Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Thea Kruse Valvatne

Assembly Port for Floating Offshore Wind Turbine

Early phase design planning

Master's thesis in Marine Systems Design
Supervisor: Stein Ove Erikstad
Co-supervisor: Marco Semini
June 2021

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Port logistics for constructing floating offshore wind turbines

Spring 2021

Background

Floating offshore wind is standing at the edge of being commercialized. As economics of scale dictates, the more units are being produced, the costs of each unit will be reduced. For this upscaling in production to happen, an effective production line in port is needed.

Overall aim

The project's overall aim is showing, by using a systematic approach, how a port layout for the assembly of floating wind turbines can be developed in an early stage.

Scope and main activities

The candidate should presumably cover the following main points:

1. Provide a short overview of the current status and important development trends related to floating offshore wind.
2. Present logistic solutions for arrival of incoming parts, activities, equipment and storage requirements
3. Systematize relations and sizes between different activities and areas
4. Use a systematic approach for time scheduling of project planning
5. Present suggestions on design layouts, and based on evaluation criteria choose the "best" design
6. Discuss and conclude

Modus operandi

At NTNU, Professor Stein Ove will be the responsible advisor.

The work shall follow the guidelines given by NTNU for the MSc Project work

Stein Ove Erikstad

Professor/Responsible Advisor

Sammendrag

Markedet for flytende vindturbiner øker, og det er forventet sterk vekst de kommende årene, og vindkraft vil bli en av de viktigste kildene til fornybar energi. I dag er flytende havvind lite utbredt, men Norge er en av få nasjoner som allerede har fått til pilotprosjekt, som for eksempel Hywind Tampen utenfor Skottland. Fordelen med flytende vindturbiner er at områdene disse kan stå på er mye mer fleksibelt enn fastmonterte, som per i dag ikke kan plasseres på vanndybder større enn 60 meter.

Det er flere metoder å bygge en flytende vindturbin, det kan deles inn i to hovedmåter: vindturbinen bygges til havs, eller at vindturbinene ferdigstilles i havn og slepes ut til vindmølleparken. Målet med denne oppgaven er å utforme ved hjelp av metode fra "Systematic Layout Planning MUTHER, R. & LEE, H. L." et design på en havn for å sette sammen en flytende vindturbin, før den blir slept ut til en vindturbinpark. Forhåpentligvis kan dette bidra til utviklingen i møte med det grønne skiftet.

Oppgaven har satt visse rammebetingelser: En vindturbin som skal settes sammen består av to tårndeler, tre vindturbinblad, en nacelle og en hub. Den flytende substrukturen er en semi-submersible plattform. Størrelsesordenen på vindturbinen er satt til 6-8 MW. Designfasen er begrenset til Fase II, som innebærer at resutlatet vil være et overordnet design av en havn, og at plasseringen av havnen ikke er lokalisert.

I denne oppgaven er metoden for å sette sammen vindturbinen som følgende: tårnkomponenter settes sammen og monteres til den flytende substrukuren, nacellen monteres på tårnet, hub og blader settes sammen på bakken før hele rotoren løftes og monteres på nacellen. Deretter blir den ferdige turbinen slept til vindturbinparken.

Planleggingen av å designe en havn starter med å identifisere alle aktivitene som må gjøres. For eksempel: transportere blader fra havn til lagringsområde, eller sette sammen nacelle og blader og en beskrivelse av hvordan disse aktivitetene utføres. Flyten av de ulike aktivitetene og deres relasjoner vil bli illustrert i et flyt-diagram. Deretter blir hver aktivitet knyttet til et område, og et relasjonskart blir utviklet ved å analysere viktigheten av nærhet mellom de ulike områdene. Dette kan være avhengig av å ha minst mulig transport, deling av utstyr for å minimere tid osv.

For å lage et tidsestimat og få oversikt over hva som er kritisk i planleggingen er nettverkdiagram blitt brukt. Da er det estimert for alle aktivtetene hvor lang tid de tar, og så hvilken avhengighet de har med tanke på hva som må være ferdig før neste aktivtet kan begynne. For eksempel kan ikke sammensetting av hub og blader begynne før disse kompoentene er brakt til sammenstillingsområdet. Ut ifra dette diagrammet, "Activity on node", kan man lese hvor mye flyt hver aktivtet har (hvor sent en aktivitet kan begynne) uten å påvirke sluttiden for sammenstillingen av en hel turbin. "Kritisk vei" blir også identifisert i dette diagrammet.

Til alle aktiveteter er et overordnet estimat av ressursbehov kartlagt, og knyttet opp til hva slags utstyr som trengs for å sette sammen både én, og fem turbiner. Utifra disse estimatene, tillegg til komponetstørrelsene til turbinen, er størrelsen til hvert av de ulike områdene kalkulert. Ved å kombinere størreslen til de ulike områdene og relasjonsdiagrammet kan et ferdig design av en havnelayout designes. Noen forskjellige forslag er blitt laget og evaluert. Evalueringen er basert på ressursbruk for hver aktivitet, avstand mellom de ulike områdene, intensiteten til flyten mellom ulike områdene og plassutnyttelse. Avsluttende en evaluering om designet er praktisk og om det realistisk kan la seg gjennomføre.

Summary

The market for floating wind turbines is growing, and strong growth is expected in the coming years, and wind power will be one of the most important sources of renewable energy. Today, floating offshore wind is not widespread, but Norway is one of the few nations with pilot projects, such as Hywind Tampen outside Scotland. The advantage of floating wind turbines is that the areas they can stand on are much more flexible than fixed ones, which as of today cannot be placed at water depths greater than 60 meters.

Several methods of building a floating wind turbine can be divided into two main ways: the wind turbine is built at sea, or that the wind turbines are completed in port and towed out to the wind farm. This thesis aims to design a port, using the method from "Systematic Layout Planning MUTHER, R. & LEE, H. L." a port design for assembling a floating wind turbine before it is towed out to a wind farm. Hopefully, this can contribute to the development in the face of the green shift.

The thesis has set certain framework conditions: A wind turbine to be assembled consists of two tower parts, three wind turbine blades, a nacelle and a hub. The floating substructure is a semi-submersible platform. The order of magnitude of the wind turbine is set at 6-8 MW. The design phase is limited to Phase II, resulting in an overall port design.

In this exercise, the method of assembling the wind turbine is as follows: tower components are assembled and mounted to the floating substructure, the nacelle is mounted on the tower, hubs and blades are assembled on the ground before the entire rotor is lifted and mounted on the nacelle. Then the finished turbine is towed to the wind farm.

Designing a port starts with identifying all the activities that need to be done—for example, transporting turbine blades from port to storage area, assembling nacelle and blades, and describing how these activities are performed. The flow of the various activities and their relationships will be illustrated in a flow diagram. Then, each activity is linked to an area, and a relationship map is developed by analyzing the importance of proximity between the different areas. This may depend on having the least possible transport, sharing equipment to minimize time, etc.

Time estimates and creating an overview of critical parts in the planning, Network diagram have been used. Time estimates for all the activities and dependency of wheat activities must be finished before the next activity is set. For example, assembly of hubs and blades cannot begin until these components have been brought to the assembly area. Based on this diagram, "Activity on node", one can read how much flow each activity has (how late an activity can begin) without affecting the end time for the assembly of an entire turbine. "Critical path" is also identified in this diagram.

An overall estimate of resource and equipment needs has been mapped for each activity. Based on

these estimates and the component sizes, the size for each area is calculated. By combining the size of the different areas and the relationship diagram, a finished configuration of a port layout design can be created. Some different proposals have been made and evaluated. Evaluation is based on resources for each activity, distance between different areas, and the intensity of the flow between the different areas. Finally, an evaluation of whether the design is practical and whether it can realistically be implemented.

Preface

This master thesis is a part of the specialization course TMR4560 - Marine Systems Design at the Norwegian University of Science and Technology. The work load counts for 30 credits.

The overall goal of the assignment is to look at different design configurations of as assembly port for floating offshore wind turbines. This involves identifying all activities that are needed to assembly a wind turbine, address spaces and it sizes needed, and put them together in different configurations.

I want to thank my supervisor, Professor Stein Ove Erikstad at the Department of Marine Technology, NTNU for guidance and helpful discussion about my thesis, and a huge thanks to co-supervisor, Associate Professor Marco Semini at the Department of Mechanical and Industrial Engineering, NTNU, for taking the time to guide me as well.

In addition I want to thank my family for support, and valuable discussions about my thesis at the end of the semester.

21th june, 2021

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1 Introduction

1.1 Background and motivation

Over the years to come, increased energy demand is expected in order to maintain and develop the standard of living for the world's population. For a long period of time, the oil and gas industry has been the main energy provider within the transportation sector. However, the demand for renewable, green energy is increasing . Offshore wind power will become increasingly important to meet this demand, and the production of wind turbines needs to be up-scaled in order to meet the needs.

Due to its natural conditions, Norway will be in a position to take a share in the production of renewable energy. Norway has long traditions from the maritime industry, well positioned to participate in developing facilities producing energy offshore, including offshore wind turbines. The market is, however still immature, affecting the access to investment capital. The energy sector is still under change, and investors' interest in renewable energy is expected to increase as non-renewable energy is gradually phased out. As an example, the Norwegian Government Pension Fund has withdrawn from investments in coal and oil, whilst interest in the renewable project is high on the agenda[18].

Like oil production, offshore wind energy may be produced from either floating or bottom fixed installations. Bottom-fixed installations have been on the market for a period, i.e. in Denmark. Due to our depth conditions, floating installations will be more applicable to Norway. The technology and cost development for floating offshore wind turbines is still more uncertain than for the bottom-fixed market. However, several countries, there under Norway, Portugal, Spain, the UK and France, have reported that they will join the pre-commercial floating offshore wind projects over the coming 3-4 years [25]. The early starters may lay the ground for designing and producing wind energy constructions, both on- and offshore.
Today's production of floating wind turbines is still in a pilot phase, and no standardized method for constructing them has been developed.

1.2 Objectives

By increasing the level of standardization in the production of wind turbines and its supporting infrastructure, the basis for up scaling of the production may evolve. The ultimate objective should be to enable the industry to benefit from economic of scale. On this background, the main objective for the thesis is to make a small contribution to the evolvement. The objective of the thesis is to summarize and systemize relevant existing knowledge and methods applicable in developing an assembly port for floating wind turbine. Furthermore, the methods are being applied in a specific case study.

Through a systematic approach, an early phase General Overall Layout of an assembly port for floating wind turbines, with pre-determined properties, will be developed and discussed.

In the thesis, the main theories are taken for ”Systematic Layout Planning” by Richard Muther and Lee Hales[32] will be used, supported by project planning based on Bassam Hussein’s book, ”Road to success” [19]. The thesis will mainly involve Phase II of layout planning. Thus, the final outcome is still in an early phase. The choice of layout will be based on investment- and operational costs related to different alternatives.

1.3 Content of thesis

The report is structured as followed:

Chapter 1: Will give an introduction of background and motivation for the thesis.

Chapter 2: A literature study about floating wind turbines. The expected development of floating wind turbines will be presented, describing the floating wind turbine, as a base 6-8MW wind turbine is presented. Information about different types of floating sub structures will be given, and discussion on advantages and disadvantages for the different types. The supply chain for floating wind turbines is presented, together with a case study on Hywind Scotland. Different assembly configurations will lastly be presented.

Chapter 3: Theory that will be used in the method chapter later is given in this chapter. The theory will mainly be based on ”Systematic layout Planning” by Richard Muther and Lee Hales ([32]), but also bring in elements on project planning from literature in ”Road to success - Narratives and insights from real-life projects” by Bassam Hussein ([19]).

Chapter 4: Will give the methodology of the thesis. In this chapter, the theory from chapter 3 will be done in practice. All the activities that need to be done and the relations between them will be mapped out, and finally, a set of layout design will be developed.

Chapter 5: The results and conclusion will be given. The result in this thesis is an overall layout design of an assembly port for floating wind turbines.

Chapter 6: A discussion on the choices that were made early in the design process and evaluation if these were good choices. A discussion on the progress towards the final design will also be presented and eventual changes that could be made to improve the results.

2 Litterature study

In this chapter, background on different aspects of floating wind turbines will be presented. This is in order to get a clearer picture of the expansion of floating wind turbine production. The market segment on wind turbines worldwide is essential in order to justify the need for expansion. It is also beneficial to get an understanding of how large and heavy the different components of a FOWT are. This is to acknowledge the complexity of assembling them, and the importance of the assembly port when large capital costs are needed. In order to see the relations between component suppliers and engineering companies, one has to learn about the supply chain. An example presented is Hywind Scotland to get an overview of how a supply chain can be done.

2.1 The turbine

The turbine itself can be divided into several parts, and the different components are often produced at different world locations. The main components constitute: floating substructure, tower, hub, nacelle, and blades. In this chapter, a short explanation will be presented, supported by a description of how they are connected. Due to its importance for the floating structure, a short explanation on anchor systems for floating wind turbines will be briefly presented.

2.1.1 Typical dimensions for a 6-8 MW floating wind turbine

Sizes of a 6-8 MW floating wind turbine is presented in table 1 and 2. This is the typical size of a floating wind turbine today, for example in Hywind Scotland where the turbine size is for 8 MW.

Part	weight of component	Geometry	Possible transportation method
Nacelle	300-400 tons	ca 15 m long and 6 m high	Either transported in one piece, or in several pieces overland
Blades	30-40 tons per blade	70-80 meters length(one blade) width: 6.2-6.5 m	Transported at sea mostly if difficult/small roads
Tower	ca 400 tons (whole tower)	Height: 75-140 m Diameter: 4-7 m	Often transported in 3-4 pieces by ship
Hub	50-90 tons	3-6 m diameter	Transported in one piece

Table 1: Typical dimensions for a 6-8 MW floating wind turbine [10][23]

Floating sub-structure	**Draft (transit)**	**Draft (installed)**	**Width(d)**	**Displacement**	**installation depth**
Spar	10-80 m (depending on installation)	80 m	8 m	13000-15000 tons	120m+
Barge	15	28	18	5000-8000 tons	40+
TLP	8-10 m	30 m	42-70m	4000-8000 tons	60m+
Semi-sub	10-12m	20m	50m	6000-8000 tons	40m+

Table 2: Typical dimensions for a floating wind turbine foundation [45][10][23]

Further in this thesis, designing a port layout, these are the main dimensions that will be used, as these are the most standard sizes used today. However, the turbine sizes are expected to grow up to 20 MW in the future. It can be argued that the wisest choice is to follow this trend, and use larger sizes as a base.

However, since the floating wind segment is still immature, and there is a desire to create an assembly port to mass-produce wind turbines, it can be advantageous not to take on too much. Instead of making the larges turbines of the future, use designs known and maintain the control, and reduce the risk of a possible failure. Especially since the investment costs are significant.

2.1.2 Floating substructure

There are several types of floating substructures available in the market. In figure 1, four different types are illustrated: Spar, Barge, Tension leg platform and Semi-submersible. The floating substructures listed use combinations of three different stabilization concepts: mooring line stabilizer, buoyancy stabilized structures and ballast stabilizing. The stability concepts can be directly linked to external "help" for stability, shown in table 3.

Gravity	Water-plane inertia	External constraints for stability
Spar	Barge Semi-submersible	Tension leg platform

Table 3: Stability for substructures [36]

A lot of skills and knowledge are transferred directly from the oil and gas industry to create these structures. Currently, 50 floating wind designs are under development, adding up to approximately 60% semi-submersible, 20% spar-buoys and 20% barge. Approximately 80% of all floating substructure designs are made of steel, as steel is a material easier used for prefabrication than concrete, the alternative material. Tension leg platforms are still considered challenging to stabilize, needing further development.

The potential is assessed as interesting due to its lightweight and minimum footprint on sea bed.[13]

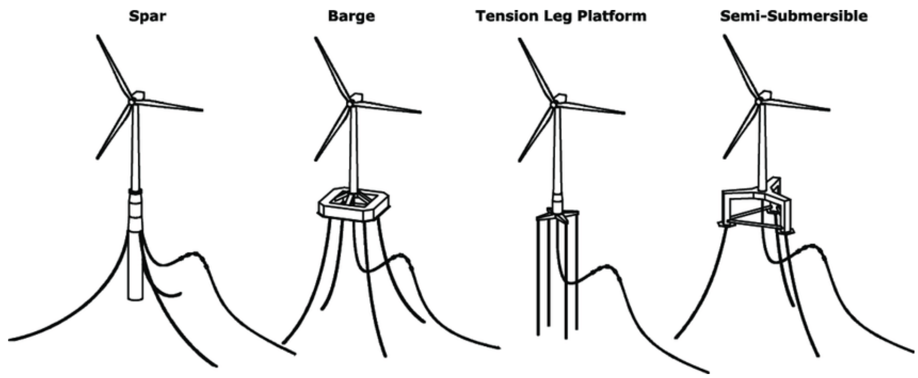

Figure 1: Substructures [40]

The advantages and disadvantages of the different floating sub structures are discussed in table 4. For the design layout, the semi-submersible platform is chosen. This is because of its relative low draft when installed and is the sub structure that is mainly used today.

Substructure	Advantages/ disadvantages
Spar-buoy The spar-buoy is maintaining its stability by having its centre of gravity bellow the centre of buoyancy	*Advantages:* Simple design. Competitive/low installing mooring costs. Withstands wave movements well. *Disadvantages:* Can have a draught up to 70-90 m making it difficult to assembly, transport and install the foundation.
Barge The hull is made of either concrete or steel. The structure has a frame, which makes the water plane area stabilise its buoyancy. The structure is assembled on shore and then towed offshore to its final destination	*Advantages:* Low draught, makes the structure fit in shallower waters. (can be beneficial for certain ports). During transport, the fully equipped platform can float on drafts below 10 m. Lower installing costs *Disadvantages:* The wave induced motions can be more critical than the other solutions. More material usage compared to the others (the frame). The fabrication is more complex compared with the other concepts (especially Spar)
Tension leg platform (TLP) The TLP is a lighter and smaller substructure. To provide stability the TLP requires full tension on anchor mooring lines. There are currently no TLP-foundations operating.	*Advantages:* Less critical for wave motions. Low mass. Can be assembled onshore/dry dock. *Disadvantages:* Unstable until the mooring lines are hooked up. Anchor has to pull up uptil 10 times the force as the other floating platform types. Because of the need for tension on mooring lines, the areas for the structure are limited to areas without tidal current and fluctuation. The costs for installing the mooring is higher.
Semi-submersible The semi-submersible foundation has a hull consisting of three columns connected to each other. The turbine is either located on one of the three columns or in the middle of them. Buoyancy force is what is keeping the structure stable.	*Advantages:* Used a lot in the offshore industry. Structure is stable at both under transit and in operational phase, this means the whole structure can be assembled in harbor and towed to its final destination *Disadvantages:* High exposure to waves and the structure has to be above the water line (parts of the steel has to be right at the water line) A very complex structure which will have a high cost support structure.

Table 4: Floating substructures [15] [36][3]

2.1.3 Tower

The primary function of a tower on a wind turbine is to give access to a desired wind resource by placing the hub and rotor at a favorable height. It also transfers the loads from the top of the turbine down to the foundation. The tower typically has a cylindrical or conical shape and hollow inside. The design of a floating offshore wind turbine is very similar to an onshore wind turbine. However, the marine environment has to be taken into consideration. Preventing corrosion from the saltwater, and wave exiting and hydrodynamic loads change a lot.[38]

2.1.4 Blades

Currently, the blades of a wind turbine are made out of glass fibers or epoxy matrix composites. However, many experiments are taking place using other composites like natural composites, hybrid and nano-engineered composites. The blade's two sides work as the suction and the pressure face. These are joined together by stiffeners linking the two parts together. The blade constitutes the highest cost component of a turbine, majorly because of the high labor costs. [30]

2.1.5 Nacelle

The nacelle houses the generating components in a wind turbine, including the generator, gearbox, drive train and brake assembly. The nacelle will rotate according to the wind direction, to maximize wind utility. Inside the nacelle, the kinetic energy from the rotating movement is transformed into electricity. [43][8]

2.1.6 Anchor system

The structure is attached to the sea bottom by use of an anchoring system. The anchor lines are under tension, ensuring the stability of the system. The anchors are embedded by pulling the anchors over the seabed, and as they are dragged along the bottom, the design of anchors makes them penetrate the seabed. The harder it is pulled, the deeper it will penetrate.[48] If there are several turbines in place, several can be attached to the same anchor. This will reduce the number of anchors per unit and thereby reduce cost. The anchor lines are made from steel chains. However, in the future other materials might be used depending on the underwater conditions. Several designs for the anchors are often similar to what is used in the oil and gas platform mooring. The depth range of the turbines to be installed will vary between 60-100 meters. If the depths are shallower than this, there will be technical challenges regarding the stretch in the shorter lines. Floating wind turbines are more competitive as the depths increase.[48]

2.2 Supply chain

In brief, a supply chain may be described as the configuration, coordination, planning, procurement, control, and follow-up of all involved actors and processes involved to create one specified product. The term supply chain management refers to the different methods, theories, and practices used to achieve the optimized logistic chain for efficiency and costs. The production milestones may be contract signing, the start of production, launching and start of activities (for example, floating wind turbine), and product delivery.

All types of industrial activity have to manage their supply chain, and procurement of commodities or production facilities often constitute a major part of the cost associated with the production. Traditionally, the yards were specialized and built certain types of ships. They were integrated, meaning that most of the parts were produced and assembled in the same yard. However, today the yards have to broaden their production to cope with the changing markets places. To take part in these markets, some of the production steps are outsourced to other companies or suppliers. Common practice today is outsourcing most of the production and different levels of outfitting to external companies. The operations in yards focus on systems procurement, integration, and complete the assembly. This is also what we see in offshore wind turbine production. [41]

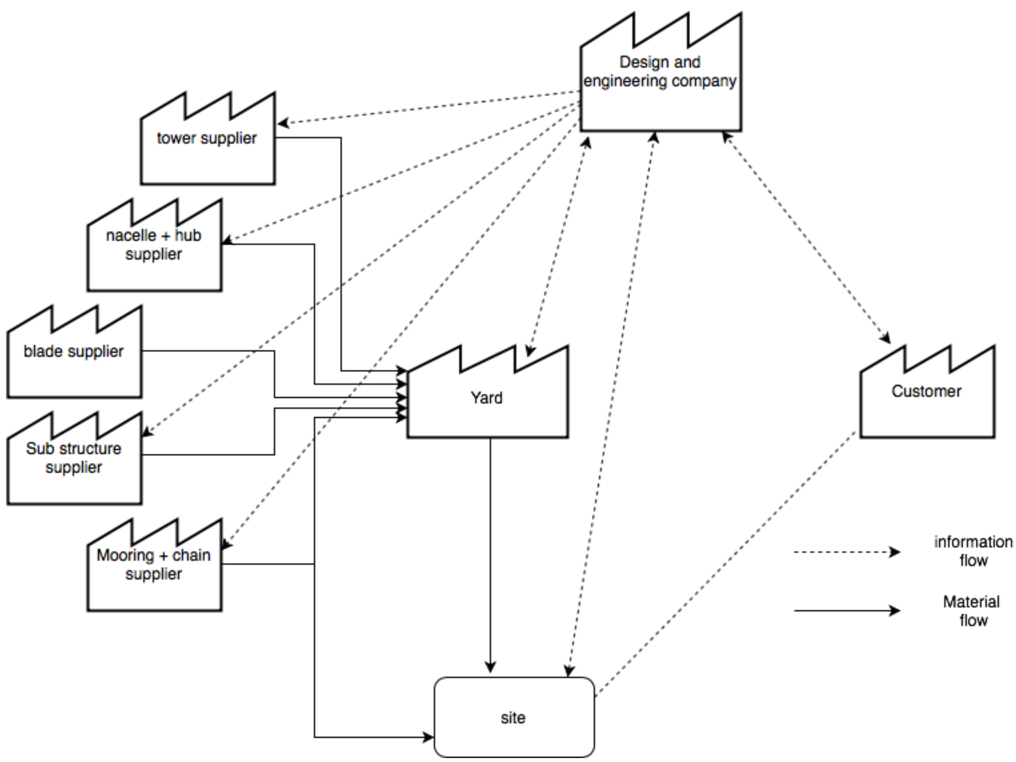

Figure 2: supply chain floating wind turbine

The supply chain decides which tasks/activities and inputs should be performed and delivered, supported by a timeline and clear descriptions of roles and responsibilities. There are different levels of integration between suppliers and sub-contractors, depending on ownership structures. Work-intensive production lines are often outsourced to low-cost countries, while production lines implying a high level of automation are dealt with by competence-intensive producers, typically located in more industrialized countries. Like most industries, yards are also moving in the direction of automation. The degree of usage of technology and digitization needs to be decided in comparison to human labor. If it is desired to reduce human labor, an automation strategy must be set and integrated with the supply chain strategy. There are different approaches for different levels of product customization vs. standardization. (however, in wind turbine case can be seen as highly standardized).

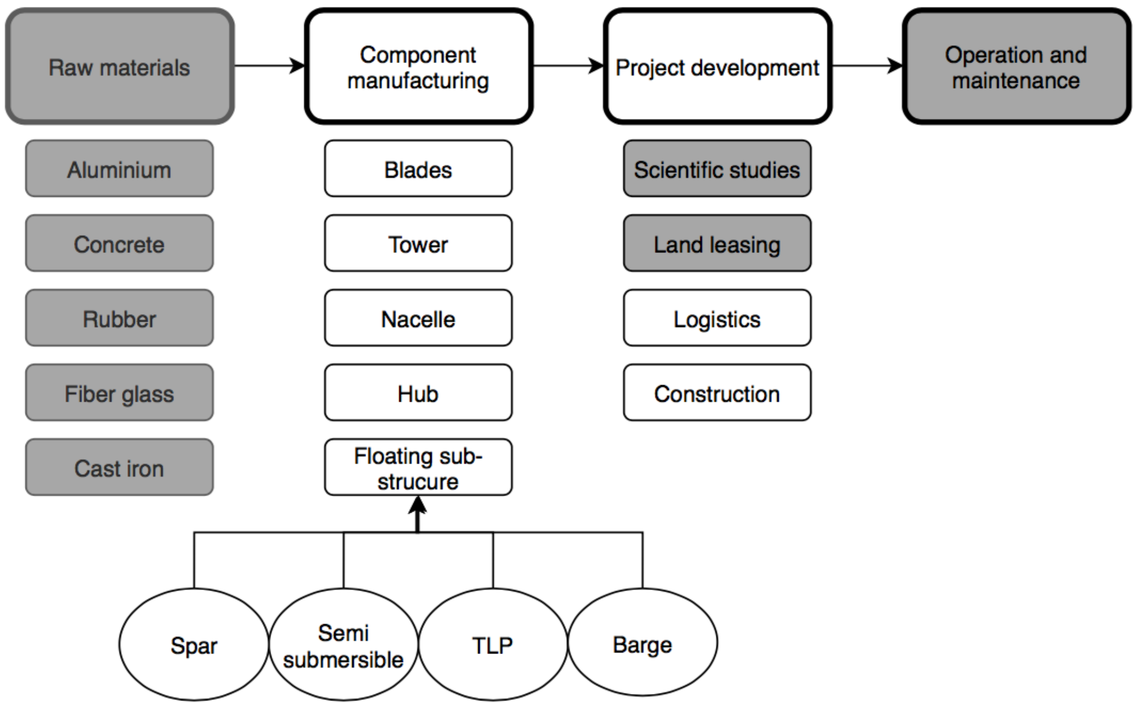

Figure 3: Simplified sketch of main actors in production of a floating wind turbine

2.2.1 Integrated supply chain

In an integrated supply chain, the chain members are or behaving as they are all under the same company. An integration approach can be designed as different "levels". One firm can merge with another firm in the supply chain or share information and work towards an exclusive collaboration with chosen suppliers and customers. This approach enables the different actors to benefit from each other, and the company/constructor has a steady, reliable business. An integrated supply chain will reduce the number of intermediaries and thereby simplify supply chain management. The approach facilitates closer coordination between delivery, warehousing and transportation. If a producer has an integrated supply chain, it can deliver orders faster and adapt quickly to market changes.

2.2.2 Example of supply chain management for floating wind projects set in production: Hywind Scotland

Commercial floating wind turbines are still at an early phase of development. Several singly turbines have been tested and installed since 2007. However, Hywind Scotland is the first, and for now, only commercialized floating wind farm. A look into Hywind Scotland's suppliers has been done.

Hywind is a floating offshore wind concept owned by Equinor. The concept consists of 3 floating wind turbine projects: Hywind Demo, Hywind Tampen and Hywind Scotland. Hywind Scotland consists of five floating wind turbines located outside of Scotland, each with a capacity of 6 MW. The farm has been in production since 2017. [20] The concept was developed in 2001, and then the pre-commercial phase started in 2017. The supply chain utilized in the production of Hywind Scotland not integrated, as seen in figure 4.

To create the floating wind turbines in the wind park Hywind Scotland, parts from different suppliers were sent to Stord, Norway, for assembly. Statoil (now Equinor) itself selected contractors for each element of the project. Before selecting suppliers, Statoil ran their supplier database to assess the potential suppliers. An essential selection criterion was that the relationship with the suppliers was trustworthy to reduce the risk of failure or miscommunication.

The blades and nacelles where sent from Denmark. The towers were constructed at Navacel in Bilbao, Spain. The mooring lines that make sure the structure stays in place and the floating substructures were brought from Spain (Vicinay the mooring lines and Fene the substructure). Nearly all parts were transported to Norway for assembly. The exceptions were the mooring lines and anchors, which were brought directly to Scotland for installation. After the assembly in Norway, the wind turbines were towed to the same site, 30 km from the coast of Scotland.

Figure 4: Supply Hwind Scotland

It was a major concern for the Scottish government that the project should have content as local as possible, and Statoil aimed at achieving this. Statoil had identified Kishorn, a port on the west coast of

Scotland, as a suitable port for assembly. This port is a former fabrication of oil and gas platforms, but there was a lack of storage space, cranes, and simultaneous installation challenges.[28] In the end, Kishorn missed the contract to NorseaGroup's Stordbase (west coast of Norway) due to lack of infrastructure, and there was no track record.[28]

The floating project developers could choose a site that met the requirements, and maybe as important - choose a port they were familiar with. Further in the project, local suppliers of required equipment could be used. This was an advantage both due to the geographical closeness and a known and trusted supplier. This contributed even further to more production in Norway rather than in Scotland. Another contributor to get supply from several countries in Europe was the market uncertainty within the floating wind industry. The local suppliers could not be guaranteed that there would be several missions after this one, and therefore the local suppliers would not make investments in infrastructure and capability upgrading. [1][35]

2.3 Assembly methods

There are several techniques for assembling the components of a turbine. Looking at the turbine itself, there are a number of ways it can be assembled and mounted to the floating sub structure.

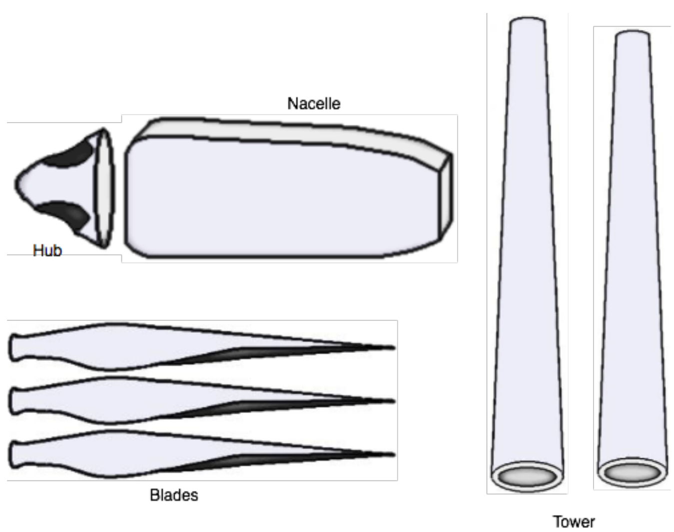

Figure 5: Turbine parts

As seen in figure 5 the turbine consists of 1 nacelle, 1, hub, 3 blades and 1 tower in 2(or several) parts. Possible ways of assembling these in port are presented in table 5.

6 lifts	**5 lifts**	**3-4 lifts**	**3-4 lifts**	**2 lifts**	**1 lift**
-Lower tower section -Upper tower section -nacelle and hub -blade 1 -blade 2 -blade 3	-Assembled tower -nacelle and hub -blade 1 -blade 2 -blade 3	-Assembled tower -nacelle -hub with blade 1,2 "bunny-ears" -blade 3	-Assembled tower -nacelle -hub with blade 1,2,3 "Star assy"	-Lower tower -Upper tower with nacelle, hub and blades attached	-Fully assembled turbine

Table 5: Assembling a turbine [39]

Each of the assembly methods requires different port equipment. For example, the six lift method only requires one heavy-lifting-crane for the nacelle. The 5-lift method might require two heavy lifting cranes, as the assembled tower must be transported after being assembled and lifted from quayside to the floating wind turbine. The same one crane can possibly do this. However, these are cost evaluations that must be done systematically later in the design process.

Further on in this thesis, the "Star Assy" method has been the base, as this is the same method that was used for Hywind Tampen [11]. Using the same method as Hywind Tampen assembly did, it might be discovered later in the design process of the port, some new solutions or combinations of the Hywind Tampen and this master thesis' solution. From this, an even better layout design can be made. However, this will be further work and will not be done in this thesis.

3 Theory

In this thesis, theory from "Systematic Layout Planning" by Richard Muther and Lee Hales, 4th edition [32] has been used as a tool to perform systematic layout planning. The purpose of designing a layout is to make a practical, cost-reducing and safe plant.

For project planning, theory from "Road to success - Narratives and insights from real-life projects" by Bassam Hussein has been used [19]. The main objective of project planning is to address when certain activities must happen and the relations. In this way, consequences of delays can be identified. Resources needed in the plant will also be presented, and evaluation can contribute to cost reductions.

3.1 Phases of layout planning

The assignment is limited to only design the general overall port layout. This means phases I, III and IV are omitted. Simple flow patterns and areas linked to the activities are put together and create initial drafts of sizes, contexts, and configurations for each main area. For further work, more detailed plans can be made in phase III.

Phase I:	This phase is about determining the location of the area to be laid out
Phase II:	**General overall layout, where a general arrangement is established. Basic flow patterns, and the areas needed, the relationships between areas are established. A rough layout is made.**
Phase III:	Detailed layout plans, where each specific piece of machinery is placed.
Phase IV:	Installations phase, where approval of the plan and making the physical moves happens.

Table 6: Phases of Systematic Layout Planning [32]

These four phases happen chronologically. However, there will be overlaps. It is assumed that an appropriate location in phase I has been chosen and that all requirements are met. The further into the project, the more details will be decided and locked. After phase II, there is still room to make significant changes. When the physical installation begins, phase IV, every detail down to the centimetre will be planned.

The steps in phase II from Systematic Layout Planning is as followed:

- **List activities** all happenings within the port has to be identified and is set in a chronological order.
- **Make activity relationship diagram or flow diagram** where various activities, departments, or areas are geographically related to each other but without actual space requirements.

- **Decide spaces for activities** All the areas, or ”things”, to be included in the layout.
- **Make pace relationship diagram** will be developed by analyzing the size of components, machinery, and other facilities. However, space must be traded with available space. Space required for each activity is connected, and the diagram can be created.
- **Make alternative layouts** Several space relationships will be made and is essentially a suggestion for a layout. It will be modified until a good result is made.
- **Select overall layout** Selection of overall layouts will be chosen from the different suggestion in the previous step.

The design alternatives will be tested for limitations, for example, costs, practicalities, storage, scheduling, safety, and employee preference. These layout suggestions will be named after what their main focus is to create a suggestion for layout design.

3.2 Activities and relations

This thesis will be limited to phase II due to time constraints. This is the phase where most decisions are made, which is relevant for the longest period. All the activities and their relations will be addressed.

3.2.1 List activities

The term activity can be described as "things" that are included in the port layout. It can be a building, an area, a department, a machine within a smaller layout. It depends on the level of planning of the project at this stage. The rest of the planning and calculations are done from this list of activities, and identifying all of the activities early in the project will save time later in the planning.

3.2.2 Deciding flow of materials

In order to determine the most effective sequence of moving materials or components through the port, the magnitude or, rather, the intensity of the moves must be addressed. An adequate flow is desired. This means that the components move progressively throughout the process, with as few detours as possible.

The flow analysis varies with quantity and number of types. As the product is standardized, the *operation process chart* or a similar flowchart can be used.

As a material, or in this context, components, are moved through the process in port, six main activities that can happen:

1. Operation: Formed, treatment, assembling, disassembling with other components/materials
2. Transportation
3. Handling (pick-up, set down, re-oriented)
4. Inspection, counting, checked
5. Storage

The different activities has different symbols to represent the activity.

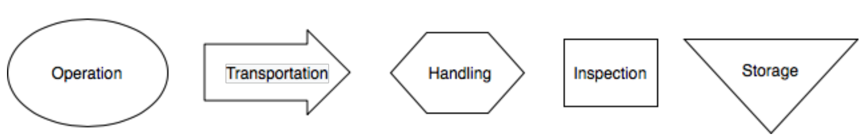

Figure 6: Activities in flow of materials

3.2.3 Relationship chart

A relationship chart shows the relationship between activities. It shows which activities have a relation to others and a rating of importance, and a reasoning code. It is an adequate representation of the different steps and makes it easy to integrate more activities later in the project by adding another row.

There is one separate "box" for every relationship, and therefore the chart is very detailed in the sense of multiple smaller actions. All the boxes are split horizontally. The upper half shows the importance of relationship, and the lower half shows reasoning for the importance.

3.2.4 Relationship diagram

For deciding the location of the different activities, an activity relationship diagram is convenient to make. This can be made from a combination of the operation process chart and the relationship chart. This diagram illustrates the flow and importance of closeness between the different activities and gives a visual picture of the data gathered. The relative importance of the closeness of each activity is transferred into a geographic arrangement.
The diagram can be presented using only closeness ratings recording on the relationship chart.

The activities in the different areas are similar as to show the flow of materials (as in figure 6), however in this case, what is happening in the specific area is described.

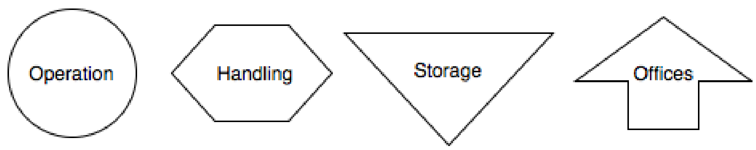

Figure 7: Activity areas in relationship diagram

Conventions for diagramming (page 6-5)

For an even more describing diagram on relationships and a clearer overview, a convention for diagramming is useful. Therefore some cedes are made in order to illustrate:

- symbol to illustrate the type of activity
- letter/number for identification of activity
- a specific number of lines to illustrate the importance of closeness (colours can also be used or added)
- Color for the types of activity

3.3 Project planning

To help planning a layout, some schedules showing when the different activities shall happen, and illustrate their relations. There are several helping tools that can be used for this, for example Network diagram, Network analysis and Resource chart.

3.3.1 Network diagram

The chart gives an overview of which tasks are dependent on each other and which tasks can not start before another has ended. In order to illustrate these dependencies, a network diagram can be used. A set of activities: A, B, C and D, can be represented as a box called a node, and the lines that link the nodes together represent the relationships. This network is called Activity On Node (AON). If activity B follows activity A, B is called a successor to A, and A is the predecessor activity of B. [19]

There are four types of dependencies between activities in a network diagram. These states weather next activity dependent on how far the first activity has gotten. To illustrate, activity A is the predecessor, followed by activity B, which is the successor:

- **FS: Finish-to-start** dependency means activity B can start when activity A is finished
- **FF: Finish-to-finish** dependency is used when activity B cannot be finished before A is finished
- **SS: Start-to-start** dependency means activity A cannot start before activity B has started
- **FS: Start-to-finish** Activity B cannot start until activity A is finished

3.3.2 Network analysis

After the list of activities has been made, an analysis of the AON network will give valuable information on how long time the project needs for completion, what activities affect the completion date, how much "extra" time is there in the project, and what are the consequences of changing the time constraint for an activity.

To analyse the AON network, information on the activities, and estimate of the duration of each activity, and the dependencies between the activities. A list of parameters will help to make an analysis and present the results:

ES	Earliest start for an activity
EF	Earliest finish for an activity
LS	Latest start for an activity
LF	Latest finish for an activity
T	Duration of activity
Float	Extra time avilable for an activity

Table 7: Variables for activities

An algorithm is developed called "the critical path method" (CPM) to calculate these variables. This will, in the end, give the total duration of the project. First, the ES and EF are found for all activities, followed by go through the network to find LF and LS. The float can be found, calculated as the difference between EC and LS, and the critical activities will be the activities with the least float.

To calculate the variables, following equations are used:

$$EF = ES + T \tag{1}$$

$$LS = LF - T \tag{2}$$

$$Float = LF - EF = LS - ES \tag{3}$$

- ES for the first activity = 0
- ES for a subsequent activity = highest EF of all predecessors
- LF for the last activity = EF
- LF for the preceding activity = smalles LS of all successors

ES		EF
	Activity	
LS		LF

Table 8: Variables in an AON network

To find LF for the different activities, one has to work backwards from the last activity. By connecting all activity in a grid with values presented as shown in table 8, the preceding activity value can be found and plotted, giving the critical path. (hassam, page 139...)

3.3.3 Resource charts

A resource chart is used to visualize resources needed with the resources available for a project to find appropriate solutions to the resource limitations that might be present. It also illustrates overloads of resources. For each activity, some recourse is needed, for example, manpower (or other type(s) of units). This needs to be addressed, the specific need, to each activity. The resource chart must be drawn up to investigate each unit of time requirements and resolve the resource limitations or constraints/optimize to find the best resource utilisation. The float is also needed to find different ranges of possible solutions, "feasible solutions".

For making a better solution with better utilization of resources, some measurements can be done:

- Utilize the float in the network chart by moving the start time of an activity
- Change relationship between activities, however, this might change the total duration
- Transfer resources to a critical activity to a less critical activity to extend the time of a non-critical activity
- Adding more resources to the project (this means increased costs)

3.4 Space determinations

Until now, the activities have been addressed. However, the space determinations have not been mentioned. Therefore, first, the activities will be addressed to specific areas, and then the activities will be broken down into sub-activities. From this, space for the areas can be calculated from the space estimations of the sub-activities.

3.4.1 Address spaces

As the activity areas have been established, it is time to measure the space needed for each area, its utilization (tight or loose), and the required shape of the area, or the overall overview. Usually, determining the required space, a ”take-off” is done on a drawing. What boundaries do the different areas have, and what is needed.

When measuring the space, there are two main strategies:

- Aisles between the activity areas are measured separately
- Aisles are allocated to the specific areas

3.4.2 Equipment needed

Before measuring the space determinations in detail, the machinery needed to perform the tasks must be identified. Each piece of equipment needed for every piece is accounted for by department or activity. The information will correspond to the activity relationship diagram and the rest of the work.
To maintain an overview of equipment, some helping tools can be used—a scheme for register and archive to record all the equipment and a classification system. Industrial data cards can be a good way of documenting equipment [5].
A classification system for the equipment is also advantageous. This can be a sort of equipment type and then establish a filing system.

3.4.3 Space requirements

There are five main ways to decide the space requirements. They are as followed:

1. Calculation
2. Converting
3. Space standards
4. Roughed-out layout
5. Ratio trend and projection

The order, 1-5, is arranged according to accuracy (number 1 being the most accurate). It is also in order of most frequent use. The different methods will briefly be explained and the method used in this thesis will be explained more detailed.

Calculation method	The most straightforward and accurate method of determining the space required is to break each activity into sub-areas that make up the total space. This one determines how much space each sub-activity needs, how many sub-areas there will be and add them together. Lastly, add extra space.
Converting method	In case of an existing yard, one can find what spaces are currently being occupied and convert it to what it will contain for the layout. However, this method is not relevant in this case, as there, for now, is no existing yard.
Space standards	One can use standards for space requirements for specific machines or space elements. Either find existing ones (however, the standards might differ from country to country, as well as regulations for different purposes). A company can still make its standards, and from this make a suitable working area.
Roughed-out	In some cases, layout planning has impractical calculations or converting and no available standards. The on-hand information can be used. For example, templates/models of equipment involved and certain critical activities. One can make rough layouts of certain areas and use them for the space requirements. This type of planning is suitable for areas with high investments and somewhat permanent systems. The method is suitable for establishing space requirements in phase II, but is expected to have significant changes in phase III.
Ratio trend and projection	The method sets a ratio between space (square meters) and another factor, for example, square meter per unit shipped, labour-hour per year etc. It describes the total/general space requirements and can not be applied to individual areas. The method is most likely the least accurate method.

Table 9: 5 ways of determining space requirements

In summary, the focus must be on specific requirements for each area, addressing space needed, shapes and configurations. The planner must document and summarize the space amount for each sub-activity, the features and the shape should be indicated as well. The detailed plans do not need to be addressed in phase II. The approximate spaces of each area is sufficient to get an overview and slowly start to combine this with the relationship diagram at this stage.

3.5 Making suggestions on layout designs

The main output of phase II is an general overall layout of a plant. Before the suggested layouts are made, the flow and activities have been diagrammed, as well as spaces required for the different activities mapped. It is time to combine these diagrams in order to create an actual layout.

3.5.1 Flow- and space relationship diagram

An overview of relations and space comparisons is recognised by starting with the flow diagram to see how flows and areas are related. This can either be done with help from a computer or with hand and paper. A paper with cross-section grid lines makes it easier to make correct-scaled areas by giving each square a scale.

To fit the spaces into the diagrams, the spaces can be applied to:

- Flow diagram
- Relationship diagram
- Combination of flow- and relationship diagram

The preferred layout design depends on the relative importance of the supportive devices' material flow and relationship. In the space relationship diagram based on the flow of materials, the intensity of flow can be illustrated with arrows representing the flow. The more arrows, the higher intensity of flow.

In the space relationship diagram, based on the relationship diagram, the importance of closeness can be illustrated with lines, just like the relationship diagram. It is desired to have as areas with many lines connecting them as close as possible.

Specific locations that already are decided is beneficial to locate first. This is only if there is no other way to make an innovative and vital solution in case of missing opportunities. The full potential of planning the layout should be done by keeping as many solutions open as possible. Therefore, it is better to work out the space relationship diagram to meet the conditions from the relationship diagram and later adjust to constraints of, for example, existing fixed features in the areas. However, a trade-off must be evaluated on the number of resources that can be spent on keeping "all solutions open", or see the constraints early and adapt to these.

When drawing the space relationship diagram, it can be done in two ways:

- Sketching with pencil on routed paper sheets
- Electronic drawing to scale and plotting the results

When drawing with pen and paper, a scale appropriate to the sheet is set, and the areas' relative sizes can be drawn together. (The scaling should be a somewhat round number, for example, 1:50, 1:100). All the areas can be converted to a number of squares first, and then start the sketching. If areas have shape requirements, this must be applied. If not, then the most "reasonable" way to draw will be making the areas square/rectangular shaped. If the sheets are complicated/with many areas and subareas that are to be illustrated, colour-coding can help to make it easier to read.

After making an overview of the relative sizes compared to each other, an even more detailed layout can be developed. The equipment outlining within an area will help to see reasonable solutions, so there will be as few detours as possible for the flows and if the solution is practical. For example, certain in/out entrances and what position they are located in, in the term of flow. However, this will be even more detailed in phase III, where templates for machines is more practical for exact placement.

To improve the block layout design further, a set of templates can be made. A method to do this can be copying each area (drawn at scale like in the space relationship diagram), and cut them out. Once cut out, the areas can be resized with scissor and tape. In this way, a large number of templates can be drawn faster than drawing the layout over and over. In this process, the number of squares is not *as* important as in the final design but is done to see what combinations that are possible. This is a method to see different possible combinations faster. A record should be made of each possible match, see advantages and disadvantages and iterate the way to a good design, and hopefully, combine the best features of each alternative.

3.5.2 Basic systems for movement of materials

It has been systematized three methods on how the material can move through the plant. The materials can move between three different systems, listed and illustrated:

1. Direct system: materials move between areas using the shortest path. Often used when the intensity of materials is high and distances short
2. Channel system: Materials move in pre-established route. Often used when intensity is low and distances long, especially if the layout is irregular or spread out.
3. Central system: Material moves in pre-established route from origin to a centralized sorting area, moving on to destination. Often used when intensity is low, and distances long, especially if the plant area is squared, and control is important.

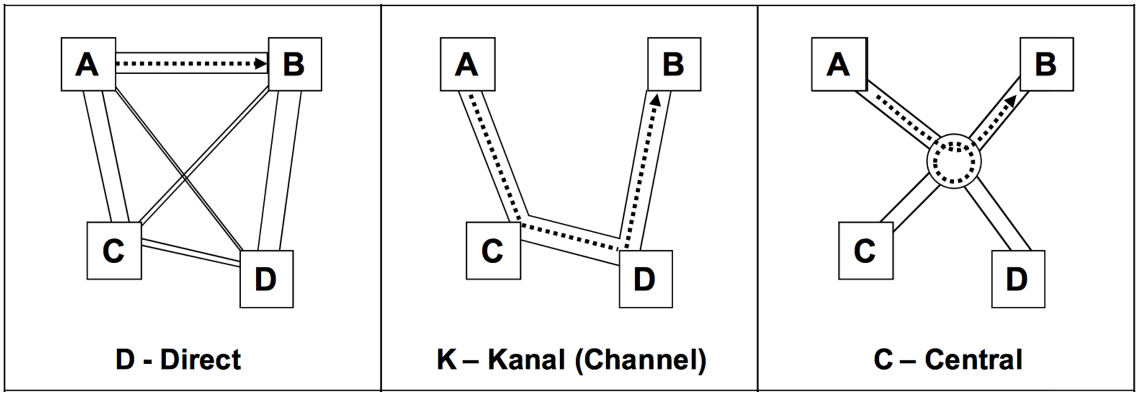

Figure 8: Systems describing how movements can be tied together [32]

These systems can also be combined in different configurations. One has to find out what is the best system for the specific design layout case.

3.5.3 Evaluation of layout design

After suggestions on layout designs has been made, an evaluation based on certain criteria must be executed. The criteria will be based on investment- and operational costs. What affects these parameters will be individual for different types of layouts. Examples can be buildings, equipment, man-hours, transport costs etc. An evaluation can be done by comparing the benefit versus cost. [31]

4 Methodology

As presented in previous chapter, layout planning is generally divided in four different phases. However, in this thesis the focus in this limited to phase 2: General overall layout. As the offshore wind industry is evolving and adapted to the specific needs for each installation to be made, there is still no standard way of doing this. Currently, each producer of wind turbines has its individual method, depending on size and sub structure type, and the facilities onshore, such as marshalling harbor and storage areas, distance to shore and country regulations. Based on theory from Systematic Layout Planning, there is a need for more standards to be developed over the years to come, capturing also foreseen up-scaling production.

In this case the construction is being assembled onshore. One important reason is to minimise expensive lifting on site. On site, the weather conditions are rougher, the wind causing motions on both the floating sub structure and the assembly vessel. In order to maintain flexibility in position of the harbor, the floating sub structure that is being used in this case is a semi submersible barge. As the draught is not as deep as for example spar buoy, this is much more flexible.

Furthermore, the star assembly method is used: the two tower components are assembled on ground, hub and all 3 blades are assembled on ground, where after the tower is mounted to floating sub structure, followed by the nacelle. Lastly the hub and 3 blades are lifted and mounted. Several factors comprise the background for the method chosen; the weight of a turbine on the tower will be skewed, making the turbine tip and challenging to lift and mount "directly down". The process will also have little flexibility in terms of weather windows, and it is therefore desired to reduce number of lifts. This is prevent bottle necks for the heavy-lifting-lifts, which is expensive and takes time to use[11].

4.1 Activities when assembling a floating wind turbine

In Systematic Layout Planning (SLP) the activities in port must be identified at an early stage [32]. Each activity is one step in the process from arrival of components to finished assembled floating wind turbine. The level of details for each step may vary. However, it is necessary to know most of the details in order to design a port, with a sufficient split of different activities in the description. The activities are presented in a chronological order, and activities listed in the process are:

1. Ship(s) docking
2. Transportation of arriving components (tower, nacelle, hub, blades) from ship to quayside
3. Arrival of floating sub structure
4. Transportation of components from quayside to storage area
5. Securing of floating sub structure to quay side
6. Storing of components

7. Transportation of tower from storage area to assembly area
8. Transportation of blades from storage area to assembly area
9. Transportation of hub from storage area to assembly area
10. Assemble tower components
11. Assemble blades to hub
12. Preparation of floating sub structure for turbine components
13. Transportation of assembled tower to quayside
14. Transportation of nacelle to quayside
15. Transportation of assembled hub and blades to quayside
16. Lifting of tower and mounting onto floating sub structure
17. Lifting and mounting of nacelle onto tower on sub structure
18. Lifting and mounting of hub and blades onto nacelle on floating sub structure
19. Finishing of floating wind turbine

At the end of each activity, a dot explains what assumptions are being made as basis for decisions going forward in the process of designing the layout. However, at an early stage it must be expected that most likely, will change come later as more analyses are done. The dots represent the decision that has currently been made, based on the assumptions considered reasonable at the design stage. As more knowledge is revealed, this has to be documented and adjustments may be needed.

4.1.1 Activity 1: Ship docking of components

During the construction of a wind turbine, different components will be brought by ship from various locations globally. Depending on the components transported, the ships will need to dock either as a cargo vessel, with long side along quay, or as a ro-ro vessel with bow or stern to quayside.

- Blades and tower components will be lifted off the vessel using cranes (Lift on/Lift off: Lo-Lo)
- Nacelle and hub will roll on and off the vessel (Ro-Ro)

4.1.2 Activity 2: Transportation of arriving components (tower, blades, nacelle, hub) from ship to quayside

As components are brought to the quay, efficient lifting of the tower component off the vessel is critical. Cranes will carry out the lifting. The cranes may be located on the quayside, or the cranes may be located on the vessel. The tower will be lifted by two cranes, as the tower's shape is oblong and can be challenging to manoeuvre with only one. The required lifting height will be from the ship side to quay at high tide. The top and bottom of the tower components both constitute assembly-points for the tower, and these points provide usable lifting attachments. The tower can also be loaded off the ship by braces around the tower [39].

Figure 9: Tower to port [39]

The nacelle has a compact body and is, therefore, easier to navigate than blades and tower. However, as the nacelle is the heaviest component of the construction, navigation may represent a challenge. In addition, the nacelle has a complex inventory, so due care must be taken when moving the component. The nacelle may be unloaded to port by cranes from the ship's deck or rolled off a ro-ro vessel on self-propelled modular trailers, as illustrated in figure 10, the latter is the less costly method [39]. Nacelle must be protected against shock, supported by shock isolates or shock absorbing pallets [47].

Equally, the hub may also be transported from ship to quay, either lifted by crane or rolled off by Self Propelled Modular Trailers. The hub must be regarded as an electrical component, equipped with several monitors. Like the nacelle, careful handling is needed. However, the weight and size are low compared to the other components, so that the handling will be less complicated from that perspective.

Figure 10: Nacelle on SPMT[12]

The process of lifting hub and nacelle to the racks is showed in figure 11. The SPMT will have space to roll underneath the racks, and then the SPMT can lift its platform to lift the component.

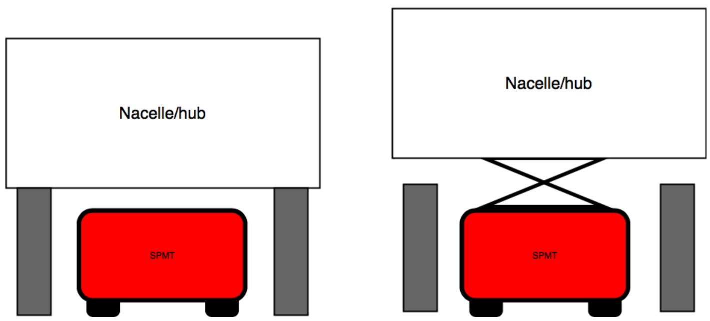

Figure 11: SPMT lifting nacelle/hub

The blades are the lightest component of the turbine (stated in table 1). For efficiency purpose it is often transported three at a time on racks, still making it one of the lightest components. However, due to its long shape, it is still challenging to handle in port. The blades requires a frame to hold it in place, one at the hub end, and one along the blade span if lifted one at a time, or two-point-contact lifting with cranes if on racks [39].

Figure 12: Blades arriving in port [46]

- Tower will be lifted off the vessel with two cranes on port side

- Nacelle will roll off the supply vessel on SPMT's that will be ready in port
- Hub will be rolled off vessel on SPMT's that will be ready in port (like the nacelle)
- Blades will be lifted off the vessel either one or three at a time

More about sizes and capacity of the SPMT and cranes will be presented later in the thesis, in chapter 4.4.1 and 4.4.2.

4.1.3 Activity 3: Arrival of the floating sub structure

For a semi-submersible floating sub structure, on-land transportation can be complex. Selfpropelled modular transporters can be used but demand a costly preparation. However, the float out can be done if there is access to a drydock. If the substructure is on the quayside with no dry-dock, the substructure may be transferred to a launching barge, which will sink and leave the substructure floating. The substructure will then need to be constructed in port. The most common way of transporting the substructure is towing by sea, particularly for low-draft structures. For storing the floating sub-structure, a wet storage area and towing vessels are required[29].

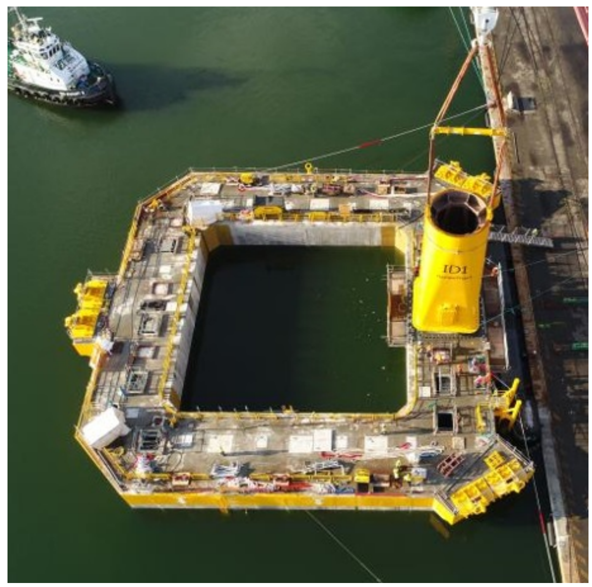

Figure 13: Storage of floating sub structure[4]

Bringing the floating sub structure to the quay side requires adequate depth within the channel/waters and enough space in width. The quayside draft will also need to be deep enough for the finished assembled wind turbine, which will have a draft of ca 20 m (table 2).

- The floating sub structure will be towed to quayside of port and repared for mounting wind turbine components onto it.

4.1.4 Activity 4: Transporting components from quayside to storage area

The tower components are usually transported by specialized trolleys, cranes or self propelled modular trailers. Specialized trolley systems can be used for pick up and rolling of the tower sections.

The nacelle and hub can be transported either by special truck, SPMT's or cranes. [47].

For efficiency purpose, blades often transported three at a time on racks, still making it one of the lightest components. However, due to its long shape, it is challenging to handle in port. The blades requires a frame to hold it in place, one at the hub and one along the blade span. The transportation of blades in the port will be executed by cranes or special trucks, which is possible due to its light weight.

- Tower component will be transported on special trucks or SPMT
- Nacelle and hub will be transported on SPMT
- Blades will be transported on special trucks or SPMT

4.1.5 Activity 5: Securing floating sub structure to quay side

For storing the floating sub-structure, wet storage area and towing vessels are required [29]. The sub-structure will be moored to the quay side, and stay attached until all components are mounted and the turbine is completed.

4.1.6 Activity 6: Storing of components

The towers can be stored on frames in the port in a horizontal or vertical position. The components are relatively easy to handle in port, and can be lifted from the transportation vehicle to storage frames by a crane. The towers are more robust for shocks/bumps compared to nacelle and blades.

The nacelle needs to be stored in a place not exposed to any external type of stresses. The nacelle should not be stored in areas where iron is handled, as this can lead to damage, for example accelerated corrosion. Covered by roof can be a good way of protecting the nacelle. Keeping nacelle off ground so that the SPMT's easily can access and bring the nacelle back and forth from this area is beneficial. A gap between the ground and nacelle, for example bolted racks to the ground, can be a solution.

Hubs are relatively easy to store, however some sort of protection against shock and surrounding conditions are necessary. Due to its compact size this is relatively easy to solve. The hub can be covered with robust tarpaulin or located indoor.

The blades will be taken off racks and stored "one at a time" in storage area. It needs careful handling and not harsh surroundings due to its fragile material.

Main importance when storing the components is that the components transported with SPMTs are stored off ground so that there is enough space for the SPMT to roll under and jack up so the components for storage or pick-up. Therefore nacelle and hub cannot be placed directly to the ground. The racks for tower and blades should have uniformly load distributed to the ground.

- Tower components will be stored horizontally on frames

- Nacelle and hub will be stored on shock isoltaing frames (high off the ground)
- Blades will be stored one at a time on frames

4.1.7 Activity 7: Transportation of tower from storage area to assembly area

This transportation will be similar to the transportation from quayside to storage area, whereas components will be picked up by cranes, and lifted to a special truck or SPMT. from here it will be transported to the tower assembly area.

4.1.8 Activity 8: Transport blades from storage area to assembly area

Figure 14: Transportation blades [44]

Transportation of blades can be similar to the transportation from quayside to storage area, with rolling special trucks, SPMT or crane from storage area to assembly area for hub and blades. The mounting of the blade to the hub requires a crane. Therefore, for logistic simplification, the blade will be transported with some sort of rolling transportation, enabling a crane in the assembly area to easily pick up the blade and start the mounting.

4.1.9 Activity 9: Transport hub from storage area to assembly area

The hub can be transported with SPMT or crane. As SPMT is cheaper, and the hub relatively easy to handle, this is a preferred method. This will also reduce the need for cranes in hub storage area, as no lifting is required.

4.1.10 Activity 10: Assembling of tower components

Before the assembly can begin, the edges need preparation and fitting. The area where the welding will take place has to be clean and clear of moisture, grease, rust, and paint to weld the components together. Furthermore, grinding and wand wire brushing will be used to rinse surfaces [34]. The top and bottom of the tower components both constitute assembly points for the tower. At these points, the towers will be mounted together by bolts and welded on both out- and inside [27]. The process of welding is planned to progress symmetrically due to the contraction of metal when heated. The shrinking on both sides of the structure must be equalized for the structure to remain its strength. The assembling can take place either horizontally or vertically. One of the advantages of on-shore assembling, as opposed to on-site, is the option of horizontal placement. In horizontal assembly, pipe turning rolls can be used to rotate the towers and assistant the welding process [37]. (The tower component must be lifted from the SPMT onto the pipe turning rolls). Welding equipment is mainly consisting of welding manipulator, submerged-arc welding system, automatic recycling feeding system and a welding rotator [6]. A detailed description of the welding process is not part of this thesis in itself. However impact on space requirements will be brought up later.

Figure 15: Pipe turning roll [37]

- Tower components will be mounted together laying horizontally
- Crane will bring the tower from the transporter onto pipe turning rolls
- Pipe turning rolls will spin the tower to be in convenient position for welding

4.1.11 Activity 11: Assembling hub and blades

The hub will be placed on a hub frame, lifted from the ground, with "snoute" facing upwards. The blades will be attached to the hub with bolts. The process is usually performed manually, constituting a high-labor intensive process. First, the blade and hub have to be aligned. Either a crane with belts can lift the blades in place, or SPMT with lifting and rolling ability can be used to position the blade to the hub. When assembling the blades to the hub, the blades have to be turned 90°. To turn the blade, a blade turning yoke can be used [49].
The bolting process includes up to 128 bolts for each blade (depending on the wind turbine) will be used. A balanced tightening process for all the bolts will have to be done manually to avoid misalignment from angular displacement, which can happen if bolts are tightened too hard on one side. [9]

- Hub will be lifted from SPMT with crane, onto assembly frame, facing upwards

- Blade will be lifted off transportation vessel with a crane to hold it in place for bolting
- Supporting crane will have a turning yoke, making sure the blade is angled correctly for mounting

4.1.12 Activity 12: Preparing floating sub structure for turbine components

Before mounting the tower component, the floating sub structure must be prepared for bolting and welding. This is done by cleaning the surface for oil and grease, and a wire brush is used to remove rust, rubber coatings and paint. [17]

4.1.13 Activity 13: Transportation of assembled tower to quayside

Transportation at this stage is a complex process due to the long and heavy shape of the assembled tower. Two SPMTs are needed to bring the tower with a total length of over 100 meters to the quayside. The assembled tower will be lifted from the turning yolks onto SPMTs and transported quayside, where the floating sub structure is located. The ends of the tower have to be prepared for bolting and welding by cleansing and rinsing.

4.1.14 Activity 14: Transportation of nacelle to quayside

This transportation will be similar to the transportation from quayside to storage area. The SPMT will roll under frame, jack it up, and drive to quayside where the floating sub structure is located.

4.1.15 Activity 15: Transportation of assembled hub and blades to quayside

The assembled rotor is a significantly bulky object, and great care must be taken when transporting it to avoid damage. The operation requires a large area if transported on SPMTs. The assembled component can also be lifted by crane, however, with a risk of losing control due to weather conditions. Transportation it laying on SPMTs is more flexible and less exposed to challenging weather conditions.

- The assembled hub and blades will be transported on SPMTs laying flat

4.1.16 Activity 16: Mounting of tower onto floating sub structure

Due to the length and weight of the tower, this is a challenging operation. In order to maintain control, two cranes will be needed, one main crane to carry the weight and another one to stabilize and steer the tower in the right direction. Several methods have been developed to upending the tower section in a safe and controlled way. A tower upending tool, for example, a J-hook, can be used. It is designed to guide the tower section, preventing it from hitting other objects or the ground. The J-Hook can rotate with the tower components from a horizontal to a vertical position. The main crane will lift the tower from the top and the J-hook from the bottom. When the tower is ca 1,5 m from the ground, the tower can be brought towards a vertical direction. The J-hook will fold together with the movement of the tower as it is being rised. When the tower is at a horizontal position, the J-hook can be released. [49]

When the tower is placed on the floating sub structure, a guidance system is needed for the turbine to be appropriately located. From here, the tower will be welded and bolted to make sure it stays in position, able to take up the momentum from wind forces when the turbine is operating.

- The assembled hub and blade will be lifted by two cranes, one main crane and one adjusting crane

4.1.17 Activity 17: Mounting of nacelle onto tower on sub structure

The nacelle is the heaviest and most fragile turbine component, requiring a crane with great capacity and preciseness. The nacelle will be lifted from the transportation vessel and mated with the tower. Due to movements from both the tower, sticking up over 100 m in the air, it most likely will oscillate back and forth. As the nacelle has sharp corners, it might experience vortex shredding in the wind. Therefore advanced computational methods are needed for a steady mounting of nacelle[21]. Due to this, the weather needs to be calm, which reduces the flexibility regarding the timing of the activity.

- Nacelle will be lifted by the main crane and mounted to the tower

4.1.18 Activity 18: Hub and blades lifted and mounted onto nacelle on floating sub structure

For installing a full rotor, considerable care must be taken. The large sweeping area will easy capture the wind. Two cranes are necessary for this operation, one large for for lifting and one smaller for holding the rotor stable. For the stabilization, a clamp is used around the blade, and controls the trailing blade and making it turn to installation position. The clamp can be customized to several types and sizes, and will have a pressure monitoring that will ensure the stress on the blade is kept at a allowed minimum. After the rotor is installed, the clamp can be released by a remote control. Even thought it is required two cranes, the same for lifting the tower, same cranes can be used by switching the stabilizing element between the operations (the J-Hook and clamp). [49]

Figure 16: Storage of floating sub structure[4]

The mounting of hub and blades will be the most complex and time demanding operation in the whole process. The sweeping area of blades will be significant large, and therefore requires calm weather.

- Rotor will be lifted directly from SPMT, both with connection in the center of rotor, and a stabilizer clamp

4.2 Activity relationships

As the individual activities have now been addressed, a temporary decision on how they will be executed has to be made. The different activities will be analysed with the perspective of what areas needed, and how the different activities are relating to each other location and time wise. An analysis of flow of materials, including the intensity of the moving of units will be adressed later in the design process after an evaluation of layouts.

4.2.1 Material flow

In order to prevent unnecessary bottlenecks, the material flow must be systematically managed. The materials are large and heavy, and handling and transporting the components are expensive compared to activities such as storage and inspection. This means that the flow diagram is a good way of representing low-cost-suggestion of the design layout. This diagram will be used later in the design process and space determinations to suggest layout design. The flow chart can be seen in following figure 17. For visualization, transportation of the different components will be split into separate activities.

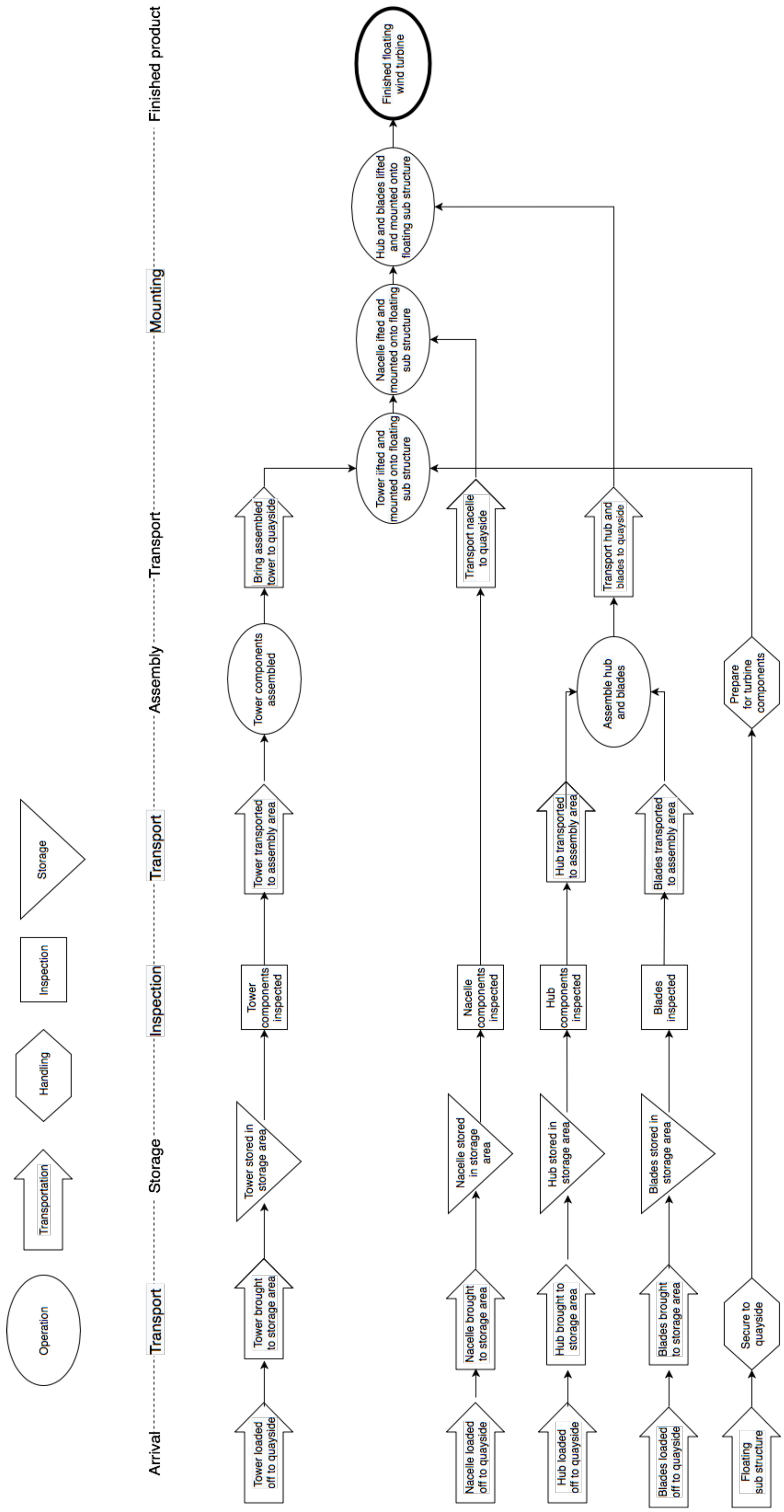

Figure 17: Flow chart

4.2.2 Relationship chart

In order to determine which activities or types of work that should be located next to each other, an activity chart can be made. This tells which activity area that should or should not be located close to each other, and gives a short reasoning for why. The importance of location in relation to each other are explained in table 38 and the reason why is explained in table 39 (see appendix B). The chart has diamond shaped relation for each of the activities. It is beneficial if large, complex components does not have to travel a long distance, in order to reduce costs.

The activity areas are:

- Offices for workers
- Quayside for arriving ships (ro-ro ramp)
- Quayside for arriving ships (crane)
- Tower storage
- Nacelle storage
- Hub storage
- Blades storage
- Assembly area tower
- Assembly area hub and blades
- Quayside for floating wind turbine

The importance of closeness between the areas in port has been analysed. Evaluation criterion to create the chart is presented in appendix B. As can be seen in figure 18 closeness between, for example, Tower storage and Assembly tower area are marked as "Closeness especially important". This means that when designing the port layout, this should be included in the design.

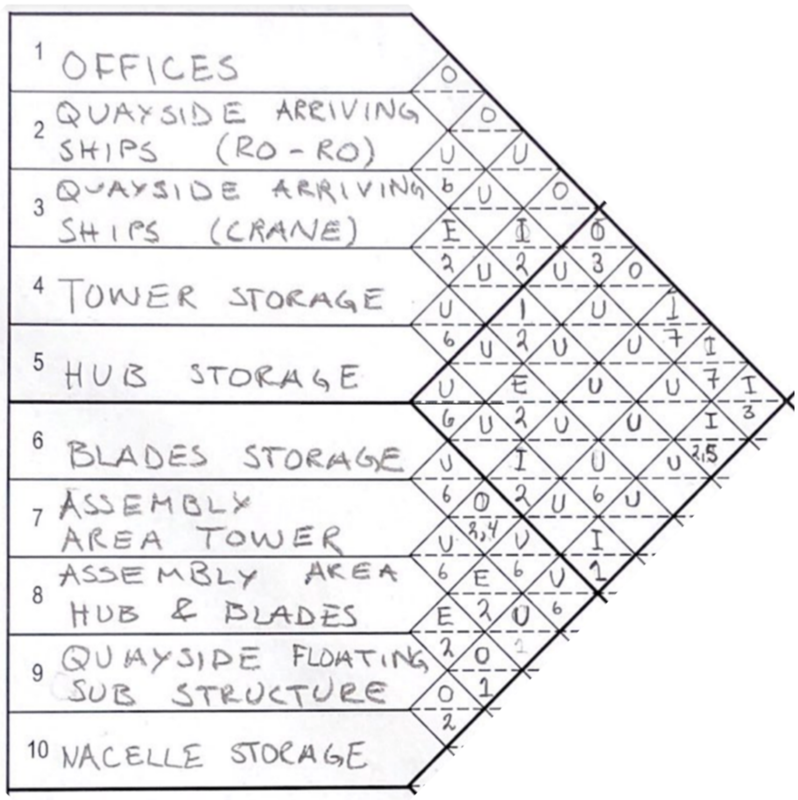

Figure 18: Relationship chart

This figure is a starting base for further analyses of what can become cost-effective by minimizing travel distances in the port.

4.2.3 Relationship diagram

To visualise the relations between areas, the relationship chart (figure 18) in combination with the flow chart (figure 17) can be used. The combination will give importance of closeness between areas and the sequence of activities in combination.

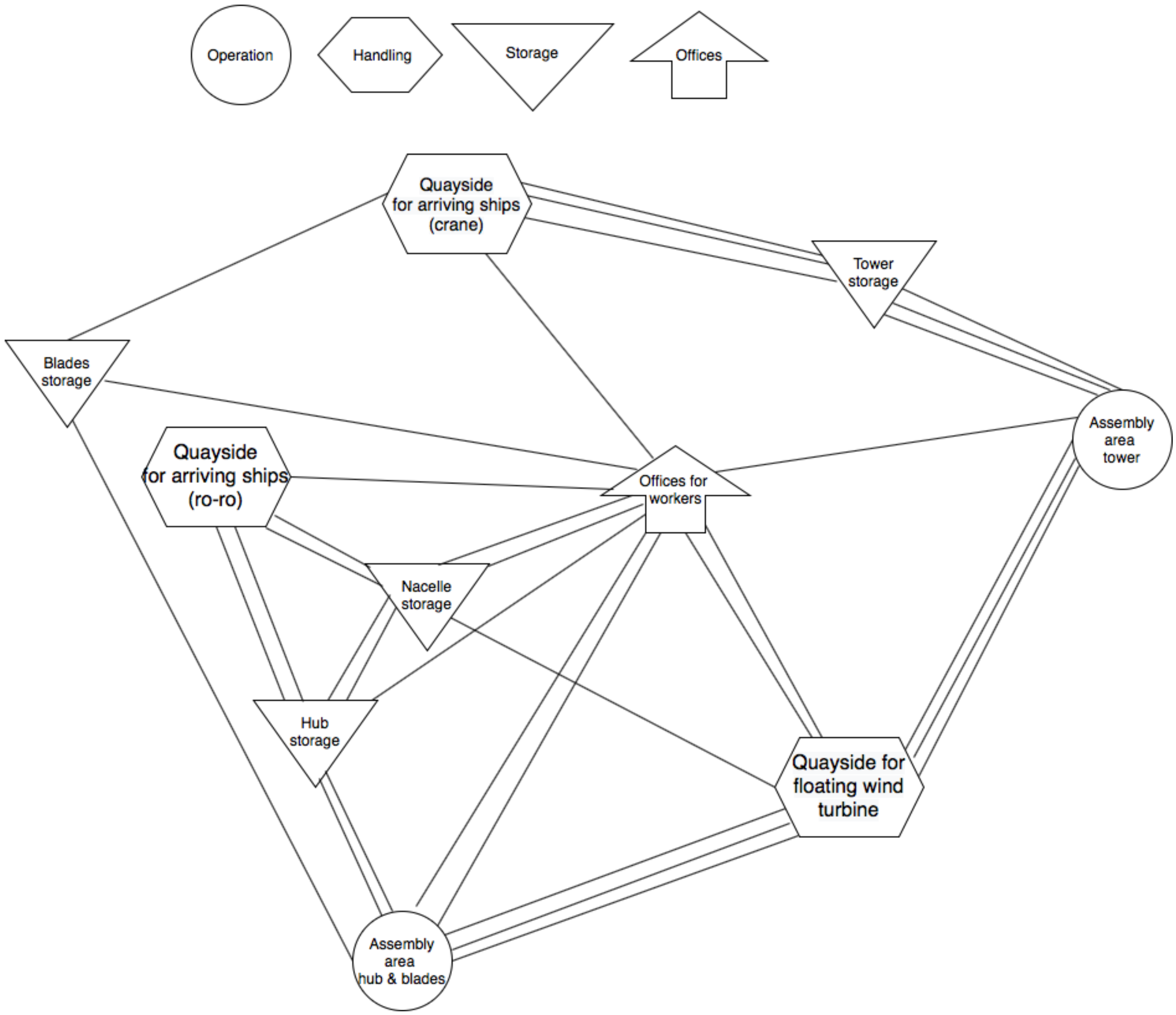

Figure 19: Relationship diagram

As the relationship diagram describes relatively few port areas, the need for colouring is seen as superfluous. The name of the activity area and the number of lines is, in this case, sufficient. An indicator on where the different areas should be located to each other is starting to visualize.

4.2.4 Service areas

Specific service areas must be added, even though they are not directly linked to the production flow. They are essential for the workers well being and effectiveness. The service areas are offices, toilets and washrooms, tool rooms, rest- and lunch room, cafeteria, dispensary, power generation areas, parking areas, etc.

4.3 Project planning

4.3.1 Network diagram/analysis

In order to establish the network diagram, a more detailed activity list has been made, consisting of 26 different activities. The increased number is due to each transportation of component, lifting and handling, being explicitly listed. The list of activities is seen in figure 21.

This has been followed by a network diagram, linking all the activities together, resulting in a finished floating offshore wind turbine. The first activity is components arriving port, and the final activity is hub and blades being lifted and mounted to the nacelle on the turbine.

From this, a mapping on what activities are dependent on each other can be made. There are many clear reasons for why an activity cant happen before another. For example, the assembled hub and blades can not be mounted to the nacelle before the hub and blades have been assembled. A nacelle can not be transported from quayside to the storage area before the nacelle has arrived in port. Therefore, each activities' predecessor has been identified, defining which activity must happen before another activity, giving a finish-to-start dependency.

An estimate on how much time each activity has also been made, given in hours. These are variables made on educated guesses from the author. A further investigation on time on activities will give a more precise results. The ES, EF, LS, LF, T and float variables have been calculated, and the critical path identified as the activities with 0 float. An example of one of the activities are given:

ES		EF
	Activity	
LS		LF

Table 10: Variables

20		28
	Assemble hub & blades	
53		61

Table 11: Variables for assemble hub and blades

The variables from table 11 will provide information to the predecessor activities *transport blades to assembly area* and *transport hub to assembly area.* A summary of the results is presented in figure 20. For simplicity, a code is given to each activity, starting with an abbreviation of component, N=Nacelle, followed by activity type, for example, t=transport.

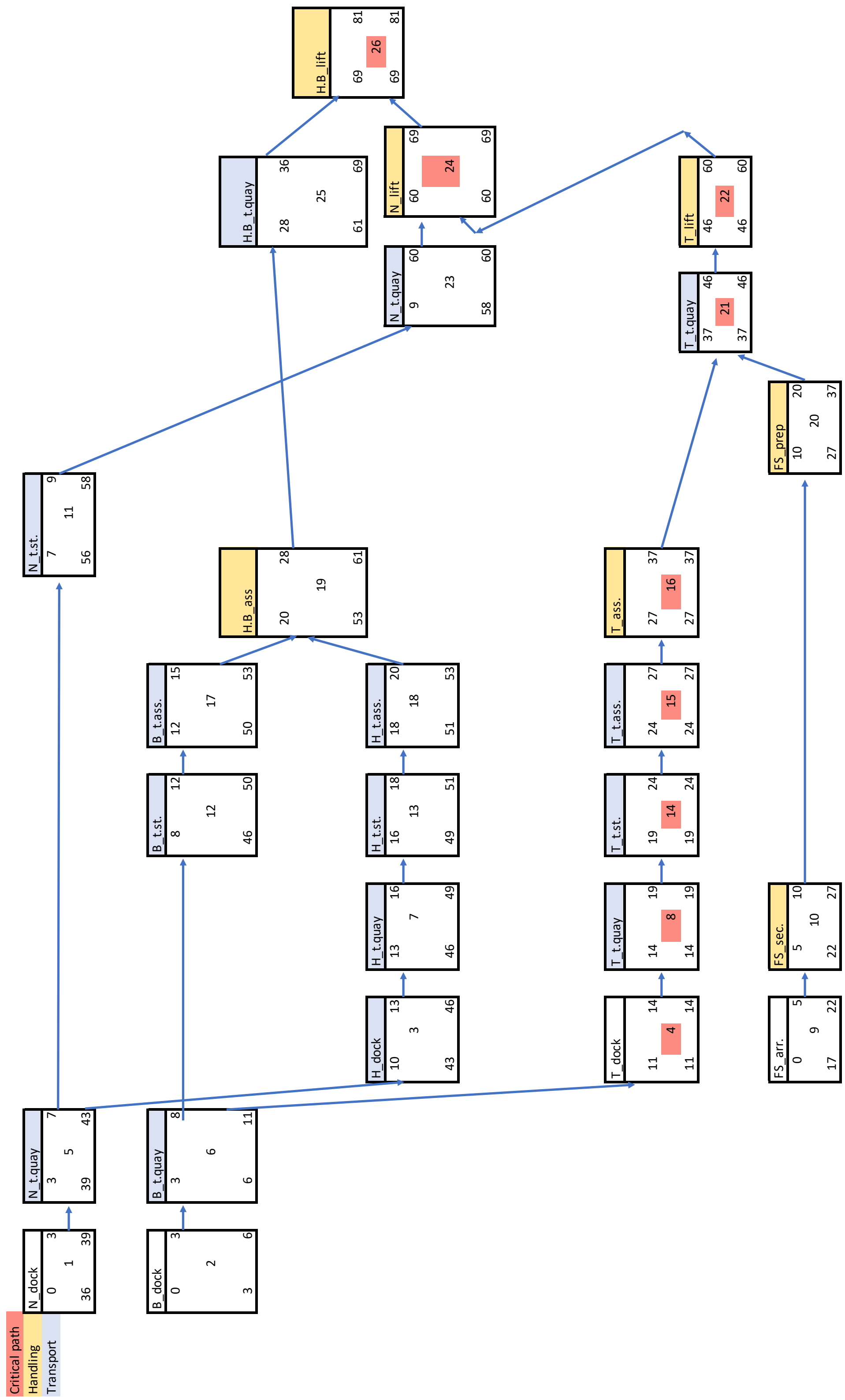

Figure 20: Activity On Node network

Activity nr	Activity	"code"	T: Duration (hours)	Proceedor	ES	EF	LS	LF	Float
1	Nacelle ship docking	N_dock	3	-	0	3	36	39	36
2	Blade ship docking	B_dock	3	-	0	3	3	6	3
3	Hub ship docking	H_dock	3	5: FS(3)	10	13	43	46	33
4	Tower ship docking	T_dock	3	6: FS(3)	11	14	11	14	0
5	Transport nacelle from ship to quayside	N_t.quay	4	1: FS	3	7	39	43	36
6	Transport blades from ship to quayside	B_t.quay	5	2: FS	3	8	6	11	3
7	Transport hub from ship to quayside	H_t.quay	3	3: FS	13	16	46	49	33
8	Transport tower from ship to quayside	T_t.quay	5	4: FS	14	19	14	19	0
9	Arrival floating sub structure	FS_arr.	5	-	0	5	17	22	17
10	Secure floating sub structure to quay side	FS_sec.	5	9: FS	5	10	22	27	17
11	Transport nacelle from quayside to storage area	N_t.st.	2	5: FS	7	9	56	58	49
12	Transport blades from quayside to storage area	B_t.st.	4	6: FS	8	12	46	50	38
13	Transport hub from quayside to storage area	H_t.st.	2	7: FS	16	18	49	51	33
14	Transport tower from quayside to storage area	T_t.st.	5	8: FS	19	24	19	24	0
15	Transport tower from storage area to assembly area	T_t.ass.	3	14:FS	24	27	24	27	0
16	Assemble tower components	T_ass.	10	15: FS	27	37	27	37	0
17	Transport blades to assembly area	B_t.ass.	3	12: FS	12	15	50	53	38
18	Transport hub to assembly area	H_t.ass.	2	13: FS	18	20	51	53	33
19	Assemble hub + blades	H.B_ass	8	17: FS 18: FS	20	28	53	61	33
20	Prepare floating sub structure for turbine components	FS_prep	10	10: FS	10	20	27	37	17
21	Transport assembled tower to quay side	T_t.quay	9	16: FS	37	46	37	46	0
22	Tower lifted and mounted to sub structure	T_lift	14	21: FS 20: FS	46	60	46	60	0
23	Transport nacelle to quayside	N_t.quay	2	11: FS	9	60	58	60	0
24	Nacelle lifted and mounted to sub structure	N_lift	9	23: FS 22: FS	60	69	60	69	0
25	Transport hub + blades to quayside	H.B_t.quay	8	19: FS	28	36	61	69	33
26	Hub and blades lifted and mounted to floating sub structure	H.B_lift	12	24: FS 25: FS	69	81	69	81	0

Critical path
Handling
Transport

Figure 21: AON table

The critical path is:

4	Tower ship docking
8	Transport tower from ship to quay side
14	Transport tower from quayside to storage area
15	Transport tower from storage area to assembly area
16	Assemble tower components
21	Transport assembled tower from assemble area to quay side
22	Lift and mount tower to floating sub structure
24	Lift nacelle and mount to sub structure
26	Lift and mount hub+blades to floating sub structure

Table 12: Critical path

As demonstrated in the float chart, the tower components represent the primary critical path. This should be expected, as the tower component is the first component that must be mounted on the floating substructure before any of the other components can be installed.

4.3.2 Resource chart

In this case, the resources are given a value based on complexity of operation, expected demand from for example human labour etc, based on my own judgement. For example, transporting a tower from the quay side to the storage area is a relatively easy and low-demanding task. On the other side, lifting a hub with three blades more than 100 m up in the air and mounting it onto the nacelle requires more resources due to its complexity and scale. Resource demand will depend on different factors like scope, man hours and special competence needed. Number of resources needed per activity is presented in appendix A, and is based on the authors' expected resource requirements.

From the number of resources required per activity, the resource chart can be made. As presented graphically in figure 22, the need for resources is very high in the beginning and flattens out eventually, as every resource is located at "Earliest Start".

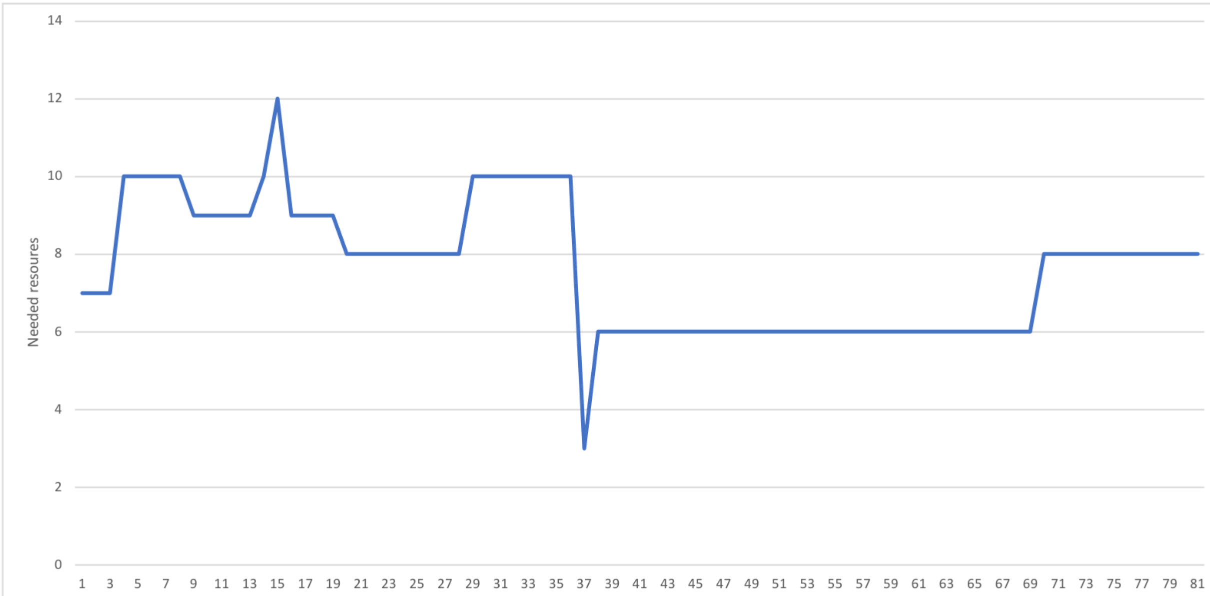

Figure 22: Number of resources per hour

In this case, it is an assumption that the total time to construct each turbine is fixed, as the assembly method used is non-reducible in terms of time. However, the use of resources can be adapted and minimized. By utilizing the float for the different activities, the number of resources can be reduced.

The resources can be optimized by using the Brute Force method in Python. This method checks for all possible combinations of distributing the resources, and the resources' timing may optimize resources needed. The Brute Force method is, unfortunately, an expensive method in terms of computer time. An attempt was made. However, complications in the code made the process stop. The coding became more complex than anticipated because of the different dependencies between the activities. For example, if activity 6, transportation of blades from ship to the quay side, takes place at hour 5, not only will activity 12 and 4 be affected, but all the following activities that are dependent on each other from this branch. The decision was made to stop this attempt and shift focus to develop the port facilities and design.

For further work, the Python code is given in appendix G, and two attempts on new compositions of resource distribution is presented in appendix H. The objective of the optimization can be limited to predefined different constraints. For example, a maximum on costs and costs to each equipment needed could be defined as an objective.

4.4 Equipment needed in the execution phase

First, some detailed data on the transportation equipment is needed, as this is the most critical feature at this stage of designing the layout. For example, the details on how components are bolted together is not essential at this stage. Per now, the logistics, transportation, and sequence order is highlighted. However, the different tasks within specific areas must be left space for.

The process of deciding space requirements for each area starts with addressing the equipment required for each area. When this has been decided, space needs is also addressed. At this phase of the layout planning, the Self Propelled Modular Trailer and cranes are essential equipment to address, as up scaling will mainly depend on transportation between the areas and lifting capacities. On the other side, the type of welding equipment, for example, is regarded as less crucial. The main aim of this chapter is to find out how much area the SPMT and cranes take up.

4.4.1 Self Propelled Modular Trailer (SPMT)

Data on a self propelled modular trailer is presented in the following table. Bearing capacity, size of the trailer and some steering information is given. All necessary for further development of space requirements of the port.

Capacity	48 tons/axle line
Weight	4 tons/axle line
Platform width	2,430
Platform length	1,4 m/axle line
Platform height	1,500 ± 350 (700 mm stroke)
Average speed	5 km/h
Steering angle	+130° / -110°
Area platform	3.4 m^2/axle line

Table 13: Self propelled modular trailer [16] [26]

The axle lines can be coupled together to increase the bearing capacity of the SPMT [2]. The lifting requirements will vary for the different activities, and therefore calculations on the weight of the components that will be carried with SPMT will be systematised. The modular trailers can either be self propelled or towed. It can be beneficial with self propelled in cases of weighty components as it gives control. However, the trailers can also be towed with a truck, which is a cheaper way. These are decisions that can be calculated more precisely later. For now, it is assumed all the modular trailers are self propelled. The number of axle lines needed for different components is calculated as followed:

$$\frac{Weight\ component\ [tons]}{48[\frac{tons}{axle\ line}]} = X\ [axlelines] \tag{4}$$

The number of axles needed must be rounded up in order to establish margins that make sure the SPMT can carry the load. Example:

$$Required\ number\ SPMT\ axles\ for\ transporting\ nacelle = \frac{400}{48} = 8,3 \approx 9 \tag{5}$$

Activity requiring SPMT	Weight of component[tons]	required number SPMT axles	Covering area of SPMT
Transport nacelle	400	9	30.6
Transport hub	90	1	3.4
Transport blade	30	1	3.4
Transport 1 tower component	200	5	17
Transport assembled tower	400	9	30.6
Transport assembled hub&blades	500	11	37.4

Table 14: SPMT activities

4.4.2 Crane

Cranes will be used for several activities in port. Starting off with som data on different cranes required is presented in table 15.

	Heavy lifting crane	Supporting crane	Lo-Lo crane	Storage blades	Storage tower
Type	LTM 1500-8.1	SHL Luffing Jib	6210 Harbour Mobile Crane	NCN 85 T	NCN 130
Lifting capacity [tons]	500	100	125	40	120
Boom range [m]	14.4	10	44	6.5	3.5
Lifting height[m]	168	84	55	11	9
Crane weight[tons]	150	48	190	70	108
Foundation width[m]	9.9	7	14.9	4.16	4.9
Foundation length[m]	14.3	13.5	9.9	11.1	14.5
Covering area[m^2]	142	95	148	46	71

Table 15: Crane data [7] [42][24][22][33]

In table 15 specific cranes are designated to the different areas. Cranes are needed for several activities, and sometimes several cranes are needed for one activity. The use of two cranes will reduce the required capacity and take up less space, particularly for the oblong components.

Activity requiring crane	Location	Weight component [ton]	Req. lifting height [m]	Needed capacity crane [ton]
Lifting blades	Quayside arriving components (Lo-Lo)	40	∼15	40
Lifting tower	Quayside arriving components (Lo-Lo)	200	∼15	120
Lifting nacelle and hub&blades	Floating sub structure quay side	520 ∼"*support*"	160 ∼80	520 100
Lifting blades storage	Storage blades	40	∼10	40
Lifting tower storage	Storage tower	200	∼10	200

Table 16: Required crane activities

The cranes lifting the tower- and blade components off the supply vessels are located at quayside for arriving component transport vessels. One heavy lifting crane will be located in "Quayside floating sub structure"-area, lifting the assembled components onto the floating wind turbine. The supporting crane will be located next to it for adjusting the components in desired angles. There will be cranes located at the storage areas of blades and towers, lifting them on and of the transportation trucks or SPMT and to the components' frames.

4.5 Space size determinations

All activities, equipment and areas needed are identified, and relations analysed. However, the size of the spaces is yet to be calculated.

4.5.1 Space requirements

As presented in chapter 3.4.3, there are five main methods of determining space requirements. For this purpose, yard for up-scaling floating wind turbines, method number 4 is seen as most prominent: *roughed-out layout*. The reasoning for this is

- Calculation method will break each activity area down into sub-areas, which is not suitable for this case, as the aim, for now, is to make a clear overview of the layout design and not go further into details.
- The converting method is unsuitable as there is no existing yard or layout as a starting point.
- Space standards can be used to some extent. However, the data on all areas is limited.
- Ratio trend and projection are neither suitable, as the design process is in parallel designing how many wind turbines are possible per unit of time.

The roughed-out layout method is suitable for projects where the activities are critical, represents high investments, and equipment is somewhat fixed. The roughed out layout can be made by calculating the spaces needed, by designate what areas need what equipment, and how much space the different components need. An approximation based on these factors will eventually culminate in an approximation of the sizes of the different areas. Again, this is phase II of the SLP process, so there might be large changes in the space sizes in the project.

How much space does the components of one turbine need? Beginning with space requirements for *one* turbine (in harbor, floating sub structure is *not* accounted for here). Sweeping area is the area a component covers when rotating around its own axis while laying flat (most relevant for tower and blades). The sweeping square area (outer edges of the circle will make up the square, blue in figure 23) will be the value rest of layout design is based on, as the planning is mainly happening in squares. The sweeping areas for the different components will base the design and size for the different areas in the assembly port.

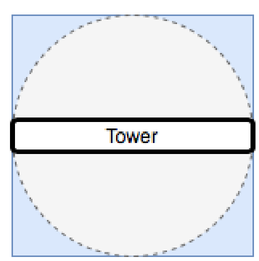

Figure 23: Sweeping area tower

Components	Dimensions	Area[m^2]	Sweeping area [m^2]	Sweeping square area [m^2]
Tower (1 component)	70 x 8	560	2848	3848
Blade (1 blade)	80x8	640	5027	5027
Nacelle	15x7	105	177	177
Hub	d=6	28	-	36
Assembled tower	2 x 70 x 8	1120	15 394	19 600
Assembled blades and hub	3x80x8+ d=6	1948	21 642	26 569

Table 17: Space required for components

The area of the wind turbine blade is assumed to be square-shaped for simplicity to calculate the required space. This will fit well when adapting to a sweeping area the component will cover but is an over-estimate regarding the storage areas for the blades. When components are handled or assembled, the *sweeping squared area* will be used, as this mos likely requires rotation and transportation of the components. However, storing components, the space that the components *take up themselves* will be used.

Equipment will take up space to perform the activities, so these will need to be addressed as well. Data on the SPMT and cranes have been given in chapter 4.4.1 and 4.4.2, sizes of components are presented in table 17, and the rest of the equipment is gathered from catalogues.

By adding the areas together and add some flexibility for movement etc., in port, the foundation for required spaces is set. By combining the scaled areas with the relationship diagram, a layout can be designed. Some of the areas might have requirements on minimum length of an area, for example, blade storage *needs* to have a sufficient length for the blades to fit. By systematically going through all the areas, this can be identified and included in the design.

Offices

The office area will contain a cafeteria, working spaces, meeting rooms etc. The details about this are unnecessary at this stage. However, the space set off to this area is 1000 m^2. The Length/width can be quadratic, or somewhat oblong, or consist of several smaller buildings. This is a flexible measure and can be adapted as the layout design evolves.

Quayside Ro-Ro and Lo-lo

From the Activity On Node network and resource requirements per hour diagram, (figure 20 and appendix C), it is seen that there is a lot of float to go on for the Ro-Ro and Lo-Lo quayside. Therefore, these areas have been merged into one area, and the same quayside is receiving both types of vessels.

The quayside for arriving components will require different features, depending on the component. SPMTs will roll off hub and nacelle, and blades and towers will be lifted off by crane.

Mooring units for docking, a ramp area for the components to roll on and off, spaces for SPMT to be ready to roll in and pick up the components, cranes for lifting off blades and towers, and a sufficient quayside length. The data are both "educated guesses" and data from previous chapters. The area needed for *one* turbine component is found to be

Feature	Number of units	Area [m^2](one unit)	Total area needed[m^2]
Mooring	2	15	30
Ramp	1	450	450
SPMT (Nacelle)	1	30.6	30.6
SPMT (hub)	1	3.4	3.4
SPMT (tower)	2	17	34
Crane	2	148	296
Blade sweeping square area	1	5027	5027
Total			**5871**

Table 18: Quayside, Ro-Ro/Lo-Lo

Note that the tower needs 2 SPMT because it requires two tower components for one wind turbine. The typical length of supply vessels of wind turbine components is approximately 100 m (mini-bulker cargo ship [14]). Therefore the required quay length is set to 150 m.

Storage areas

Towers and blades will be stored laying flat on storage frames. The spaces that will be taken up is mainly from the component itself, and there will be a need for cranes to lift the components on and off SPMTs or trucks to frames. Nacelle and hub will also be stored flat, located on tall enough frames for the SPMT to roll under, and place the component. The different components will need room for handling. The blades are the longest and component with largest sweeping coverage, and it is therefore given space for one blade components' sweeping square area. The areas needed for *one* wind turbine will be:

Component	Area (1 component)	Number of components	Space for cranes	Total storage area
Tower	560	2	71	1191
Blade	640	3	46	1966
Nacelle	105	1	-	105
Hub	28	1	-	28

Table 19: Storage area for tower, blade, nacelle, hub

The towers and blades require a certain length in order for spaces - therefore, the minimum length of tower storage must be ∼70 meters, and blades ∼80 meters. For hub and blades, this is not as distinct, and the area can be approximately quadratic.

Assembly area tower

For assembling the tower components, several types of equipment are needed, and the process is described in chapter 4.1.10. The data on welding- and bolting equipment are made as educated guesses and based on talks with co-students who have been working in the industry and gained more knowledge to make some estimates. The area needed contains everything needed for the activity to be done. There will be a need for cranes to lift the tower components onto pipe turning rolls and lift the assembled tower component back onto two SPMTs. The tower needs space for turning, and therefore the sweeping square area has been used to calculate the space needed.

Feature	Number of units	Area needed $[m^2]$	Total area needed$[m^2]$
Bolting equipment	1	20	20
Pipe turning roll	4	10	40
Welding equipment	1	20	20
Sandblasting and painting	1	20	20
Cranes	2	71	142
Tower component itself	2	560	1120
Sweeping area assembled tower	1	1120	19 600
Total			**20 962**

Table 20: Assembling tower components space requirements

The length of assembled tower will be 140 meters, this will require significantly area, especially in order to make turns. In addition it is taken into account that there must be room for the next tower to enter directly, so there is room for two towers. It can also be considered transport the assembled component vertically with crane. Following there will be need for large cranes, which might take up as much space. Finer calculations on this can be done in phase 3.

Assembly area hub and blades

For the assembly of hub and blades, a large sweeping area is needed and is the feature that is mainly taking up space. There will also be a need for a suitable hub frame (to carry both hub and three blades), bolting- and welding equipment. Crane for lifting the blade, both lifting and positioning it with a blade turning yoke.

Feature	Number of units	Area needed [m^2]	Total area needed[m^2]
Hub frame	1	28	28
Bolting equipment	1	20	20
Welding equipment	1	20	20
Crane(Blade)	1	46	46
Crane(turning yoke)	1	46	46
SPMT (transporting finished assembled hub)&blades	1	37	37
Hub&blade assembled	1	26 569	26 569
Total			**26 766**

Table 21: Assembling hub and blades space requirements

The sweeping area of the assembled hub and blades are significantly large. However, the shape is circular, implying the space can be designed approximately quadratic.

Quayside area for floating wind turbine

As the largest component in the port will be the finished assembled hub and blades, the area will need space sufficient for this and space for a heavy-lifting crane in addition to an assistant ”turning” crane. Storage house for supporting equipment like clamp and J-hook will also be needed. Mooring units to make sure the substructure stays in place.

Feature	Number of units	Area needed [m^2]	Total area needed[m^2]
Heavy lifting crane	1	142	142
Supporting crane	1	95	95
Storage house	1	50	50
Mooring units	2	15	30
Hub&blades	1	26 569	26 569
Total			**26 886**

Table 22: Quayside floating sub structure requirements

The semi-submersible sub structure length/width (quadratic) is 25 m. However, as the full rotor is arriving horizontally, the space required is at least 86570 m^2 (stated in table 22) when the rotor will roll into the area. Therefore the quay length must be the span length of the rotor: length of 2 blades + diameter of hub

$$2 \cdot 80m + 6m = 166 \tag{6}$$

There must be space for a heavy lifting crane and supporting crane. These can, however, be located in between the blades, and there is therefore no need to address extra room for them.

4.5.2 Main aisles

The main aisles, meaning spaces where the different components are available to move between, must also be addressed, as large components need to move through the port. From time to time, these aisles will also be used to move large equipment back and forth. In this case, most of the equipment (cranes, SPMT's) are movable, so the aisles spaces will be accounted for as designated spaces are located in the port.

4.5.3 Up scaling (to five turbines)

Until now, it has been assumed spaces needed are only for *one* wind turbine. It will not be cost-bearing with only one turbine, and as an example to show how to increase the number of turbines, the number is increased to five turbines. To determine spaces for the production of five turbines before the next vessel bringing components arrives. The up-scaling will only need to be fitted for the component storage area and some added extra spaces for the SPMTs/ trucks. This will be done in chapter 4.5.4.

4.5.4 Total space needed

A summary of the different spaces required for **one** turbine in port is presented in table 23.

Area	Space for 1 turbine [m^2]
Offices	1000
Quayside (Ro-ro/Lo-lo)	5827
Storage tower	1120
Storage blade	1966
Storage Nacelle	105
Storage hub	28
Assembly tower	20 962
Assembly hub& blades	26 766
Quayside floating structure	26 886

Table 23: Area spaces for one turbine

The only increases needed will be storage areas, and some quayside (Ro-ro and Lo-lo) as this is where the components will arrive, and the required extra equipment for the up-scaling is located (for example SPMT). However, in assembly- and substructure areas, components will only float through, so no need for increased sizes are necessary in theory. In practice, some enlargements will be necessary, and this will be included later. Simplifications on SPMT sizes have been made, and it is assumed the size is approximately 18 m^2.

There will be a need of total 10 SPMTs for Quayside Ro-ro/Lo-lo, picking up blades and towers from quayside (assumed that some of the SPMT's will make it back from delivery of blade components to pick up more), a total of 5 SPMT's must be room for picking up hub and nacelles. The components (blades and tower, hub and nacelles) will arrive at different times to use the same storage for SPMTs.

What is needed extra: in addition to 1 wind turbine.

$$Area\ component \cdot Number\ of\ extra\ components + existing\ area\ = new\ total\ area \tag{7}$$

The areas will be added 5% for flexibility, in case of larger turbine parts and changes is turbine design.

Area	**Whats needed extra**	**Required extra space**	**Area new total**	**Area + 5%**
Quayside Ro-ro/Lo-lo	8 SPMT	144	6015	6316
Storage tower	space for 8 tower components	4480	5671	5955
Storage blade	space for 12 blades	7680	9646	10 128
Storage nacelle	space for 4 nacelles	420	525	551
Storage hub	Space for 4 hubs	112	140	147
Offices	-	-	1000	1050
Assembly tower	-	-	20 962	22 010
Assembly hub& blades	-	-	26 766	28 104
Quayside floating sub structure	-	-	26 886	28 230
Total			97 611	102 491

Table 24: Area needed for 5 wind turbine-construction

4.5.5 Space Relationship Diagram

In order to decide how the various areas should be placed in relation to each other, a space relationship diagram was made, using routed sheets. By scaling the areas down to fit the routes, a relation ratio was calculated. One worksheet consists of 58 X 36 cross-section grids, which gives a total of 2088 squares. Dividing the total area necessary by number of available squares, gives the scale size of 1 square grid, shown in equation 8.

$$\frac{102566}{2088} = 49 \approx 50 \tag{8}$$

However, to make some flexibility and availability to move the areas and have spaces between, one box is set to be **100** m^2. Dividing the area needed by 100, the required number of boxes per area is calculated (some round-up/down has been done for simplicity).

Area	Areal $[m^2]$	Number of squares (1:100)	Configuration requirements
Quayside Ro-ro/Lo-lo	6316	63	Min quaylength: 150 m (15 sq)
Storage tower	5955	60	Min length: 70 m (7 sq)
Storage blade	10 128	101	Min length: 80 m (8 sq)
Storage nacelle	551	6	
Storage hub	147	2	
Offices	1050	11	
Assembly tower	22 010	221	min length 140 m (14 sq)
Assembly hub& blades	28 104	281	min length: 166 m (17 sq)
Quayside floating sub structure	28 230	282	min length: 50 m (5 sq) min width: 166 m (17 sq)

Table 25: Scaling the layout

The configuration requirements come from the area that needs to have a specific length.

4.6 Evaluation of design layouts

The areas have been assigned spaces and given the required number of squares and required lengths. Now, different layout configurations can be put together and compared. For the layout designs, different systems have been used to make the basis. Each layout will be evaluated based on transport distance, flow intensity, and required resources to perform the activity. Further on, a discussion on the ability to shear equipment and whether the layout has a practical design will be considered.

The different area requirements and equipment locations are examined to see if some components should enter one end of the area or similar configurations that make handling less complex and more practical. However, in this case the activities taking place within and between the specified areas generally do not depend on components entering a specific end. The equipment, cranes, welding etc., can be placed after the design layout has been made at a suitable location within the area and facing a suitable direction.

The different compositions and variances of the layout design are endless. Some set shapes of areas have therefore been made and are shown in appendix I. The scale is 1:100. The areas do not need to have precisely these given shapes for the layouts, but it is a starting point in the design process. Changes will most likely be made later in the design process.

Five layout designs have been made, each with a distinct approach.

1. Design based on flow diagram
2. Design based on relationship diagram
3. Design based on basic systems for the movement of materials, combining Direct and Central system (chapter 3.5.2)
4. Design with oblong storage areas
5. Design based on basic systems for movements of material (combining Direct and Central system), with relocated main aisles

For each of the five design layouts, several evaluation criteria are used to decide the "best" layout design. An analysis of different parameters will be the foundation. The evaluation criteria are:

4.6.1 Combination of distance, flow intensity and resource need

For each individual activity, in this case travel, a cost related parameter can be developed by multiplying the the travel distance(D), flow intensity(F) and resource requirements(R). The reasoning behind this is that the value for each of the parameters are individual for every activity (except the flow intensity, which must be seen as a weighting number). One can link this multiplication to operational cost because it becomes more expensive the longer distance, more often, and resource-intensive an activity is. The evaluation will be done by comparing the points provided by multiplying D,F and R.

Travel distance

The travel distances for components is calculated as the distance from and to the centre of the areas.

Flow intensity

Flow intensity is given as the number of components to be moved per supply of 5 turbines (for example, there will be ten (un-assembled) tower components for five turbines, and five assembled tower components). This will be a constant for every activity and can be registered as a weight number.

Resource requirements

The resources required is given in appendix A. However, there will be a reduction in resource requirements if the layout design gives the ability to share a resource. This resource requirement is linked to both investment- and operational cost. For example, if a crane can be used in two areas, as they are located close together, and there is much float for two activities, the crane can be shared. The float can be seen in the diagram in appendix C (Resource requirements per hour).

Components with approximately same weight is suited to share lifting equipment. It is assumed that it is easy to adapt the equipment so that it can be used for several activities. Relevant examples are:

- SPMT for assembled rotor - SPMT for the assembled tower - SPMT for nacelle can share
- The heavy lifting crane can lift "everything" (but is in fixed position)
- Sharing welding- and bolting equipment for the assembly of tower components, and hub and blades
- Crane for lifting tower components can be used for lifting blades in storage areas
- Sharing crane lifting the assembled tower off the pipe-turning-rolls onto self propelled modular trailer, and the crane that will lift the fully assembled rotor (hub&blades) from the hub frame onto SPMT.

For clarity purpose, the starting point for resource allocation, assuming no sharing, for the transport activities is given in table 26. Activities like lifting the components from quayside and mount them to the sub structure are not included in this analysis. This is because the activity will not vary depending on the layout configuration. The heavy lifting crane is needed to lift all of the components onto the floating sub structure, and these stages has no float, so the crane is not available to be shared.

Transport activity	Needed resources
Transport tower (quayside - storage area)	3
Transport tower (storage area - assembly area)	3
Transport nacelle (quayside - storage area)	2
Transport nacelle (storage area - quayside)	2
Transport hub (quayside - storage area)	2
Transport hub (storage area - assembly hub&blades area)	2
Transport blades (quayside - storage area)	3
Transport blades (storage area - assembly area)	3
Assembled tower (assembly area - quayside)	6
Assembled hub & blades (assembly area - quayside)	7
Total	23

Table 26: Resource requirements for transportation

4.6.2 Space utilization

The space utilization can be linked to investment costs. Space utilization is calculated by making a square around the area, which will create the area and constitute the total area that needs to be "set aside" for the port layout. Utilization can be calculated by dividing the area the activity areas take up themselves by the square-area. The total activity area is presented in table 24, **102 491** m^2.

$$\frac{\text{"}Activity\ area\text{"}}{\text{"}Squared\ area\text{"}} = utilization\ factor \tag{9}$$

4.6.3 Risks and opportunities

Risks and opportunities for the different layout designs will be included in the design evaluations. For the different layout designs, there will be made an evaluation on whether the design is practical applicable. This can be for example sharp-edge corners, if the workers have to walk long distances to working areas etc.

4.6.4 Possibility for expansion of design

4.7 Design layouts

4.7.1 Design based on flow diagram

The layout design based on the flow diagram from figure 17 is presented in figure 24. The design is compact, which reduces the total area. However, the port layout requires water on two ends, which considerably reduces the flexibility of choosing a port. If choosing to build a new port, the investment costs will most likely exceed the extra travel distance costs compared to the other designs.

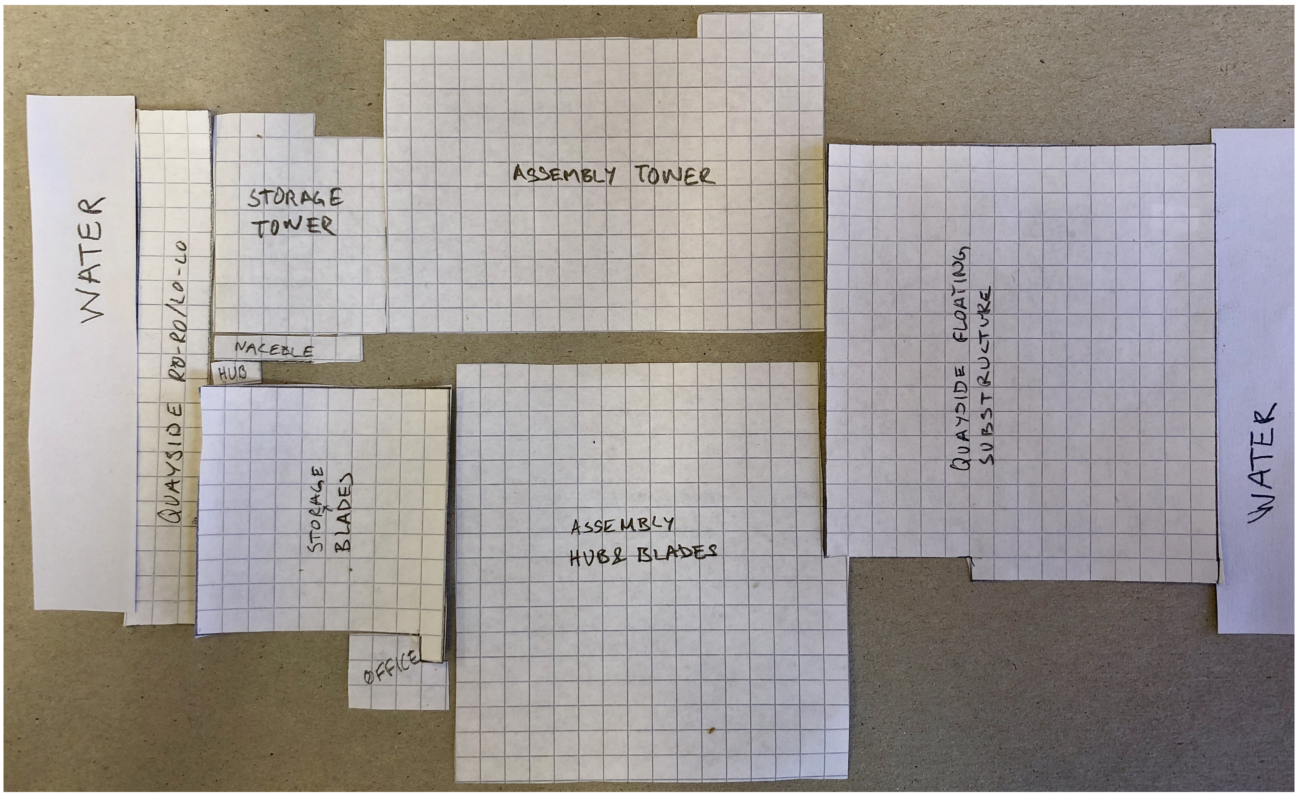

Figure 24: Design layout based on flow diagram

Possibility for sharing resources:

- All the storage areas are close to the quayside for arriving components. This allows sharing of resources. Until now, it has been assumed that the lift-off-vessel cranes are fixed to the quayside. However, they can transport the components directly from quayside to the storage area if they can move. The SPMTs/trucks transporting the components to the storage area and the cranes that are supposed to lift the components onto storage frames can be replaced. As seen in the Resource requirements per hour (appendix C), the components arriving schedule can happen at different times.

- The welding and bolting equipment is possible to share, as these two areas are relatively close and the time slot is flexible for the two activities.

- The assembly area of hub and blades and assembly of tower components are located close together, and crane lifting the blades and tower on- and off SPMTs can be shared.

The heavy lifting crane can pick up both the rotor and assembled tower. However, the heavy lifting component is lifting all three components (tower, rotor and nacelle). The critical path consists of mounting assembled tower - nacelle - rotor, so there is no float here for the heavy lifting crane to replace the transportation from the assembly areas to quayside. It can only lift the components and mount them. Same for the supporting crane adjusting the angle.

Activity	D, Travel distance [m]	F, Flow intensity	R, Needed resources	D·F·R
Transport tower (quayside - storage area)	70	10	1	700
Transport tower (storage area - assembly area)	130	10	3	3900
Transport nacelle (quayside (roro/lolo) - storage area)	50	5	2	500
Transport nacelle (storage area - quayside)	310	5	2	3100
Transport hub (quayside - storage area)	30	5	2	300
Transport hub (storage area - assembly hub&blades area)	180	5	2	1800
Transport blades (quayside - storage area)	90	15	1	1350
Transport blades (storage area - assembly area)	130	15	3	5850
Assembled tower (assembly area - quayside)	200	5	5	5000
Assembled hub & blades (assembly area - quayside)	180	5	6	5400
Total				27 900

Table 27: Data port based on flow diagram

Length [m]	280
Width [m]	310
"Squared area" $[m^2]$	136 400
Space utilization	0.751

Table 28: Utilization for design based on flow diagram

Risks and opportunities:

- Components travels smoothly through port
- Expensive to build this type of port
- Offices located far from center

4.7.2 Design based on relationship diagram

The design based on relationship diagram seen in figure 19 is presented in figure 25. The importance of closeness between the different areas is now considered as accurate to the relationship diagram as possible. The areas with the most important of closeness have successfully been placed accordingly. For example, closeness between quayside for floating substructure, assembly area hub&blades and assembly tower. The closeness between storage area for tower and assembly tower + quayside for arriving ships.

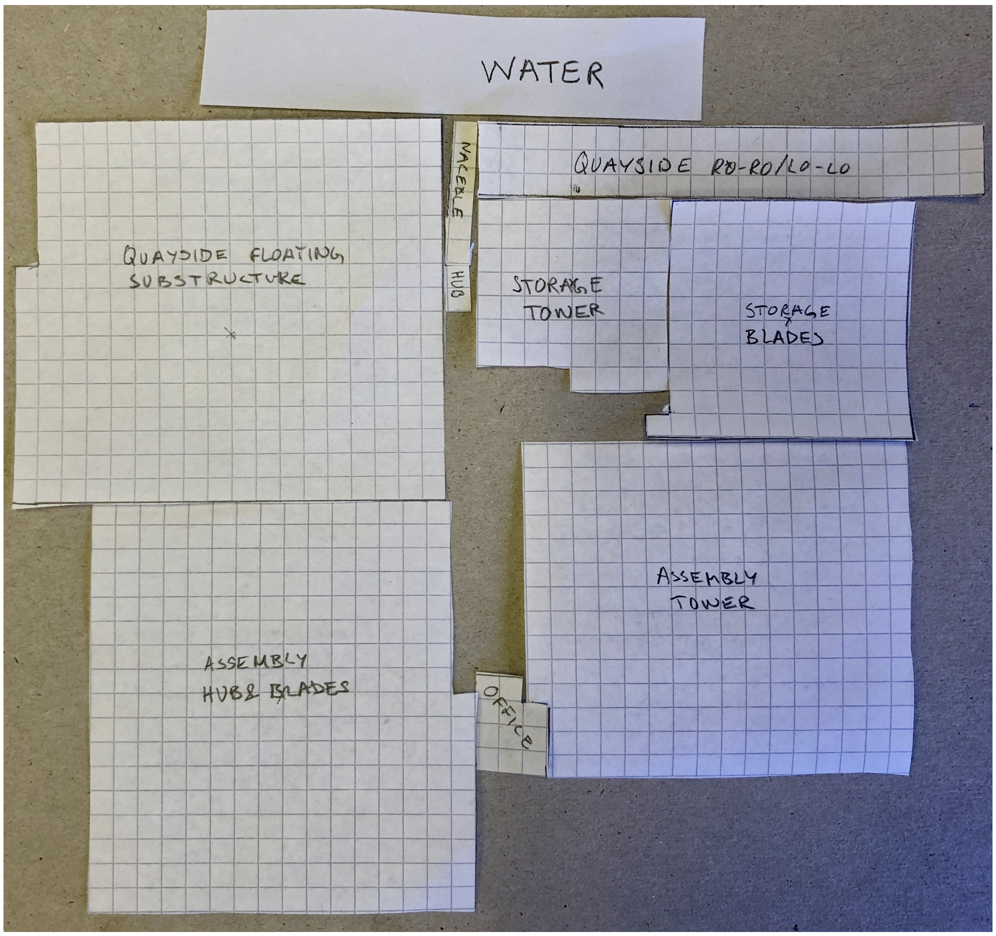

Figure 25: Port layout based on relationship diagram

Possibility for sharing resources:

- Storage area for blades and tower is located next to each other close to quayside. Resources for the transportation between quayside and storage area can therefore be reduced
- Nacelle, hub and tower component can share SPMTs for all distances, as these three areas are located close to each other. There is space to have the SPMTs ready close to the areas.
- Cranes needed to lift the blades/towers in storage areas can also be used to lift the tower components on and off the pipe turning rolls in assembly area for towers.

Activity	D, Travel distance [m]	F, Flow intensity	R, Needed resources	D·F·R
Tower (quayside - storage area)	80	10	1	800
Tower (storage area-assembly area)	150	10	3	4500
Nacelle (quayside - storage area)	110	5	1	550
Nacelle (storage area -quayside)	110	5	1	550
Hub (quayside - storage area)	120	5	1	600
Hub (storage area - assembly area)	180	5	1	900
Blades (quayside - storage area)	70	15	1	1050
Blades (quayside - storage area - assembly area)	260	15	3	7200
Assembled tower (assembly area - quayside)	120	5	4	2400
Assembled hub & blades (assembly area - quayside)	150	5	6	4500
Total				23 050

Table 29: Data port based on relationship diagram

Length [m]	400
Width [m]	330
"Squared area" $[m^2]$	120 000
Space utilization	0.776

Table 30: Utilization for design based on relationship diagram

Risks and opportunities:

- Traffic through center might cause dealys
- Offices far from center
- Narrow corners the oblong components have to navigate through
- If the tower assembly area is moved further from the storage areas and assembly of hub and blades area (down and to the right) it is adaptable for larger turbine sizes. This will not affect the space utilization.

4.7.3 Design based on combination of Direct and Central system

The suggested basic systems from theory (chapter 3.5.2); direct, channel and central have been used to make a design suggestion. However, the channel method is not seen as suitable as several parallel methods are happening simultaneously. Therefore, a combination of the Direct and Central method has been tried, as it is desired to minimize the travel distances for the different components. The intensity of the different components is low, but the area is square shaped and there is a need for control.

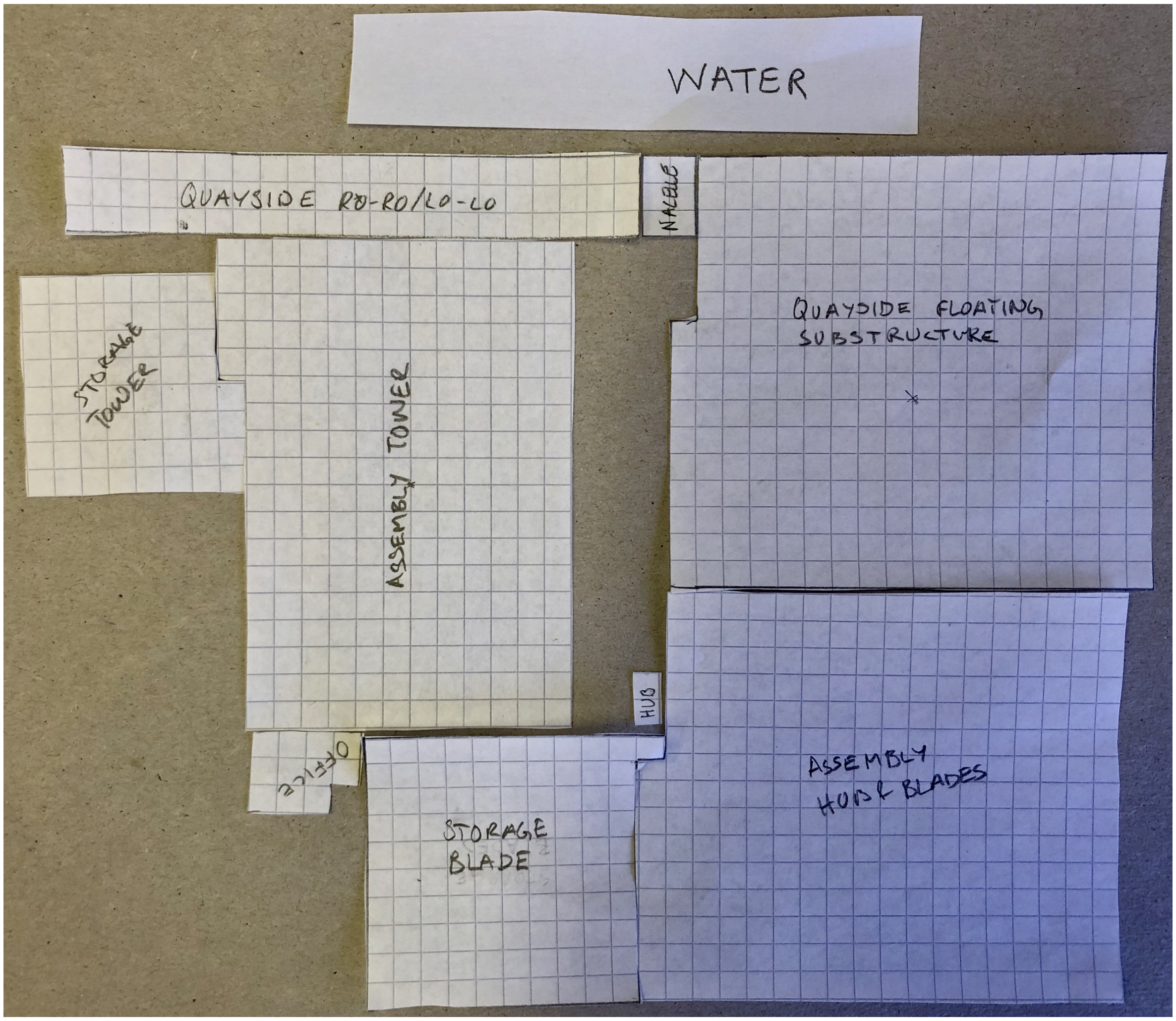

Figure 26: Port design based on Direct and Central flow of components

Possibility for sharing resources:

- First two tower components can be lifted off the vessel and brought directly to tower assembly area instead of storage area
- The crane that is meant to lift tower component on/off SPMTs in storage area and assembly area can replace the SPMTs and transport the component itself. By doing this, the need for SPMTs is reduced.
- If the crane lifting blades and tower components off arriving vessels can roll, it can lift the assembled tower from the pipe turning rolls onto SPMTs.

- Cranes that are lifting blades on/off truck at storage area can be used to transport the blade to assembly area hub and blades, this will reduce need for special trucks.

Activity	D, Travel distance [m]	F, Flow intensity	R, Needed resources	D·F·R
Tower (quayside - storage area)	100	10	2	2000
Tower (storage area - assembly area)	110	10	1	1100
Nacelle (quayside - storage area)	110	5	2	1100
Nacelle (storage area -quayside)	110	5	2	1100
Hub (quayside - storage area)	220	5	2	2200
Hub (storage area - assembly area)	100	5	2	1000
Blades (quayside - storage area)	250	15	3	11 250
Blades (storage area - assembly area)	150	15	1	2250
Assembled tower (assembly area - quayside)	180	5	5	4500
Assembled hub & blades (assembly area - quayside)	150	5	7	5250
Total				31 750

Table 31: Data port based on Direct and central travel routes

Length[m]	310
Width[m]	420
"Squared area" [m^2]	130 200
Space utilization	0.787

Table 32: Utilization for design based on combination of Direct and Central system

Risks and opportunities:

- Offices far from center
- Hub area might be in the way for smooth transport of blades to storage area

4.7.4 Design with oblong storage areas

A suggestion on layout is made, and the aim is to find a configuration with as reduced travel distance as possible. The layout is based on the previous layout (Direct and Central system) to see if oblong storage areas will improve. This suggestion will hopefully achieve this, as the distance to the centre of the area will be smaller than the other storage areas. Room is left in the center for blades and hubs to pass through.

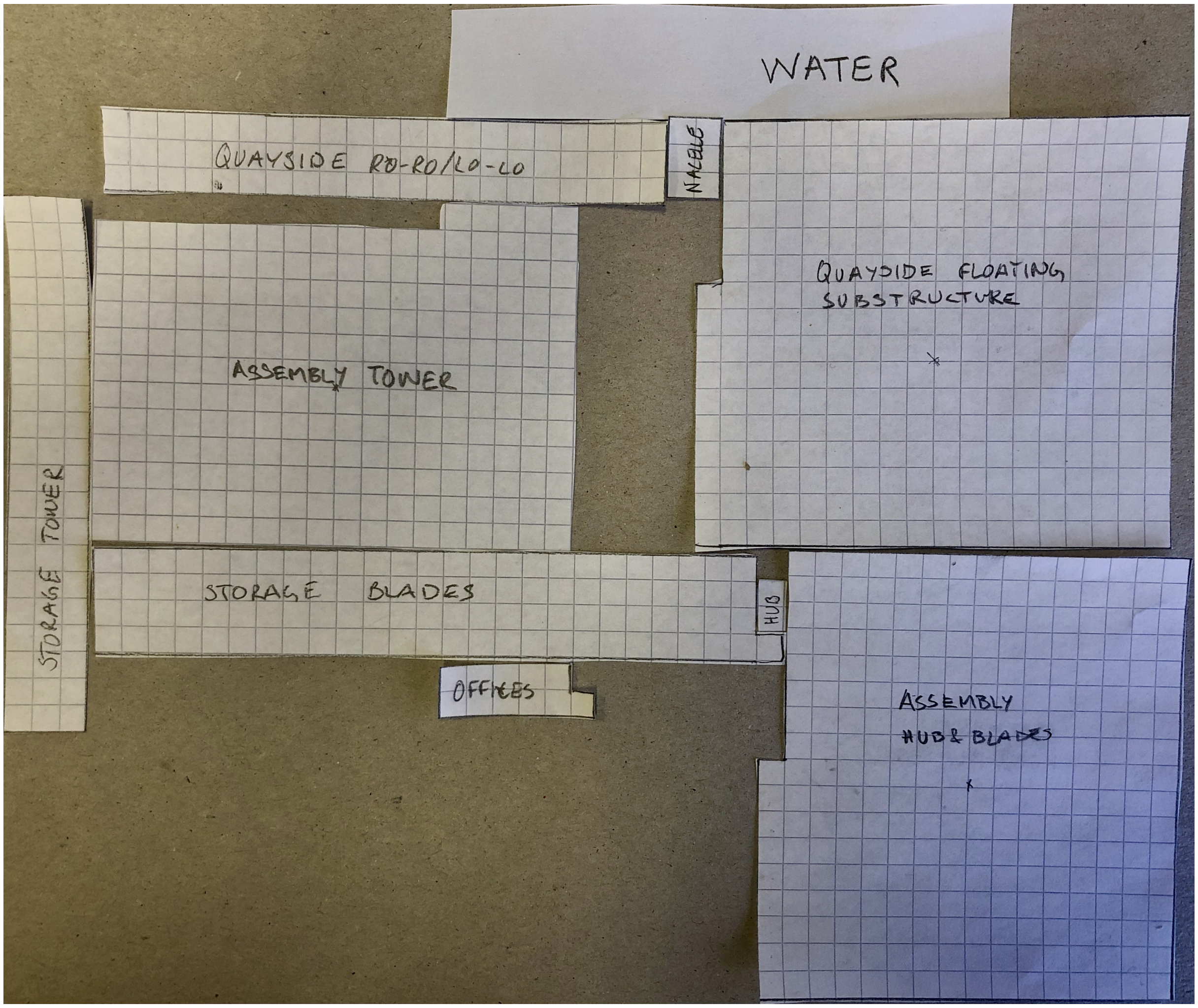

Figure 27: Design with oblong storage areas

This design is very similar to previous design, so the sharing of equipment will be very alike:

- First two tower components can be lifted off the vessel and brought directly to tower assembly area instead of storage area
- The crane that is meant to lift tower component on/off SPMTs in storage area and assembly area can replace the SPMTs and transport the component itself. By doing this, the need for SPMTs is reduced.
- Cranes that are lifting blades on/off truck at storage area can be used to transport the blade to assembly area hub and blades, this will reduce need for special trucks.

Activity	D, Travel distance [m]	F, Flow intensity	R, Needed resources	D·F·R
Tower (quayside - storage area)	150	10	2	3000
Tower (storage area-assembly area)	120	10	1	1200
Nacelle (quayside(roro/lolo) - storage area)	110	5	2	1100
Nacelle (storage area -quayside(floating sub struct)	110	5	2	1100
Hub (quayside - storage area)	230	5	2	2300
Hub (storage area - assembly area)	100	5	2	1000
Blades (quayside - storage area)	160	15	3	7200
Blades (storage area - assembly area)	230	15	1	3450
Assembled tower (assembly area - quayside)	230	5	5	5750
Assembled hub & blades (assembly area - quayside)	160	5	7	5600
Total	1040			31 700

Table 33: Data port with oblong storage areas

Length [m]	330
Width [m]	430
"Squared area" $[m^2]$	141 900
Space utilization	0.722

Table 34: Utilization for design based on oblong storage areas

Risks and opportunities:

- Towers must "sneak" through the tower assembly area to get to storage area
- Blades might be challenging to navigate between the tower assembly area and offices
- Offices are located close to the center of port
- Not very adaptable for larger turbine sizes as it is difficult to sneak through areas when larger and more turbine components are passing through

4.7.5 Design with advantages from the direct-and-central-layout, relocated main aisles

Another attempt was made to try to improve the design from Direct and Central system. In this suggestion, the main aisles have been moved and narrowed. The hub location is also moved, and the assembly area for the tower refitted to be a bit slimmer. The result is seen in figure 28.

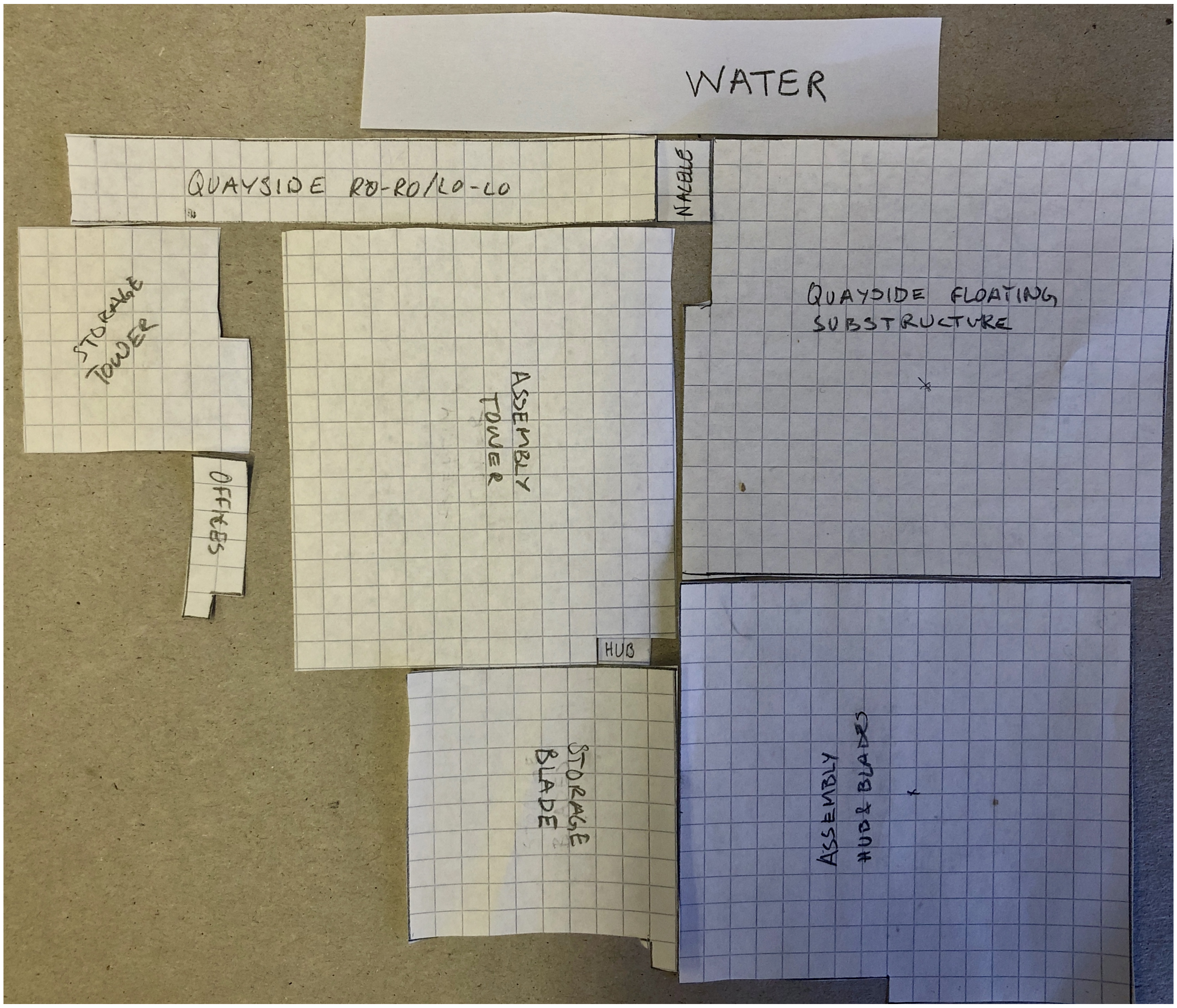

Figure 28: Port design with advantages from direct and central and relocated main aisles

Possibility for sharing resources:

- First two tower components can be lifted off the vessel and brought directly to tower assembly area instead of storage area
- The crane that is meant to lift tower component on/off SPMTs in storage area and assembly area can replace the SPMTs and transport the component itself. By doing this, the need for SPMTs is reduced.
- Cranes that are lifting blades on/off trucks at storage area can be used to transport the blade to assembly area hub and blades, this will reduce need for special trucks.
- The lifting off assembled tower and assembled hub and blades can share a crane, as the assemble of tower component area and assemble hub and blades area is located close together.

Activity	D, Travel distance [m]	F, Flow intensity	R, Needed resources	D·F·R
Tower (quayside - storage area)	100	10	2	2000
Tower (storage area-assembly area)	130	10	1	1300
Nacelle (quayside - storage area)	110	5	2	1100
Nacelle (storage area -quayside)	110	5	2	1100
Hub (quayside - storage area)	190	5	2	1900
Hub (storage area - assembly area)	120	5	2	1200
Blades (quayside - storage area)	230	15	3	10 350
Blades (storage area - assembly area)	140	15	1	2100
Assembled tower (assembly area - quayside)	170	5	4	3400
Assembled hub & blades (assembly area - quayside)	150	5	6	4500
Total				28 950

Table 35: Data port with advantages from the direct-and-central-layout, relocated main aisles

Length [m]	320
Width [m]	420
"Squared area" $[m^2]$	134 400
Utilization	0.762

Table 36: Space utilization for design based on advantages from the Direct-and-Central-layout, with relocated main aisles

Risk and opportunities:

- Easy navigation for oblong components
- Difficult navigation for hubs
- Little crossing traffic
- Suitable for upscale production as increase of the storage areas will not affect overall layout design

5 Evaluation and conclusion

5.1 Evaluation

A systematic comparison of scores related to different layouts were made to support the conclusion on selection of design. In the table below, a summary of the evaluation of each of the designs is presented. For each of the five design layouts, a value is given on the criteria “flow, distance and resource requirement (FDR)” and space utilization respectively, ref definitions in chapter 4.6. Based on the value, a positive or negative mark was given. In addition, some common and some individual risks and opportunities for each design are evaluated.

For the design based on flow diagram, the components will be streamlined through the port with no detours. The travel distances for the components might be reduced further by implementing slim and oblong storage areas. However, implementing this might reduce the space utilization. Even though the design provides a highly effective route for the components, the design requires a high capital cost due to its need for water on both sides of the port, and this might require building a new port. Therefore, the downside of investment cost is weighted heavily, and the design rejected.

The design based on relationship diagrams has the lowest operational cost and one of the highest space utilizations. Unfortunately, the design will result in several crossings through the centre which might cause delays. Also, there might be challenges for the blades to be navigated passing the corner of assembly tower area. With minor adaption, moving the assembly area for tower to the right and down in the figure, this problem may be solved. The space utilization remains the same, however travel distance for assembled tower might be slightly increased. Due to the low operational cost and relatively good space utilization the design is accepted.

The port design based on Direct and Central flow of components gives the best space utilization in port. Further space utilization could be given by closing the gap in the middle. However, due to extensive transport in the area, it was kept open. The blades might face challenges in navigating between the tower assembly area and hub storage area. In addition, the design has the largest operational costs of all the designs, and is therefore rejected.

For the design with oblong storage area, the operational costs are relatively high, and the design has the lowest space utilization. This, together with difficult maneuvering for blades in the transportation to storage area, makes up the reasoning for rejecting this design.

The port design with advantages from direct and central design with relocated main aisles, gives medium score on operational- and investment costs. The navigation of oblong components are relatively easy in this design compared to the other designs. The hub in its way to storage area must find a way between storage of blades area and assembly tower area. As an isolated solution, the design provides a smooth flow. However, the low ability to facilitate sharing of resources is demonstrated in the relatively high FDR, and the design is therefore rejected.

Design based on flow diagram		
FDR Utilization Risks and opportunities	27 900 0.751 Office far from center Design adaptable for larger turbine sizes Smooth flow of components Expensive to build the port	+ - - + + -
Design based on relationship diagram		
FDR Utilization Risks and opportunities	23 050 0.776 Office far from center With small modifications the design is highly adaptable for larger turbine components Narrow corners for oblong components Traffic through center	+ + - + - -
Design based on combination of Direct and Central system		
FDR Utilization Risks and opportunities	31 750 0.787 Office far from center Difficult for upscale production Narrow corners for oblong components	- + - - -
Design with oblong storage areas		
FDR Utilization Risks and opportunities	31 700 0.722 Offices central Might be difficult for up-scaling Narrow corners for oblong components	- - + - -
Design with advantages from the direct-and-central-layout, relocated main aisles		
FDR Utilization Practical limitations	28 950 0.762 Office far from center Suitable for upscale production No sharp corners	- - - + +

Table 37: Evaluation of designs

5.2 Conclusion

For this case, using SLP, phase 2, it is concluded the design based on the relationship diagram, stands out noticeably. The conclusion is supported by both the FDR rating a good score in space utilization. The port design is shown in figure 29, and a suggestion on what the port will look like in figure 30.

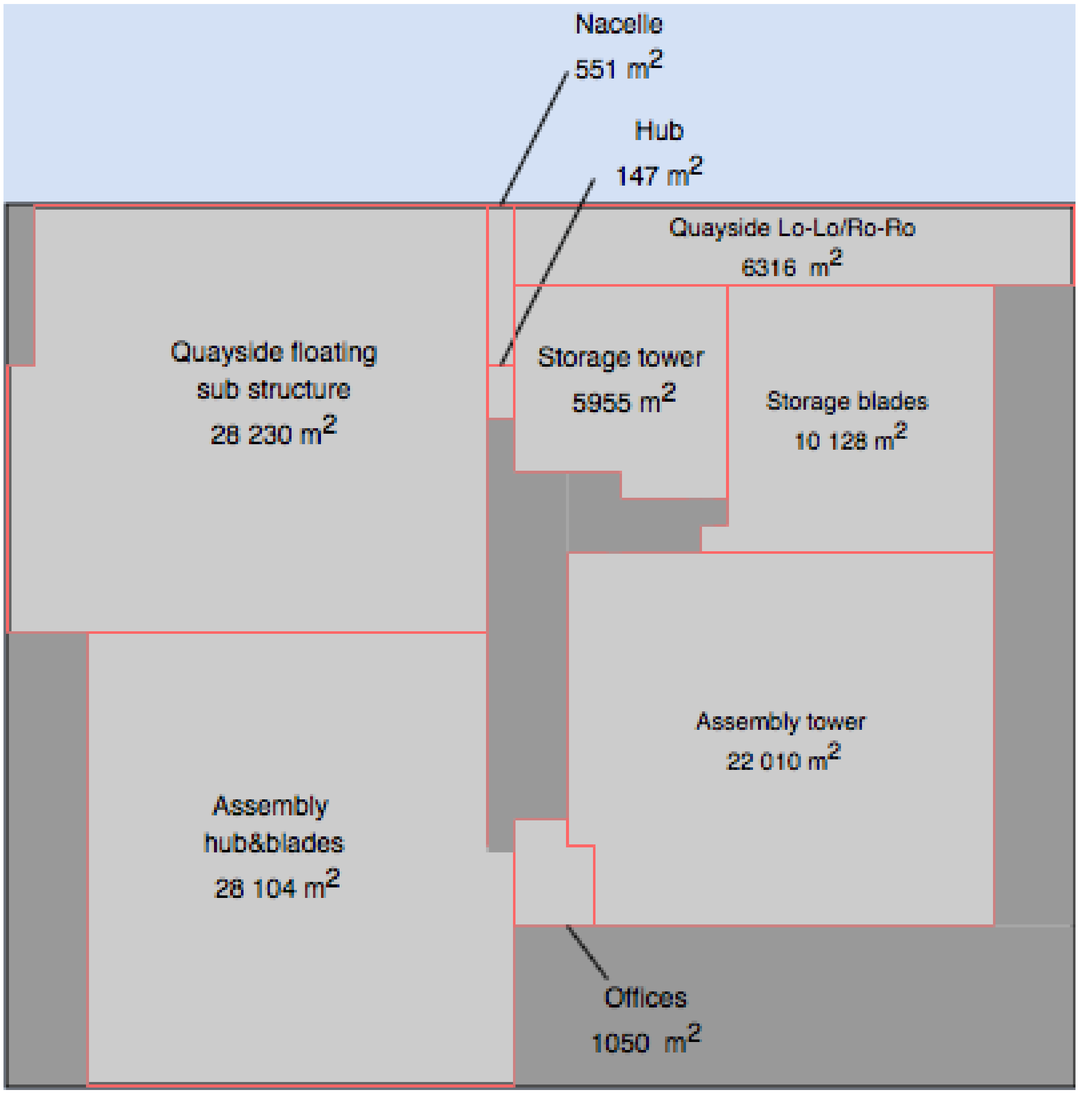

Figure 29: Final layout design: design based on relationship diagram

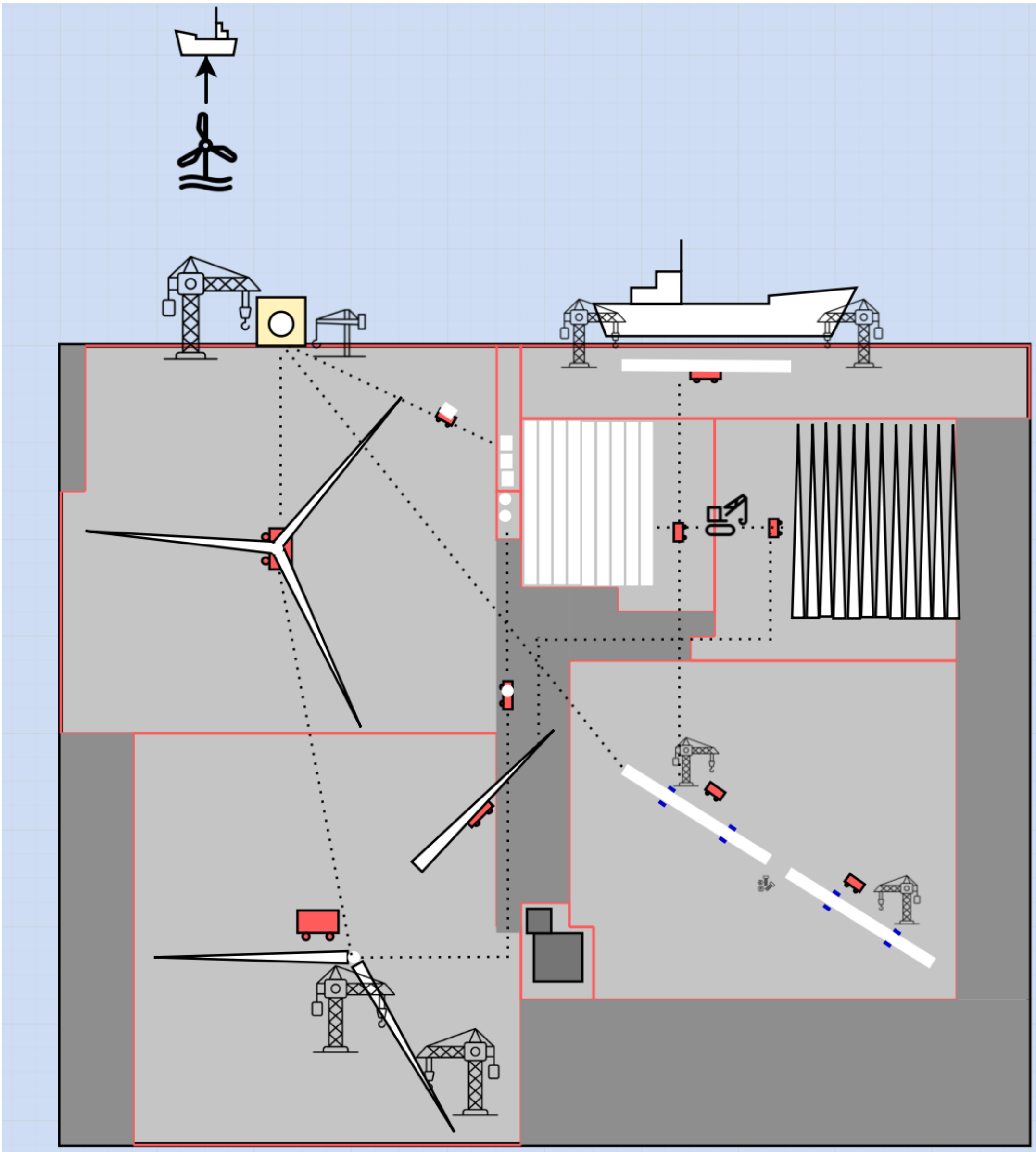

Figure 30: Suggestion on final design

6 Discussion

6.0.1 Early choices

Selection of floating sub structure concept

The turbine itself consists of well known and to some degree standardized components; tower, blades, nacelle and hub, can be a highly standardized concept. However the floating sub structure choices of concepts have to be consciously made. Four well acknowledged concepts available; spar buoy, barge, tension leg and, semi submersible. The choice of concept must be based on port facilities, site and costs related to these.

- Spar buoy has a simple design with relatively low cost. At the downside the draught is high, and it has to be transported horizontally to waters where the draught is deep enough, which makes the transportation cost and maneuvering to vertical position at sea high.
- The barge platform has a low draught which makes the structure fit in shallow waters, and easier to assemble in port. Unfortunately the structure needs more materials, and the stability of structure is more uncertain compared to the others.
- The tension leg platform has a low mass and can be assembled in port, however it is unstable until mooring lines are hooked up on site and the concept has not yet been tested, so the knowledge and reliability about the method and cost is still to be experienced.

The semi submersible sub structure is stable both at transport to site and in operational phase. On the downside, the component is difficult to manoeuvre in port, and is preferable to be constructed in a dry-dock.

The different sub structures each have advantages and disadvantages, and the choice in this thesis fell on the semi submersible sub structure. Other structures choices could have been selected. If the waters are deep enough, for example if the port is a floating barge, spar buoy can be used. Although the port design will depend on the structure chosen, the approach demonstrated in the thesis is applicable for most solutions.

Selection of 6-8 MW wind turbine

The size of the wind turbine is, in this case, set to 6-8 MW turbine, a typical capacity for existing wind turbines. It should be noted that the expectations for future offshore floating wind turbines amount to sizes up to 15-20 MW. The wind turbine size selection is scalable, and the port can be adapted to increasing sizes of wind turbines. This can be achieved by increasing the capacity of cranes, trucks, SPMTs, and the sizes of storage areas. The layout configurations can in this case be kept, however with some adaptions.

The choice fell on a 6-8 MW turbine. One of the reasons is that the Hywind Tampen size is 8 MW, thus deemed relevant. Although the cases themselves does not include expansion in the first "round", some considerations are made on the options.

Selection of assembly method

For this thesis, a choice of assembly method had to be made. Most wind turbines are currently assembled at the site. In this case, the turbine is assembled in port, allowing for effective for the up-scaling of the assembling. One future vision from a profitability perspective is to have as many operations running at the same time, for maximizing production, and utilizing of port areas.

However, the fully assembled rotor takes up a considerable space of ground. If the focus was to reduce the port size, another method should be used. In this case, the focus is to examine and identify a systematic method for design of port layout that also will work for up-scaled production.

6.0.2 Systematic Layout Planning

For this thesis, a method from "Systematic Layout Planning" has been selected to design a port layout. The SLP method is a trusted and well tried method. The book is based on broad experience and has been applied for 50 years, demonstrating that the framework and process is highly acknowledged. The theory is based on experience gained from over 200 layout planning projects, and the SLP method has been applied in more than 1000 projects [32]. There are however some limitations related to applicability needed to be addressed and discussed.

The SLP method is mainly addressed for either low variance-high volume production or high variance low volume production. Normally, for low variance high-volume production, the product is physically small, and for the high variance-low volume the product is physically big. However, in this case, the final aim is to make an assembly port where the product has high volume and is physically large. In a longer term, the applicability of the method must be assessed in this light.

During the process of this thesis, the theory was of great help. It provided detailed information on how to systematically develop and present design stages. However, the theory fell short for the author at one point. When addressing space needs, the need for equipment was to be addressed in detail. Seen in retrospective, the equipment details could in this case be moved to Phase 3. This dissonance is most likely connected to the volume/variance-relation discussed in the previous paragraph. If the work was to be done over again, less detailed orientation on space needed for the equipment would be done, and rough estimates would be considered sufficient.

Uncertainties

Due to expected evolvement of the industry with scalability needs, the thesis is not built on existing yards and their solutions and sizes. This may imply a risk of not taking advantage of valuable experiences already gained. It should also be noted that some factors that are built on judgmental evaluations may be too optimistic or pessimistic. Due to the uncertainty, an extra margin was added to estimated area needs. Still the uncertainty may give rise to both upside and downside economic consequences. On the other side, not focusing on existing designs, may open for new and more innovative solutions. By looking at existing designs, it might narrow innovative thinking, and make bad solutions over and over again. The final layout should however, be compared with existing with the aim to understand the rationale behind earlier.

When listing all the activities, evaluations are made of how the different components can be transported within the yard. From literature, it is found that SPMTs generally are cheaper to operate than cranes. However, finer calculations should be made as to reduction of transportation costs. For example if a crane can replace X numbers of SPMTs, it may impact the conclusion of choosing the SPMT. The potential for cost reduction might not be significant for the assembly of 5 turbines. However, in cases of up scaling of production to for example 50 turbines, the cost aspect may become more significant. .

Adding a 5% margin to parameters may be an exaggeration,. Nevertheless, margins have to be incorporated to maintain flexibility in future turbine design as well as equipment needs. In light of future up scaling and new turbines new and more precise calculations most probable must be made based.

If time allowed it, a deeper analysis of future development could include the prediction of future needs for area sizes based on different parameters. By assuming X number of turbines to be made, the components will have the size of X, triggering need for X size of equipment, adding up to relationships to find total area.

The design layout that has been made at the stage of my case is rough and have to be further refined in Phase 3 of SLP. Changes must be expected as more details evolve The same point is valid for the time assumptions related to the different activities. One example that can be mentioned is electrical wiring, a complex operation that may impact the timeline.

6.0.3 Project planning

The project planning was executed based on theory from Bassam Hussein's "Road to success" [19]. This was an efficient and straightforward method of identifying the total time needed in order to produce a wind turbine. A critical path was identified in accordance with this method, important for resource allocation in order to optimize transport solutions in port.

For the project planning, all the activities have been allocated an amount of time assumed needed. In phase 2 these are still rough estimates. However, the system used is highly adaptable to changes of duration. A relevant example also in a scheduling perspective is the wiring system still not included. Timing may affect the critical path, and the total duration may as a consequence be longer.

Resource allocation

The resources that are included in the allocation comprise educated guesses. This can be regarded as uncertain data , but serve as preliminary figures until later phases of SLP. It should be noted that uncertainty in the prognoses for man hours may influence the cost control, particularly in the critical path. In addition to the critical path, some activities with minor float imply a risk. Examples are blade docking and transport of blades from ship to seaside, as seen in the figure in appendix C.

Another factor that has to be considered in a later phase in a real project is the specific kind of resources that must be allocated. Some of the resources needed, will as an example be scarce due to its specialized profile. These considerations were not a part of the resource map. The intention behind the map was to generically allocate resource such as general labor, various cranes, etc. The need for more refined planning may become even more relevant when the port size is scaled up, and several of the same activities occur in parallel. However, an opportunity was shown to allocate resources using computer tools. The attempt to optimize the resource map by use of Python did however not have the intended result, mainly due to the volume of data involved. Future computerized optimizations should aim at isolate and break down the various parameters.

In the case of no active resource distribution, the resource need will be at its top in the beginning and flatten out eventually. In order to obtain evenly distribution of resources need during the project, effective resource planning is key. As the scale of production of turbines increases, effective and even utilization of resources over time may be a key success factor for profitability. By looking at appendix C one can see that this can be changed. The green areas represent the float, the extra time that an activity can be moved within.

6.0.4 Space determinations

For the space determinations of each area, the components and the equipment is the one highlighted as space deciders. Flexibility has been added on later, for both change in turbine design and equipment that has not been mentioned.

Some careful calculations were made, but it can be noticed that the sweeping area of components is the one's dominating the space determinations. Therefore, in retrospect, precise space calculations for equipment such as cranes and SPMT's can be seen as superfluous. Therefore, one could argue that an estimate on equipment area is enough at this early stage (Phase II). This can be noticed for further development of port layouts. The concrete estimates are necessary for phase III.

It has been assumed that the areas can not have any overlap. For example, it can be tempting to say that the rotor (assembled hub&blades) can be transported into the quayside area for the floating substructure and lifted, still with some of the blade left in the previous area (assembly hub& blades). In this case, this is not accepted because if the rotor is taking up space from the assembly area, there might not be room for the next assembly to happen. This is a conservative choice, which in real-life can be somewhat accepted.

6.0.5 Developing design layouts

In developing the composition of different design layouts, the areas have been cut out in paper and put together in different arrangements. This procedure has its benefits and disadvantages. It is relatively easy to make new arrangements, as moving the areas is done very fast. Therefore many layouts can be made and either accepted or rejected before making any calculations.

Some different shapes of the areas have been made, for example, squared and oblong storage areas. There are infinite numbers of shapes and compositions of the different areas. In this thesis, only a tiny fraction of the possibilities have been looked into. By using computer programming, many more combinations of layouts and area shapes can be evaluated. However, at this stage (in Phase II), the cut paper has been effective and provided valuable information in finding the best design.

6.0.6 Evaluation criteria

The designs are evaluated on different types of evaluation criteria. This will give a concrete comparable value estimate on operational- and investment costs in the distance, resources, flow and space utilization.

The evaluation based on "risks and opportunities" for the design can be perceived as a vaguer evaluation. However, some of the designs are very clear on this type of evaluation, whether the design is applicable or not, for example design based on flow diagram is clear that will be too expensive to build a new port, and the flexibility of choosing port considerably reduced. Other comparisons, like applicability for production expansion, is difficult to evaluate, and is therefore based on "educated guesses". This can be seen as a weakness in this analysis, nevertheless, it must be included to have a real-life estimates.

More evaluation criterion that could have been included to investment costs, is the quay length. By using as little quay length as possible, but keeping most activities "in-land" the cost could have been reduced further, but this could have lead to increased travel distances for components. By investigating this, an even more nuanced analysis could have been done. However, in this case, the reduction of quay length would be difficult as there already is a required quay length for the arriving vessels, and the diameter of assembled rotor has made a limitation. If some considerations should have been taken, the storage of nacelle would not have been located between the two quay areas.

There are several other evaluation factors regarding "risks and opportunities" that could have been included in this report as well, for example human safety, worker comfort, sustainability etc., however this can be done in later phases when more details are addressed. In addition, this evaluation is more suitable when an actual port is located.

6.0.7 Conclusion

The design coming out as best by using SLP Phase 2 has been chosen based on operational- and investment costs, as well as some physical limitations and advantages. In the process leading to the conclusion, several assumptions have been made. For example, the FDR and space utilization have been given a high weight. A different weighting would affect the conclusion. A stress test demonstrating these effects could be done.

Retrospectively it has been acknowledged through further examination, that a favourable design could be to switch the location of storage area for tower and blades. By doing this, the narrow-corner challenge could be solved, and the travel distance for blades reduced. In addition, the change will not necessarily affect the space utilization. Furthermore, a more central location of offices can be found, which would be beneficial for employees and efficiency. However, different configurations based on this design can be developed in later phases as more details develop.

There are an infinite number of combinations and shape designs for the areas examined. To identify this final design already in phase 2 of SLP, a well structured method has been used. A significant number of tiny adjustments can be done to improve the design further, evolving during the project. The design presented in this thesis can be seen as a starting point for further choices to be made as the detailed layout process develops.

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Appendix

A Resource requirements per activity

Activity	Resource requirements
Nacelle ship docking	1
Blade ship docking	2
Hub ship docking	1
Tower ship docking	2
Transport nacelle from ship to quayside	2
Transport blades from ship to quayside	4
Transport hub from ship to quayside	2
Transport tower from ship to quayside	4
Arrival floating sub structure	4
Secure floating sub structure to quay side	4
Transport nacelle from quayside to storage area	2
Transport blades from quayside to storage area	3
Transport hub from quayside to storage area	2
Transport tower from quayside to storage area	3
Transport tower from storage area to assembly area	3
Assemble tower components	3
Transport blades to assembly area	3
Transport hub to assembly area	2
Assemble hub + blades	5
Prepare floating sub structure for turbine components	3
Transport assembled tower to quay side	6
Tower lifted and mounted to sub structure	6
Transport nacelle to quayside	2
Nacelle lifted and mounted to sub structure	6
Transport hub + blades to quayside	7
Hub and blades lifted and mounted to floating sub structure	8

B Area relationship reasons

Value	Closeness rating
A	Closeness **a**bsolutely necessary
E	Closeness **e**specially important
I	Closeness **i**mportant
O	Ordinary closeness **O**K
U	Closeness **u**nimportant
X	Closeness **not** desirable

Table 38: Rating the importance of closeness between activity areas

Code	Reason
1	Same equipment
2	Minimize travel distance
3	Need for regularly check-up
4	Relatively easy to transport
5	Relatively complex transport
6	Components does not have anything to do with each other at this stage
7	complex operation

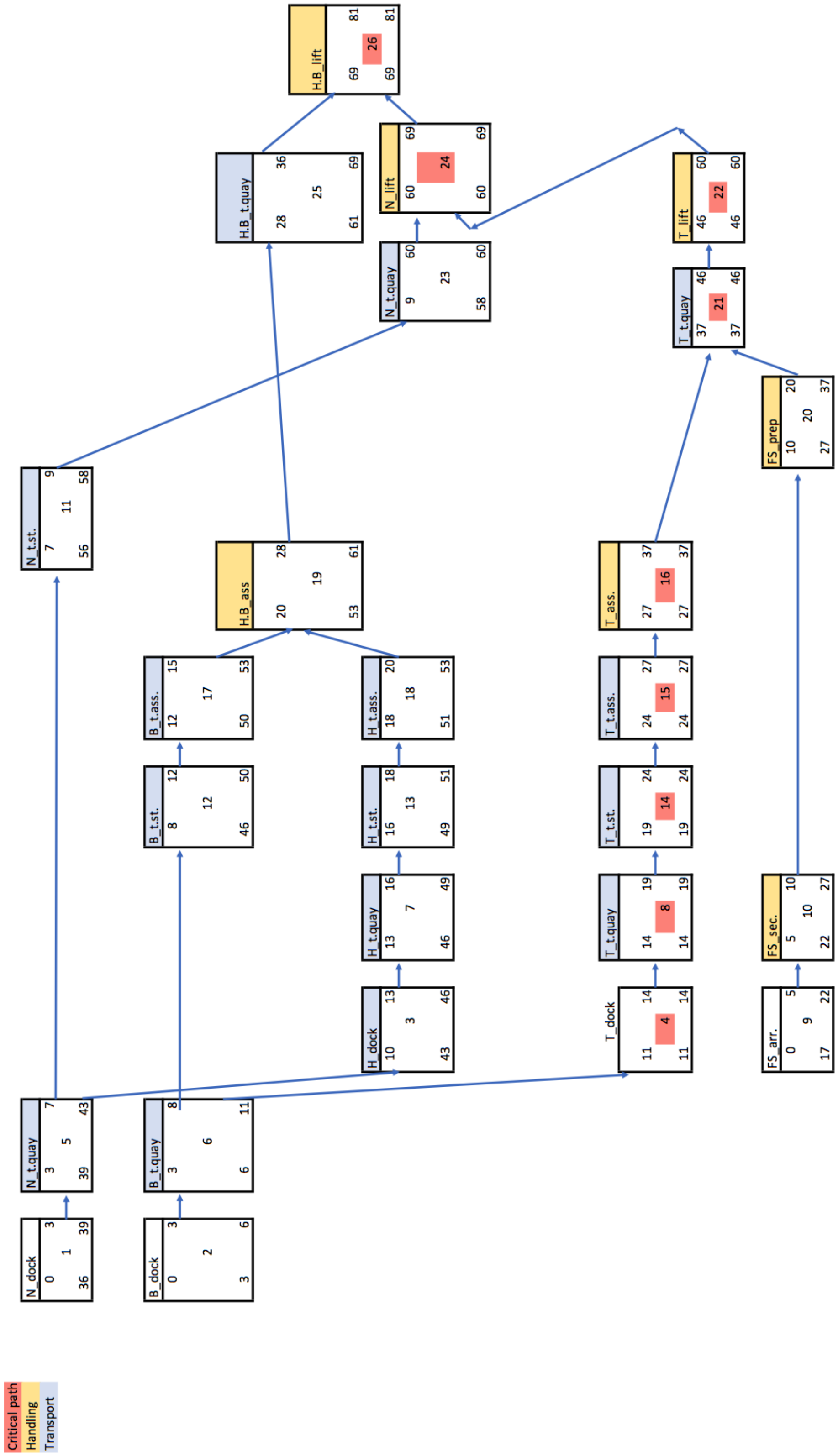
Table 39: Reasons for closeness

C Resource requirements per hour

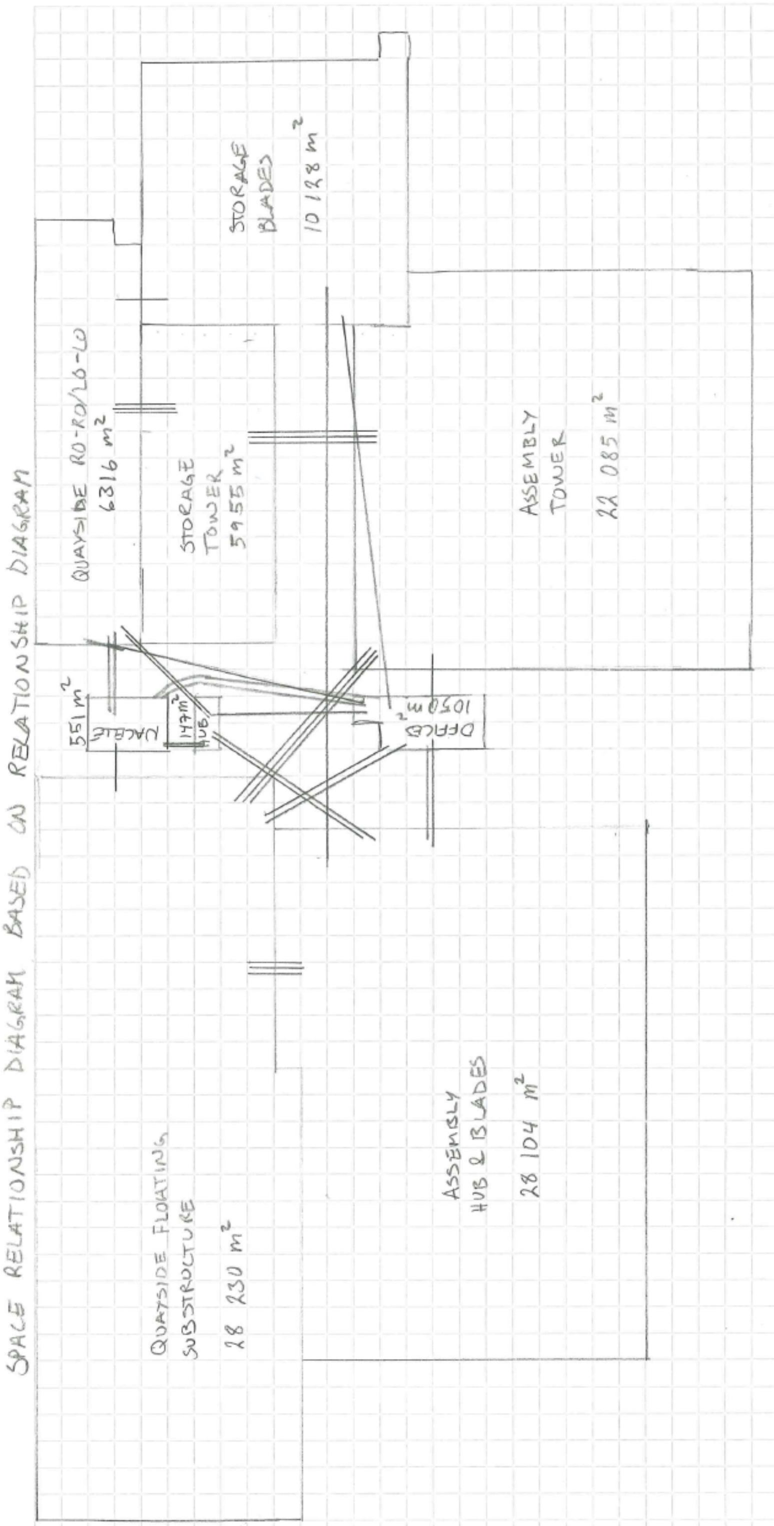
Hour							Total
31	3				7		10
32	3				7		10
33	3				7		10
34	3				7		10
35	3				7		10
36	3				7		10
37	3						3
38		6					6
39		6					6
40		6					6
41		6					6
42		6					6
43		6					6
44		6					6
45		6					6
46		6					6
47			6				6
48			6				6
49			6				6
50			6				6
51			6				6
52			6				6
53			6				6
54			6				6
55			6				6
56			6				6
57			6				6
58			6				6
59			6				6
60			6				6
61				6			6
62				6			6
63				6			6
64				6			6
65				6			6
66				6			6
67				6			6
68				6			6
69				6			6
70						8	8
71						8	8
72						8	8
73						8	8
74						8	8
75						8	8
76						8	8
77						8	8
78						8	8
79						8	8
80						8	8
81						8	8

Activity nr	Activity	Resource requirement	Time line:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	Nacelle ship docking	1		1	1	1																											
2	Blade ship docking	2		2	1	2																											
3	Hub ship docking	1												1	1	1																	
4	Tower ship docking	2													2	2	2																
5	Transport nacelle from ship to quayside	2					2	2	2	2																							
6	Transport blades from ship to quayside	4					4	4	4	4	4																						
7	Transport hub from ship to quayside	2															2	2	2														
8	Transport tower from ship to quayside	4																4	4	4	4	4											
9	Arrival floating sub structure	4		4	4	4	4	4																									
10	Secure floating sub structure to quay side	4							4	4	4	4	4																				
11	Transport nacelle from quayside to storage area	2									2	2																					
12	Transport blades from quayside to storage area	3										3	3	3	3																		
13	Transport hub from quayside to storage area	2																		2	2												
14	Transport tower from quayside to storage area	3																					3	3	3	3	3						
15	Transport tower from storage area to assembly area	3																										3	3	3			
16	Assemble tower components	3																													3	3	3
17	Transport blades to assembly area	3														3	3	3															
18	Transport hub to assembly area	2																				2	2										
19	Assemble hub + blades	5																						5	5	5	5	5	5	5	5		
20	Prepare floating sub structure for turbine components	3												3	3	3	3	3	3	3	3	3	3										
21	Transport assembled tower to quay side	6																															
22	Tower lifted and mounted to sub structure	6																															
23	Transport nacelle to quayside	2											2	2																			
24	Nacelle lifted and mounted to sub structure	6																															
25	Transport hub + blades to quayside	7																														7	7
26	Hub and blades lifted and mounted to floating sub structure	8																															
				7	6	7	10	10	10	10	10	9	9	9	9	9	10	12	9	9	9	9	8	8	8	8	8	8	8	8	8	10	10

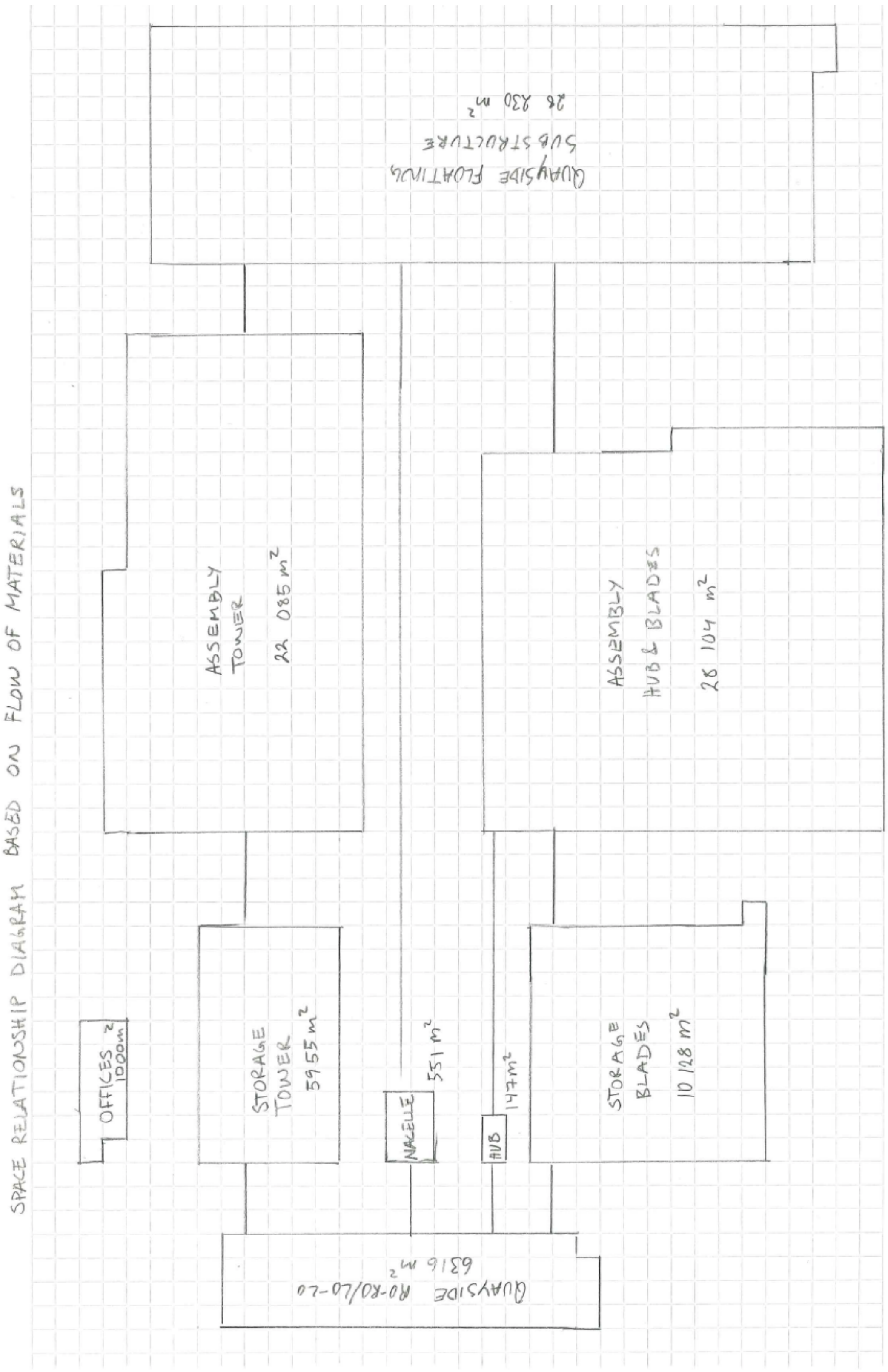
D Activity On Node network



E Space relationship diagram based on relationship diagram



F Space relationship diagram based on flow of materials

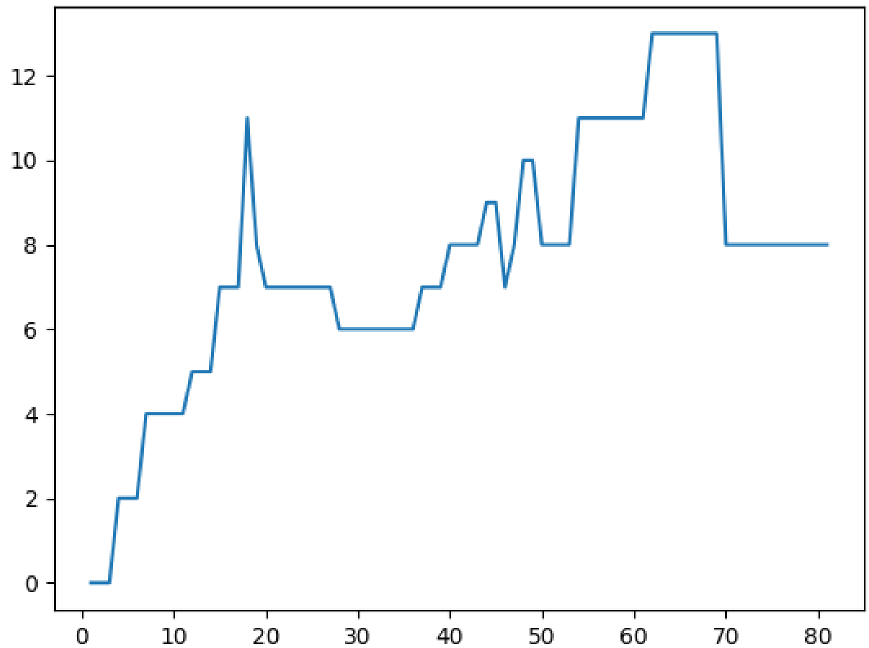


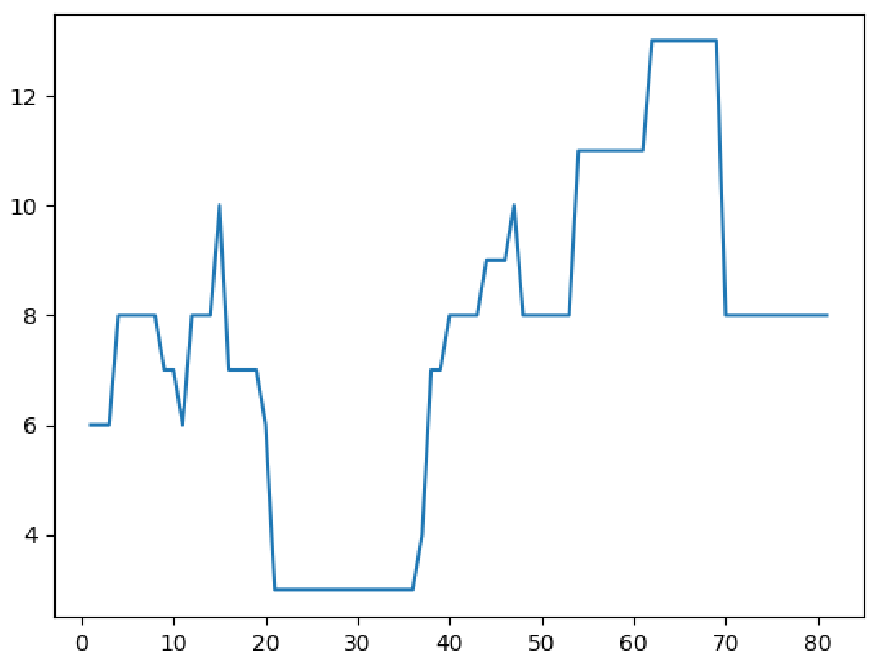
G Python code for resource optimization

```
import os
import numpy as np
import matplotlib.pyplot as plt
import sys
import time
np.set_printoptions(threshold=sys.maxsize)

chart = np.zeros((26,81))
original = chart
activityDuration = np.array([3,3,3,3,4,5,3,5,5,5,2
,4,2,5,3,10,3,2,8,10,9,14,2,9,8,12])
activityRange = np.array([[0,0,10,11,3,3,13,14,0,5,7,8,
16,19,24,27,12,18,20,10,37,46,9,60,28,69],[38,5,45,13,
42,10,48,18,21,26,57,49,50,23,26,36,52,52,60,36,45,59,48,68,68,80]])
activityResources = np.array([1,2,1,2,2,4,2,4,4,4,2,3,2,3,3,3,3,2,5,3,6,6,2,6,7,8])
dependancies = [[4],[5],[6],[7],[2,10],[11,3],[12],[13],[9],[19],[22],[16],
[17],[14],[15],[20],[18],[18],[24],[22],[21],[23],[23],[25],[25],[]]
moved = 0
hours = []

# populating the matrix
# 0-25
for i in range(0,len(activityDuration)):
        chart[i][0:activityRange[0][i]] = None
        chart[i][activityRange[1][i]+1:] = None
        chart[i][activityRange[0][i]:activityRange[0][i]+activityDuration[i]] =
        activityResources[i]

def resourcesPerHour(chart):
        global hours
        hours = []
        for i in range(0,81):
                hours.append(np.nansum(chart[:,i]))


def iterateTask(i):
```

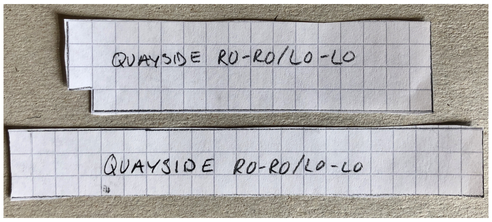
```
        possible = True
        while possible:
                now = np.where(chart[i] == activityResources[i])
                if now[0][-1]+1 == 81:
                        break
                if np.isnan(chart[i][now[0][-1]+1]):
                        possible = False
                else:
                        chart[i][now[0]] = 0
                        chart[i][now[-1]+1] = activityResources[i]
                        updateChart(i,False)
                        resourcesPerHour(chart)


def moveTask(i):
        global moved
        moved += 1
        now = np.where(chart[i] == activityResources[i])
        if now[0][-1]+1 != 81:
                if not np.isnan(chart[i][now[0][-1]+1]):
                        chart[i][now[0]] = 0
                        chart[i][now[-1]+1] = activityResources[i]

def updateChart(i,self):
        global moved
        if self:
                moveTask(i)
                moved += 1
        for x in dependancies[i]:
                updateChart(x,True)

move = range(0,26,1)
for i in move:
        iterateTask(i)
        plt.plot(range(1,82,1),hours)
        plt.show()
```

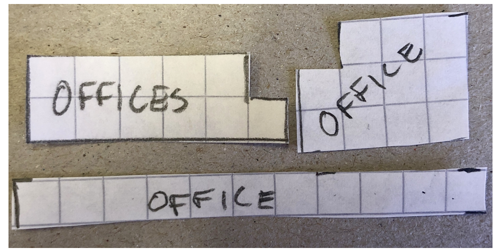
H Python results, first attempt

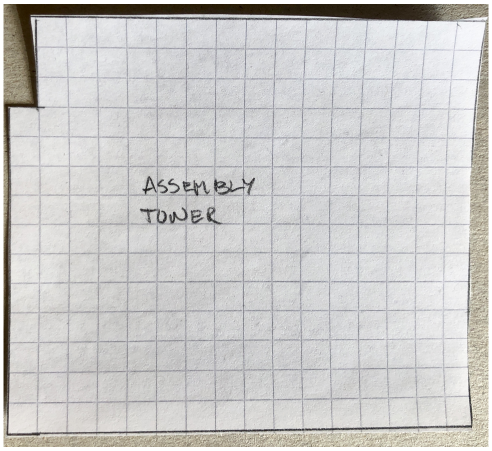


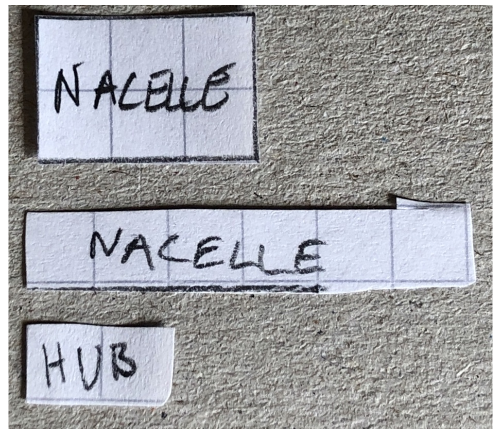


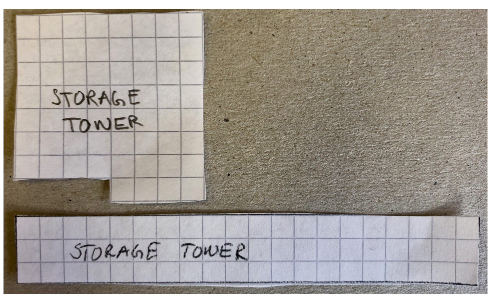
I Scaled areas in port

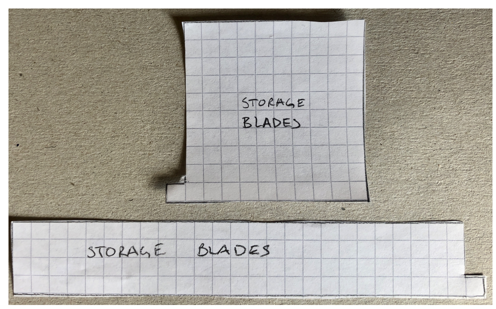


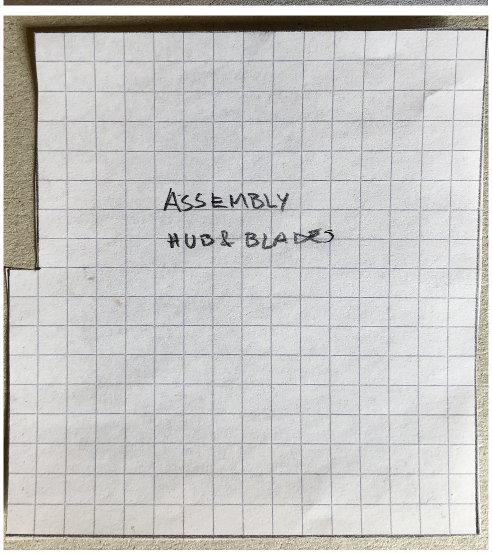


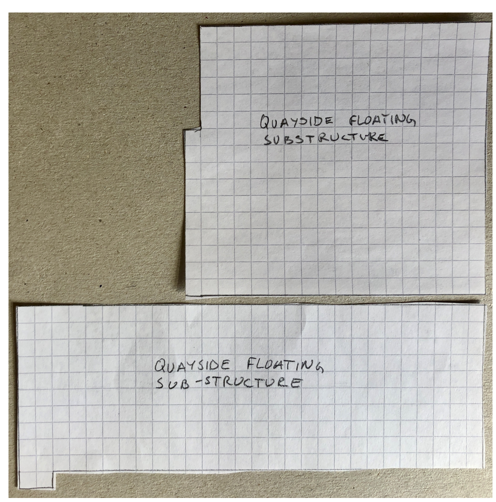












Thea Kruse Valvatne

Assembly Port for Floating Offshore Wind Turbine

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