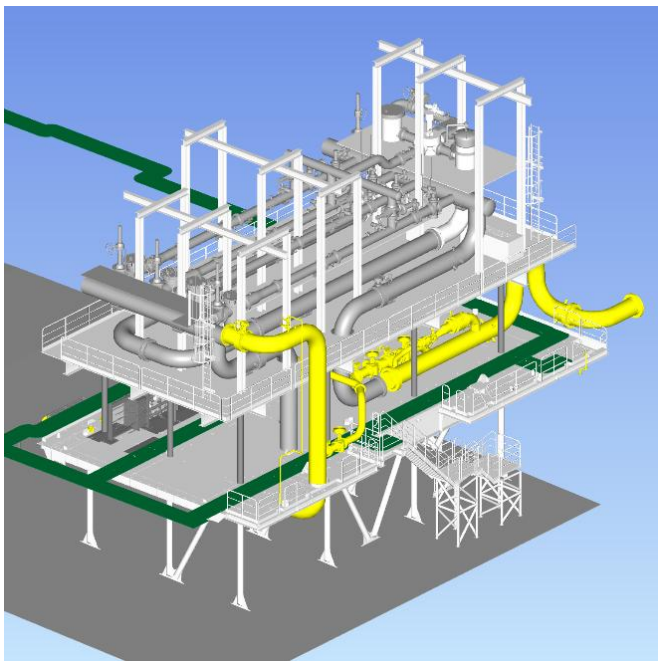
Metering module

Designing and optimization of structural metering module



SBM OFFSHORE

Fedor Perelaer

TU Delft

Summary

This bachelor end project report focused on the design and optimization of a structural metering module skid for use on a Floating Production Storage and Offloading unit (FPSO). The existing design showed inefficiencies in its space utilization and integration with surroundings, leading to congestion problems.

The main objective of this research was to develop an improved skid design that can be applied across different FPSOs. This is done by identifying critical load cases, load combinations, and potential failure mechanisms, such as stress and buckling.

This is done by starting with research on the topic, continuing with hand calculations, and using Finite Element Modeling (FEM) to do final calculations. This was done in Sesam GeniE. Hand calculations were first used to estimate cross sections needed for the chosen design. The initial design was modeled and evaluated under all different load combinations. These load combinations include gravity, vessel motion, wind loads and live loads.

Three different design concepts were considered, of which the selected solution solved existing problems by raising the skid by 4 meters on columns. This reduced congestion, eliminated the issue of double layering of steel, and created additional usable space.

Different designs were made and iteratively improved upon, until a final design was developed. All designs were checked using structural codes, and results were used in the next iteration of design. The results of the final design show that it satisfied all structural requirements, with maximum ratios of 0.83 for columns and 0.77 for beams, and a maximum deformation of 37mm. The introduction of a new level of the skid increased the steel used by 21%, raising the total weight by only 9%.

In conclusion, the raised metering skid design provided a solution to the problems that arose with the original design. It makes room for more usable space, solves the congestion problem, and solves the double steel layer. This design can be used for future FPSO projects.

Preface

This report was made as part of both my Bachelor End Project and internship at SBM Offshore. The project aimed to design a raised skid for a metering module, used in the field on different FPSOs.

I would like to thank my supervisors:

Jacques van Dartel, SBM Offshore

Craig Whyte, SBM Offshore

Dr. Pierre Hoogenboom, TU Delft

Dr. Trayana Tankova, TU Delft

My supervisors helped me get started at the company, provided help throughout the course of my internship, and gave feedback on my report. I would also like to thank both:

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Both part of the structural department, for providing support in the structural design of the skids and helping throughout the design process in Sesam GeniE.

This project provided me with the opportunity to apply my knowledge in the field, in the form of an internship at one of the biggest companies in this industry. I hope my findings in this report contribute to further development of the skids on FPSOs of SBM Offshore.

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1. Problem description

SBM Offshore has called for a redesign of the structural configuration of a metering module used on their FPSOs. The current design has problems with its use of available space and effective use of materials, alongside other smaller issues. These issues can be solved with an optimized design, focusing on the structural aspect.

1.1. Problem objective

The objective of this project is to design a metering module skid which can be used on different FPSOs. Identified are the dominant load combination, essential structural elements, and the governing failure mechanisms (stress or buckling).

The improved design can be used on future FPSOs, giving SBM Offshore more flexibility when it comes to choosing their module skids. The current design may still be beneficial in certain situations, but the improved design can be chosen in any case as well.

2. Problem approach

This is done by researching the topic, doing hand calculations, and using FEM software to check and improve the design made based on the hand calculations.

In this chapter the problem approach is described, along with background information and providing information on the work that has already been done on the topic.

SBM Offshore

SBM Offshore is an offshore company responsible for building FPSOs. They have a unique approach by building before the final details of the FPSO are agreed upon and start building the FPSO right away. The FPSO built does not have any topside equipment installed, this is built by a vendor and installed later. This means that when details are agreed upon, the FPSO is already built and only the specific topside equipment needs to be installed, improving efficiency.

The downside of the strategy is that the FPSO built is designed for heavy topside equipment where it may not be necessary. This means that some parts of the vessel are overdesigned, and other parts are not well prepared for skids designed by a vendor. The prime example of this is on the pancake layer, a layer of steel where different skids will be placed on, where a skid uses steel as its bottom layer resulting in two overlapping layers of steel. This leads to an inefficient design which can be improved. Other issues are related to congestion around the metering module, and lack of integration with nearby modules. One of the nearby modules is reserved for accommodation, which means an improved design which is integrated into the accommodation module can mean improvements in the efficiency of workers, and efficiency in materials used as both these modules could share a staircase.

This calls for an investigation into a redesign of the metering module skid. This is done in the following subchapter.

2.1. Redesign

The question of redesigning the metering module skid has been reviewed before inside the office. Three main options are addressed to combat current problems. Before presenting the options, an overview of the problems is as follows:

- Congestion problems connecting the metering skid to crude tanks. Pipe connections can only be installed after the skid was placed, leading to inefficiency when constructing the skids.
- Skid creating double steel layer after being placed on top of the pancake.
- Skid is not integrated in surroundings; accommodation of workers is next to metering module. If skid is better integrated it could save steel on, for example needing one flight of stairs less, as they could be used for both the metering skid and access to accommodation.
- Pancake beams are overdesigned for this specific module due to a standardization approach, they are prepared for the heaviest skids available, but this is not the case with a relatively light skid like the metering skid.

Solving these problems can be done in different ways. From changing the size of the skid, to a whole new design. Three options are reviewed shortly below, where one is chosen to work out. Integration of the skid in surroundings is not part of the scope but is kept in the back of the head when making decisions on the design.

Option 1:

Change the configuration of the skid. If the flow metering starts to use V-Cone flow meter, this can reduce the total length by approximately 3 meters. This would work on the congestion problems, as the footprint of the metering skid would be reduced, leaving more space for piping and offloading lines. This option would, however, not solve any of the other problems.

Option 2:

Leave all the designing to a vendor. Doing this would mean any of the overdesigning or double steel problems would be solved, as the vendor could design the beam and pancake specifically for one FPSO and would not overuse any materials, Again, the integration would not be worked on specifically, and congestion is still present as the footprint does not change.

Option 3:

Lifting the metering module one level to reduce congestion level. This raised model also creates additional space for dewaxing and water draw skid. Other problems could be solved as well because this option takes all current problems into account and solves them all.

Although all options would solve some existing problems and deserve to be looked at in the future, the third option has been chosen to dive into in this report. The metering module will not be placed directly onto the skid, but on a set of columns. Doing so would solve the congestion problem by adding lots of space under this skid, reducing the standard pancake size on topside and removing the doubling up of the steel. Integration would be possible as well, as the raised skid would be level with the accommodation close by.

The third option would look something like the model in Figure 1. As can be seen by comments in the figure, this figure is made early into their design phase and focused on visualizing the

idea. This option already added the addition of an oil-wax and a Water Draw skid. A deeper look will be taken at this option in the following chapters.

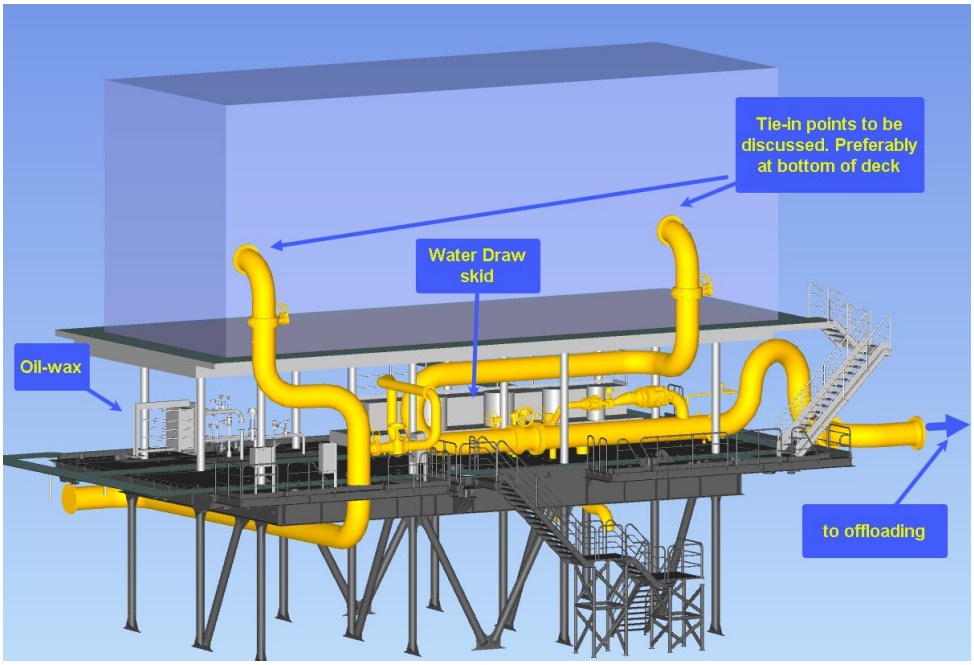


Figure 1: Model of raised metering skid

2.2. Research

Before diving into the calculations and modeling software, some research into the topic has been done based on the questions below. This is done to give context to the problem, and to inform the reader on the topic.

What is a Metering Module Skid on an FPSO?

An FPSO stands for Floating Production, Storage and Offloading unit. This is a huge vessel, typically used in deep sea areas where oil is hard to come by. The vessel is placed on the spot where oil is located underneath the ocean bed. As the name suggests, the FPSO can produce, store, and offload the found oil. All this is done while staying in the same spot in the ocean, typically for a period of around 10-20 years.

On an FPSO lots of modules are installed on the deck. This is called the topside of the vessel, or the topside environment. Examples can include modules related to the crude oil pumped out of the ground, like a Crude Separation Module or Crude Oil Storage and Offloading System. Other topside modules are related to managing heat or removing different impurities and elements form the crude oil (Raymond, 2026). The module being investigated in this report is the Metering Module. The Metering Module is a small part on the deck of the ship which is responsible for measuring the volume of oil being offloaded. The metering is equipment to measure the amount of oil leaving the FPSO and financial transaction is made on basis of this measurement, hence the importance for accurate measurement. An FPSO can produce up to 250,000 barrels per week, with a maximum of 125,000 per day. The total storage is around 1,400,000 barrels and metering is typically offloading 1,000,000 barrels at once as a parcel. This

means that, with the current price of ~100 dollars per barrel, a revenue of 100 million dollars can be realized within a month. This information is provided from within the SBM office.

A skid is a steel frame, in which any module is preassembled. This means the skid is self-contained and allows testing onshore before being placed on the FPSO. The skid is the most important part of this study, as this is the part changing from its previous design. This will be further explained in 5.3, where different designs are made.

What are the typical Metering Skids on FPSOs?

SBM Offshore is working on multiple different projects who use different metering skids, as they have different functions. These different skids differ in size, and functions can differ as well. In Figure 2 a metering skid can be seen, which uses 3 monorails as part of its set up. This is one of the functionalities which change when the dimensions are smaller.

What is a pancake in the context of an FPSO?

A pancake is a platform used on the topside of an FPSO designed to carry the weight of heavy topside equipment, like a metering module. A pancake is a crucial part of the design of a vessel, as heavy topside equipment is placed on top of a pancake.

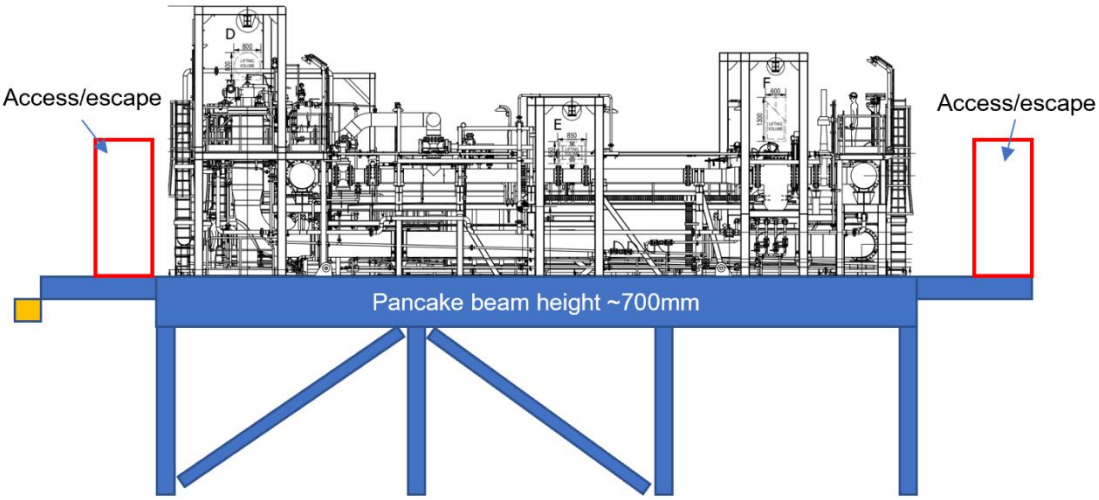


Figure 2: Pancake on an FPSO

What are the typical locations and footprints of Metering Modules on FPSOs?

The location of metering modules of FPSO is generally the same, as shown in Figure 3 below. The metering skid is placed close to the cabin as it is an important part of the FPSO. Dangerous parts of the vessel are kept far away from the accommodation, such as the flare tower or any skids making use of heat. The metering module is not considered dangerous as it consists of

pipes and metering equipment. Thus, it can be placed right next to the cabin and accommodation unit.

Rough size of a metering skid would be about 20x10 meters, which gives an indication of the size of the whole vessel which reaches lengths of over 300 meters. This puts the metering module in perspective of the size of the whole vessel, as it is a small part.

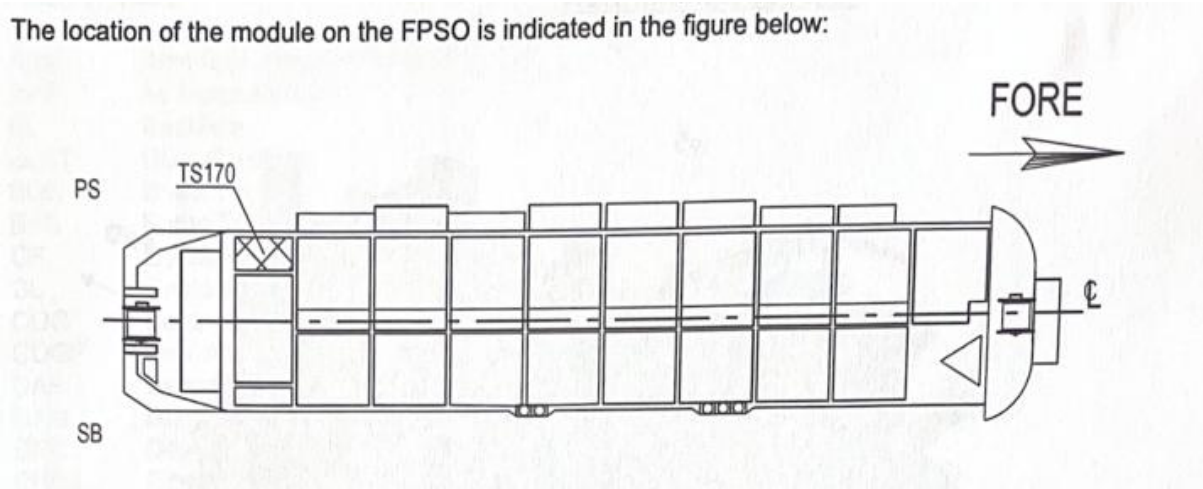


Figure 3: Location of Metering Module TS170 on FPSO

What are the interfaces between Offshore Industry vendors and FPSOs?

SBM collaborates with vendors to create topside equipment. As explained in the project description, SBM Offshore takes a risk by building an FPSO without knowing details of the project it will be used for and thus without any topside equipment installed. SBM then relies on vendors to create the equipment needed for the specific project. These are installed onshore and that way the FPSO is ready for use in a relatively short time frame. The inefficiency of this approach has been discussed as well.

3. Hand Calculations

In this chapter hand calculations will be made. The main objective of this chapter is to propose cross sections which can be used in the first design of the skid in the software. The proposed design can be seen in Figure 4, giving more insight into the goal of this report.

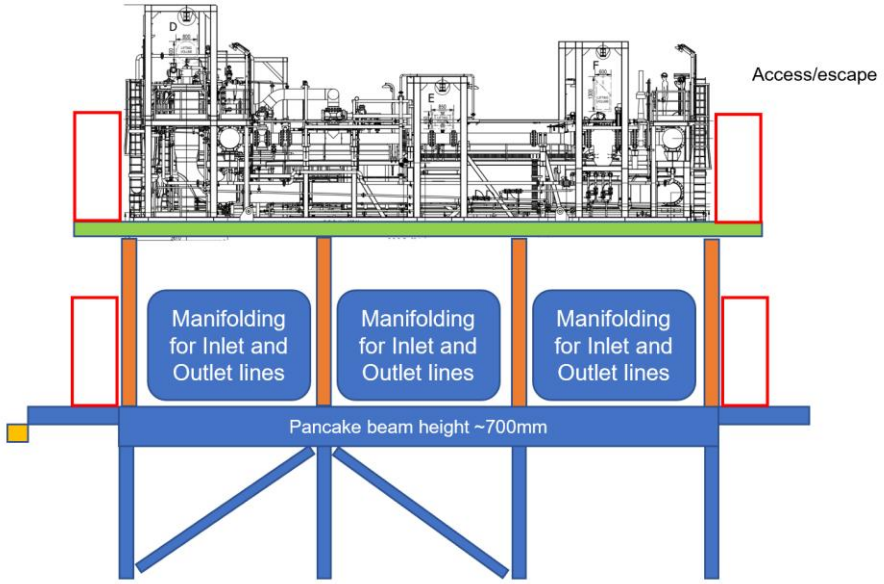


Figure 4: Side profile of Raised Metering Skid

3.1. Cross section calculations

This subchapter aims to calculate the sections needed for the columns on the new design. This is done based on information from different documents which have looked into the redesign of the skid before. These documents are:

A Navisworks design, made by a vendor. Navisworks is a 3d program, mainly being used as a viewer as it has the option to combine different 3d program files into one. The design in the file received had a first design of the raised skid, alongside the most used cross sections for similar structures. The column sections are checked by hand calculations.

A calculation report was made on the old design of the metering skid (SBM Offshore, 2025). This gives an insight into the weights of different elements of the skid, alongside the calculations being done on the skid, which is reserved for chapter 5.

The dimensions of this metering skid are given as 22780 x 10500mm. This has an area of 239.19 m^2. The weight of the skid is carried by 12 columns. The column placement is import and found to be as follows:

In X direction, the columns are 5650 mm apart in x direction, this leaves an overhang of 2915 mm.

In Y direction the columns are not evenly placed, with one being 4005 mm apart, and one 3670 mm.

Simplified version:

To simplify the hand calculations, a simplified version of the design is made: This means the columns are evenly placed with similar overhang in both directions. The weight used in the

calculation comes from the calculation report on the earlier design. Weights are split into different disciplines: structural, mechanical, piping, and electrical, instrumentation & safety and loss prevention. Structural would be the weight of the columns and beams themselves, the rest would be the weight of everything on top the skid. On the raised skid the weight that the columns would need to be able to manage would be the total weight of the skid, minus the structural weight. This is equal to:

$$445.08 - 148.94 = 294.14\ t$$

This weight is used in the following calculations. For now, all columns are assumed to be evenly placed. A sketch with distances is given below. In x direction, the overhang is 3290mm and 2540 mm. On average this is equivalent to 2915 mm, which is used in the next calculations. In y direction, the overhang is 1431 and 1393 mm. On average this is equivalent to 1412 mm. The critical load would be placed on of the middle two columns, with a loaded area of 3838x5650mm. The simplified version of the raised skid would look like this from above:

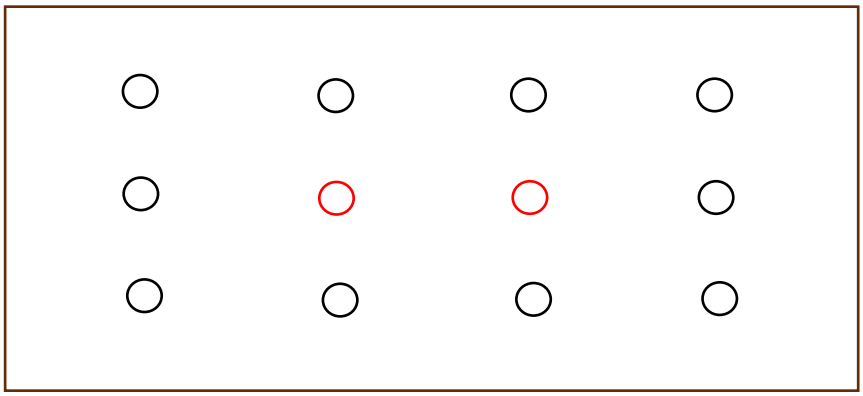


Figure 5: simplified version raised skid

The load placed on one of the two middle columns is calculated as follows. First the total weight is spread out over the area:

$$\frac{294140\ kg}{239.19\ m^2} = 1229.73\ \frac{kg}{m^2}$$

This is then converted into Newtons:

$$1229.73 * 9.81 = 12063.69 \frac{N}{m^2} = 12.1 \frac{kN}{m^2}$$

The part of this distributed load that is placed on one of the two middle columns is as follows:

$$A = 3.838 * 5.650 = 21.6847 m^2$$

The total load on one of the two middle columns then follows:

$$F = 12.1 * 21.6847 = 262\ kN$$

This load of 262 kN is used in the following calculations regarding buckling.

Buckling

What should the moment of inertia be, so the column does not collapse under this load? The skid is raised four meters, and the steel used has a Young's modulus of

Use Eulers buckling formula:

$$F_{crit} = \frac{\pi^2 EI}{(kl)^2}$$

Where:

$$F_{crit} = 262000[N]$$
$$E = 206\ [GPa]$$
$$l = 4\ [m]$$
$$k = 0.5\ [-]$$

The k value is given based on the end conditions. If both ends are fixed, then rewriting the formula and filling in the values gives:

$$I = \frac{F_{crit} * (k * l)^2}{\pi^2 * E} = \frac{262000 * (0.5 * 4)^2}{\pi^2 * 206 * 10^9} = 5.15 * 10^{-7}\ m^4$$

If both ends are pivoted, this means the k factor is equal to 1. This gives the following required I:

$$I = \frac{262000 * (1 * 4)^2}{\pi^2 * 206 * 10^9} = 2.06 * 10^{-6}\ m^4$$

If one end is pivoted, the k factor is equal to 0.7. This gives the following required I:

$$I = \frac{262000 * (0.7 * 4)^2}{\pi^2 * 206 * 10^9} = \ 1.01 * 10^{-6}\ m^4$$

In this case, it is assumed that both ends are pivoted, thus choosing $I = 2.06 * 10^{-6}\ m^4$

Compressive strength

To check if the column can withstand the load without being crushed, the following formula is used:

$$\sigma_c = \frac{N}{A}$$

If S345 steel and the found load of 262 kN are used, the required area will be:

$$A = \frac{262000}{345 * 10^6} = 0.00076\, m^2$$

Based on the calculations made, and to keep aligned with the Navisworks model provided, the chosen section is a pipe section with diameter 0.2731 m and a thickness of 0.01509 m. For the next chapter on the software being used, the pipe section is called P273p1x15p9.

	Pipe section	Required	Meets requirements
$I\ [m^4]$	$1.02 * 10^{-4}$	$2.06 * 10^{-6}$	Yes
$A\ [m^2]$	0.0122	0.00076	Yes

As can be seen, the chosen pipe section might be over designed, but this is done to be ready for different loading conditions being applies when out in the ocean. This can be wind loads, water getting on the ship, extra equipment like piping or safety measures being added later, acceleration forces and simply to be sure it is safely designed. In the next chapter these chosen column designs are evaluated and if needed, changed.

4. Software

In this chapter Sesam GeniE will be used to model the skid.

GeniE is a finite element modelling (FEM) tool used for conceptual modelling and analysis of offshore structures. It is used in the field to calculate designs based on all different combinations of loads imaginable. This way it is ensured that the skids can withstand all loads possible on the FPSO.

4.1. Modeling

Modeling is done based on the GeniE model and calculation report based on the old module skid, and the Navisworks file made on the new proposed skid. Assumptions made in this chapter are based on the assumptions made in the calculation report. This model will be modified to create the proposed raised skid.

The way the actual metering module is modeled in GeniE is shown below in Figure 6. To make sure the metering module is added in GeniE, without the need to model every single pipe or column of the metering module, it is modeled as a big box. The pyramid of pipes in the GeniE model is a way to simulate the center of gravity of the module, and to link its movement to the edges of the module. In the following subchapters, the GeniE model is subjected to different loads and load combinations, and using its FEM software, the whole model is checked according to different codes.

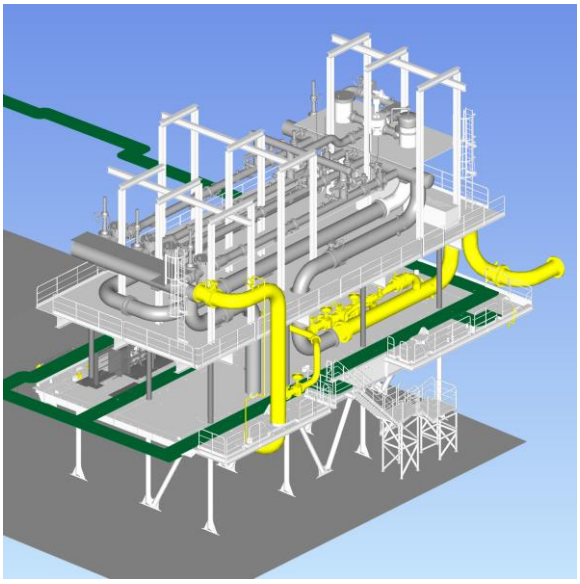
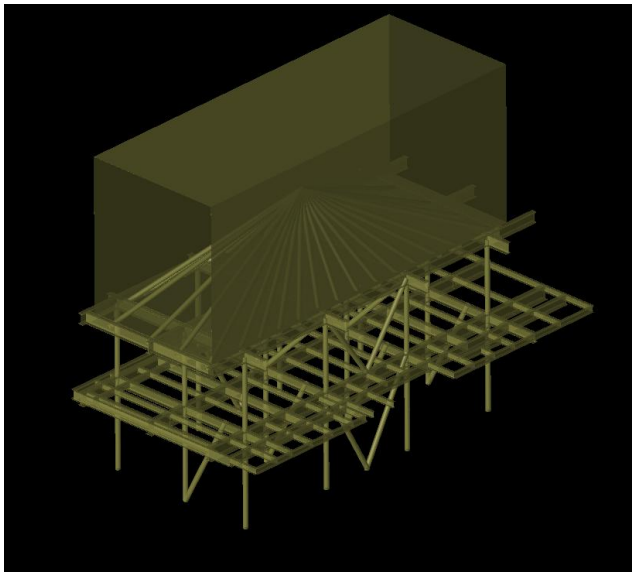
Autodesk Navisworks	Sesam GeniE
	

Figure 6: Navisworks and GeniE comparison

4.2. Weights

Weights are divided based on four disciplines: Structural, mechanical, piping, and others, which include electrical, instrumentation and safety loss protection. The differences between the old model and the modified model can be seen in Table 1. This is because structural weight includes additional trimmer beam (6.5% of piping gross), 10% weight contingency and module support weight (14.52 mT which is not included in WCR).

Table 1: Weight differences GeniE models

Discipline	Weight [t]	Weight [t]	Difference [%]
Structural	148.83	189.6	27.4
Mechanical	214.5	214.5	0
Piping	71.31	80	11.6
Electrical, Instrumentation & Safety	10.34	10.34	0
Total	**445.08**	**494.44**	**11.1**

This raised skid leaves more room for piping, which is also added in the form of a de-waxer and a water draw skid being added on the main floor. The mechanical and Electrical, Instrumentation & safety disciplines do not change.

4.3. Load Cases

In the GeniE model, load cases are created to simulate the actual loading condition to which the module is subjected to in the different design conditions. These load cases are a linear combination of basis loads as defined in Table 2.

Table 2: Basic load cases

No	Description	Unity case
1	Gravity	-9.81 m/s^2
2	Longitudinal acceleration	1 m/s^2
3	Transverse acceleration	1 m/s^2
4	Vertical acceleration	1 m/s^2
5	Vessel Vertical deformation	1mm relative longitudinal deflection (hogging condition) between columns of two consecutive topside frames
6	Wind load pos. longitudinal x direction	10m/s wind velocity
7	Wind load neg. longitudinal x direction	10m/s wind velocity
8	Wind load pos. longitudinal y direction	10m/s wind velocity
9	Wind load neg. longitudinal y direction	10m/s wind velocity
10	Live Load	4.51 kN/m^2 for the access areas; reduction for higher decks at higher elevation

Accelerations

Basic load describes the loading as result of gravity which is equal to -9.81 m/s^2. Basic load cases 2 through 4 consist of an acceleration of 1 m/s^2 in the x, y, and z direction due to motion of the vessel itself.

Vessel deformation

Basic load case five describes the displacements at main deck level due to vessel deformation. These deformations are applied at the support points where the module is connected to the vessel. The vessel deforms due to all the load applied by different modules.

Exact displacements due to deformations are modeled based on the deformations of the original model. As the skid footprint remains unchanged in the updated design, these values are considered applicable. Table 3 displays the deformations of the support points. The columns called *dx*, *dy* and *dz* are the movements in meters in their respective direction, which are relatively small. Their influence should however not be underestimated, as even minor movements can cause tilting of the skid. Given that the revised design features an increased height and a higher center of gravity, these effects may significantly influence the overall load distribution.

Table 3: Information on deformation

Support point	x-coord	y-coord	z-coord	dx [m]	dy [m]	dz [m]
PDisp_FR45.20	1.7	17.99	-0.39732	-0.003	0	0
PDisp_FR46.20	5.65	17.99	-0.39732	-0.001	0	-0.00008
PDisp_FR47.20	11.3	17.99	-0.39732	0.001	0	-0.00008
PDisp_FR48.20	16.95	17.99	-0.39732	0.003	0	-0.0007
PDisp_FR45.25	0	22.485	-0.51634	-0.003	0	-0.0007
PDisp_FR46.25	5.65	22.485	-0.516343	-0.001	0	-0.00008
PDisp_FR47.25	11.3	22.485	-0.516343	0.001	0	-0.00008
PDisp_FR48.25	16.95	22.485	-0.516343	0.003	0	-0.0007
PDisp_FR45.30	0	26.49	-0.622392	-0.003	0	-0.0007
PDisp_FR46.30	5.65	26.49	-0.622392	-0.001	0	-0.00008
PDisp_FR47.30	11.3	26.49	-0.622392	0.001	0	-0.00008
PDisp_FR48.30	16.95	26.49	-0.622392	0.003	0	-0.0007

Wind Loads

The basic load cases six through nine describe the wind loading due to a wind velocity of 10 m/s. The wind velocity results in pressure that is applied at the pancake, superstructure, and large equipment.

The wind pressure p_{wind} $\left[\frac{N}{m^2}\right]$ is calculated as follows:

$$p_{wind} = \frac{1}{2}\rho . v_{ref}^2 C_s$$

Where:

ρ = mass density of air 1.22 kg/m^3

v_{ref} = wind speed [m/s]

C_s = shape coefficient

Since the wind load is projected on the overall projected area of the module, the shape coefficient is 1.0. Standard temperature and pressure are assumed in the mass density.

In the calculation report of the base design, the total applied wind loads were as follows:

Table 4: Total applied wind load summary

Basic Load Case	Total applied force [kN] X-direction	Total applied force[kN] Y-direction
BLC_WXp	10.63	-
BLC_WXn	-9.54	-
BLC_WYp	-	20.33
BLC_WYp	-	-20.33

This total applied load was applied in the form of two line loads, one on the pancake level and one on the mechanical part itself. In the first iteration of the calculations, the line load applied on the pancake level was also applied on the first level of the raised skid. This gave high wind loads, which are shown in the table below.

Table 5: Total applied wind summary first calculation

Basic load case	Total applied force old case [kN] X or Y-direction	Total applied force new case [kN] X or Y-direction	Difference [%]
BLC_WXp	10.63	13.9	30.8
BLC_WXn	-9.54	-13.9	45.7
BLC_WYp	20.33	27.0	32.8
BLC_WYp	-20.33	-27.0	32.8

Live load

Basic load case ten describes the load applied to the skid, as the skid is accessible for people. Live loads are calculated according to Table 6.

Table 6: Live load for accessible areas

Local design	4.51 kN/m^2	All decks
Primary design	4.51 kN/m^2 * 100%	Pancake level
	4.51 kN/m^2 * 50%	1st deck above pancake level
	4.51 kN/m^2 * 25%	2nd deck above pancake level
	4.51 kN/m^2 * 12.5%	3rd deck above pancake level
	4.51 kN/m^2 * 6.25%	4th and further deck above pancake level
Global strength	Live load same as primary design	

These live loads are considered as vertical loads of these areas.

The effective area load will be equally distributed over the entire deck per elevation. The calculations of the pancake and 1st level are done as follows:

The walking paths on the redesigned skid can be seen in Figure 7. The total area of the walking paths is calculated and used in the calculation of the weight.

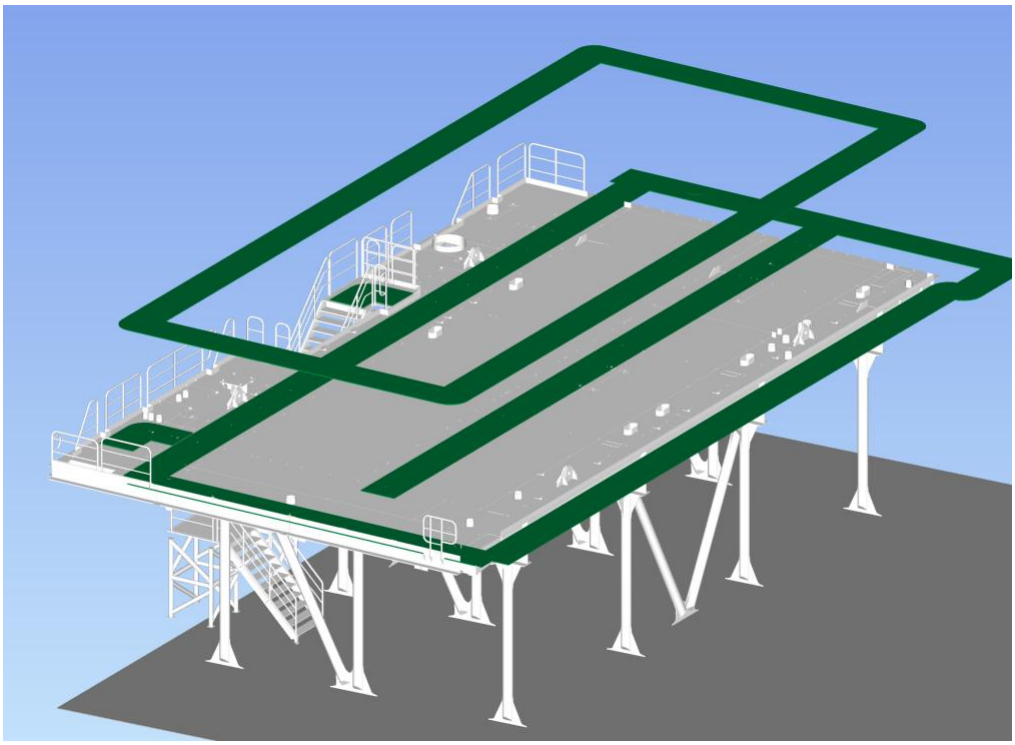


Figure 7: Walking paths of both floors

For the ground floor the total area of walking paths follows from the lengths and widths. Width is 1 meter, which is the same everywhere. The parts giving access to the steps down are added to the length of the middle path which does not fully extend, roughly giving the same total area as a full length path. A length of 11.5 m on the short sides, and length of 23 m on the long sides gives:

$$(11.5 * 2 + 23 * 3) * 1 = 92\, m^2$$

A live load of 4.51 kN/m^2 is used, this gives:

$$92 * 4.51 \frac{kN}{m^2} = 415\, kN$$

This is spread out over 239.19 m^2, which gives a distributed load of:

$$\frac{415}{239.19} = 1.74 \frac{kN}{m^2} = 174 \frac{kg}{m^2}$$

A total weight is found as:

$$174 * 239.19 = 41619\, kg$$

This weight is modeled as a blanket with the dimensions of the ground level.

The same is done for the first level above the pancake. The total area of walking paths is found as follows:

$$(11.5 * 2 + 23 * 2) * 1 = 69\, m^2$$

The same calculations are made, with an added factor of 50% according to Table 6. This gives a total weight of 15560 kg.

4.4. Load Combinations

The load cases described in chapter 4.3 are used in load combinations to evaluate the metering skid. All loads receive a safety factor, and a different combination of loads is used in each load combination. An example of a load combination can be seen in Table 7. This combination simulates the situation that the vessel is accelerating in positive x- and z direction, and negative y, on a deformed vessel, with wind going in the positive x direction. There are 48 different load combinations considered. The results can be seen in the next chapter.

Table 7: Example load combination

Load Combination 20101	Factor
BLC_Ax	1.05
BLC_Ay	-1.38
BLC_Az	1.66
BLC_Def	2.48
BLC_Gravity	1
BLC_Liveload	0
BLC_WXn	0
BLC_WXp	2.9584
BLC_WYn	0
BLC_WYp	0

5. Software Calculations

In this chapter GeniE calculations are done. The first iteration of calculations is shown below. To follow the regulations made for code checks, the beams and columns are checked separately, according to different codes as there are different standards for columns and beams. These differences are explained in the next two subchapters.

5.1. Beams

The beams are checked based on AISC ASD 2005. This refers to the American Institute of Steel Construction Allowable Stress design from 2005. This steel design code is widely used for code checking beams.

The beams are selected as a subset and run through the simulation which results in a table of code checks.

The way GeniE presents the results is very insightful, as it presents the option to display the results in the worst case scenario. If the worst case scenario is selected, every member will display its worst code check in one of the 48 load combinations. This gives the opportunity to check if the beams can withstand any load in one look. This is displayed in Figure 8.

Not only the code check is displayed in the table, but also the way it was reached, for example due to shear stress or compression. Even the position in the beam where this maximum was reached is visible.

As can be seen in Figure 8, all beams pass the check. Even the pancake sections which are reduced from 1500mm to 700mm easily passed the check.

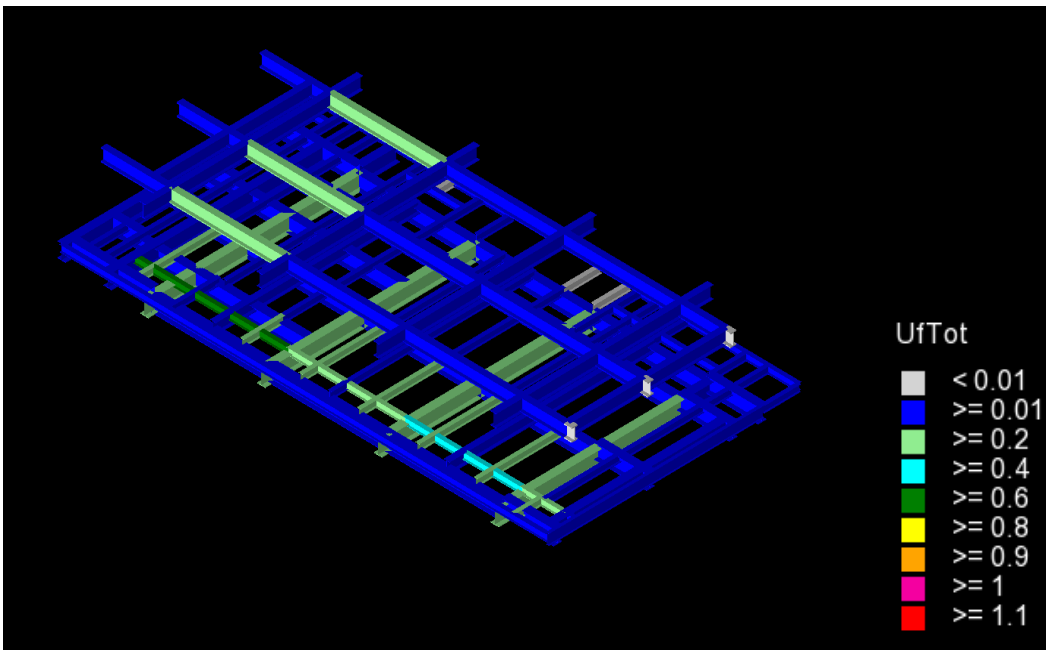


Figure 8: Results code check Beams

5.2. Columns

The columns are checked based on API WSD 2014. This stands for America Petroleum Institute Working Stress Design from 2014. This code is made specifically for fixed offshore platforms (American Petrolium Institute, 2014). As the columns are fixed to the FPSO, this code applies to this metering module.

The code checks the columns based on different formulas. These formulas check the axial tension, axial compression, buckling, and shear. They will be shown and explained below.

Axial Tension

The allowable tensile stress, F_t, for cylindrical members subjected to axial tensile loads should be determined from:

$F_t = 0.6F_y$

where:

F_y is the yield strength, [MPa]

As an example, this F_t is calculated, where a yield strength of 345 MPa is used:

$$F_t = 0.6F_y = 0.6 * 345 = 207\ MPa$$

Axial Compression

Axial compression is checked based on column buckling. The allowable axial compressive stress, F_a, should be determined from the following equations:

$$F_a = \frac{\left(1 - \frac{\left(K\frac{l}{r}\right)^2}{2C_c}\right)F_y}{\frac{5}{3} + \frac{3(K\frac{l}{r})}{8C_c} - \frac{\left(K\frac{l}{r}\right)^3}{8C_c^3}}$$

For $K\frac{l}{r} < C_c$

$$F_a = \frac{12\pi^2 E}{23\left(K\frac{l}{r}\right)^2}$$

For $K\frac{l}{r} \geq C_c$

Where:

$$C_c = \left(\frac{2\pi^2 E}{F_y}\right)^{0.5}$$

E is Young's Modulus of elasticity, MPa;

K is the effective length factor;

l is the unbraced length, m;

r is the radius of gyration.

As an example, one of the top columns allowable axial compressive stress F_a is calculated below:

$$l = 4m, K = 1, E = 2.06 * 10^{11} Pa, A = 0.01225\, m^2, I = 9.93 * 10^{-5} m^4, F_y = 345 * 10^6 Pa$$

From this data, radius of gyration is calculated:

$$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{9.93 * 10^{-5}}{0.01225}} = 0.091m$$

The slenderness ratio is calculated like this:

$$K\frac{l}{r} = 1 * \frac{4}{0.090} = 44.4$$

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}} = \sqrt{\frac{2\pi^2 * 2.06 * 10^{11}}{345 * 10^6}} = 108.8$$

Since $K\frac{l}{r} < C_c$, the top formula is used.

$$F_a = \frac{\left(1 - \frac{\left(K\frac{l}{r}\right)^2}{2C_c}\right) F_y}{\frac{5}{3} + \frac{3(K\frac{l}{r})}{8C_c} - \frac{\left(K\frac{l}{r}\right)^3}{8C_c^3}} = \frac{\left(1 - \frac{(44.4)^2}{2 * 108.8}\right) * 345 * 10^6}{\frac{5}{3} + \frac{3(44.4)}{8 * 108.8} - \frac{44.4^3}{8 * 108.8^3}} = 174\ MPa$$

Bending

The allowable bending stress F_b is considered based on the $\frac{D}{t}$ ratio.

For $\frac{D}{t} \leq \frac{10340}{F_y}$, $F_b = 0.75F_y$,

For $\frac{10340}{F_y} < \frac{D}{t} \leq \frac{20680}{F_y}$, $F_b = \left(0.84 - 1.74\frac{F_y D}{Et}\right) F_y$,

And for $\frac{20680}{F_y} < \frac{D}{t} \leq 300$, $F_b = \left(0.72 - 0.58\frac{F_y D}{Et}\right) F_y$.

In the example column, this comes to the following conclusion:

$$\frac{D}{t} = \frac{0.2731}{0.01509} = 18.10$$

$$\frac{10.340}{345} = 29.97$$

Since $18.10 < 29.97$, the first equation is used:

$$F_b = 0.75F_y = 0.75 * 345 = 268.75\ MPa$$

Overall column check

From these calculations, the allowable stresses are found to be $F_t = 207\ MPa, F_a = 174\ MPa$ and, $F_b = 268.75\ MPa$. The lowest allowable stress is used in the code check, which is $174\ MPa$

in this case. If, for example, a stress of $100\ MPa$ is put on this specific column, a code check would be equal to:

$$\frac{100}{174} = 0.57$$

The calculations for allowable stresses like in the example are done for every column, based on every load combination. This means that one code check for the columns calculates 3 different stresses, 48 load combinations + 8 load cases, for ~25 columns, $3 * 56 * 25 = 4200$ stress calculations. Sesam GeniE of course has no problem with these calculations, and can put the result in a clear overview, which is done in the next paragraph.

Results column check

The value 0.57 will be displayed in the form of a color like the beam design. A code check is conducted on the first design and layout of the columns. As can be seen in Figure 9, some columns of the current design do not pass the code check. Figure 9 shows the worst case scenario of each column. This means that there is no possibility that the 6 columns failing in the figure all fail at the same time. Almost all failures come from different load cases, where especially the wind seems to have a significant impact on the columns on the opposite side of the skid.

Failure of columns is not acceptable and thus needs to be changed.

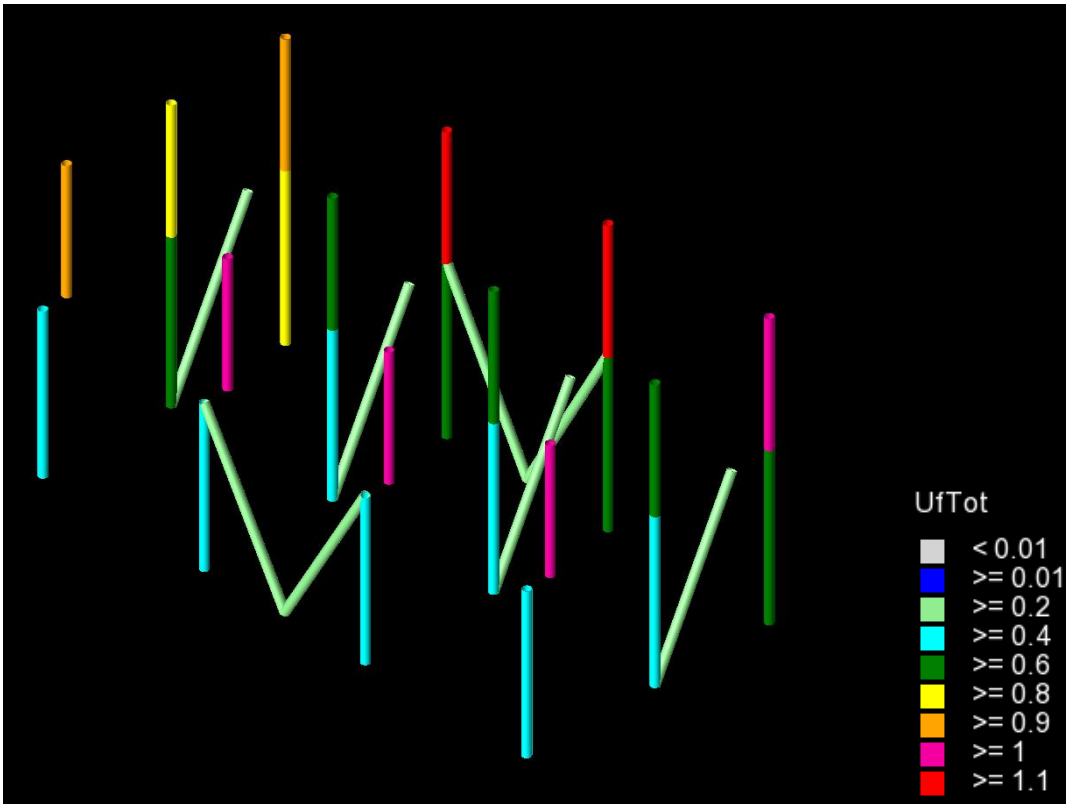


Figure 9: Results code check columns

5.3. Designs

In this subchapter, different designs are shown. The first design check is shown in subchapters 5.1 and 0 as an example of the code checks. The code checks are done for each design and then improved upon. These designs all make changes to the pancake layout and work further

on the changes made in the previous design. The first design change. focuses on the following changes:

- Unnecessary beams removed in the bottom floor, as most of the load goes straight to the beams,
- Changed the layout of the columns, to make sure columns of both levels are placed above each other.
- Added diagonal columns to help with wind loads.
- Wind loads changed

These changes are explained thoroughly, for the next designs only the code checks are shown until the final design which shows all the relevant results.

5.3.1. First design

As can be seen in Figure 10, the beam design is made for heavy loads on one side of the pancake. This was understandable, as heavy loads were applied in the old design on this side in the form of piping. This is however not relevant anymore as most of the piping is moved upwards to the first level. In the first optimization beams were removed. This can be seen in Figure 11.

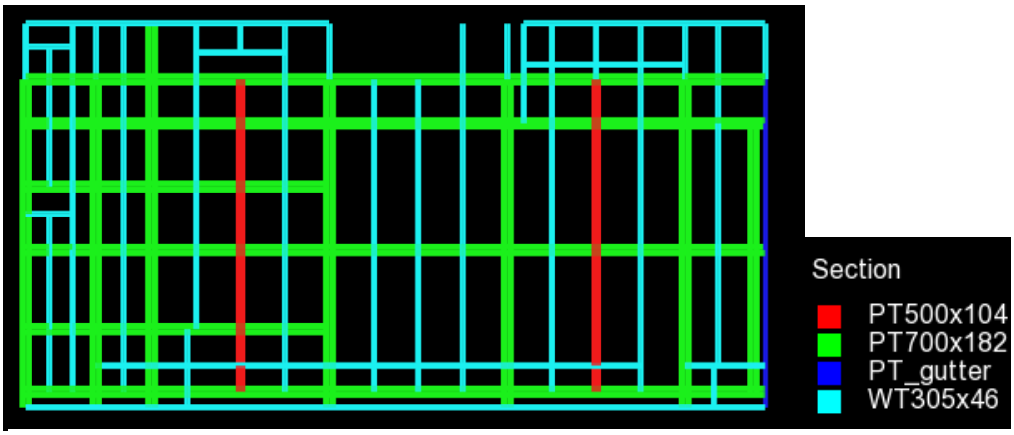


Figure 10: Beam layout first design

The main changes can be seen on the left side of the skid.

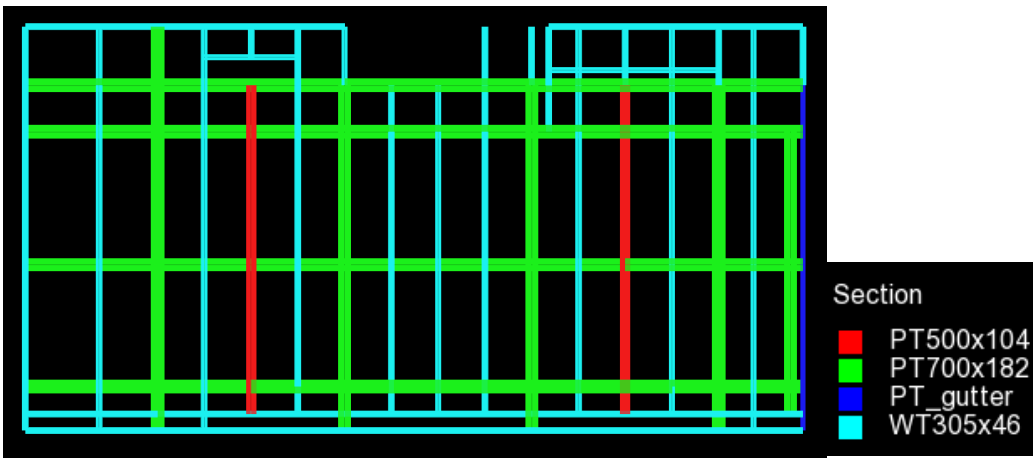


Figure 11: Beam layout second design

Layout change columns

As can be seen in the pictures below, the first design made use of a set of columns on the pancake that was not placed directly above another set of columns. This means that around one third of all weight carried from the skid placed on the top level rested on just 4 beams. Alongside the new placement of the columns, diagonals were added to help with the wind loads. Alongside the four diagonal beams added, 2 beams were added in the form of a V on the second level. These can be seen in the results.

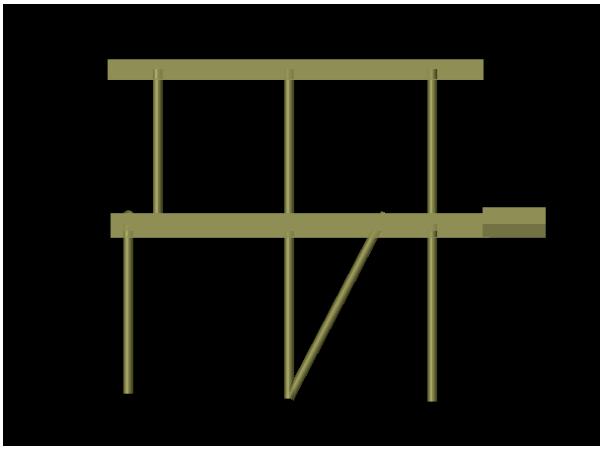
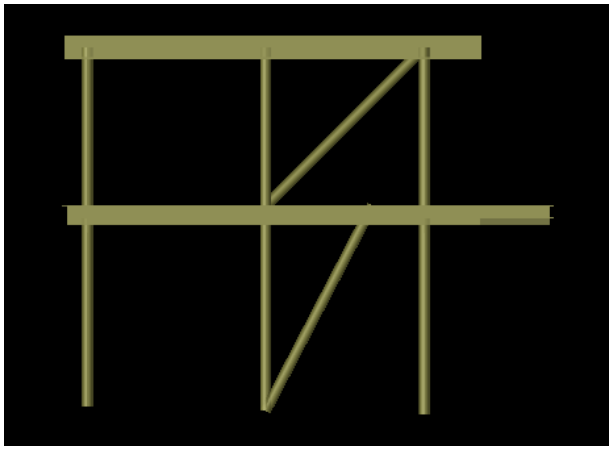
Old	New
	

Figure 12: Difference column designs

Wind loads

Another problem of the first iteration was the wind loads. The columns on the opposite side of the wind load that was applied to the module on the top level were prone to failing, due to the high wind load applied. Shown below is the same table as before, showing the wind loads applied in the old calculations, and the ones used in the first iteration of this report. BLC_WXp stands for Basic Load Case of Wind in X direction, Positive. BLC_WYn is the negative y-direction.

Basic load case	Total applied force old case [kN] X or Y-direction	Total applied force new case [kN] X or Y-direction	Difference [%]
BLC_WXp	10.63	13.9	30.8
BLC_WXn	-9.54	-13.9	45.7
BLC_WYp	20.33	27.0	32.8
BLC_WYn	-20.33	-27.0	32.8

For this iteration, the old wind loads are used and spread out over three line loads. This is done by keeping the line load on the mechanical part the same as before and spreading out the line load that was originally on the pancake out over the two levels. This way the total wind load is more top heavy than before.

Wind used:

Basic load case	Total applied force [kN] X or Y-direction
BLC_WXp	9.54
BLC_WXn	-9.54
BLC_WYp	19.9
BLC_WYn	-19.9

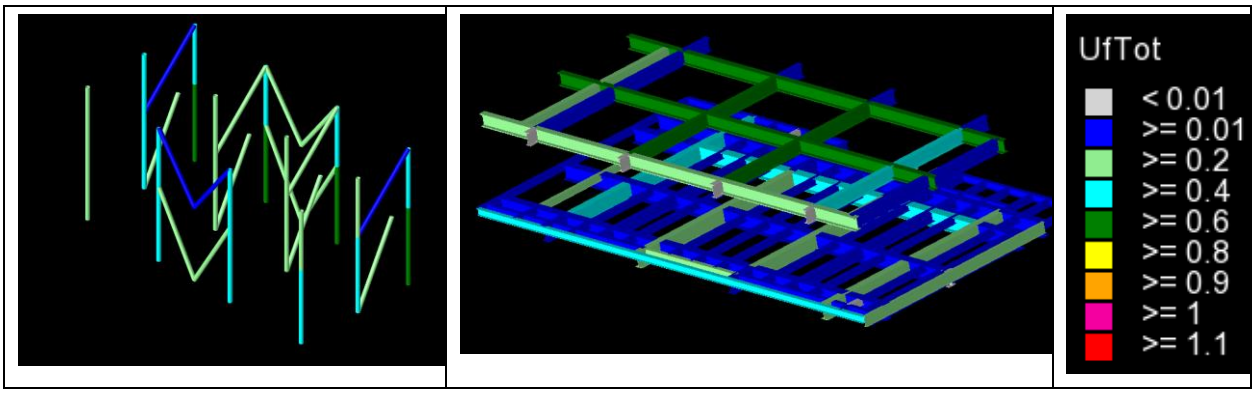
Results first design cycle

In the results of the changes made can be seen in Table 8. These pictures once again show the highest code check of each individual column. This means that this is not one of the load cases being shown, but that these highest code checks are likely to be from different load cases.

The columns are clearly better designed than before, as none of the columns are close to failing. Four of the four columns added can be seen to have a code check of <0.2. In the next design these columns will be deleted as they do not have enough impact on the overall design.

Table 8: Code checks second design

Column code check	Beam code check	Code check legend



Several design iterations were done by modifying the layout of beams and columns, introducing additional columns, adjusting existing column configurations, and varying beam cross section of the pancake level. The results of these models are provided in Appendix A and Appendix B, as including them in the main report would add limited value.

5.3.2. Final design

The final design changed from the first design, focusing on the same parts as the first design iteration. The final design is shown in Figure 13. Main differences from the first design are:

- Column layout. The final design has changed where the diagonal columns are connected, which is now in the connection point with the other beams and columns, instead of halfway connected to a beam. The first level now has two sets of diagonal columns, two on each side.

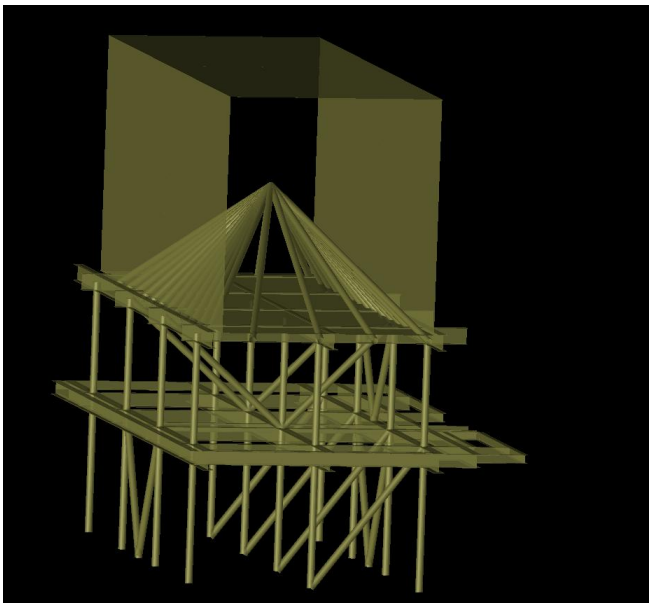


Figure 13: Final Design

The final design has an optimized pancake design as well, which can be seen in Figure 14. The pancake design changed significantly from the first design, seen in Figure 10. This was expected, as the first design was made to hold all weight, and now most of the weight is moved to the first level, leaving the pancake overdesigned.

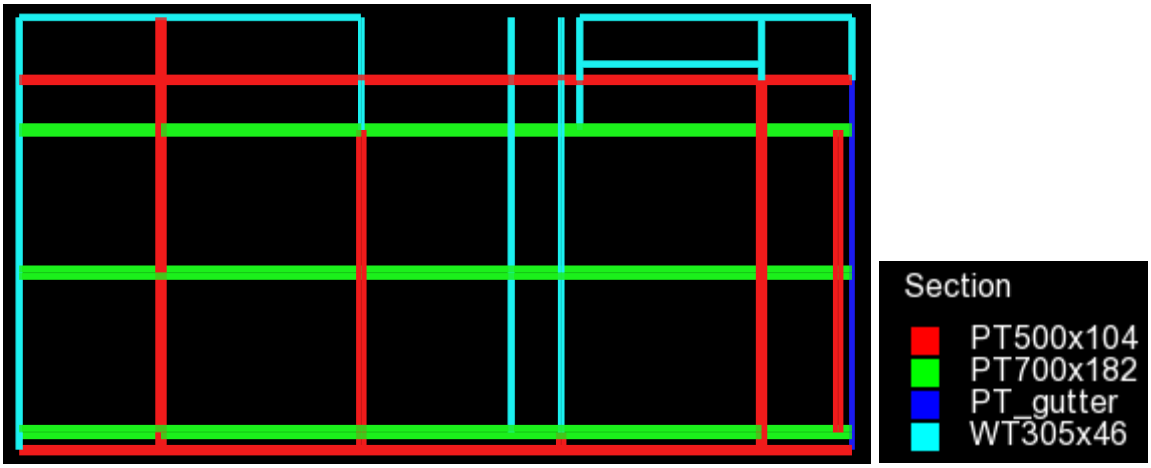


Figure 14: Final Pancake Design

The first level has not changed significantly since the first design. This design was based on the Navisworks file and the hand calculations, which means it was already thought out quite well. The location of one of the beams did change, making sure it was directly above the set of columns connected to the vessel. The beam section can be seen in Figure 15. As can be seen in this figure, all beams on this level use section with height 600mm. PG600x312 has one difference, which is in the thickness. The web being 25mm instead of 16mm, and the flange being 45mm instead of 25mm.

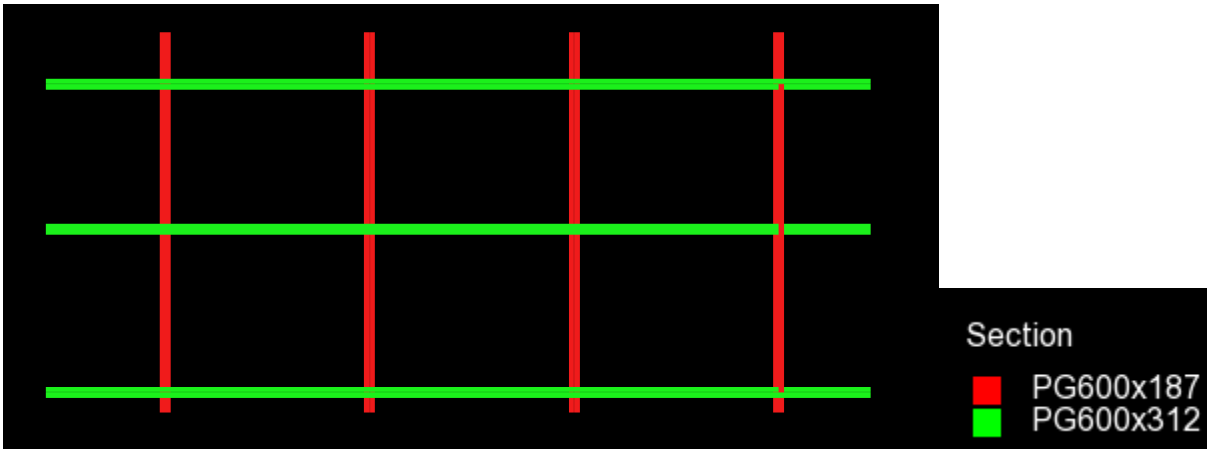


Figure 15: Final beam design first level

The final design is again checked according to the codes explained earlier. The deflections of the plate at the top level are also checked. The results of the redesign are shown in chapter 6, Results.

The weights of the currents design are shown in Table 9 below. As can be seen from the weights, the changes lowered the structural weight a little bit, due to the changes in the pancake beam design, while still adding two columns. This lowered the weight by 5%.

Table 9: Weights different designs

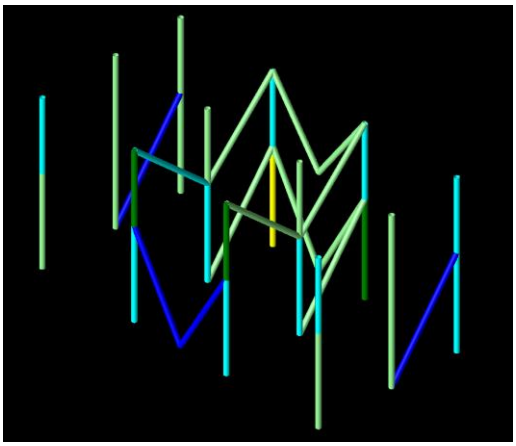
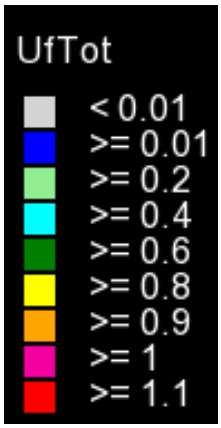
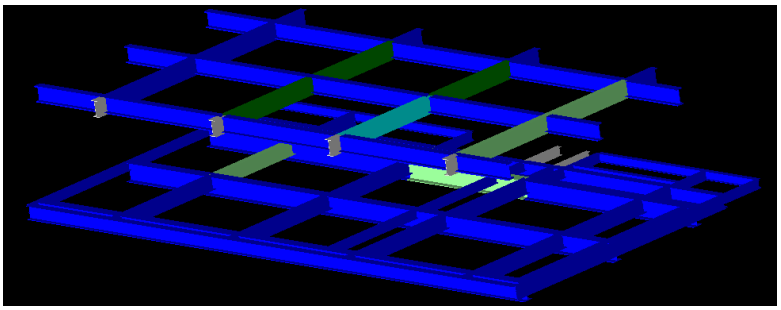
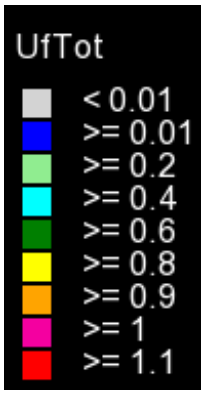
Discipline	Weight first raised design [t]	Weight last raised design [t]	Difference [%]

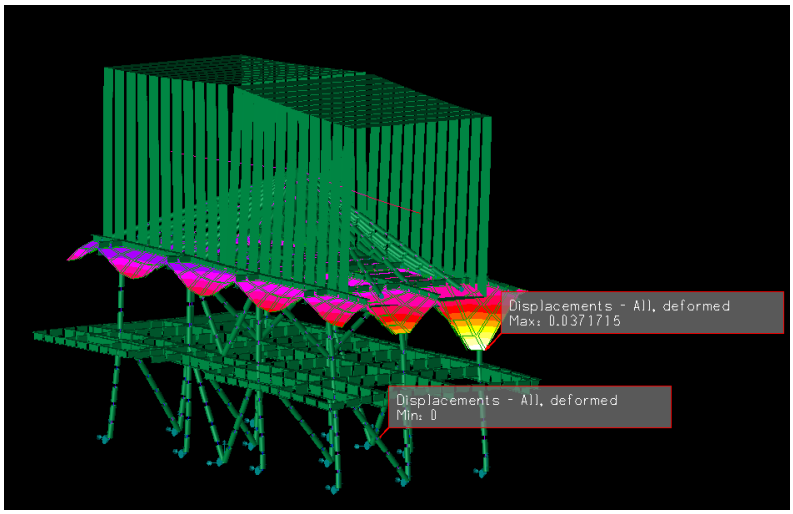
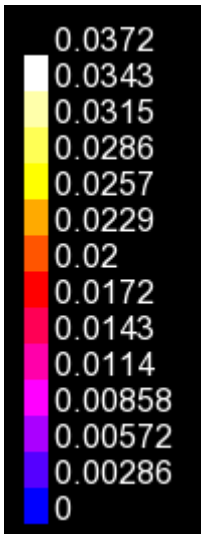
Structural	189.6	180.5	-5.0
Mechanical	214.5	214.5	0
Piping	80	80.0	0
Electrical, Instrumentation & Safety	10.34	10.34	0
Total	**494.44**	**485.34**	**-1.8**

6. Results

The final design can be seen in 5.3.2, the results of this design are shown in this chapter. Maximum code check of the columns is equal to 0.83, which can be seen in the yellow column of the bottom level. While the highest code check of the beams is equal to 0.77, which is one of the dark green beams on the first level and can be seen in Table 10. The maximum deflection of the plate at the top level in all different load combinations is found to be equal to 37mm. These results are all acceptable, and thus the final design is deemed to be ready for use.

Table 10: Code check results final design

	Code check results	**Legend**
Columns		
Beams		

Deflections		

The support reactions can be seen in Figure 16. This figure shows the support reactions in Newtons, for the 14 different supports. The highest support reaction can be seen in the middle and is equal to 584.871 kN.

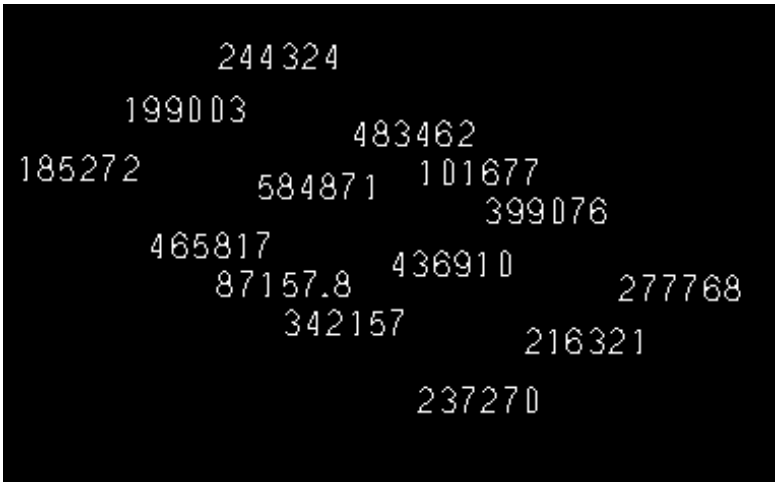


Figure 16: Support reactions final design

In Table 11 the weight increases from the base design, without the raised skid, can be seen. The total weight increased by only 9%, even though a new level was added. This is due to the redesign of the skid, as the pancake was previously overdesigned since heavier skids could also be placed on the pancake.

Table 11: Weight comparison base design and Final raised skid design

Discipline	Old Weight [t]	Weight last raised design [t]	Difference [%]
Structural	148.83	180.5	21.3
Mechanical	214.5	214.5	0
Piping	71.31	80.0	12.1
Electrical, Instrumentation & Safety	10.34	10.34	0
Total	**445.08**	**485.34**	**9.05**

7. Discussion

In the design process described in Chapter 5.3, several key observations were made. When adding diagonal braces, the wind loads became significantly easier to withstand which highlights the importance of stability in the design. The limiting factor in most of the designs was the columns, which were therefore redesigned most frequently. This is primarily due to the initial design causing multiple columns to fail code checks, requiring modifications to the structural layout. The relatively small span of the beams between the columns resulted in non-governing behavior. The pancake level being overdesigned in the base design meant that during the design phase, while columns were added, beams could be removed or lowered in height.

The difference between the first design based on the hand calculations and the final design shows a difference of only 5% in steel used. When only looking at this figure, it might suggest that the first design was already similar to the final design. However, the design changed noticeably. This is because the load distribution changed after adding the second level, as most load goes directly to the columns. During the design phase, columns were identified as the governing structural elements, and thus diagonal columns were added to withstand the loads applied.

Looking at the results in chapter 6, the main takeaways can be seen from weight changes. Comparing the weight of the base design to the final design with a raised level, the increase in steel used was 21%. This is low, as a second new level was added. The total weight increased by only 9%, which included more equipment in the form of piping. This increase is minor compared to the increase in usable space, which can indicate an efficient design.

The pancake level was significantly improved, as the base design used beams with 1500mm section, together with other smaller beams on the same level. The final design makes use of three main beams above the columns with a 700mm section, with the rest being 500mm or smaller. The diagonal braces were placed to avoid interference with equipment and thus maximizing usable space. Although the overall weight increases by 9% to approximately 485 tons, this can be justified by the usable space on the pancake level.

8. Conclusion

This report aimed to develop and design a raised metering module skid, according to constraints set by SBM Offshore. The design was based on an existing project, and different raised designs were modeled and checked. Based on the results of these models, several design iterations were performed to achieve an optimized solution.

The design process started with hand calculations, which formed the base of the initial design modeled in Sesam GeniE software. GeniE allowed for efficient evaluation of different design alternatives. The results show that the final design meets all structural requirements. The columns were checked according to API standards and showed a maximum check of 0.83. For the beams, AISC standard was used to check the design of the beams. This showed a maximum of 0.77, which is within acceptable range. The final deformation of 37mm demonstrates the structural integrity of the final design.

The final design resulted in an increase in steel used of 21%, and a total increase in weight of 9%. The final design increased functionality, as a new level of 23x11 meters was introduced, which can be used for equipment or piping.

This design improves the way SBM Offshore can conclude business with different clients. The top module design remains unchanged, but the usable space introduces options for project specific equipment to be installed later.

Overall, the proposed design offers a practical solution for SBM Offshore, and solved the problems identified earlier. The raised skid design can be used in future FPSO projects.

9. Recommendations

Future work on optimizing the design can be performed on the pancake design, and the column layout. The pancake level beam layout design was not designed in this study, only adjusted based on the base design and code check results during the design phase. Starting from scratch while designing a skid with two levels will mean a more optimized design can be found, especially for the pancake level. Currently the distances between the columns are not the same, which means the load placed on top is not evenly distributed. This can improve in a future design.

If further optimization of the current design is needed, the first point should be to check the design in different working conditions. The current design only looked at the skid in operation condition, but other conditions like lifting, the condition where the skid is being lifted and placed on the vessel, or transit survival condition, when the skid is in transit, should be checked. These results could be the start of a new design phase if any failure is found.

Finally, additional loading conditions could be considered as well. Loading conditions such as fatigue or green water loads, which is ocean water getting on the ship and impacting the support columns, were not considered in this study, but could have impact on the design of the skid.

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American Petrolium Institute. (2014). *Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design.* Washington D.C.: American Petrolium Institute.

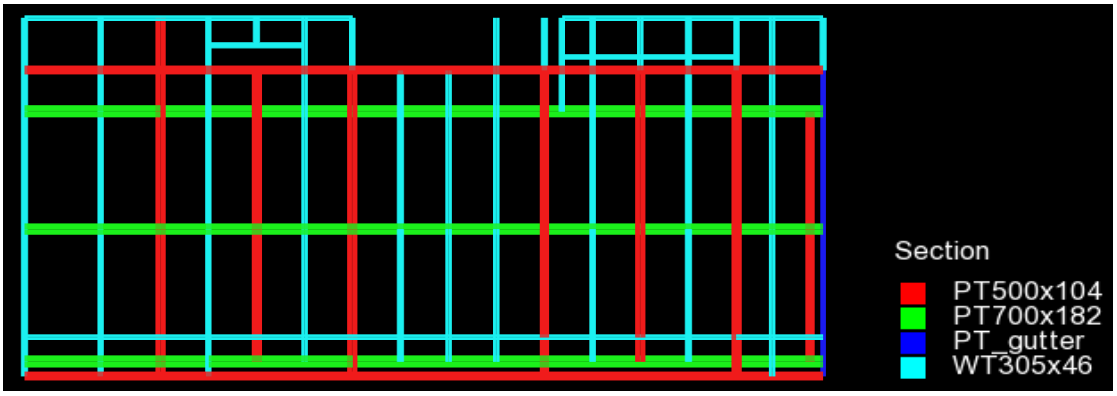
Raymond, X. (2026, February 06). *Understanding FPSO: How Does It Work from Hull to Topsides Modules*. Retrieved from Blackridgeresearch: https://www.blackridgeresearch.com/blog/understanding-fpso-how-does-it-work-from-hull-to-topsides-modules

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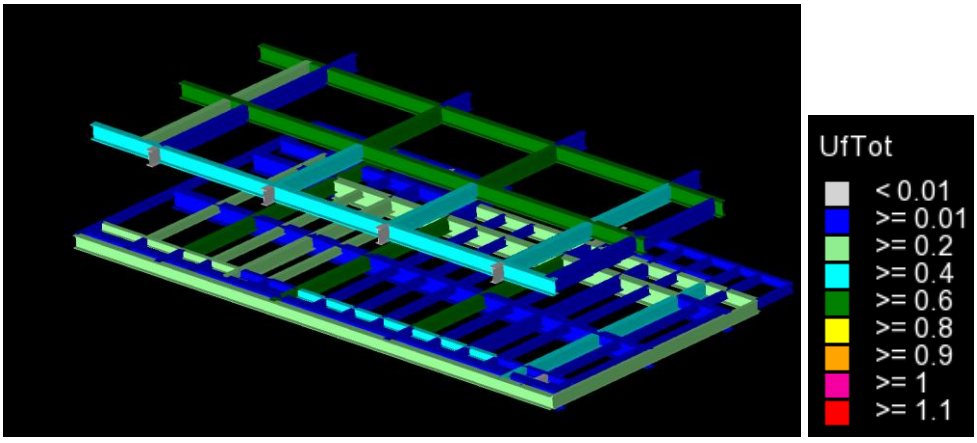
Appendix A

New Design 1

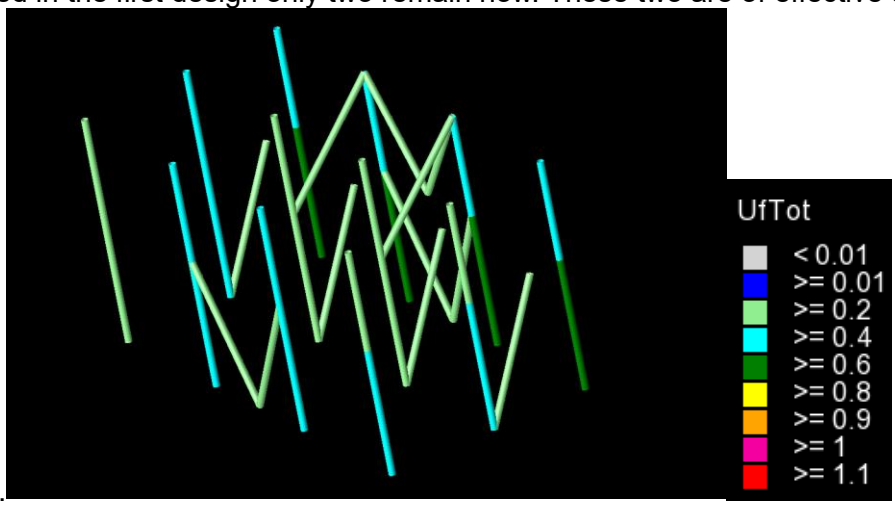
After changing the cross sections of the pancake, the focus is on the beams over the columns to be stronger. The final beam structure looks like this:



The code checks are done once again and look like this for the beams: This was a good optimal design, as none of the beams have a code check higher than 0.8, and none of the beams seem useless.



The columns look good as well, with again no code checks over 0.8. Of the six added diagonals added in the first design only two remain now. These two are of effective use and will stay for now.



Weights of last design

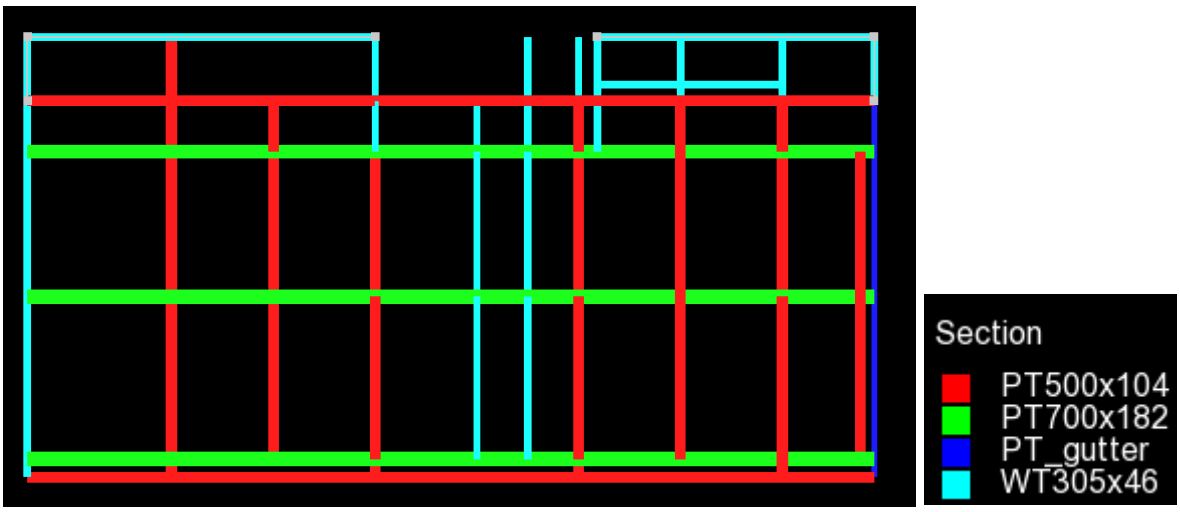
The designs seen in the last few paragraphs are all based on the base design. A comparison of the weights can be seen below. As expected, the total structural weight increased with the addition of the second level.

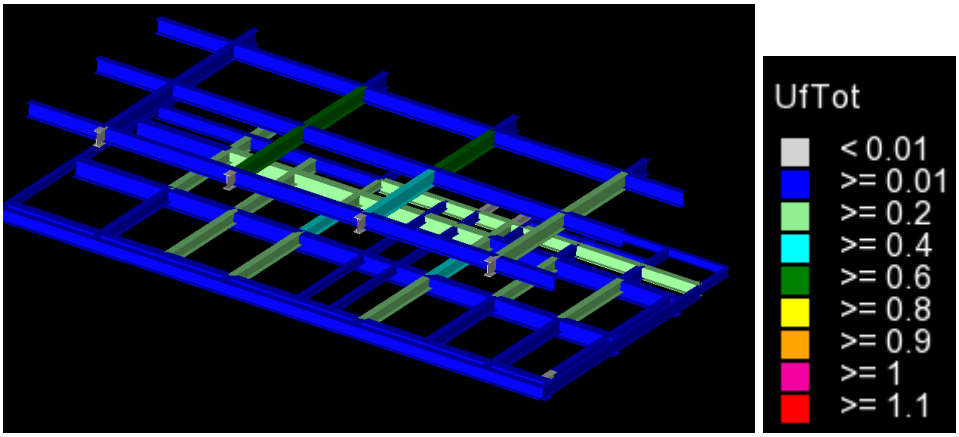
Discipline	Old Weight [t]	New Weight [t]	Difference [%]
Structural	148.83	189.6	27.4
Mechanical	214.5	214.5	0
Piping	71.31	80	11.6
Electrical, Instrumentation & Safety	10.34	10.34	0
Total	**445.08**	**494.44**	**11.1**

Appendix B

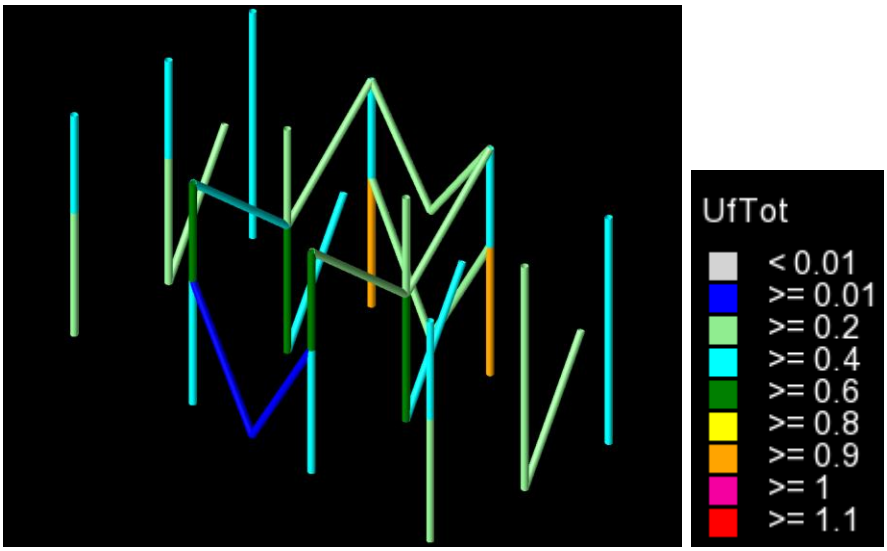
New design 2

In the next design, some geometry changes were made to the beams which can be seen in the image below. Beams were removed and others were modeled differently to make sure the code checks are done correctly by the software. That is why some of the beam parts have a lower code check than previous designs without any changes made to that part. The beams at the elevated skid have a code check of around 0.66-0.77, which is OK.





Alongside this, two diagonal columns were added to combat the wind loads. The code checks can be seen below.



As can be seen in the figure above, the code checks of the columns are higher than the beams. Two of the columns at the bottom have a final code check of above 0.9, but none are higher than 1.0 so all code checks are OK.