Present and future possibilities of software to predict the stability of container ships

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Topics

- Introduction to SARC.
- Locopias on-board loading and stability software.
- Automatic measurement of container weights, based on measured draft variations.
- A proposal for probabilistic assessment of container ship stability.

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1. INTRODUCTION TO SARC

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SARC hightlights

- Founded in 1980.
- 7 trained Naval Architects.
- Specialized in software for maritime design purposes.
- Over 15 years experience with on-board loading software.
- Custom build software.

www.sarc.nl

Products and services

- PIAS (**P**rogram for the **I**ntegral **A**pproach of **S**hipdesign)
- FAIRWAY (Hull design and fairing)
- LOCOPIAS (Loading computer software for on board use)
- Photoship (Hull shape measurement by photogrammetry)
- Services:
  - Naval architectural calculations
  - Hull fairing and shell plate expansions
  - Inclining experiments
  - Courses, for example in stability of ships

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Deliveries

PIAS	**: 150 users**
Fairway	**: 50 users**
LOCOPIAS	**: > 800 ships**
Projects	**: > 2800**

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2. LOCOPIAS ON-BOARD LOADING AND STABILITY SOFTWARE

Locopias ship types

- Seagoing cargo ships (container, tanker, crane ships).
- FPSO.
- Barges (flat and pipe laying).
- Naval vessels.
- Submarine.
- Inland waterway tankers (abt. 200).
- IWW and short sea container vessels.
- Full list on www.sarc.nl/locopias/references.

Locopias operation

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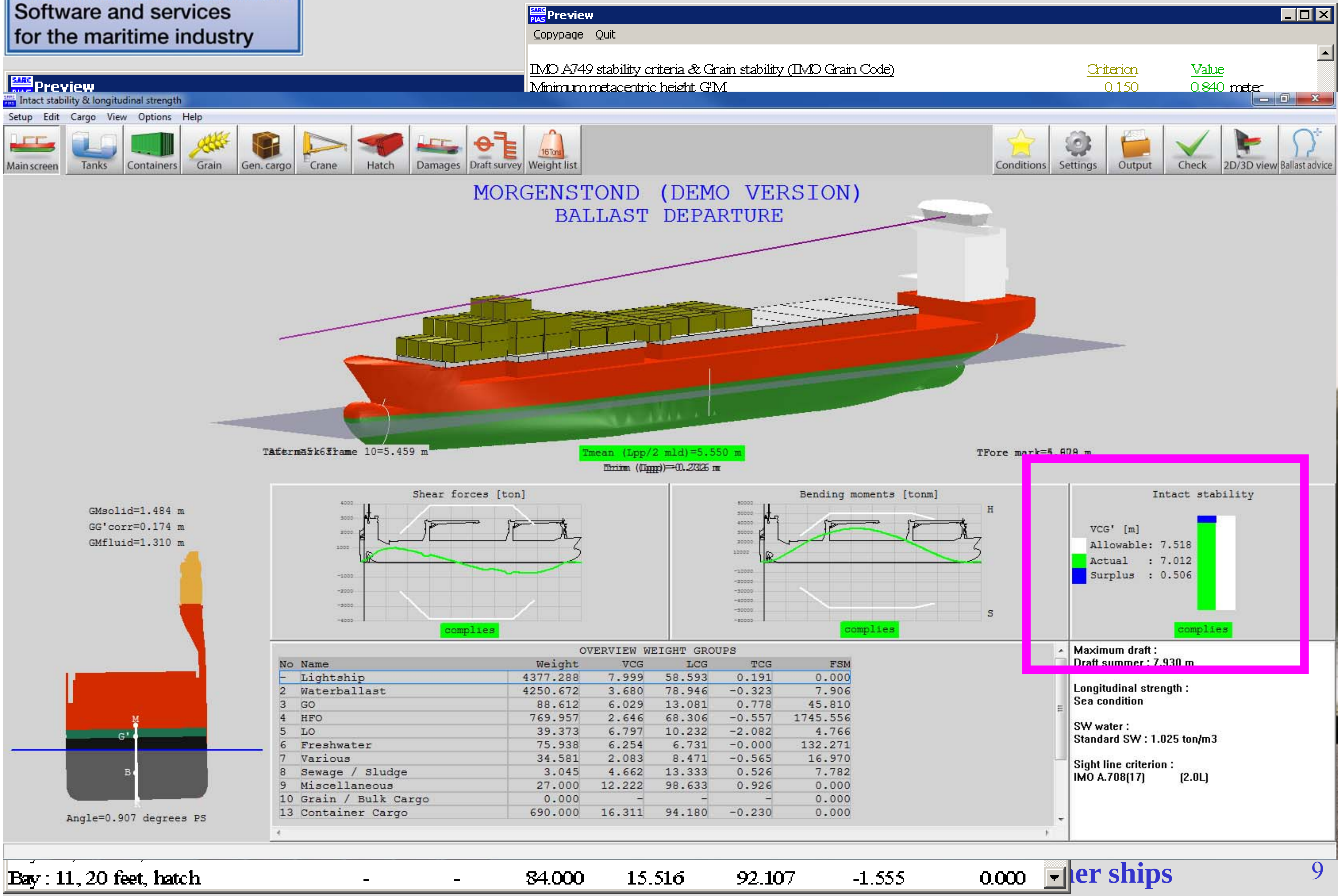

No	Name	Weight	VCG	LCG	TCG	FSM
-	Lightship	4377.288	7.999	58.593	0.191	0.000
2	Waterballast	4250.672	3.680	78.946	-0.323	7.906
3	GO	88.612	6.029	13.081	0.778	45.810
4	HFO	769.957	2.646	68.306	-0.557	1745.556
5	LO	39.373	6.797	10.232	-2.082	4.766
6	Freshwater	75.938	6.254	6.731	-0.000	132.271
7	Various	34.581	2.083	8.471	-0.565	16.970
8	Sewage / Sludge	3.045	4.662	13.333	0.526	7.782
9	Miscellaneous	27.000	12.222	98.633	0.926	0.000
10	Grain / Bulk Cargo	0.000	-	-	-	0.000
13	Container Cargo	690.000	16.311	94.180	-0.230	0.000

Bay : 11, 20 feet, hatch	-	-	84.000	15.516	92.107	-1.555	0.000

...er ships

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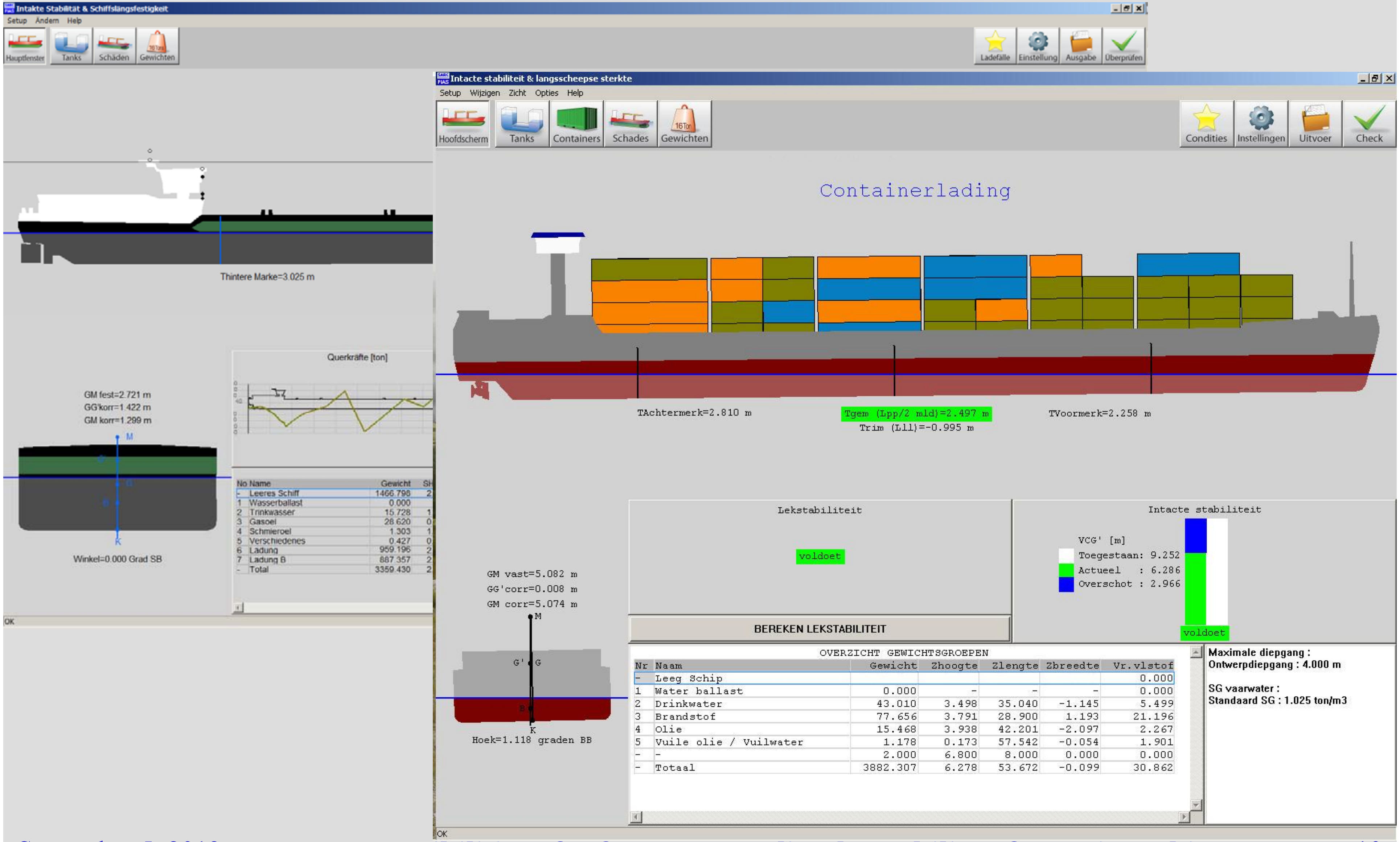
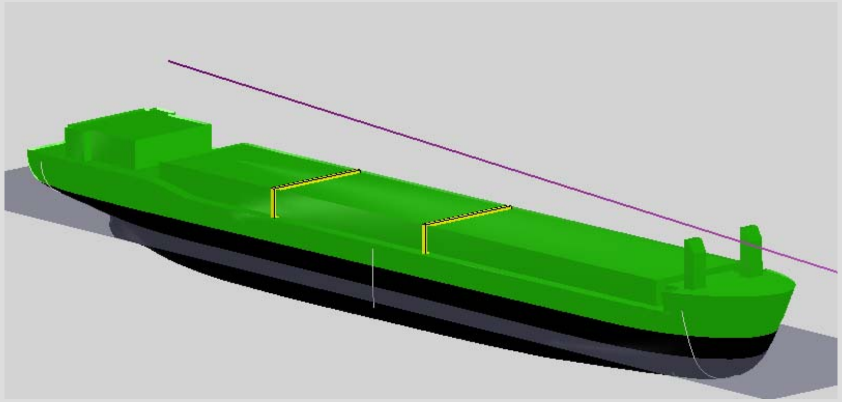
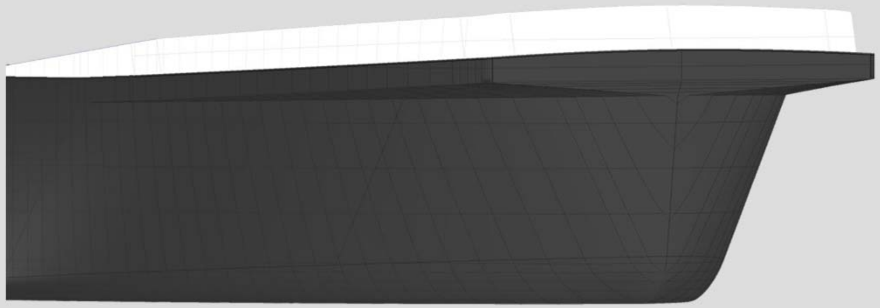
IWW vessels



Locopias highlights (1)

- All computations are based on actual 3D geometries.





Locopias highlights (2)

- Graphical User Interface (GUI) permanently updates the actual stability situation.
- Free surface effects taken into account either as Free Surface Moment (FSM) or as actual ship of liquid.
- Stability check against criteria (direct) as well as maximum allowable KG.
- Approved/accepted by LR, GL and BV. See www.sarc.nl/locopias/certificates.

However,

What are the uncertainties / inaccuracies whith this kind of computations?

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Uncertainty in hull shape related stability component

- Inadequate calculation method (omitting trim effects, no actual shifts of liquids with large free surfaces).
- Improper input data (incorrect lines plan). Type and position of openings!
- Hull deflection (hogging or sagging)
- With proper software and verified input data the hull shape component is reliably taken into account.

Uncertainty in weight related stability component

- Light ship weight and KG obtained by means of an inclining test. Generally reliable.
- Ballast and tanks from tank plan. Generally reliable.
- Container weights and KG not always reliable.

3. AUTOMATIC MEASUREMENT OF CONTAINER WEIGHTS, BASED ON MEASURED DRAFT VARIATIONS

Background

- Idea: Use draft sensors to automatically determine the weight of (un-)loaded containers. So no special or additional equipment required.
- For smaller container vessels (48 TEU).
- Partners:
  - Mercurius Shipping
  - Autena Marine
  - Sygo
  - SARC

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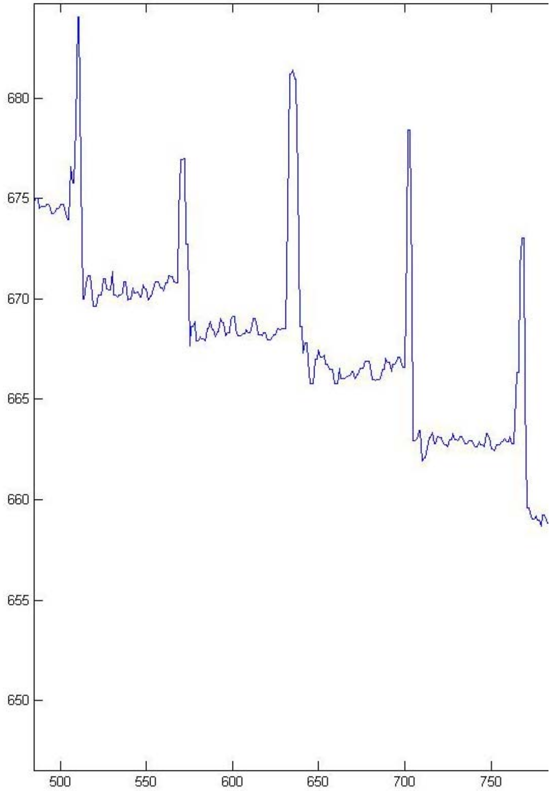
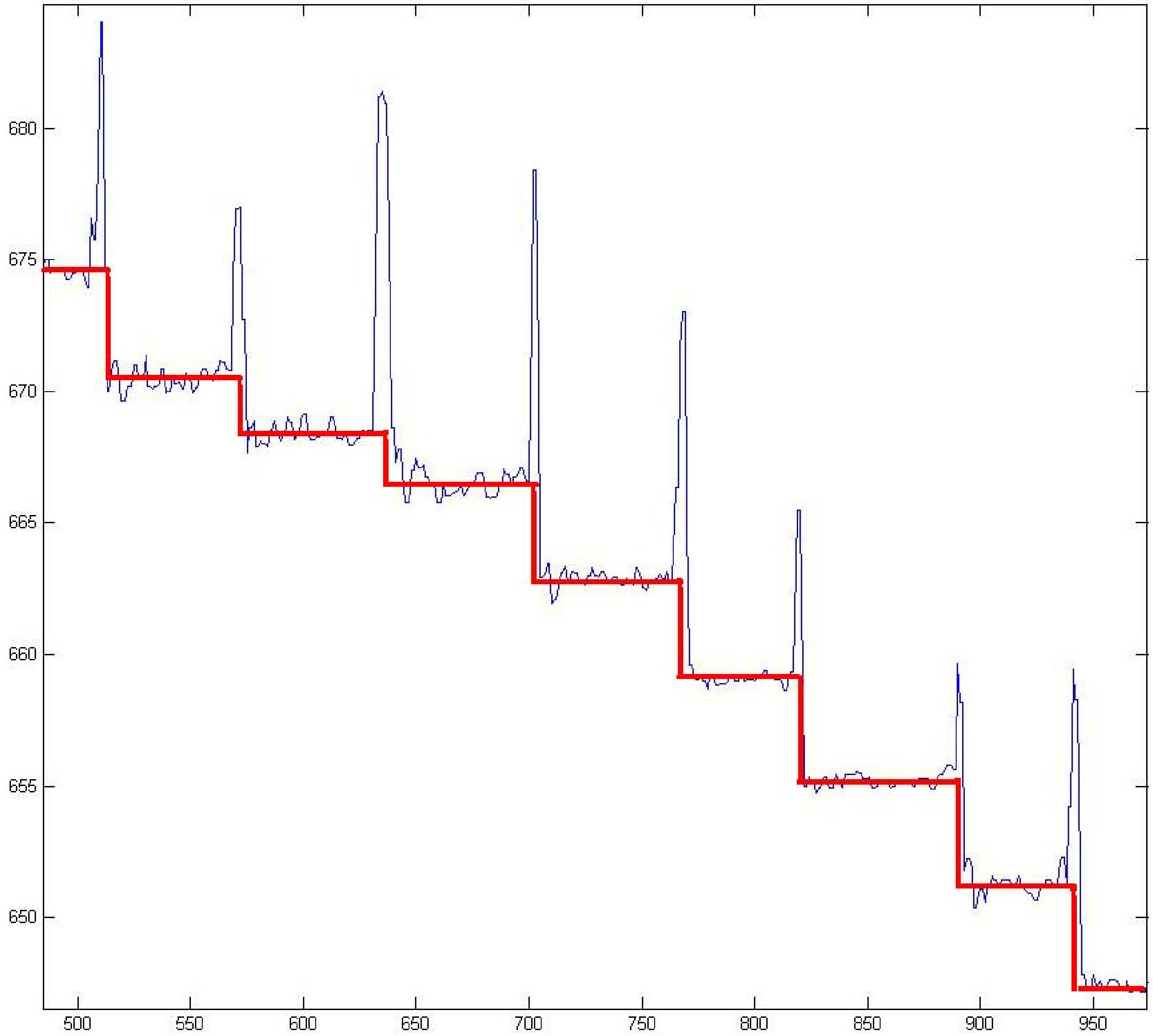
Measurements





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Challenges

- Movements due to waves and wind.
- Spreader weight.
- Determine optimal measuring time (long for high accuracy, although sufficiently short to discriminate between two subsequent containers).

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Intermediate results

- Rather promising: 98 to 99% of the container loads are accurately recognized.
- Spreader is recognized and omitted.
- Restrictions: ballasting and twin-loading.
- Open issue: HMI (interface to operator).
- Further experiments planned on larger vessels.

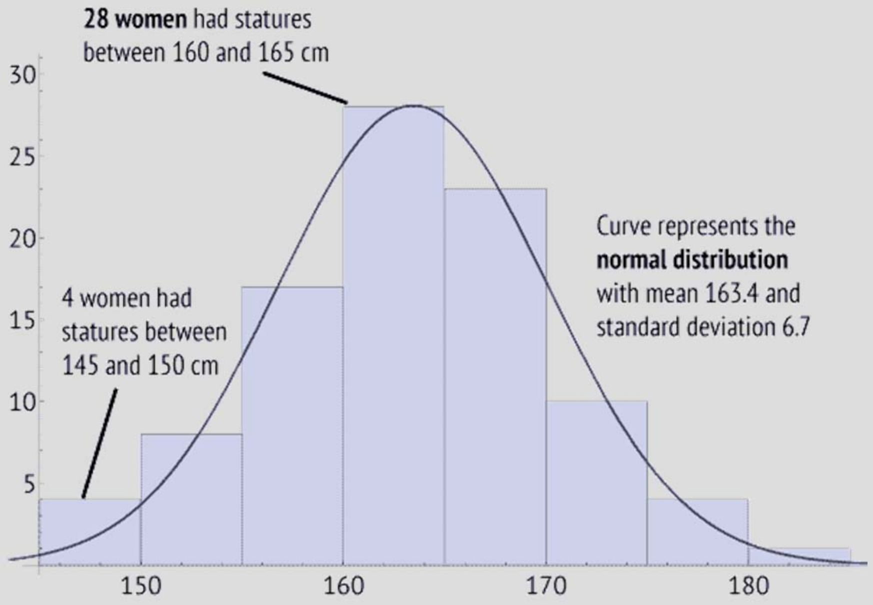
4. A PROPOSAL FOR PROBABILISTIC ASSESSMENT OF CONTAINER SHIP STABILITY

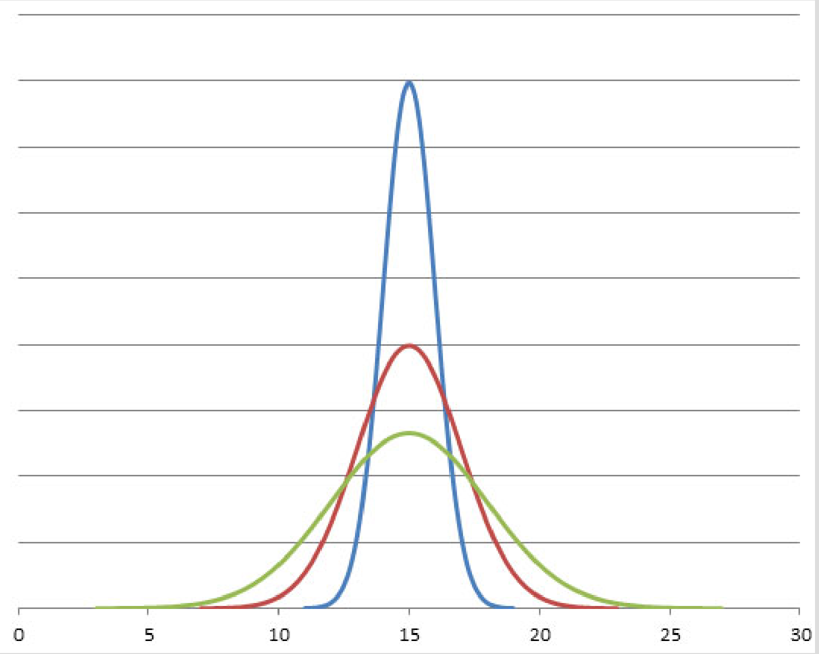
Analogy: SOLAS damage stability

- Past: crisp damage boundaries (e.g. a penetration of 20% of the ship's breadth (B/5)).
- Present: probability of survival attained index (A) should be larger than the required index (R).
- All damages can occur → many damage cases.
- Statistics on probability and on survival of damage.
- Probability of damage dependant on size and location.
- Survival dependant on residual stability.

Basis of statistical modelling

- Measurements → histogram.
- PDF (Probability Density Function).





Probabilistic proposal

- To accept inaccuracies in container weight and KG, and to process them in a probabilistic fashion.
- The basic of the method are samples of real container weight measurements (collected in histograms).
- Stability threshold is an accepted probability of capsize.
- See paper on CCNR website for elaboration.

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Advantages

- Uncertainty of the weights and KG of containers is explicitly taken into account.
- Results in a publicly known and accepted probability of capsize.
- Computationally not too complex.
- Can be implemented as addendum on current ship stability software.
- Reliability of the cargo manifest container weight can be taken into account, and is rewarded in case of high quality.

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CONCLUSION

Conclusions

- Loading software is adequate if
  - proper software is used,
  - ship hull input data are verified thoroughly,
  - loading weight data are reliable.
- Determination of container weights by measurements of draft variations is feasible for smaller vessels. Larger vessels are subject of research.
- Processing container weights in a probabilistic fashion is feasible and has advantages.

A proposal for the probabilistic assessment of container ship stability

September 5, 2013

Dr. ir. H.J. Koelman

1. Introduction

A reliable assessment of the stability of container ships is hampered by the fact that the weights of individual containers are not always known with sufficient accuracy. This also applies to Inland Waterway (IWW) vessels, and in order to address this problem the Central Commission for the Navigation of the Rhine has organized a workshop on the 5^{th} of September 2013 in Bonn.

In this paper, which is written as a contribution to that workshop, a proposal is formulated to take the uncertainty in container weights explicitly into account by processing it in a statistical, or probabilistic, fashion. This approach has some similarity with the current regulations on damage stability for seagoing vessels. In sections 2 and 3 first some introductory material is discussed on ship stability and probabilistics in general, the proposal itself is presented in sections 4 and 5.

2. Transverse stability of container ships

2.1 Stability components: hull shape, displacement and center of gravity (COG)

Commonly, the stability of a vessel (regardless of its type, and whether seagoing or inland) is expressed in the righting lever (GZ) as function of the inclination φ, an example of such a GZ-curve is depicted in fig. 1. For upright vessels the tangent, or slope, at the GZ curve at φ=0˚ is an indication of the initial stability, which is commonly named GM, or metacentric height, which is also shown in fig. 1. In order to guarantee a minimum of stability statutory regulations require certain minimum values of GZ and GM. As illustration the minimum stability criteria for seagoing vessels are reprinted in fig. 2 [IMO, 2008].

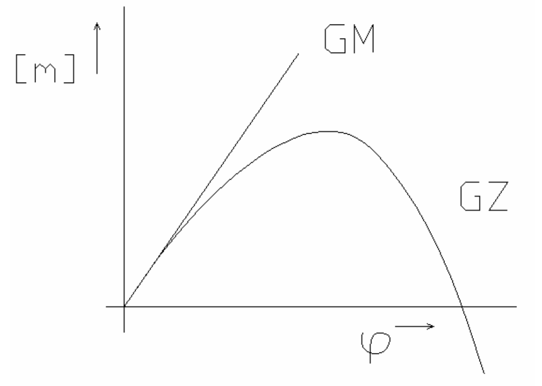

Figure 1. GZ-curve and GM.

2.2 Criteria regarding righting lever curve properties

2.2.1 The area under the righting lever curve (GZ curve) shall not be less than 0.055 metre-radians up to φ = 30° angle of heel and not less than 0.09 metre-radians up to φ = 40° or the angle of down-flooding φ_f* if this angle is less than 40°. Additionally, the area under the righting lever curve (GZ curve) between the angles of heel of 30° and 40° or between 30° and φ_f, if this angle is less than 40°, shall not be less than 0.03 metre-radians.

2.2.2 The righting lever (GZ) shall be at least 0.2 m at an angle of heel equal to or greater than 30°.

2.2.3 The maximum righting lever shall occur at an angle of heel not less than 25°. If this is not practicable, alternative criteria, based on an equivalent level of safety,† may be applied subject to the approval of the Administration.

2.2.4 The initial metacentric height GM_0 shall not be less than 0.15 m.

Figure 2. Intact stability criteria for seagoing vessels.

So, ultimately, for a given loading (and, consequently, displacement), stability is expressed as a number (GM), or a function (GZ=f(φ)). Although all stability factors are taken into account in this number and function, it is common practice to decompose the matter into two components: one which is dependant on the shape of the ship, and one depending on the height of its COG, the KG. This is expressed in the stability equations:

$$GZ = KN\sin(\varphi) - KG.\sin(\varphi).$$

$$GM = KM - KG.$$

where the first terms on the right hand side represent the effects of the hull shape, and the second terms the effect of the height of the COG.

2.1.1 Hull shape aspects

Given a representation of the shape of the ship hull, for example in a lines plan, a body plan, a table of offsets or a CAD drawing, the KNsin(φ) can be computed by means of (numerical) integration. Essentially, these computations, which are attributed to Atwood (1798) and Mosely (1850), are relatively simple, albeit arithmetically intensive and consequently laborious to be performed by man. Fortunately, the digital computer has brought quite some relief for this task. The detailed recipe to compute the KNsin(φ) falls beyond the scope of this paper, it can be found in text books, such as [Biran, 2003].
Two more hull shape-related aspects play a role:

- The downflooding of openings through which the vessel is flooded, such as air vents, ventilation ducts and hatches. It is obvious that in this case the vessel will ultimately sink, and GZ and GM will vanish. This effect is not difficult to take into account, but it must not be overlooked.
- The effect of trim on stability. KNsin(φ) is dependant on the displacement of the vessel, so it should be available for a range of displacements (or drafts, which are unambiguously linked to displacements). However, it should be realized that the trim also has an effect on the stability: take for example a vessel with a pram-type of aft body. In case of trim by the stern (fig. 3a) the wide upper part of the aft ship submerges, which enlarges the waterline and thus increases stability, while with trim by the bow (fig. 3b) the waterline is significantly smaller, leading to a reduced stability. Adequate stability software bases its computations on a three-dimensional model of the hull shape, thus taking the effect of trim into account.

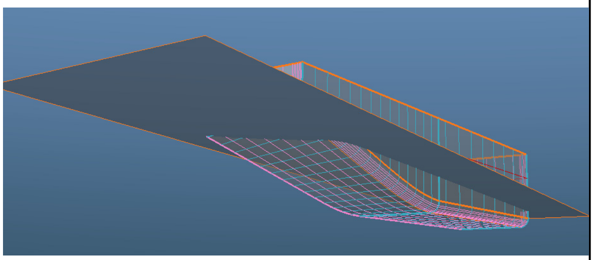
Figure 3a. SB aft part of pram-type aft body with trim by the stern.

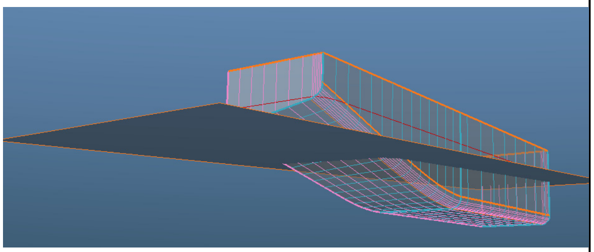
Figure 3b. The same aft body with trim by the bow.

2.1.2 KG aspects

Displacement and KG of the vessel can easily be computed by summation of all masses and vertical moments of all items of ship, consumables, ballast and cargo. The effects of the free liquid surfaces of cargo liquid or ballast are usually taken into account as a 'virtual rise of KG', which is called the 'free surface correction'. A KG which is corrected for free surfaces is written as KG'. Although this concept is perfectly valid for the upright vessel, one should realize that it remains an approximation, applicable only for small heeling angles. For larger angles and/or large trims this approximation can better be replaced by a realistic computation of the real *shifts of liquids* in the tanks.
Furthermore, we should introduce the concept of 'maximum allowable KG', which is frequently used. With the framework as discussed sofar, given a KG, the stability GZ and GM can be computed with the stability equations, and assessed against the applicable stability criteria. However, this is quite some arithmetic to be performed for each and every loading of the ship during its lifetime. It will be easier for the master or skipper if this stability computation process is inverted, which results in a *maximum KG with which the vessel just complies with all stability criteria,* commonly called the *maximum allowable KG*. The task to be performed on-board is to check whether the actual KG is not higher than the maximum allowable KG. Although this maximum allowable KG (KGmax) concept is rather *user-friendly* because it minimizes the required manual computations, it has some properties that may not be overlooked:

- Obviously, the KGmax is dependant on the draft (or displacement) of the ship, so in practice a table or graph of KGmaxs for many drafts (and/or displacements) are provided.
- In §2.1.1 it is motivated that the trim may have a significant effect on stability, so for an accurate stability assessment the maximum allowable KG values should also be available for multiple trims.
- If free surface effects are taken into account by means of a virtual rise of KG, then instead of the KG, the (virtually risen) KG' is compared with the KGmax. However, if the free surface effects are computed with the more accurate *shift of liquid* method they are not accounted in the KG, so the whole concept of maximum allowable KG is not applicable in this case.

Finally, it must be emphasized that the maximum allowable KG is an auxiliary concept, intended to relieve human computation tasks. If the stability is assessed by means of a fully computerized procedure, it can just as well be done without this concept because a computer is very good in massive computing.

2.1.3 Stability calculation software

Stability calculation software comes in many flavours, from simple, based on pre-calculated tables of maximum allowable KG values, to advanced, based on three-dimensional models of ship hull and tanks. Our company is the manufacturer of the design software PIAS [www.sarc.nl/pias/general] and the related LOCOPIAS loading software for on-board use [www.sarc.nl/locopias/general], from which a screen shot is shown in fig. 4. Its highlights are:

- All computations are based on actual 3D geometries.
- Its Graphical User Interface (GUI) permanently updates and presents the actual loading and stability situation.
- Free surface effects can be taken into account either by means of a virtual rise of KG, or as the more realistic shift of liquid.

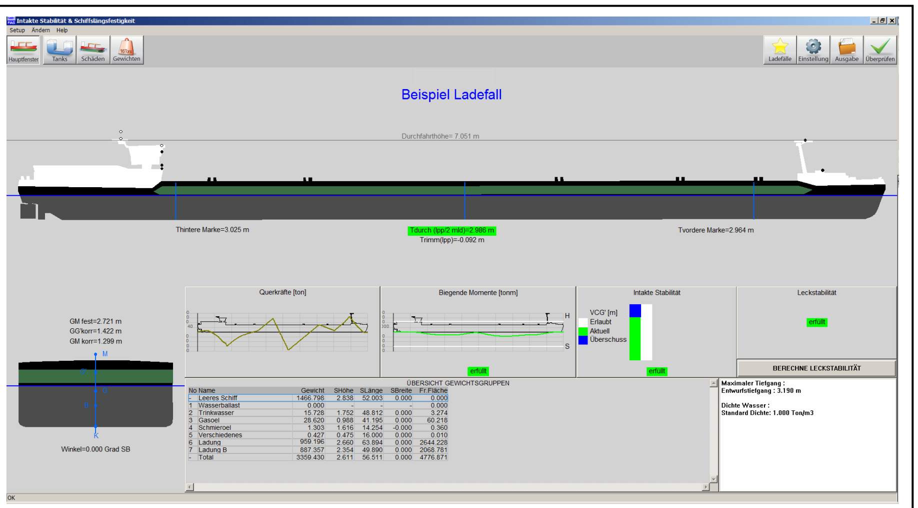

Figure 4. Main screen of LOCOPIAS loading computer of IWW tanker.

- The stability is directly checked against the applicable criteria. In addition, also the maximum allowable KG is shown in order to give a notion of the stability margin.
- Stability criteria are included for a large variety of vessels, such as seagoing, naval, inland waterway tankers, inland waterway container vessels etc.
- Has been delivered for more than 800 vessels up to now, see www.sarc.nl/locopias/references for an overview.

2.2 Uncertainty of the stability components

In an ideal world, where all dimensions, locations, weights, COGs, quantities etc. are exactly known, with the methods as discussed the stability can be determined. However, in practice these input data might not all be available with sufficient accuracy or reliability. The hull shape related component of stability (KNsin(φ) and KM in the stability equations) can be computed with a high accuracy on the basis of a lines plan or other 3D shape representation. In practice, however, inaccuracies can occur due to:

- The unavailability of a lines plan, or the use of the wrong one (for example, by assuming that two vessels are sisters, while they are not).
- Omitting the openings, or using incorrect data of their type or location. Experience shows that the reliability of data of openings on drawings is remarkably low.
- Deflection (hogging or sagging) of the hull due to uneven loading.
- Using approximation formulae instead of first-principle calculations. For example, in the regulations for stability of container vessel on the Rhine, [RheinSchUO, 1995], approximations for some shape-related parameters are provided. These regulations date back to 1986, and in those days the computer was not so ubiquitous as today, while the availability of lines plans of IWW ships was much lower, so it was rational to provide easy-to-use approximations. But times have changed, in case of an update of these regulations it could be considered to skip the approximations, and to revert to the basis.

The uncertainties of this kind can in principle be avoided, the first two by proper working practices and thorough data verification, the third by advanced stability software. So possible hull shape related inaccuracies are not intrinsic.

For the second component of ship stability, weight and COG, we have to distinguish between the fixed weight (light ship), and the variable weights such as ballast, stores, consumables and cargo:

- Although the light ship weight and COG can in theory easily be computed from lists of all ship parts and components, their uncertainty and huge amount makes it practically impossible to do that with sufficient accuracy. It is therefore common practice to perform an *inclining test* after the ship has been completed. If performed according to the rules and standards, the results of the inclining test are considered to be sufficiently accurate, although one should always be careful with later modifications and a 'natural' increase in weight gradually over time. In case of doubt it is recommended to repeat the inclining test.
- Weight and COG of ballast and liquid consumables can be determined on the basis of sounding/ullage measurements and associated tank sounding tables. Under the premise that geometries of tanks and sounding pipes have been modelled correctly, and that the sounding tables are available for multiple trims, their accuracy is deemed to be sufficient.
- Weights and COG of the cargo are another story, at least for container vessels. There have been some accidents with container vessels which are attributed to inaccuracies of the weights and COGs of the individual containers, for example with the seagoing Dongedijk in the Mediterranean in 2000, see http://nl.wikipedia.org/wiki/Dongedijk, where the investigation of the accident revealed that the real weights of quite some containers exceeded the weights of their cargo manifests. Addressing this uncertainty is the subject of the remainder of this paper.

3. Modelling of uncertain phenomenae

The world knows uncountable phenomenae which cannot be predicted or computed in a direct manner. If sufficient recordings are available, such phenomenae can be modelled in a *statistical* fashion. In this section in the first place the general method of statistical modelling is introduced, and subsequently technical applications are discussed.

3.1 Basics of statistical modelling: histogram and probability distribution

In general, constructing a simple statistical model comprises the following steps:

- Measure quite some events. This is called the *sample*.
- Draw the sample in a histogram.
- Generalize the histogram into a smooth curve, which is called the *Probability Density Function* (PDF). There are PDFs in all kinds of flavours, for example for continuous or discontinuous events, or asymmetric events. The most commonly applied PDF for continuous events is the *Gauss distribution*, a.k.a. the *normal distribution*, or *bell-curve*, see www.youtube.com/watch?v=iYiOVISWXS4 for an introduction.
- This PDF can be applied to predict the probability of a certain phenomenon. See the PDF of fig. 5, where the yellow area between *a* and *b*, divided by the total (yellow and grey) area under the curve represents the probability of occurrence of a phenomenon between *a* and *b*.

Such phenomenae can be virtually everything; life expectancies, persons' wealth, bicycle kilometers per person per year etc. etc. For example applied on the height of women in some population, as depicted in fig. 6 (from http://johnhawks.net/courses/principles/all?page=6), the steps become:

- Take a sample, in this case of 94 women.
- Divide the measurements into classes, and draw those in the histogram. Those are the blue bars in the figure.
- Generalize the histogram to a Gauss distribution. This shows an average height of 163.4 cm.
- Now this distribution can be used to predict, for example, the probability that the first person from this population you meet on a day is longer than 170 cm. This probability is given by the area under the Gauss curve at the right of 170 cm, divided by the total area under the curve, which is approximately 0.15, or 15%.

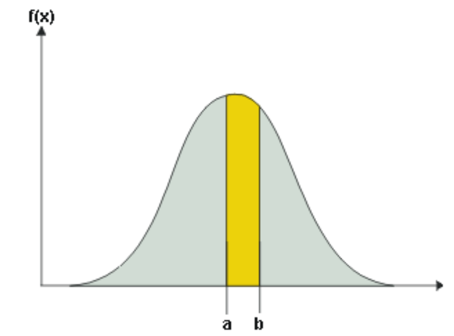

Figure 5. Example of a Probability Distribution Function (PDF).

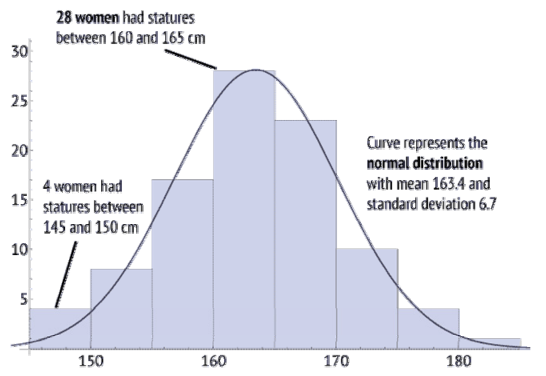

Figure 6. Distribution of women's heights of a certain population.

So with a PDF the probability of an event can be determined. Please notice that the shape of the PDF indicates the amount of variation in the sample, take for example fig. 7 which represents three different samples of the same phenomenon, for example the weight of a 20' container. They all have the same mean weight of 15 tons. However, in the wide PDF (in green) there is much more variation than in the narrower ones. In other words, in the narrow PDF (in blue) most of the containers have a weight in the vicinity of the mean of 15 ton, 95% of the containers weights lie between 12½ and 17½ ton, to be exact. On the other hand, in the widest PDF the weights are much more dispersed, with 95% of the containers between 8 and 22 ton.

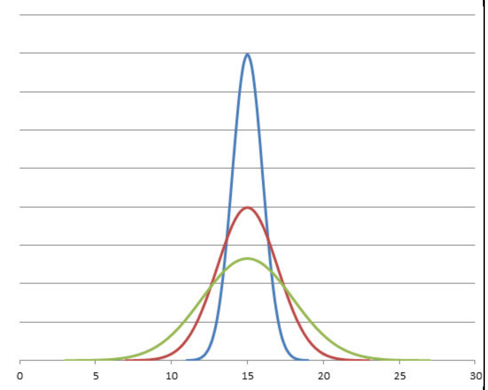

Figure 7. PDFs with the same mean, but different variations.

3.2 Application examples of probabilistic methods

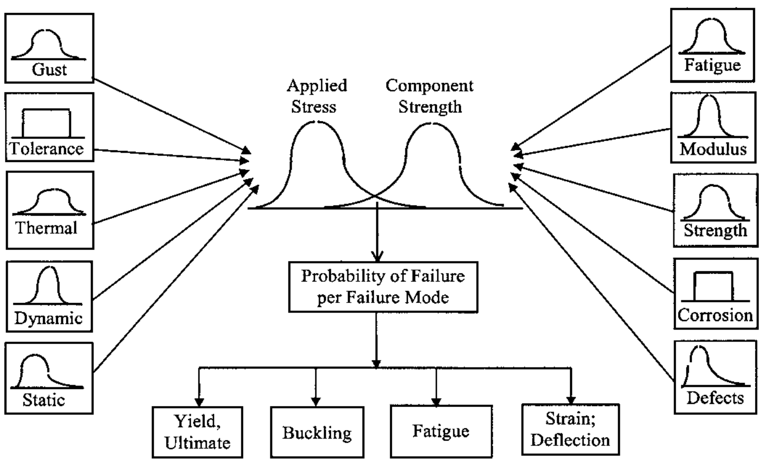

Figure 8 Outline of probabilistic strength calculation.

The probabilistic concept is an alternative for the deterministic one. The latter, which is traditionally applied in the engineering practice, is based on fixed limits of material properties, forces and quantities, while in the statistical (or probabilistic) method their uncertainty is explicitly taken into account. This has the advantage that the safety, or the risk, of a design or construction is explicitly known; it can be expressed as a probability of failure. A nice example of a deterministic calculation is the conventional strength calculation of a girder; in the end the explicit inaccuracy or uncertainty of such a calculation is unknown, in the absence of which a safety factor of e.g. 3 is commonly applied, however, even after this safety factor the remaining risk is still unknown. A probabilistic assessment of the same question is depicted in fig. 8, [Long & Narciso, 1999], where in the middle part the essence of the strength calculation can be recognized, being the actual stress vs. the component strength. With a deterministic calculation this stress and strength are each expressed in one single number, and the construction is accepted if stress is less than strength. With the probabilistic method, on the contrary, stress and strength are expressed as *probability distributions*, while the probability of failure is expressed by the small area where the strength is less than the stress. As can be seen in the figure the stress distribution is composed of other distributions, such as for gusts, tolerances and the several loading components. Similarly, the strength distribution is constituted by sub-distributions of the different strength aspects.

Other examples of the use of *probabilistics* in technology-related areas are:

- The safety assessment of Dutch sea dikes, which have a failure probability of once every 10,000 year ([Schultz van Haegen, 2003]).
- Estimation of oil reservoir quantities ([NRC-Handelsblad, 2004]).
- Seakeeping calculations for ships, where the results are expressed as probabilities of exceeding certain displacement or acceleration limits, see e.g. [Bertram, 2011].
- Damage stability for seagoing vessels. Traditionally, damage stability regulations required the survival in case of a damage of certain fixed dimensions, e.g. a damage penetration of B/5, which is a deterministic criterion. Since 1992 (for dry cargo vessels) and 2009 (for passenger vessels) *probabilistic* regulations apply, see [SOLAS, 2008], where the probabilities of damage and survival are explicitly addressed, and where the overall probability of survival is required to be higher than a minimum required probability. Background of this method can e.g. be found in [Pawlowski, 2004] and [Koelman, 2007].

4. Probabilistic modelling of container ship stability

We have seen in §2.2 that the uncertainty of weights (and COG) of individual containers is the predominant factor in the unreliability of container ship stability assessment. This uncertainty could be countered by some 'rule of thumb' additional safety margin, such as 'let us assume all containers are 10% heavier than according their cargo manifest', however, nobody knows whether a '10%' would be adequate, too low or too high. Essentially, such a '10%' would be a deterministic safety factor, and as motivated in §3.2 there is a tendency from deterministic to probabilistic methods, and it could be considered to tackle our container ship stability problem in a fully probabilistic way. An outline of such a method is sketched in the remainder of this section.

4.1 General framework

The main idea is that the stability assessment is not based on two sharp values of ship weight and KG, but on probability distributions of weight and KG instead. With those PDFs the most probable intervals of ship weight and KG can be determined. For the extreme values of these intervals stability calculations are performed, and if these all comply with the stability criteria, then the probability of capsize is lower than the accepted limit. Required steps in this process are:

1. Determine generic PDFs of weight and KG of containers. All statistical models start with measurements from the real world, and use them to construct a histogram. For our application this means the measurements of quite a number of containers, a subject which will be elaborated in the next paragraph. This step will result in public PDFs (or classes of PDFs) which should be included in legislation or standards.
2. For each individual container of a particular loadcase of a ship the applicable PDFs have to be chosen from the publicly available.
3. Use these PDFs of container weight and KG to construct one aggregated PDF for the total ship weight, and one for KG of the loaded ship[1]. This step requires some statistical processing, with the well-known *Monte Carlo* method[2], see e.g. [Kalos, 1986]. Essentially, with this method a large

[1] In the total weight and KG, the contributions from the light ship play an important role. The sharp values as resulting from the inclining test could be applied for this purpose. It is an option, however, to construct PDFs for these parameters too, so that also the uncertainty in light ship parameters is explicitly and integrally taken into account.

[2] This process is able to take into account containers whose weights are not independent from each other, as may occur frequently in practice.

amount of different load cases, even up to 1000 or 10,000, are simulated and used to construct the aggregated PDF.
4. Acceptable probabilities of capsize have to be determined, by the authorities and on forehand. All probabilistic methods have some accepted probability of failure, which is a recognition of the fact that absolute safety does not exist. In the examples of §3.2 this is expressed in the probability of a Dutch sea dike collapse of 1/10,000 per year, and the probability of non-survival[3] in SOLAS damage stability rules. For our containers ship stability subject this probability can, for example, be determined on basis of an accepted number of capsizes in the Rhine area per hundred year, but should in the end be formulated as an accepted capsize risk per ship per journey.
5. Given the two PDFs (for ship weight and KG) and the accepted capsize probabilities, upper and lower limits of weight and KG can be determined. These parameters will have to be used in a conventional stability calculation[4].
6. If that stability calculation shows compliance with the conventional stability criteria[5], then the ship is considered to be sufficiently stable.

4.2 Measuring distributions of weights and COG's of individual containers

The proposed statistical method is founded upon generic PDFs of weight and KG of containers, for which the basis is formed by means of measurements. It must be assumed that those PDFs may be dependant on other properties, so with those measurements other container parameters should also be collected, such as:

- Container size (20', 40', odd sizes etc.) and heights.
- Container type (dry cargo, tank).
- Container weight according to the cargo manifest, as well as the reliability of this parameter. The purpose of this 'reliability parameter' is that it might be reasonable to define different realiability classes[6], with different PDFs, in order to reward operators who measure their container in a reliable way with less uncertainty in their final PDF, and consequently with more loading on their vessel without impairing safety. Reverting to §3.1 and fig. 7, a reliable class has a narrow PDF, and an less reliable class a wider PDF.
- Port, and direction (e.g. seabound or landbound).

It will be evident that those measurements should be in random samples of sufficient size[7].

Finally, it must be recognized that measuring the weight of a container should be fairly easy. However, that is not the case for the KG. So further research should be devoted to an applicable KG measurement method[8]. However, if it should have to be concluded that KG measurement is not feasible, then the conventional estimation of 45% of the container height can be applied anyway, although it is a deterministic criterion.

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[3] Which lies between about 10% and 30% per collision, depending on the type and size of the vessel.
[4] It will be likely that the combination of the largest weight and the highest KG will result in the worst stability. To be on the safe side, however, it could be considered to calculate stability for all four combinations of minimum and maximum weight and KG.
[5] The present stability criteria express sharp limits on required stability parameters, and are in that sense deterministic. It could be considered to introduce the concept of probability also in the criteria, just as has been done in SOLAS damage stability.
[6] Such classes could e.g. be 'container weight unknown', 'weight specified without mentioning of source', 'weight determined by non-calibrated weighing machine', 'weight determined by calibrated weighing machine' and 'weight determined by means of measurement of draft difference'.
[7] As reference we can look at the probabilistic damage stability. The first SOLAS regulation was based on a sample of 296 past damages, the current one on a sample of about 3000 damages.
[8] It is an option to hoist the container with one or two wires and then give it a push so it will gently swing. Measuring the oscillation period gives the length of this 'pendulum', and consequently the KG of the container (after correction for the length of the wire, and the weight of a possible spreader).

4.3 Incorporation of the probabilistic method in loading and stability software

For each anticipated or real loading of a vessel the steps 2 to 6 of §4.1 should be traversed, and it will be obvious that this is not suitable for manual processing. However, they may fairly well fit in the framework of loading software, which might be installed on-board anyway. Extensions compared with conventional loading software are:

- Maintain a database of PDFs, or, alternatively, maintain a link with a public database of that kind on Internet.
- Support PDF classes of containers.
- Perform the Monte Carlo process of constructing the aggregated PDFs.

Implementation of these tasks will involve some work for suppliers, but it is certainly no rocket science.

5. Evaluation and conclusion

In this paper we have sketched a proposal for the probabilistic assessment of container ship stability, aimed at inland waterway vessels. This method is in line with other probabilistic methods that are gradually being employed in industry, also in the shipping and shipbuilding sectors. The main advantages of this method are:

- Uncertainty of the weights of containers, and their centers of gravity, is explicitly taken into account, resulting in a publicly known, well deliberated and accepted probability of capsize.
- Computationally not too complex.
- The method can be seen as an extension on the existing stability calculation methods, so it can be implemented as addendum on current ship stability evaluation software.
- Reliability of the cargo manifest container weight can be taken into account, and is rewarded in case of high quality.

However, a prerequisite for using this method is that on forehand statistics of real container weights should be collected, which will cost time and money. Other objections against this proposal might arise, such as the implicit acknowledgement that guaranteed safety does not exist, but those will be left for future discussions.

Given the concise nature of this paper, our proposal could only be sketched roughly. Quite some aspects and details should be elaborated and discussed much more extensively in order to mature the proposed method.

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