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Design of Floating Terminals as Integrated Project for Multi-machine Systems

Jovana Jovanova, Wouter van den Bos, and Dingena Schott

Abstract Design of floating terminals requires integrated approach as it requires multi-machine systems. Master students in mechanical engineering from Multi-machine engineering track at TU Delft were assigned design of floating terminals as part of their Integration Project course. Each of seven student groups designed a specific piece of port equipment that was later integrated in the floating terminal design. This required different design approaches: a detailed one for the equipment design (structure and functionality), and conceptual one for the floating terminal (overall layout and operational strategy). This encouraged the students to develop skills needed in real working environment, managing the design process and decision making within their own group and discussing setup, basic designs and dimensions together with the other groups. Owning their design throughout the entire process was in particularly important to the students, as they wanted other groups to use their equipment design. For the terminal design they needed to make a case for the feasibility of the floating terminal, including logistics simulations and cost. This paper shows the benefits of integrated design project course, the methods used for its implementation, as well as addressing current challenges of online group design work and supervision. Being part of European Horizon 2020 project motivated the students even more to contribute to an overall bigger objective.

Keywords Integrated project · Design · Floating terminal · Port equipment

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1 Introduction

Floating platforms for different and multiple purposes have gained major interest in the last years because on land challenges occur from lack of space, lack of resources or natural and manmade disasters [1]. Designing floating platforms is an engineering challenge in development, as required competences are found in different engineering disciplines [2, 3]. However, future engineers need to become aware of this trend for design of floating platforms and to be ready to design machines ready to operate in floating conditions, taking in consideration design requirements based on the application. Large floating islands for living [4], aquaculture [5] or renewable energy production [6, 7] will need to be equipped with floating terminals to enable access and exchange of goods. Different designs of multipurpose floating platforms [8] and mega floating cranes [9, 10] have shown potential in the design of full size floating terminals.

To prepare the students for the future design engineering challenges, project-based learning has become part of curricula in all highly ranked engineering programs. Active learning is at the core of any design course as it requires participation and contribution from the students to deliver their results. Both Problem-Based and Project-Based Learning enable educators to prepare their students for their future professional life as opposed to simply being able to pass exams [11].

The curriculum for Master studies (MSc) in Mechanical Engineering (ME) at TU Delft is based on a solid scientific foundation, deep engineering knowledge and agile engineering design skills. Courses, projects and other modalities are designed to be mutually stimulating. For example, knowledge from courses is applied in projects and, conversely, in their design projects students experience the need for and utility of basic knowledge and engineering methodology. The MSc ME program focusses on three connected didactic goals: (1) To give students an understanding of all mechanical engineering disciplines, with a firm root in theory and a wide focus on applications; (2) To train students to handle the entire process of innovative design, manufacturing, and operation; (3) To coach students to perform research on mechanical engineering topics at an academic level. The essence of the Multi-Machine Engineering (MME) track is to develop, design, build and operate maritime and transport equipment and systems. The mechanical analysis of transport equipment and the interaction between transported material and equipment are fundamental topics for MME. The MME track addresses challenges related to efficiency, sustainability, and safety of complex processes with an integrated perspective that combines core (mechanical systems) design with real-time operation and distributed machine-machine interactions. Specifically graduates in MME track are able to analyze and explain the characteristics and mechanical behavior of material during transport and storage, analyze and model different types of transport equipment and transport facilities, analyze and model the logistics of complex transport systems and networks.

Design of a floating container terminal was a challenge accepted in the master design course Integrated Project Multi-Machine Systems at the MME track. In this course the students were assigned different European port locations with variable local conditions and connections with land transportation (Antwerp, Genoa, La Spezia, Thessaloniki, Constanta and Hamburg), and one group designed a disaster relief floating container terminal for the Mediterranean Sea. This integrated project design course resulted in 7 floating terminal designs in the framework of the Horizon 2020 Space@Sea project (spaceatsea-project.eu). The methodology of the course, the terminal designs and the students' feedback are presented in this paper.

2 Methodology: Integrated Project Multi-machine Systems

The course Integration Project Multi-Machine Systems is obligatory in the MSc ME for the MME track. The course is project-based and runs over the entire spring semester in the first year of the master program, as one of the final courses the students take before going into their second year focusing on their personal assignments (literature, research and graduation). The course brings together most of the skills students develop throughout their studies, from theory to methodology and engineering practice. The students' groups work together to develop designs of complex systems (in this year example that is floating terminals). Students are encouraged to use acquired knowledge (theory, simulation skills, calculations, etc.) from their previous courses and apply it to solve design problems. They need to make multiple decisions in the design process and justify it based on their previous knowledge and experience, which increases their critical thinking.

The course is organized by two lecturers that support the students in their design process. The course Integration Project Multi-Machine Systems simulates an engineering working environment and encourages the students to apply their already accumulated knowledge. The students are highly motivated as the design process resembles real-live engineering work and they take ownership of their designs. The student groups were given a task to design a piece of equipment and then all groups had to design a terminal with multiple equipment from other groups. This mimics real engineering environment: teamwork, understanding requirements and deliver results, communicate, iterate on design improvements, responsibility, etc. There were 44 students following the course Integrated Project Multi-machine Systems in spring semester 2020. They formed 7 groups each consisting of 6–7 people.

The learning objectives of the course are: Apply design methods for multi-machines; Use standards for equipment design; Study and recommend system integration including market availability and custom designs; and Design a project for a multi-machine system. The students applied design methods they have already learned in different courses to develop a piece of equipment. Then they exchanged their designs, went through round of improvements based on feedback, and at last they used their own and other teams' equipment designs for their floating terminal solutions. At the end of the course they showed highly integrated functional terminal designs and were able to communicate the benefits of floating terminal at their specific location.

The lecturers organized topic-specific lectures and provided additional literature once they noticed lack of knowledge. For example this semester, they invited a professor from the Ship Hydromechanics and Structures section to give a lecture on wave motions to help the students understand how to model floating terminal dynamics. In feedback sessions the lecturers supported the students in their design assignments with expertise, advice, calculations and suggestions for improvements.

After the first few weeks of the course, measures to go completely online were implemented because of the Covid-19 pandemic. The lecturers organized immediately everything online and the frequency of meeting with the students twice a week remained throughout the entire semester. Each group had sufficient time to get support in the design process. The students were directed where to look for design solution online, challenged to defend their decisions and given critical feedback on the feasibility on their designs.

At the end they prepared detailed drawings, reports, final presentation, banners and videos that showed high level of enthusiasm for their designs. The assessment of their designs was split into 4 equally weighed parts: terminal design, detailed design, report and presentation, see Fig. 1. The presentation was assessed by a jury

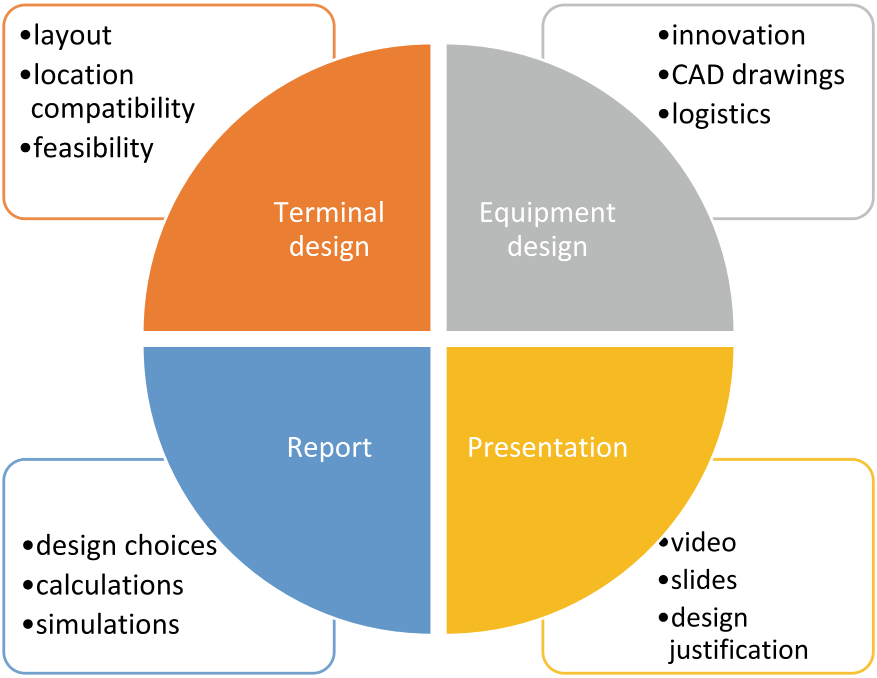

Fig. 1 Student assessments of the floating terminal designs

consisting of the 2 course lecturers, an external professor who is the TU Delft project coordinator for Space@Sea and the project leader of the Space@Sea project. Even though it was challenging to do it online, the course finished with successful presentations and at the final exam all students passed the course with high grades.

3 Port Equipment Designs

In the very first week of the semester the course structure and expectations were delivered to the students and the 7 detailed equipment design assignments, previously prepared by the lecturer, were presented. Each group picked their specific equipment assignment based on personal interest on first come-first served basis. The assignments included pontoons with crane designs, automated guided vehicles (AGVs) and rail bound electric container carriers (RECCs) with bridges to enable motion between pontoons. The pontoons are made of building blocks of minimum 50 m × 50 m with 5 m space in between, which usually came to pontoons with 45 m width and 95 length. Each of the specific designs is briefly presented below.

3.1 Design of Floating Stacking Modules

Design 1 is a dedicated pontoon with a rail mounted gantry (RMG) crane for stacking containers. In a floating terminal it will serve as a storage for containers until they are transferred further to/from the floating island. The configuration consists of two RMG cranes covering the complete surface of the platform, Fig. 2 (*left*). The cranes differ in height so they can move over each other. Three transport lanes in the middle provide space for AGVs to move in the terminal. Pontoon specifications: stack capacity 1,500 TEU (5 × 10 × 15 = 750 40 ft containers for an example length of 145 m); large RMG height 10 m, boom length 45 m, crane width 16 m; small RMG height 7.0 m, boom length 40 m, crane width 9.5 m.

Design 2 is a floating overhead container crane, Fig. 2 (*right*). The shape of the pontoon resembles the hull of a ship. A triple rail system runs along the length of the pontoon. The system consists of three lanes above each other, the top rails are for direct loading and unloading of RECCs along the entire length of the pontoon, while the lower lanes are for longer distance transport. The lanes enter and exit through the sides of the pontoon. The containers are stacked five high and fourteen wide. Seven containers fit in the longitudinal direction: six of which are reserved for 40 ft containers and one for 20 ft containers. Overall, there is a capacity of 490 containers on each pontoon.

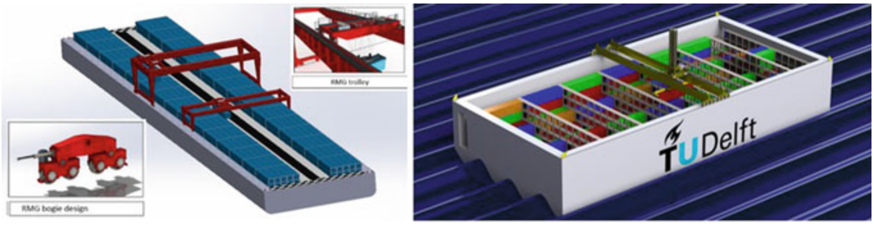

Fig. 2 Stacking module Stacking module with a rail mounted gantry (RMG) crane (*left*) with overhead container crane (*right*)

3.2 Design of Horizontal Transportation Systems: AGVs and Bridge, Rail-Based Conveyor System and ECCs

Design 3 was dedicated to AGV’s that drive in the pontoons, either in a separate driving pontoon or in a pontoon with port equipment and they can drive onto other pontoons via a bridge. The AGV is designed to carry all standard container sizes and should also be able to drive on the road. Therefore there are a total of 8 axis per side, totaling a number of 32 wheels with standard truck tires and rims, Fig. 3 (*left*). To remain in contact with the road surface at all times, the AGV has active suspension on every axle with coupled hydraulic cylinders to keep the wheel loads constant. For individual steering angles every axle rotates around a king pin which is controlled by hydraulic cylinders. These cylinders are powered by a hydraulic system, located at a central location in the AGV. For the use of the AGV in combination with the ramp, these suspension pistons need to be able to displace a maximum of 200 mm.

The concept of the bridge is inspired by a stern ramp. The bridge has 2 stable positions: down (working position) or up (during storm). Because the terminal

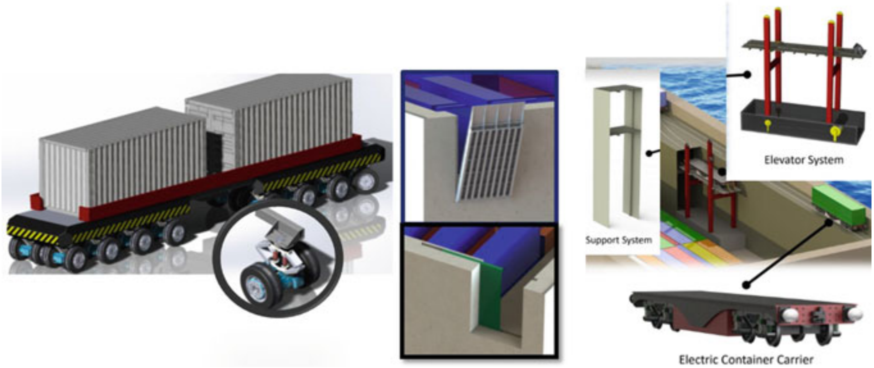

Fig. 3 AGV design (*left*), bridge design (*center*) and rail conveyor system with ECC (*right*)

being located at open sea, the bridges and pontoons will be sensitive to the formation of algae causing problems with slipperiness. Anti-slip coating was selected as the best option to provide high friction with an even surface. An important measure is the cleaning of the drive lanes of the pontoons and bridges once every three months, all formed algae should be removed with a "fleet-cleaner" AGV. The top deck is 5 by 7 m and has a thickness of 14 mm, Fig. 3 (*center*). The height of the bridge is 500 mm. The bridge is lifted using a hoisting mechanism that is placed in the side of the pontoon. The design of the connection point makes it possible to lift the bridge 90°. On the opposite side of the bridge, the inlet of the pontoon will be closed off by a rolling gate. The gate is designed to withstand the slamming pressure the waves of a rough sea.

Design 4 is a rail-based transport system that serves the crane pontoons and the stacking modules. The design includes the rail bound electric container carriers (RECCs) to serve the pontoons and an elevator to provide switch tracks for the carriers, Fig. 3 (*right*). The RECCs exists of a standard train container wagon adapted to fit a 48 V battery pack and 4 electric motors. The Lithium-ion battery pack has a capacity of 924 kWh, weighs 9.4 tons and can run the RECC for 8 h.

3.3 Floating Crane Designs: Rotate Crane, Double Sided Carrier Crane and Feeder Crane

Design 5 was a crane that rotates the containers, Fig. 4 (*left*). For some floating terminal concepts this concept can be beneficial as it offers a unique feature that the containers can be picked up and rotated for maximum use of space in stacking.

Design 6: The Double sided carrier crane, shown in Fig. 4 (*center*) is a variant of the carrier crane, Fig. 5, developed by the Marine and Transport Technology section of the TU Delft as a new concept to solve the problem of increase of cycle times per container moves due to the increase in travel distance with ever increasing vessel sizes [12]. By splitting the (un)loading cycle into 3 separate cycles (vertical transport at ship side, horizontal transport and vertical transport at quay side, the overall cycle time is drastically reduced. For unloading a vessel, the trolleys above the ship lift the containers on carriers which transport the containers along the main

Fig. 4 Floating cranes design: rotate crane design (*left*), double-sided carrier crane (*center*) and feeder crane (*right*)

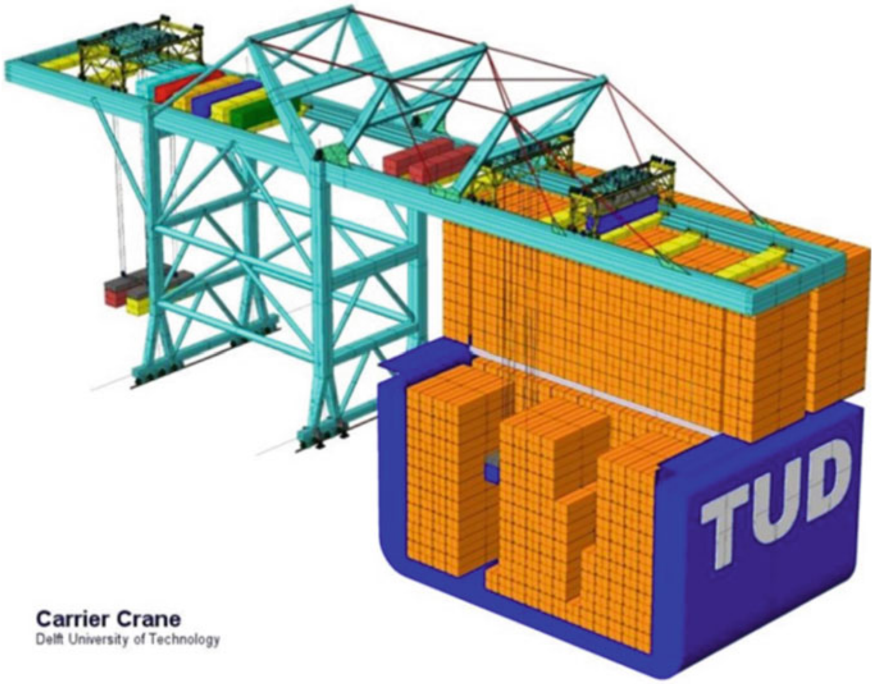

Fig. 5 Carrier crane

beam on the boom and bridge. The carriers are separately moving along 2 trail tracks on the beam, the top rail is for the loaded carriers, while empty carriers are moving on the lower track. The trolley on the quay side picks up the containers from the carriers and lowers them on the quay for further transport. The overall cycle time of the lifting and lowering at the quay and above the vessel is around 1/3 of the cycle time of a traditional full (un)load cycle. With a buffer of queuing carriers small mismatches in cycle times between the sea and land processes are leveled. The total productivity of the carrier crane is inverse of the cycle time and therefor 3 times higher than a traditional Ship to Shore crane (STS-crane).

The double-sided carrier crane shown in Fig. 4 (*center*) is equipped with 32 carriers to allow horizontal container transportation across the boom. Each carrier has its own drive system and serves both as a horizontal support and allows for a buffer function. The ship trolleys (1) place the containers onto horizontal carriers (2), which will transport the containers across the boom (3) until they are positioned above the pontoon (4). Here, a total of four trolleys will load the containers from the horizontal carrier onto the AGVs (5). The AGVs will transport the containers to their respective stacking area. The total technical unloading capacity of the carrier crane is up to 110 containers (or moves) per hour for each moored ship. The only uncontrolled motion is vertical lifting compared to a normal crane which need to combine the vertical motion with a movement to or from shore. The pendulum motion of the container or sway makes a traditional STS crane very vulnerable for wave motions of the pontoon.

To serve smaller ports, design 7 is a feeder crane with a variable level lifting platform, shown in Fig. 4 (*right*), which can handle ships with a capacity up to 5,000 TEU, 300,000 TEU per year and 8,880 TEU storage. Because of the reduced distance to the vessel the ship to shore motion can be controlled better which results in a 20% reduction of cycle time. The variable height platform is connected to the trolley with a scissor system. This allows the platform to remain stiff while being in lowered configurations during operations. Note that the scissor system is only there to provide stiffness by guiding the cables. It does not lift the spreader, this is all still done by the pulley systems for hoisting.

4 Floating Terminal Designs

Floating terminal locations were assigned to each of the students' groups taking in consideration different locations, throughput, boundary conditions and connections. Each of the layouts is discussed separately in this chapter.

4.1 Thessaloniki Port Extension

The port of Thessaloniki is the second biggest harbor of Greece. Its location gives the port a natural barrier for rough sea conditions. It is aiming to become a gateway to the Balkans and South Eastern Europe because it could serve over 20 million people in its direct hinterland and the capitals of 5 different countries within 600 km from the port. The port is connected to a double track railway to the national rail network of Greece. The bay of Thessaloniki, near the container terminal, is 9–12 m deep which has been a limitation for bigger ships to reach the port. Further away from the current port location the water depth reaches more than 20 m. At approximately 1.5 km the depth is 17 m which will allow ULCVs to dock there. The wind in Thessaloniki is 31% of the time dead calm coming from the North-Northwest. Only 0.1% of the wind is a strong breeze or more (meaning 6–8B). The waves that are encountered in the port are usually below 2 m, there is no current, the tide is less than 0.5 m and the significant wave height is approximately 0.5 m. The tide in the gulf is favorable, less than half a meter. This calm environment makes this location very suitable for a floating terminal. The proposed layout contains shown in Fig. 6 consists of: STS module (can handle ULCV, 450 m quay); Stack modules, ground slots (capacity of 5,000 TEU); Terminal transport (AGV or rail system that connects to the land). The specifications are: Quay length 800 m, Depth (without excavation) 16 m, 5 RMG stacking modules Total Capacity

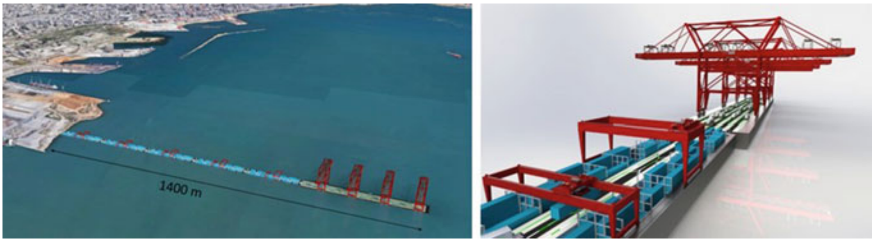

Fig. 6 Thessaloniki port floating terminal

7,500 TEU, Average cycle time < 60 s, 1 Double-sided STS module Unloading capacity (one-side) 880 TEU/hr, 50 AGVs.

4.2 *Floating Terminal on the River Elbe, an Extension for Hamburg Port*

The waterway towards the port of Hamburg, the river the Elbe, is characterized by many tight curves. Recently, the government of Hamburg has invested in dredging and widening the way, thereby allowing for easier maneuverability for larger ships. However, it would be much easier if the ships of the largest size could navigate up to a point halfway, and let inland waterway transport do the rest of the route to Hamburg. This could be done by creating a new port location further downstream the Elbe at Brunsbüttel. Furthermore, since a bulk terminal already exists at the location, this means that certain connections with the hinterland are already present.

The layout of the terminal, Fig. 7, consists of two types of storage pontoons, and two pontoon types to unload the vessels. The pontoons will be connected via a rail system running through the terminal, via a vehicle bridge at the land side, and via overhanging cranes of some of the storage pontoons. Terminal specifications: 1,315 m quay; 2,510 TEU/hr; 7.3 M TEU/year; 13,408 TEU storage; fully

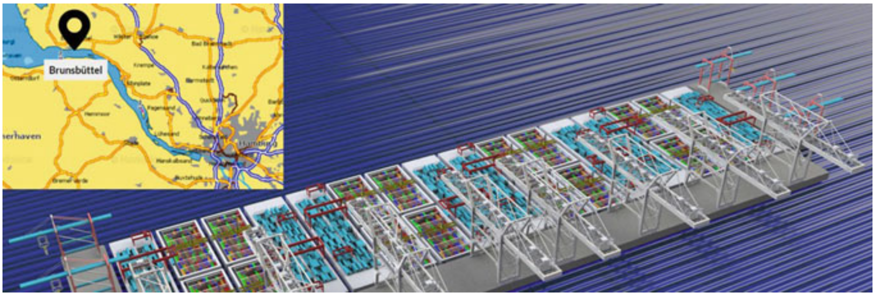

Fig. 7 Hamburg port floating terminal

automated; connected via truck and train. Because of the floating units the natural water flow in the river remains undisturbed and perturbations and swirls further downstream can be avoided.

4.3 Mediterranean Floating Terminal: A Mobile Port for Disaster Relief

The group started with their design requirements: the port should be Quick, Efficient, Smart and Safe, as after a disaster, relief should be available in the shortest time period. The disaster relief port should also be useful for temporary capacity increase (while waiting for port expansion for example) and use units which can be reused in another location afterwards. They set criteria: operating area is the Mediterranean Sea; port reaches a destination within 10 days; operates in different locations; modular design; has ship-to-shore pontoons, storage pontoons and driving pontoons, see Fig. 8.

The carrier crane has been chosen as Ship-to-Shore crane (STS crane), because of the possibility of direct transfer to another ship and the capability of serving all types of container vessels. The original design is made for a fixed quay but in the disaster relief port the carrier crane will be placed on a floating pontoon. For the storage the pontoon with the overhead crane is selected, because it has a compact structure that catches less wind during shipping and the possibility for the AGV's to drive through the pontoon. The transfer of the containers from the STS crane to the storage pontoon is done by AGV's. When the port is out of use as an emergency port, the modules can contribute to the port where it is stored (for example in a port in Greece). The shipment from the pontoons to another port is done with tugboats.

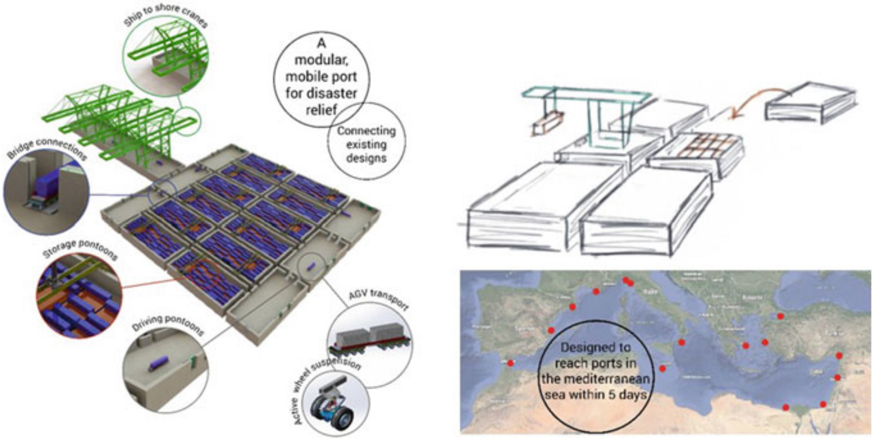

Fig. 8 Disaster relief port

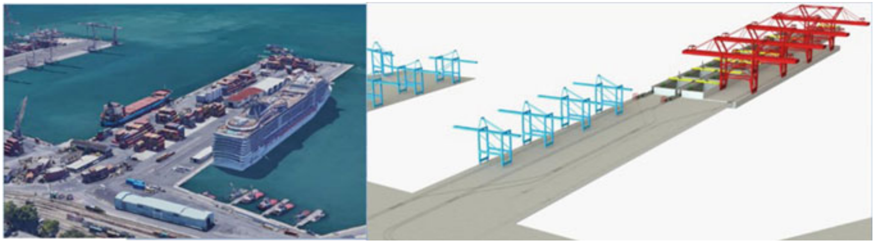

Fig. 9 La Spezia floating port extension

4.4 La Spezia Port Extension

The port in La Spezia, Italy is known for its connection to the rail network running from Italy across Europe. To meet the supply and demand of the container transport an expansion plan is created for the port of La Spezia. This plan includes not only changes to the existing harbor, but will include the use of a modular floating terminal. A floating terminal is more flexible than a standard expansion and the throughput and storage capacity can easily be expanded separately, Fig. 9. Terminal capacity: Stacking capacity 40,000 TEUs with 15 pontoons; handling capacity 2 million TEUs per year with 19 STS cranes (4 on floating pontoon) and 4 mobile cranes, 5 simultaneous vessel operations.

4.5 Port of Genoa Extension

The Genoa area is very crowded and free space is limited. A floating terminal gives the possibility to increase the port capacity without the need for expensive land reclamation in relative deep water. The position of the floating terminal in Genoa is selected close to the existing container terminal and rail service center. The floating extension, shown in Fig. 10, is feasible due to the elongation of the breakwater and the depth of the harbor is deep enough (20–40 m). The containers will be offloaded using double sided carrier cranes (yellow) which are able to offload two ships at the same time. The containers will be placed on top of RECCs which carry them along rail tracks from the quay through a 90° turn. After unloading, there are several locations the containers can be transported to. First location is the storage or stacking pontoon (green). In order to transport the containers to the stacking pontoon, the containers are picked up by the own developed Lift Carry Rotate (LCR) crane (light blue). Behind the LCR the containers are lowered and rotated onto another RECC. These RECCs transport the containers towards the stacking pontoon where the containers will (temporarily) be stacked. The second location where the containers can be transported to is the truck loading station. These containers can be transported directly from the quay or can be taken out of the

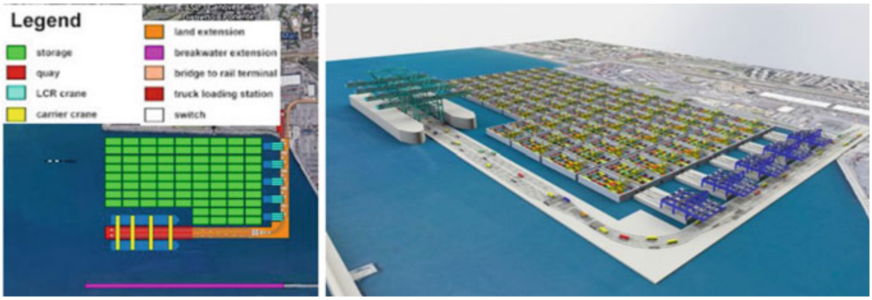

Fig. 10 Genoa floating port extension

storage pontoon. At the truck loading station several Rubber Tire Gantry Cranes (RTG's) are placed. These RTG's transport the containers from the RECCs to the trucks. The third location is the rail transport location. This location is located in the existing container terminal and is currently equipped with Rail Mounted Gantry Cranes (RMG's).

4.6 Floating Port Antwerp

The harbor of Antwerp is located in the center of the city, which means that the harbor cannot be expanded inland, even though the harbor has a yearly increase in cargo flow. Thus, a floating terminal design can be a good alternative for capacity extension. The design of such a terminal is based on many different aspects, such as the desired cargo flow that the terminal needs to handle, the environment in which the terminal is built, and the storage capacity needed. For the location of the port few criteria were analyzed: Antwerp is a Belgian city the port has to be placed in Belgian territorial waters; the port is outside of protected nature areas like the Vlakte van de Raan and the special protection zone in front of the harbor of Zeebrugge; stay clear of any existing North Sea wind farms; the water depth is taken into account, as the biggest container ships have a depth of about 15 m; major route from the North Hinder South route to the Westerschelde. The floating port, presented in Fig. 11, has handling capacity of 582,772 containers per year; storage capacity of 48,720 containers and the storage capacity is expendable as a respond to the expected annual growth of 5%. The floating terminal is completely focused on maritime transport and does not need a direct road or rail connection with the hinterland.

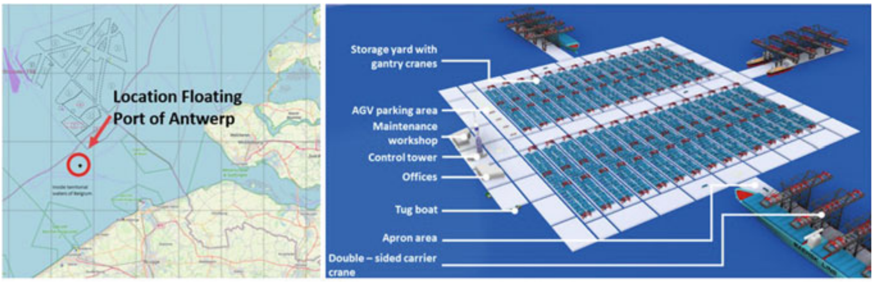

Fig. 11 Antwerp floating port

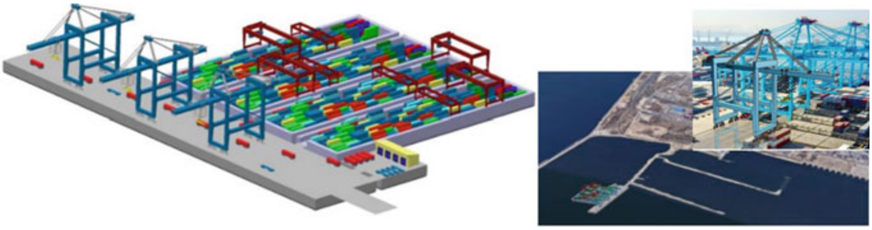

Fig. 12 Constanta floating port extension

4.7 Port of Constanta, Romania

The port of Constanta is located at the Black Sea and is the main port of Romania. It is connected to the hinterland via road, train and the Danube-Black Sea canal. Based on the development strategy the design of the proposed floating terminal, Fig. 12, will be able to process 300,000 TEU per year. Examination of existing terminal designs concludes that a storage capacity of 8,880 TEU is sufficient for this terminal.

The design consists of one large quay pontoon with three feeder cranes. Alongside are four storage pontoons installed and one service pontoon. A connection to land is established by a bridge connecting the quay pontoon to an existing dam. Via this dam the main container terminal is reached. To transport containers between the feeder cranes, storage pontoon and land, 12 AGVs are used. The quay length is 345 m, sufficient to process a feeder ship and a barge at the same time.

5 Students' Competences and Feedback

In this course the students were working on integrated projects where they designed machines and floating terminals. They were encouraged to critically think in the design process. They were able to look for solutions in literature and apply them in their designs. They had to communicate within their team and coordinate with other teams. In the final presentations they showed the benefits of their systems in current ongoing scenarios and put them into a commercial value.

The floating terminal design projects were inspired by an ongoing Horizon 2020 project Space@Sea that explores the viability of floating structures. TU Delft led the development of the Transport and Logistic hub with aspects ranging from selection of cargo, to design of terminals and coordination of multi-machines [13–15]. This motivated the students even more and was noticeable through their creativity and dedication to the course. The students' feedback stressed the importance of the course and the active learning design process they went through. They felt as they were part of a bigger challenge and felt as their contributions are valued beyond the scope of the course itself.

During the course durations the students spark discussions about trends in port design, environmental issues, energy efficiency, safety, sustainability and other societal challenges the world is facing right now. This makes them aware of the technical challenges and responsibilities they have once they practice engineering outside the student role. They developed critical thinking and reflection; carrying out research; designing; developing an academic approach; communication and collaboration in interdisciplinary and intercultural teams; taking into account the temporal and social context of technological solutions, which is expected from all Graduates of the TU Delft. This aligns perfectly with the TU Delft's vision: Making a contribution to solving global challenges by educating new generations of socially responsible engineers and by pushing the boundaries of the engineering science goes far beyond education.

6 Conclusions

In this work we have showed a successful active learning approach through integrated design course inspired by the Horizon 2020 Space@Sea project. The students raised their engineering design confidence in this course and learned how to combine the skills gained from other courses to design complex multi-machine systems, though project-based design and active learning. The first quarter of the course was first focused on single piece of equipment detailed design and the second quarter on the overall terminal layout. The students need both approaches when working in industry, a detailed design and more abstract conceptual design.

They showed at the end of the course that a graduate from MME track is able to model, calculate and simulate the interaction between equipment and containers, design unique port equipment for floating terminals, automate the transport equipment, design floating terminals taking in consideration location specific design constraints as well as the logistic systems. This course Integration Project Multi-Machine Systems brings them a step closer to a real engineering environment.

This course successfully changed into an online version due to the Covid-19 pandemic, which makes the course adaptable for any blended learning scenario.

The positive experience with online feedback showed potential that for active learning. The combination of online and in person activities in education is likely to stay in the future. Visiting port terminals and equipment manufacturers will remain as part of planned activities. European projects such as Space@Sea are a great inspiration for the project assignments and are beneficial for the students' motivation and commitment to the course.

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