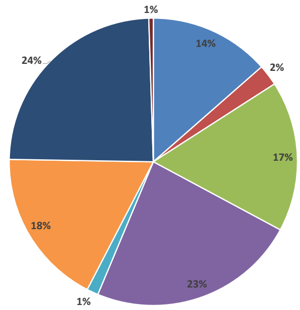
   From the individual plotted results, a definite 'elbow' point can be seen. This point relates to a position where the relative error changes begin to plateau. For the coarse grouping studies, the associated errors do not meet the accuracy requirements as such are not appropriate to be evaluated. However, when only the JDOC and non-grouping cases are considered, it does an admiral job of evaluating the positions. Unfortunately, the technique slightly overpredicts the necessary amount of item inputs by a factor of $\sim 2-4$, depending on the case. However, this only corresponds to an associated time deviation of 2.81%. As such, while solely relying on weight information, this technique is a slightly conservative approach with lower error margins. It also has significant time reductions comparable to the completed study cases.

### 5.2.3 L$^2$JDOC

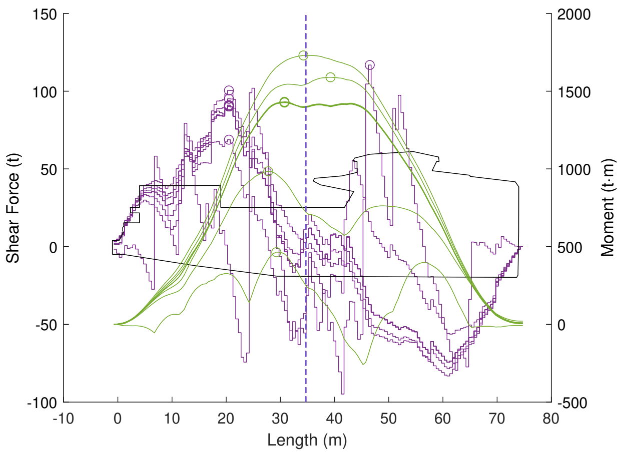
This section outlines the sensitivity results for the double lumped JDOC item grouping. Figure (39) contains both weight and count percent representations as well as the sensitivity iteration results for both point-wise grouping and trapezoidal distribution techniques.



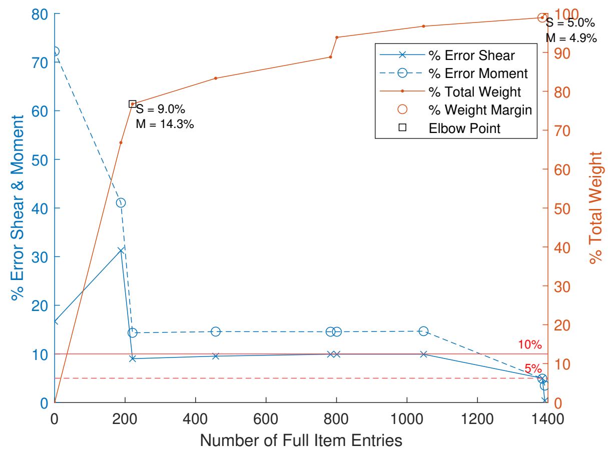

(a) Item Weight Breakdown (8 Groups)



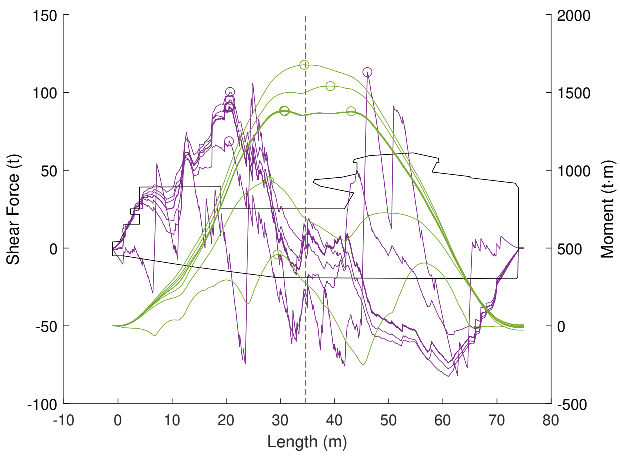

(b) Item Count Breakdown (1391 items)



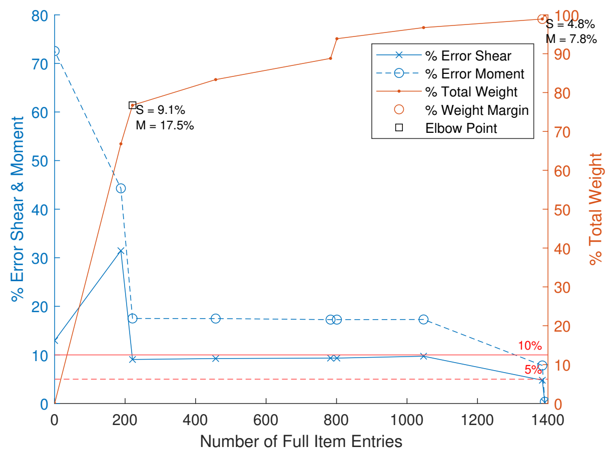

(c) Grouping Shear and Bending (n=2)




(d) Grouping Resultant Error




(e) Trapezoidal Shear and Bending (n=1500)

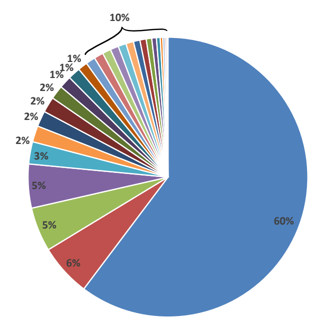



(f) Trapezoidal Resultant Error

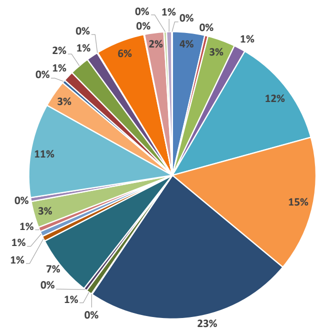
Figure 39: L$^2$JDOC sensitivity analysis (YS7512)

### 5.2.4 LJDOC

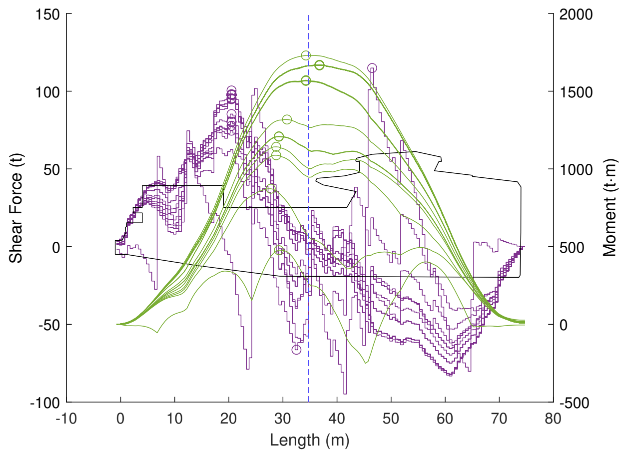
This section outlines the sensitivity results for the lumped JDOC item grouping. Figure (40) contains both weight and count percent representations as well as the sensitivity iteration results for both point-wise grouping and trapezoidal distribution techniques.



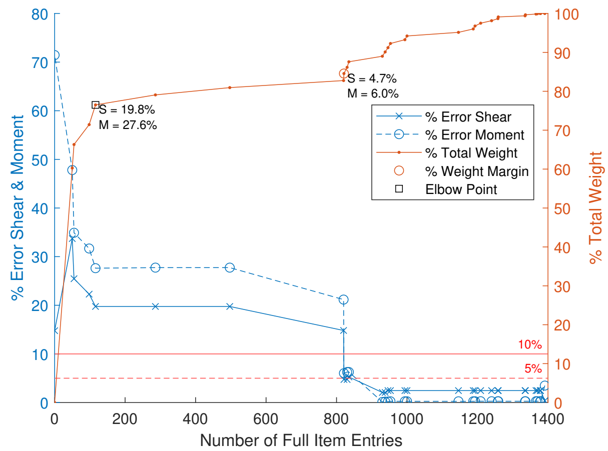

(a) Item Weight Breakdown(30 Groups)



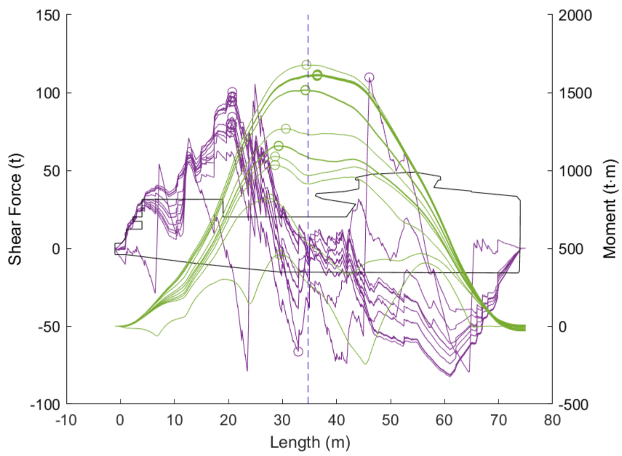

(b) Item Count Breakdown (1391 items)



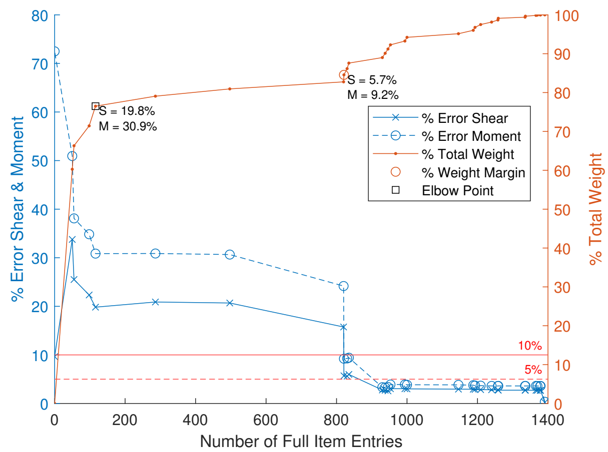

(c) Grouping Shear and Bending (n=2)




(d) Grouping Resultant Error




(e) Trapezoidal Shear and Bending (n=1500)

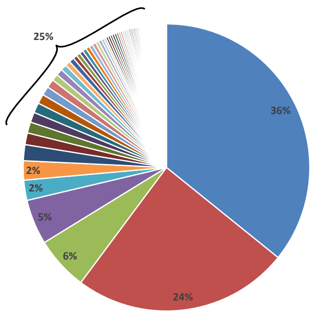



(f) Trapezoidal Resultant Error

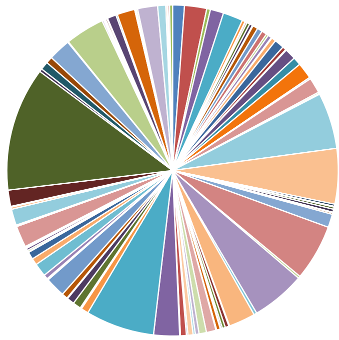
Figure 40: LJDOC sensitivity analysis (YS7512)

### 5.2.5 JDOC

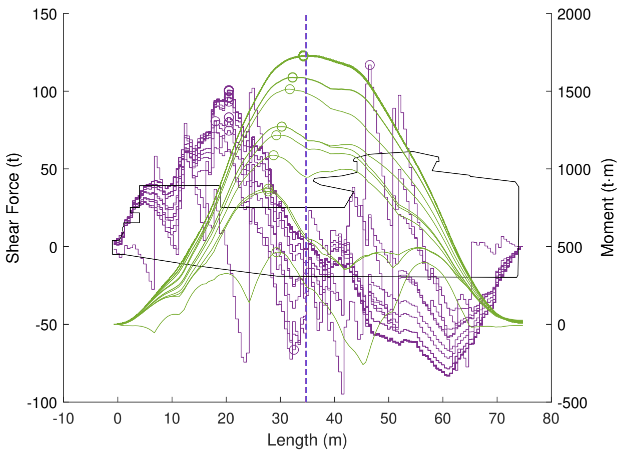
This section outlines the sensitivity results for the traditional JDOC item grouping. Figure (41) contains both weight and count percent representations as well as the sensitivity iteration results for both point-wise grouping and trapezoidal distribution techniques.



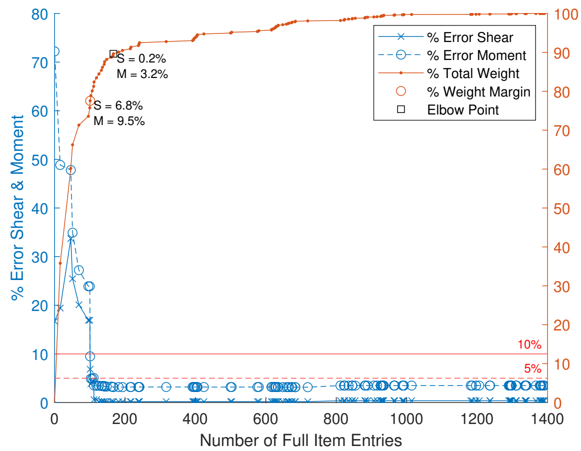

(a) Item Weight Breakdown (113 groups)



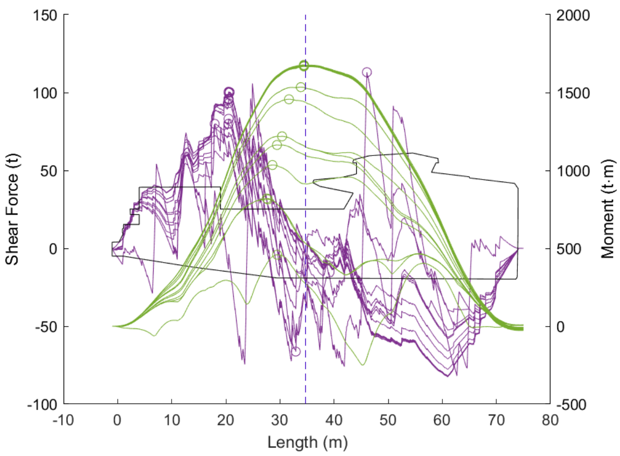
(b) Item Count Breakdown (1391 items)



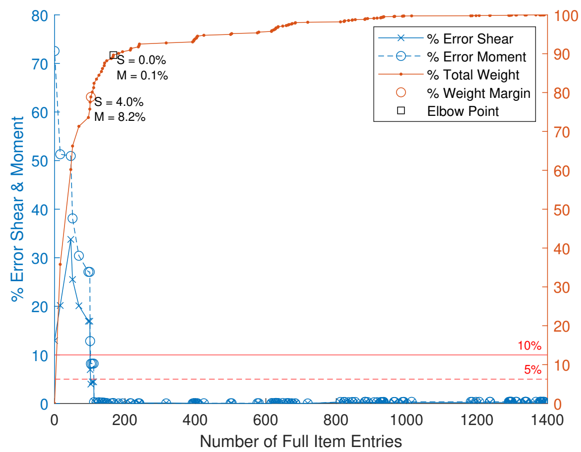

(c) Grouping Shear and Bending (n=2)




(d) Grouping Resultant Error




(e) Trapezoidal Shear and Bending (n=1500)

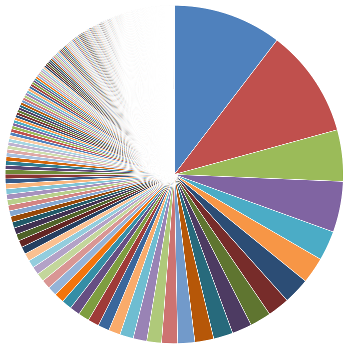



(f) Trapezoidal Resultant Error

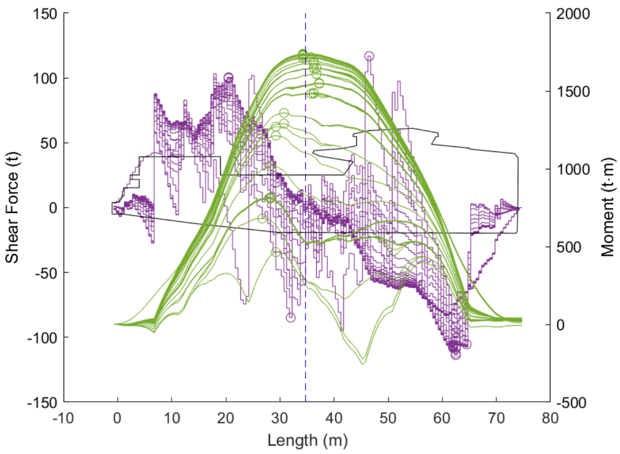
Figure 41: JDOC sensitivity analysis (YS7512)

### 5.2.6 Individual

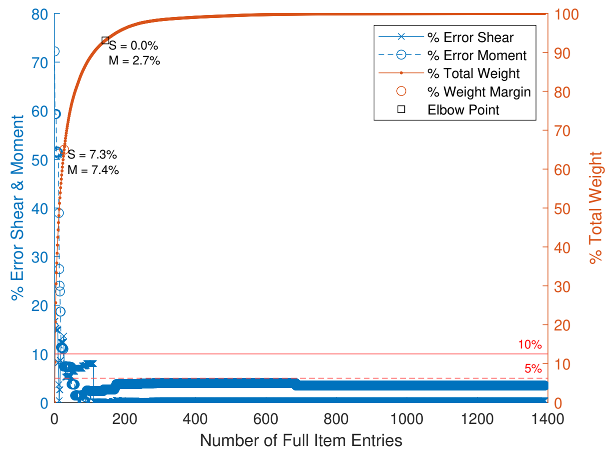
This section outlines the sensitivity results for the non-grouped individual weight items. Figure (42) contains a singular weight representation as well as the sensitivity iteration results for both point-wise grouping and trapezoidal distribution techniques.



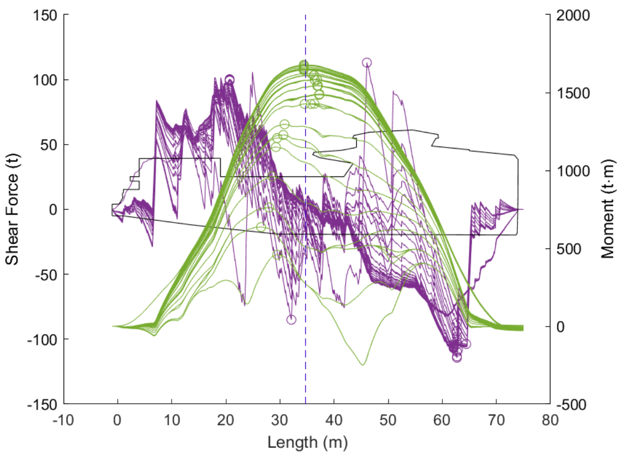
(a) Item Weight Breakdown (1391 items)



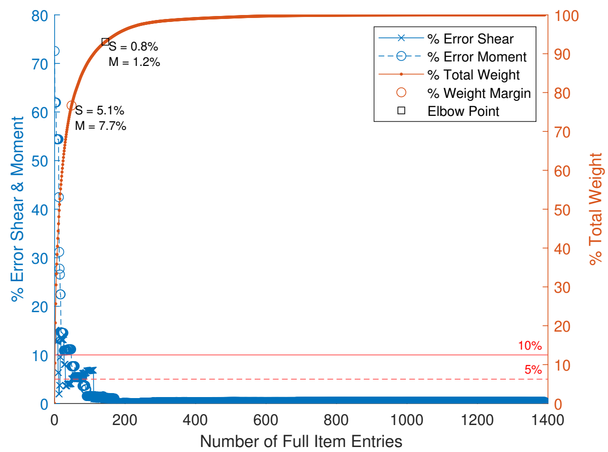

(b) Grouping Shear and Bending (n=2)




(c) Grouping Resultant Error




(d) Trapezoidal Shear and Bending (n=1500)




(e) Trapezoidal Resultant Error

Figure 42: Individual item sensitivity analysis (YS7512)

## 5.3 Additional Case Verification

While the sensitivity results have been favourable, this is only considered as a single data point solution. As such, drawing conclusions is difficult due to the lack of evidence suggesting this methodology can be repeated for different vessels. Therefore, two additional cases will be analyzed to provide supporting verification. This study will follow the same procedure outlined in section (5). First, a description of the test vessel will be outlined. This will be followed by a brief results analysis consisting of both MAXSURF to MATLAB results as well as MATLAB trapezoidal results. Next, a full sensitivity will be done with the corresponding comparison metrics previously outlined. This will ultimately lead to a full sensitivity results breakdown.

It should be noted that only the trapezoidal direct distribution technique will be used to evaluate the case. As previously concluded, the grouping distribution was used only as a secondary model verification tool to assess whether any potential modelling errors occurred internally. The previous sensitivity study showed that both models provided sufficiently similar results, thus providing further verification of each model.

### 5.3.1 *AMELS* LE242 Case Study

The first case investigation will focus on the popular limited edition 242 vessel, issued by *Damen Yachting* brand *AMELS*. The Limited Editions range of superyachts offers a proven technology platform with custom interiors. This innovative business model of upfront investment in engineering and construction, while maximizing customization, represents the perfect balance between full custom and semi-custom – and reduces delivery time from several years to as little as a few months [15]. The vessel exterior can be seen in figure (43) along with its general specification seen in table (13).

Table 13: LE242 specifications

| | |
|---|---|
| Length overall | 74.00 metres (242 ft) |
| Beam overall (at hull) | 12.45 metres (41 ft) |
| Draught (full load) | 3.85 metres |
| Gross Tonnage | 1790 GT |
| Maximum speed | 16.5 knots |
| Range @ 12.5 knots | 5,000 nautical miles |
| Guests | 12 |
| Crew | 18 + Captain |
| Staff | 4 |

Figure 43: AMELS Limited Edition 242 yacht [15]

While having a standardized general construction, these limited-edition vessels can have interior designs that vary greatly. As such, the loading distributions between each limited edition model can vary substantially. Thus, making this second verification study an ideal choice as this craft's loading distribution is vastly different in methodology and inspiration compared to the *Damen Yachting* YS7512.

### 5.3.2 LE242 MATLAB longitudinal strength results

As outlined in both sections (5.1.1) and (5.1.2), the longitudinal strength evaluation process first begins with the baseline comparison development. This is achieved through the importation of MAXSURF data to the MATLAB platform. The results of this procedure can be seen in figure (44). Based on the results seen in the table (14), it is clear, the relative error between the two platforms is negligibly small. Therefore, the associated maximum shear and bending moment results can be utilized as a baseline comparison.

Next, the MATLAB trapezoidal model evaluation is completed. The results of this evaluation can be seen in figure (45) and table (15) respectively. From the general curve shapes and low relative errors, the distributions are properly captured within the model. As such, even with associated discretization and irregular geometry errors, a large degree of confidence can be considered in the remainder of the study.

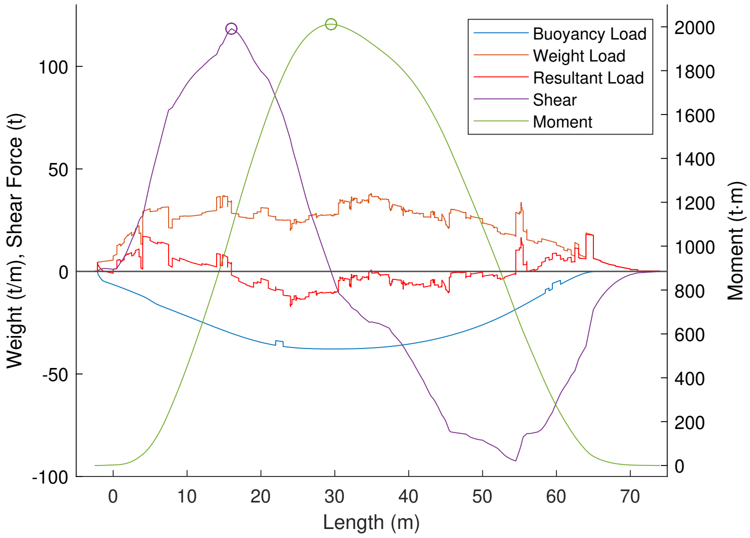



Table 14: MAXSURF to MATLAB shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 118.37 | 0.0 |
| $M_{max}$ (t.m) | 2011.9 | 7.2e-3 |

Figure 44: MAXSURF to MATLAB imported shear and bending moment results

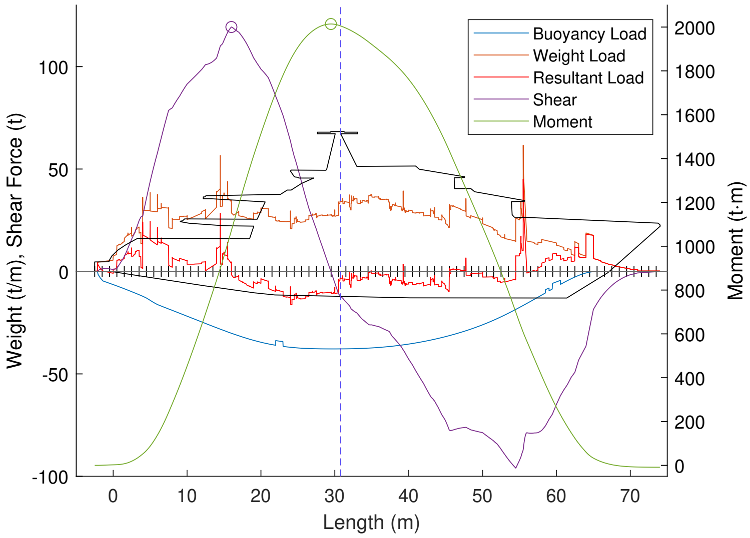



Table 15: Trapezoidal distributed shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 119.34 | 0.82 |
| $M_{max}$ (t.m) | 2013.90 | 0.10 |

Figure 45: Trapezoidal distributed shear and bending moment results (n=1500)

### 5.3.3 LE242 Individual item sensitivity analysis

Upon successful confirmation of model longitudinal strength results, the sensitivity procedure outlined in section (5.2) will be evaluated. This evaluation will consider the same general process as previously completed, along with the implementation of the same comparison metrics. Additionally, this verification deals with an engineering phase that aligns closely with that of the previous analysis. Therefore, the time evaluation baseline metric can be determined as,

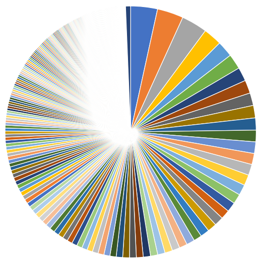
$$T_{total} = 331 \text{ items} \cdot \frac{6 \text{ inputs}}{1 \text{ items}} \cdot \frac{0.3 \text{ minutes}}{1 \text{ input}} = 595.8 \text{ minutes } (9.93 \text{ hours})$$

It should be noted that this case data is based on a later design within a series of vessels. As such, some of the individual item distributions have unfortunately been internally grouped. From the previous analysis, the grouping of individual items does not provide any additional opportunity for relative time-savings (table (12)). As such, the results have the potential to be lower than an individual item weight breakdown. While this does not provide an ideal case verification, items are still based on single item inputs. Therefore, findings using the outlined procedure will help to verify the overall research simplification goals.

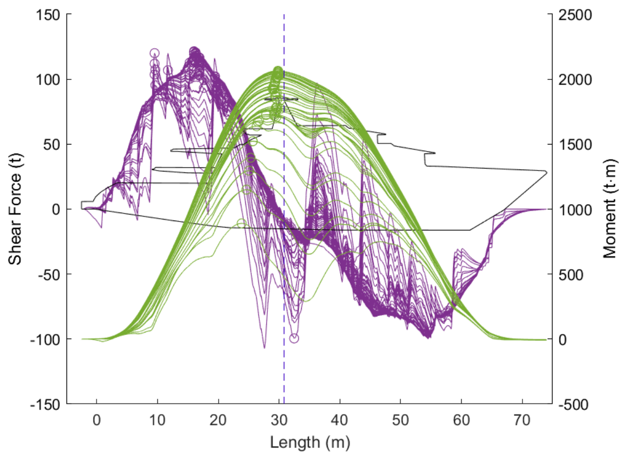
The full sensitivity results for the non-grouped individual weight items using the trapezoidal direct model can be found in figure (46). The corresponding results summary can be found in the table (16).

Table 16: LE242 sensitivity results summary

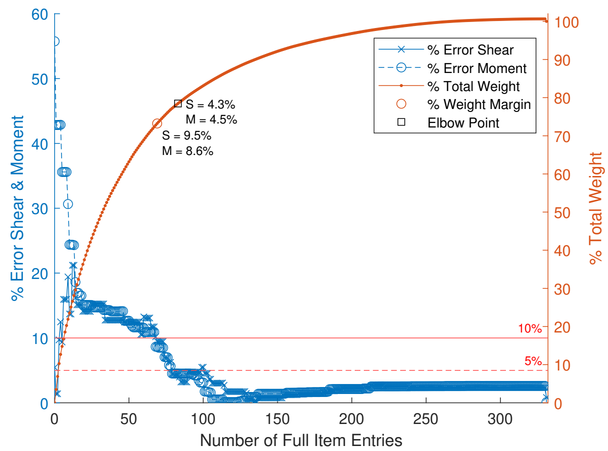
| Method [1] | % Mass | %E Shear | %E Mom. | Full Input [2] | Time (hrs) | Partial Input [3] | Time (hrs) | Total (hrs) | % Time Reduction |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Individual** | | | | |
| T - Exact | 73.23 | 9.5 | 8.6 | 69 | 2.07 | 262 | 5.24 | 7.31 | 26.38 |
| T - Elbow | 78.46 | 4.3 | 4.5 | 83 | 2.49 | 248 | 4.96 | 7.45 | 24.97 |



(a) Item Weight Breakdown (331 items)




(b) Trapezoidal Shear and Bending (n=1500)




(c) Trapezoidal Resultant Error

Figure 46: Individual item sensitivity analysis (LE242)

Based on the results, substantial time-savings is still potentially present within the analysis. Much like the previous YS7512 study, the relative time reduction is highly notable between the exact and elbow point comparison

[1] G & T are short for Grouping and Trapezoidal respectively
[2] Full Input relates to the amount of items leading up to the threshold point requiring all input parameters
[3] Partial Input relates to the amount of items after the threshold point requiring only the partial input parameters

metrics. While the relative savings have been slightly reduced, the overall simplification process still allows for a minimum of $25\%$ time reduction when only considering simple elbow point approximation.

### 5.3.4 *AMELS* LE212 Case Study

The second case investigation will focus on the smaller limited edition 212 vessel, issued by *Damen Yachting* brand *AMELS*. This vessel follows the same standardization process of the Limited Edition methodology. The vessel exterior can be seen in figure (47) along with its general specification seen in table (17).

Table 17: LE212 specifications

| | |
|---|---|
| Length overall | 67.60 metres (220 ft) |
| Beam overall (at hull) | 12.28 metres (40 ft) |
| Draught (full load) | 3.85 metres |
| Gross Tonnage | 1518 GT |
| Maximum speed | 17.0 knots |
| Range @ 12.5 knots | 5,000 nautical miles |
| Guests | 12 |
| Crew | 15 + Captain |

Figure 47: AMELS Limited Edition 212 yacht [14]

Much like the LE242, the LE212 can have interior designs that vary greatly. As such, the loading distributions between each limited edition model can vary substantially. Thus, making this additional verification study a suitable case as it is quite different from the other two previous investigations.

### 5.3.5 LE212 MATLAB longitudinal strength results

As previously outlined, both the imported and trapezoidal longitudinal strengths are evaluated in figures (48), and (49).

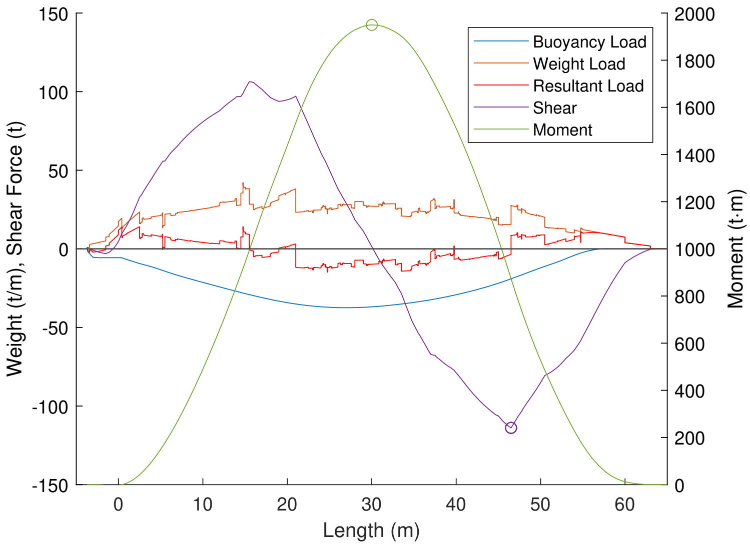



Table 18: MAXSURF to MATLAB shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 113.89 | 0.0 |
| $M_{max}$ (t.m) | 1949.62 | 0.0 |

Figure 48: MAXSURF to MATLAB imported shear and bending moment results

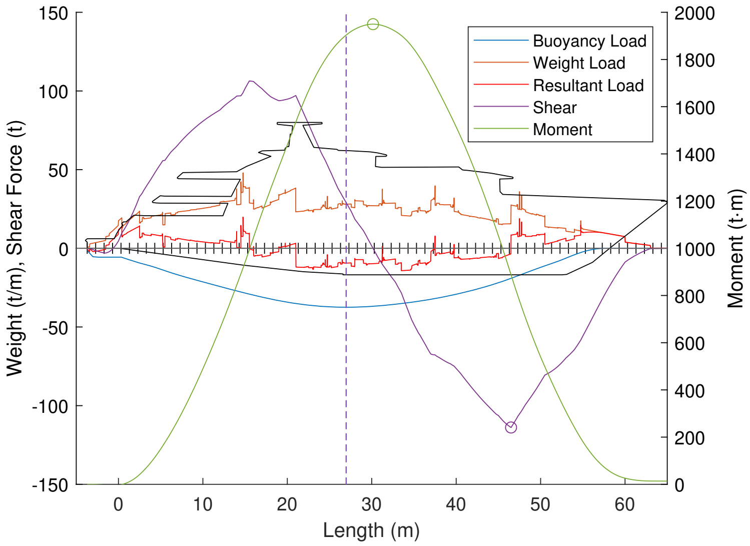



Figure 49: Trapezoidal distributed shear and bending moment results (n=1500)

Table 19: Trapezoidal distributed shear and bending moment summary

| SWS&B | Results | Error (%) |
|---|---|---|
| $S_{max}$ (t) | 113.88 | 3.3e-3 |
| $M_{max}$ (t.m) | 1949.67 | 2.7e-3 |

From the general study, results align very closely with that of the baseline case. As such, continued confidence in the remainder of the study can be considered.

### 5.3.6 LE212 Individual item sensitivity analysis

The following sensitivity evaluation will consider the same general process as previously completed, along with the implementation of the same comparison metrics. Additionally, this second verification also deals with an engineering phase that aligns closely with that of the previous analysis. Therefore the total time baseline can be determined using the same process as above,

$$T_{total} = 300 \text{ items} \cdot \frac{6 \text{ inputs}}{1 \text{ items}} \cdot \frac{0.3 \text{ minutes}}{1 \text{ input}} = 540.0 \text{ minutes } (9.00 \text{ hours})$$

Once again, this case data is based on a later design within a series of vessels. As such, some of the individual item distributions have unfortunately been internally grouped. As previously mentioned, the grouping of single items does not provide any additional opportunity for relative time-savings (table (12)). As such, the results have the potential to be lower than an individual item weight breakdown.

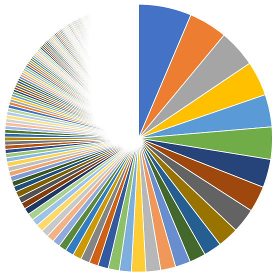
The full sensitivity results for the non-grouped individual weight items using the trapezoidal direct model can be found in figure (50). The corresponding results summary can be found in the table (20).

Table 20: LE212 sensitivity results summary

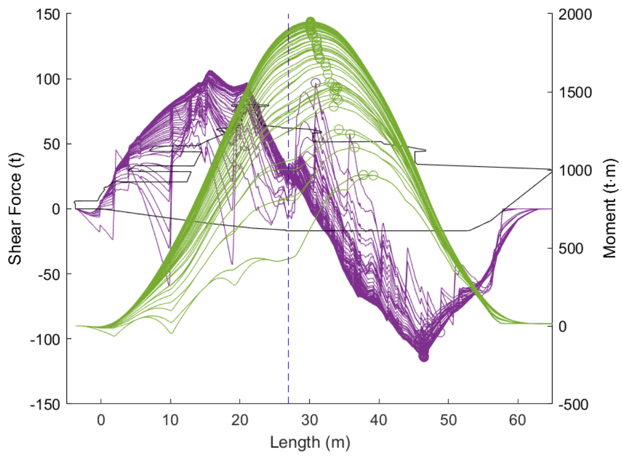
| Method [1] | % Mass | %E Shear | %E Mom. | Full Input [2] | Time (hrs) | Partial Input [3] | Time (hrs) | Total (hrs) | % Time Reduction |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Individual** | | | | |
| T - Exact | 78.62 | 7.1 | 9.4 | 54 | 1.62 | 246 | 4.92 | 6.54 | 27.33 |
| T - Elbow | 79.75 | 5.2 | 9.0 | 57 | 1.71 | 243 | 4.86 | 6.57 | 27.00 |

The second verification study reaffirms the previous sensitivity studies that the potential for time-savings exists within all future projects. Much like the last two cases, YS7512 and LE242, the relative time reduction is highly notable. In this specific case, it can be seen that the exact and elbow cases produce very similar relative saving results. Unquestionably, this shows that using the established procedure and comparison metrics, time-savings

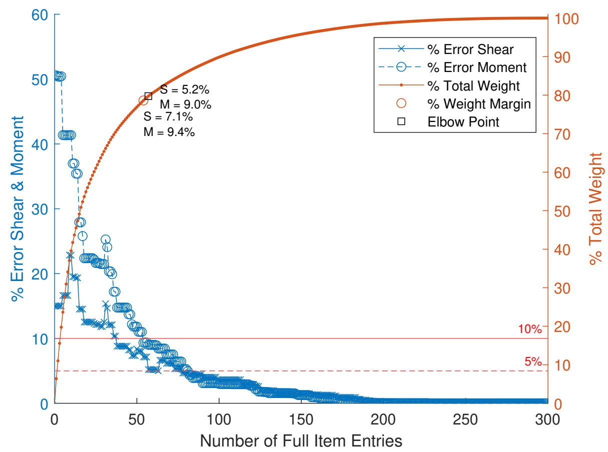
[1] G & T are short for Grouping and Trapezoidal respectively
[2] Full Input relates to the amount of items leading up to the threshold point requiring all input parameters
[3] Partial Input relates to the amount of items after the threshold point requiring only the partial input parameters



(a) Item Weight Breakdown (300 items)




(b) Trapezoidal Shear and Bending (n=1500)




(c) Trapezoidal Resultant Error

Figure 50: Individual item sensitivity analysis (LE212)

can be transferred between different situations. Therefore, further confidence in the utilization of individual weight item sorting and triangle threshold elbow points are accepted and ultimately deemed verified.

# 6 Conclusions

The investigation's primary purpose was to determine and apply a proposed methodology to save valuable time during the weight input stages of the basic engineering phase. This goal was accomplished through an in-depth local sensitivity approach focusing on the influence of distributed loading versus point-loading with respect to the maximum still water shear and bending moment results. To further help achieve this final objective, a series of research questions were addressed throughout the study.

*'What is the Damen Yachting longitudinal strength minimum requirements and what literature methods regarding weight distribution techniques and sensitivity approaches can be applied to investigate these general guidelines?'*

After a series of internal interviews and literature investigations, the establishment of a 10% relative accuracy was deemed appropriate for the investigation. This baseline comparison metric was estimated from an internal design package investigation. Additionally, the literature search highlighted three weight distribution techniques: Parabolic Approximate, Point-wise Grouping, and Trapezoidal Direct. Upon outlining each distribution method, two sensitivity procedures, Local and Global, were also summarized. From the literature investigation, it was determined that the three weight models using a Local sensitivity approach was deemed most appropriate in the current study.

*'How do the various weight distribution models behave under irregular loading conditions and how can these inconsistencies be overcome?'*

After developed the three weight distribution models, a small-scale investigation incorporating both a robustness and verification study was conducted. It could be concluded that both weight equilibrium and LCG/LCB alignment was crucial for each numerical model to operate successfully under any loading condition. Additionally, through means of a verification study, relative accuracy was evaluated for each model. Ultimately, the parabolic approximation method was deemed inadequate as the basic general requirements were unattainable in all instances.

*'Can distributed loads be fully represented by concentrated point loads occurring at each weight's center of gravity?'*

Upon scaling-up the models to evaluate real *Damen Yachting* case vessels, it was determined that a full point loaded evaluation is not possible. The influence of the length parameter in the heaviest weight items proved substantial. This consequently resulted in both shear and bending moment curves that were highly inaccurate and irregular as compared to the baseline investigations.

*'How do various weight distribution techniques contribute to the accuracy of still water longitudinal strength output parameters?'*

Furthermore, a large-scale direct comparison between the remaining models was completed. From the results, it was determined that the trapezoidal direct method provides the most accurate results. Whereas, the point-wise grouping method produced slightly less precise results using a similar calculation approach. However, the grouping method, while not as accurate, did allow for an easy and high degree of control over each item's implementation. This regulation offers a hidden academic benefit for potential future studies.

*'If not, at which point (if any), can the loads be mixed between distributed loads and concentrated point loads to obtain similar longitudinal strength output results?'*

A clear transition point between distributed and concentrated point loading was found through the implementation of a modified sensitivity approach. The final location could be determined and transferred to other cases using a series of simple comparison metrics. Therefore, it could be determined that only a handful of individual weight items are significant to the calculation of longitudinal strength parameters such as shear force and bending moments.

These questions gradually built towards a systematic design procedure that guaranteed time-savings while meeting the established general accuracy requirements of $10\%$. Ultimately, the proposed method can have a theoretical maximum time reduction of 33.33%. This can only be reached if every input item is approximated as a concentrated point load. Therefore, instead of 6 input parameters per weight item, there are only 4 (neglect fore and aft limits). This decrease inherently represents a relative reduction of 1/3rd in the overall data entry procedure, which can be directly linked to the relative time-savings. Unfortunately, as seen in section (5.1.3), this is not likely to be achieved since such discrete approximations create shear and bending moment curvatures that are no longer representative of the actual longitudinal strength output results.

However, as seen in the sensitivity summary tables (12) and (16), the degree of relative time reduction can still be quite substantial. From the three case studies, the number of items requiring full input parameters is associated with $10\% - 25\%$ of the total item count. This amount of items consisted of $80\% - 90\%$ of the entire ship weight. Additionally, the elbow point metric only varied between $0.3\% - 2.3\%$ of the fully detailed cases. Ultimately, these evaluations allow for a relative time-savings order of magnitude of $30\% - 25\%$, respectively. Therefore, of the maximum theoretical time-reduction, $75\% - 90\%$ can successfully be attained when applying the proposed comparative metrics and procedure. Thus, the investigation successfully achieves the overall research goal of implementing an efficient strategy to reduce valuable time spent within the basic engineering phases.

## 6.1 Methodology Recommendations

Based on the full sensitivity investigation and corresponding conclusions, a clear input strategy can be recommended to create reproducible time-savings. These steps can confidently be suggested for the end basic design stage with margins of accuracy deviations less than $10\%$. While this method may be applicable in different design and engineering phases, further analysis is required to ensure the appropriate levels of accuracy are maintained in each stage.

1. **Input all item weights first**
   - Apply no JDOC groupings i.e. maintain individual item weights
   - Sort heaviest $\longrightarrow$ lightest items
   - Apply triangle threshold technique on cumulative weight percentage to determine 'elbow' threshold stopping point
2. **Full data entry - LCG, FWD limit, AFT limit, TCG, VCG**
   - Heaviest item $\longrightarrow$ 'Elbow' threshold point.
   - From the study this level of input items will produce slightly conservative results based on the study. It should be noted that the percentage of cumulative weight ranges between $\sim 80\%$ to $\sim 90\%$.
3. **Partial entry of remaining items - LCG, TCG, VCG**
   - 'Elbow' threshold point $\longrightarrow$ Lightest Item
   - The partial entries assume a negligible item length influence, thus can be assumed as point loads. The investigation used a distribution length factor of $0.5\%$ to reduce the associated item spans.
4. **Determine longitudinal strength output parameters using commercial software packages**

## 6.2 Future Work

Both numerical distribution models and sensitivity studies have the potential to be improved. If the models are further developed, uncertainties and confidence in numerical results can be improved. This improvement has a direct effect on overall investigation and can provide further understanding between numerical and physical longitudinal strength results. Additionally, alongside the models, the general sensitivity investigation process can be improved by looking at both current and alternative methods. This further review will allow for a broader understanding of the input/output relationships, which can potentially lead to additional time-savings (or at least why time cannot be further utilized).

### 6.2.1 Model Improvements

- **Implementation of alternative equal discretization spacing functions within the MATLAB environment**

  All MATLAB weight distribution models (parabolic, grouping, trapezoidal) rely on equi-incremental spacing for the discretization process. This spacing allows for station positions to be decomposed into smaller points equally spaced within each point. However, suppose the length increments are not a factor of the total length. In that case, the MATLAB built-in technique has the potential consequence of over/underpredicting the lengths in general by ignoring the remainder. Unfortunately, this can have a direct effect on both weight equilibrium and the center of gravity locations. As such, it is recommended to apply MATLAB *'linspace'* function to ensure the length is always conserved. This function will ensure the discretization points are fully captured in the event of non-factor incremental lengths. While the overall effect is quite small, this improvement will ultimately provide further model accuracy confidence.

- **Creation of a buoyancy distribution method and perform a full comparison investigation**

  The weight models cannot produce self-determined buoyancy distributions. Currently, the models require the importation of an existing buoyancy distribution produced from commercial stability software tools. Thus, the LCB is fixed in all load cases. Unfortunately, if the weights are shifted, the buoyancy will not be an exact representation as trimming effects, and LCB position shifting is not considered. As such, an additional investigation into how the buoyancy distribution is developed and implemented will provide additional capability and robustness to the overall longitudinal strength evaluations. This feature will incidentally solve artificial trimming moments created by unequal longitudinal gravity and buoyancy alignment.

- **Perform an individual discretization sensitivity analysis on the effect of accuracy and simulation time**

  Depending on the degree of discretization, each model has an associated accuracy with varying computational simulation demands. General sensitivity studies rely on accurate output information through an efficient numerical solution. From the case studies, it could be seen that a performance disparity between the different distribution models due to the exceedingly long simulation times. Therefore, the effects of discretization on the overall longitudinal strength accuracy and computational efficiency will provide valuable insight into both the global model creation process and future sensitivity studies.

### 6.2.2 Sensitivity Investigation Improvements

**Current Sensitivity Process:** These suggestions will solely focus on the current sensitivity procedures implemented throughout the report. These improvements will hope to expand on the knowledge gained and provide additional insights into how or why simplifications can be achieved.

- **Evaluate multiple sensitivity cases using different vessels for further method verification**

  To improve the current sensitivity procedure, additional cases must be considered. The cases will be used to compare and evaluate differences between results occurring in the same design and engineering stages. In this study, conclusions were drawn from only two case studies. As such, while the process and findings were favourable, the chance of accidental coincidence may exist. However, additional cases will provide valuable verification information about all future investigation findings.

- **Evaluate the effects of varying design and engineering phase weight changes on longitudinal strength**

  An additional improvement can be made within the defined general requirements. As stated in section (2.1.3), the shear and moment deviation metrics are established arbitrarily. Therefore, it is highly recommended to perform a similar sensitivity study between each critical design and engineering phase. This study will provide additional insight into the still water shear and bending moment changes as the weight distribution adjusts. With this new knowledge, exact accuracy requirements can be established for any vessel class and engineering phase.

- **Investigate alternative comparison techniques and their influence on overall time-saving**

  A critical comparison metric used in the investigation is the triangle threshold elbow point. This point allows for a clear indicating marker where weight effects have negligible effects on the overall shear and bending moment accuracy using limited information. Ultimately, the evaluation tool was deemed sufficient in terms of time-savings. However, this is one of the many different evaluation criteria that could have been implemented. As such, a more comprehensive study into the feasibility of other comparison procedures should be completed. This additional insight can potentially lead to even better solutions, which ultimately can increase time-savings even further.

- **Evaluate the full shear and bending moment curve differences using a comparative metric approach**

  The sensitivity procedure focuses on the maximum shear and bending moment magnitudes. However, as the distributions are shifted between fully distributed to point loading, the shape of each associated curve changes. This changed curvature may have a comparable peak loading but, the form could incidentally be vastly different than the original. As such, a look into a comparison between each iteration case with the initial curve should be considered. This additional comparison metric will eliminate any doubts within the results and further refine the sensitivity process.

**Alternative Sensitivity Process:** The current sensitivity procedure focuses on purely a weight comparison metric. However, the effects of distribution lengths influence the longitudinal strength results. Unfortunately, these individual item lengths are impossible to determine without including additional inputs, hence negating investigation learnings. As such, an alternative sensitivity method is suggested.

- **Investigation of individual compartment/room groupings and analyze their effects on longitudinal strength**

  This study will allow for the evaluation of which regions have the most significant impacts concerning both weight and lengths. Since each compartment length is known, individual items can be grouped and distributed across each compartment. This method will allow for the implementation of length information without having to acquire each span manually. To achieve this investigation, a modification of the grouping method is suggested. While this technique solves the length prediction grouping, it does not allow for unequal spacing between stations. As such, a further investigation of how uneven point spacing can be applied should be considered. This spacing type can further enhance the grouping distribution model by providing an alternative grouping scheme. Ultimately, this enhancement will allow for more control over the applied weight distributions. While this technique may prove not to offer any additional global simplification, it will allow for a deeper understanding of how length distribution can be applied and simplified without any other available data.

## 6.3 *Damen Yachting* Comments and Suggestions

Upon conclusion of the investigation, additional insight was gathered from *Damen Yachting* colleagues. In addition to the above future works, additional suggestions and comments are presented which may serve to provide practical future benefits for both the study and company interest.

- **Investigation of new build projects versus refit projects and the effects of longitudinal strength parameters**

  The sensitivity study focuses specifically on new build projects. However, refit initiatives make up a large portion of *Damen Yachting* business. As such, the way individual item information is provided generally is not as systematically laid out as that of entirely new projects. Therefore, the current investigation may not be the most relevant, and the insight gathered in this study may not be transferable to specific refit projects. As such, a secondary look into refit projects is proposed to further understand the associated level of detail available and achievable upon evaluation of longitudinal strength parameters. This investigation may use a similar sensitivity approach however, alternative distribution techniques may need to be considered due to general item data gaps.

- **Investigate the influence of the individual frame spacing/intervals on the longitudinal strength parameters**

  Another topic to further the study suggested is the look into the effects of frame spacing on the longitudinal strength parameters. This additional study will significantly benefit the structural department as frame spacing optimization is a difficult metric to evaluate. As such, a further sensitivity study relating to the spacing interval size is suggested. The current point-wise grouping numerical model can achieve this objective. However, one key point from the model improvement future works is crucial in completing this objective. Establishing and implementing the alternative MATLAB numerical spacing function *'linspace'* will allow for spacing intervals of any size and not only spacing attributed to factorization. Once the technique is implemented, a similar sensitivity study can be completed to evaluate interval spacing effects on the longitudinal strength parameters.

## References


[1] T. N. Arch. Longitudinal strength of ships - an introduction, 2017. URL https://thenavalarch.com/longitudinal-strength-ships-introduction/.

[2] y. Bai and W.-L. Jin. *Marine Structural Design*. Elsevier Ltd., 2016.

[3] C. Barrass. *Ship Stability Notes & Examples*. Butterworth-Heinemann, 2001.

[4] E. Groen. An uncertain climate: the value of uncertainty and sensitivity analysis in environmental impact assessment of food. *Wageningen University*, 2016.

[5] D. Laurence. Methods of determining the longitudinal weight distribution of a ship. *Hampton Roads Section of the Society of Naval Architects and Marine Engineers*, 2008.

[6] H. G. Mayor. Teh marine survey practice, 2013. URL https://marinesurveypractice.blogspot.com/2013/01/que-mirar-donde-mirar.html.

[7] M. Moradi, B. Van Acker, K. Vanherpen, and J. Denil. Cyber physical systems. model based design. *Computer Science: Springer International*, 2019.

[8] R. Munro-Smith. *Applied Naval Architecture*. Elsevier Ltd., 1967.

[9] M.-I. Roh and K.-Y. Lee. *Computation Ship Design*. Springer Nature Ltd., 2018.

[10] V. Satopaa, J. R. Albrecht, D. E. Irwin, and B. Raghavan. Finding a "kneedle" in a haystack: Detecting knee points in system behavior. *2011 31st International Conference on Distributed Computing Systems Workshops*, 2011.

[11] M. Sobol. Sensitivity estimates for nonlinear mathematical models. *Mathematical Model Computational Experiments*, 1993.

[12] S. Tennøe, G. Halnes, and G. T. Einevoll. Uncertainpy: A python toolbox for uncertainty quantification and sensitivity analysis in computational neuroscience. *Frontiers in Neuroinformatics*, 2018.

[13] E. C. Tupper. *Introduction to Naval Architecture*. Elsevier Ltd., 2004.

[14] D. Yachting. Le220 - amels, 2019. URL https://www.amels-holland.com/range/amels-212/range/amels-242/#1.

[15] D. Yachting. Le242 - amels, 2019. URL https://www.damenyachting.com/yacht/amels-242/.

[16] D. Yachting. Ys7512 - damen yachting, 2019. URL https://www.damenyachting.com/yacht/ys-7512/#brochure.

[17] D. Yachting. *Manual Engineering, REV G*. Damen Yachting, 2019.

# A Appendix

## A.1 Damen Yachting Interviews

To gain additional insight into the general engineering and design processes used within *Damen Yachting*, semi-formal interviews were held with respected members. This appendix hopes to summarize the key findings from each member and thus is not a word-for-word replication but instead an interpretation and summarization of critical information.

**Interview 1.** Jeroen van der Sande - Naval Architect (Design and Proposal)

1. **What is the Damen Yachting formal design process (i.e. What design method is generally followed)?**
   (a) **Systems Engineering Approach (i.e. V-approach)?**
   (b) **Traditional Spiral Method?**
   (c) **Self-established (Internal workflow)?**

   The design department closely follows a traditional spiral approach in the early design stages. However, the design process, in general, is highly flexible, as early-stage design teams are composed of 4-5 members with varying specializations. This helps the design flow as internal idea conflicts are generally avoided and more streamlined.

2. **What are the general design stages a product goes through? Does *Damen Yachting* do all the designs in-house?**

   The general build process consists of both design and engineering phases, which can further be broken into multiple sub-stages. The design process can generally be broken into three main sections; idea phase, concept design, and basic design.

   The idea phase generally consists of evaluating the market needs/client needs. At this point, a general brief composed of program requirements is created. This requirements sheet describes the overall vessel critical functions and objectives, such as performance characteristics, general timelines, etc.

   Once the requirements are created and approved between management/clients/marketing, the concept design phase begins. This design phase investigates the preliminary vessel calculations, such as weight, stability, and general arrangements (layouts). Since information is highly lacking at this stage, it is usually accomplished through comparative studies. At this point, small design teams are established with 4-5 people of varying specializations tasked with the initial design.

   Then upon completion of the concept design and approved by management, the basic design begins. This stage is essentially the same as concept design; however, more detail is added to each component. Additionally, 3D modelling, construction elements, and engine rooms are added to the initial package. Upon completion of the basic design, a product development package (PDP) is completed. This package is then transferred to engineering, where the design check is begun.

3. **For each stage of design what level of detailed is needed?**

   Idea Phase: The associated level of detail for the idea phase is low, as no design has begun. This consists only of the general requirements and brief the yacht should meet.

   Concept Design: The concept design phase generally consists of generally low detail with an initial investigation into the project's feasibility. At the end of the concept development, highly preliminary calculations are completed, which are generally based on comparative vessels. If there are no red flags, the design process continues.

   Basic Design: The basic design phase has the highest level of detail. Technically, this phase has a low-detail level compared to the engineering phases; however, the PDP consists of a design that is approximately 95% feasible.

4. **How long does the design process last?**

   For full custom yachts generally, less time is spent in design, and more time is spent in production. In comparison, limited editions (series yachts) are usually spent more in design and less in the production stages. As such, the general design process can last between 5 - 8 months, depending on the requirements and timelines.

**Interview 2.** Elena Tonyuk - Naval Architect (Engineering)

1. **What is the current *Damen Yachting* weight input approach required to evaluate longitudinal strength?**

   Currently, the approach is as follows,

   (a) individual items are entered manually into an excel data list. Each item is composed of six critical inputs: Weight, LCG, Aft Limit, Fore Limit, TCG, VCG. The items are grouped within their item specialization codes, known as JDOCs.

   (b) To determine each input parameter, multiple resources are required; however, the item locations are typically found from a CADmatic model. This model is periodically updated to include each item (nearly all). From this 3D integrated model, exact item locations can be found.

   (c) When all inputs are determined for each item, the list is copied and pasted within the commercial software MAXSURF. This program, depending on the loading conditions and tank fluid levels, calculates the longitudinal strength parameters.

   Unfortunately, depending on the design stage, item amounts can vary drastically. A completed vessel after the detailed engineering is known to consist of $\sim 5000$ individual weight items. Therefore, the entire process of inputting all six parameters for each item can become extremely tedious and time-consuming work.

2. **What is your (*Damen Yachting's*) goal for the outcome of this investigation?**

   Currently, the time allotted and the time required to input all weight items are highly disproportional. Therefore, we seek to shrink this gap by reducing the amount of time needed to input the weights.

   Heavy items, such as engine stabilizers, have much more of an impact on the longitudinal strength than lightweight light bulbs. Instead of determining the exact distribution lengths of such items, it would be much simpler to assume they act as concentrated point loads. However, the point at which the output results are still accurate reflections of the full inputs is unknown. Therefore, we hope the study will investigate the effects of point-loads versus distributed loads on the longitudinal strength parameters. We also hope that any simplifications can be replicated with other vessels by establishing a general procedure or linking global conclusions. Simply put, a more straightforward way to get the same detailed results.

3. **What are some general requirements that must be fulfilled when establishing the longitudinal strength output results?**

   After an internal investigation into ten vessels ranging from 55-75 meters, a definite weight difference was established for each associated phase of the design and engineering. It can be seen that first-of-series and customs on average have a $\sim 10\%$ $(6.4\%)$ deviation from the final detailed engineering weight to the PDP weight estimate. Thus, longitudinal strength parameters should not be larger than this amount at any stage in the design. Therefore, $10\%$ margin - Yachts < 80m will be the initial accuracy margin for the study as an initial conservative estimate.

   Additionally, while it may not have a direct impact on the study, a maximum displacement for the available design speed is required. If the loading is exceeded and the general vessel displacement is too large, additional resistance will reduce the estimated design speed. As such, a strict weight limit is established for each vessel to ensure displacement conserved.

   Finally, as a rule of thumb, the maximum allowable trim of a vessel should be one-half of the length of the ship in centimetres. For example, if the ship is 60m in length, the maximum allowable trim should be 30cm or 0.3m.