NTNU – Trondheim
Norwegian University of
Science and Technology

Concept development of all-new flood protection system

Simen Strømsnes

Mechanical Engineering
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Supervisor: Torgeir Welo, IPM

Norwegian University of Science and Technology
Department of Engineering Design and Materials

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SIMEN MARSTEIN STRØMSNES

PREFACE

This master's thesis was written and conducted during the spring 2015 at the Norwegian University of Science and Technology (NTNU) at The Department of Engineering Design and Materials with Professor Torgeir Welo as supervisor.

I would like to thank my supervisor, Torgeir Welo, and postdoc. Christer Westum Elverum for guidance and good discussions.

ABSTRACT

Flood is a common nature disaster, and among all occurring disasters, flood is the one leading to biggest economic losses in Norway. Aquafence, which is the company that have requested this work, is a Norwegian company in the process of developing an all-new temporary flood protection system. A temporary flood protection system is a moveable water barrier. AquaFence aims at introducing their new system in 2020. The project is in the early stages of development, and this report is a contribution to the process. The work highlights a systematic approach on how to identify and solve requirements for a new temporary flood protection system, and it presents novel solutions to meet these demands.

During an exploration of the existing market, areas were discovered that the available temporary flood protection systems do not cover. The temporary flood protection market anno spring 2015 is in the need of satisfying solutions regarding rapid deployment combined with a sufficient protection height. To deal with identified issues, ten different concepts are presented which all have solutions that could contribute in the development of a new temporary flood protection system. Novel solutions like the design of the presented free-standing V-barrier ascertain the ability of a rapid deployment. For a system to have the capability of being rapidly deployed, the possibility of including preconnected parts to the flood protection system was examined. The preconnected modules should either be light weighted or have wheels which gives them the possibility to be pulled out in numbers and in that way provide a rapid solution.

SAMMENDRAG

Flom er en av de vanligste naturkatastrofene, og blant alle naturkatastrofer er flom den ene som fører til størst økonomisk tap i Norge. AquaFence, som er arbeidsgiver bak dette prosjektet, er et norsk selskap som er i ferd med å utvikle et helt nytt mobilt flomvernssystem. Et mobilt flomvernssystem er en vanntett barriere som kan flyttes av mennesker. AquaFence tar sikte på å introdusere sitt nye system i 2020. Prosjektet er i en tidlig fase av utviklingen, og denne rapporten er et bidrag til prosessen. Arbeidet fremhever en systematisk tilnærming på hvordan man kan identifisere og løse krav til et nytt mobilt flomvernssystem, og den presenterer nye og innovative løsninger for å møte disse kravene.

En gjennomgang av det eksisterende mobile flomvernsmarkedet, synliggjorde områder som de eksisterende systemene ikke dekket. Det mobile flomvernsmarkedet anno våren 2015 mangler tilfredsstillende løsninger angående rask utplassering av flomvernssystemet kombinert med at systemet har en tilstrekkelig beskyttelseshøyde. For å utvikle et system som kan løse de identifiserte problemene, er ti ulike konsepter presentert. Alle konseptene har løsninger som kan bidra i utviklingen av et nytt mobilt flomvernssystem. Nye løsninger og innovative løsninger som utformingen av den frittstående V-barrieren viser hvordan et system potensielt sett kan utføre en rask utplassering. For at et system skal ha evnen til å bli satt opp hurtig, bør delene være forhåndskoblet og ha evnen til å være koble under lagring. For at systemet skal få full utnyttelse av de forhåndskoblede delene bør delene ha lett vekt, eller ha hjul sånn at man på den måten kan trekke ut flere deler av gangen, og på den måten spare tid.

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1 INTRODUCTION

1.1 Background - AquaFence

AquaFence is an industrial and innovating Norwegian company that develops and produces temporary removable flood protection systems. AquaFence's mobile flood protection systems is world leading and the product is sold worldwide.

AquaFence are using module panels to build their flood protection system. They have four types of standard modules: V1200, V1800, V2100 and V2400, which vary in height, width and weight. AquaFence are packing the panels in a folded state in crates when storing. During transportation they use containers with the capacity of 18 crates [1]. The flood protection system AquaFence delivers today is designed for rapid deployment and can be installed by few persons. Estimations made by AquaFence show that 8-10 people can assemble 46 m fence within one hour [2]. The modules are made of laminate and are designed as flaps which come in different sizes. Depending on the size, one module weighs between 85-110 kg [1].

Despite that AquaFence deliver a competitive system today they want to evaluate new solutions. The flood protection market is growing and it has been a big technological development the last couple of years. In order to have a competitive advantage in Norway and internationally, AquaFence are aiming to improve their system. It is important to be innovative and able to offer the best solutions on the market. To sustain their leading position, AquaFence have decided to develop an all-new flood protection system for the future, called Systemflomvern 2020.

1.2 Flood protection

A flood occurs when water inundate land that is normally dry. Heavy rain, stormy weather, melting snow, sea waves or breached dams or levees can cause the occurrence of a flood. Different variants of floods can be divided into five categories: river flood, coastal flood, storm surge, inland flood and flash flood. Flash flood is considered to be the most dangerous because it is unpredictable and involves rapid rise of water. [3] [4]

Among all nature disasters, flood is the one that leads to the biggest economic loss in Norway. Flood statistics from Norway in 2014 show that floods alone cause economic damages worth 443 million Norwegian kroner [5].

Forecast predictions show that the number of floods will increase in the years to come (link forecast), and while cities around the world gets more populated the risk for catastrophic floods will increase. Therefore it is so important to have a precautionary approach and develop solutions that could potential minimize future damages.

The purpose of a flood protection system is to keep water away and give protection from floods. Some of the available systems have multiple applications, like having the possibility to retain water as an alternative to directing the incoming flood into streams. Regardless of the function, a flood protection system should control the water and keep one side of the barrier dry.

Today there are many different flood protection systems on the market, and to make it easier to get an overview of the existing systems, they can be grouped into three main categories:

- Temporary flood protection systems
- Demountable flood protection systems
- Permanent flood protection systems

A temporary flood protection system has no preinstalled permanent parts. This is what makes the system advantageous or unfavorable, depending on the current situation. In case of a flood, the temporary systems are brought to the location of impact, and the parts are assembled into barriers. After the flood, the system is disassembled and put back into storage. The mobility of a temporary system offers versatility and potential of multiple uses. Some of the existing temporary solutions could also be used as dams holding water, and some are used in river construction to ensure dry working space in the area. However, most of the temporary systems are dependent on a proper bedding surface, which requires preparation time to prevent seepage. A temporary system can be designed to a specific location. Knowing the location makes it easier to plan the installation and save time during the preparation of the bedding surface. Temporary flood protection systems also go under other names such as mobile- or moveable flood protection system.

A demountable flood protection system is a partly moveable system. The foundation is preinstalled and permanent, but the protection wall is moveable. Demountable systems have their strengths in installation time compared to the temporary systems, and their small impact on the environment compared to permanent systems. Both demountable and temporary systems need more time installation and have a smaller impact on the environment compared to a permanent system.

Permanent systems are fully preinstalled and do not need setup-time. A permanent system is often a fence when visible and do not need operation during a flood. It can be hiding in the ground when it is not needed, and during a flood it requires some sort of external force or operation to get it standing.

In general, permanent flood protection systems provide the safest and fastest systems. During a flood, demountable and temporary systems need installation, operation time and experienced workers. A permanent system should therefore be considered when possible. However, when buying a flood protection system, many conditions have to be considered when choosing which system to buy. In many cases, a firm does not own the property outside the building, and therefore it can be legal issues related to construction of the system. A permanent system in cities and urban areas may interfere with the surroundings, or be perceived as disturbing by people.

When deciding which flood protection system to use, it can be convenient to systematically evaluate the requirements using a schematic decision process chart like the one in Figure 1. During the decision process of choosing the appropriate flood protection system, there are several aspects which have to be evaluated. First of all, since a permanent system provides the best protection, this alternative should be considered. If this is not an option, the decision process chart should be followed to find other solutions, and so forth.

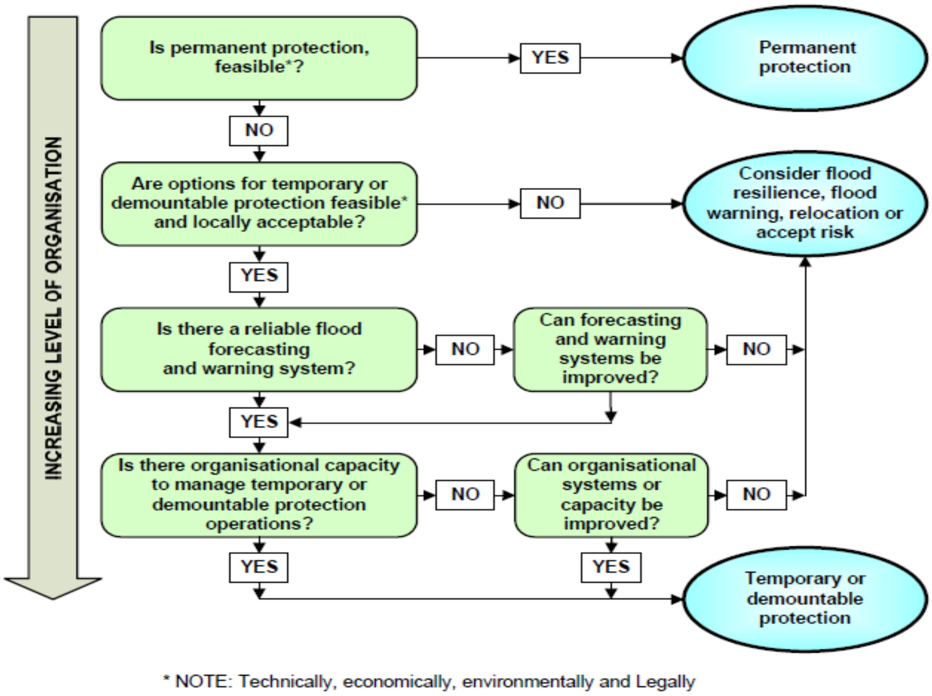


Figure 1 - The decision process. This chart is presented in [6]

Figure 2 shows a chart of different flood protections systems. The three main categories; demountable-, temporary- and permanent flood protection systems have many subcategories like those listed in Figure 2. The green boxes are temporary flood protection systems, which is one of two categories AquaFence competes in, the other being demountable systems. To narrow the objectives, this report focuses on the temporary flood protection market, searching for properties that could help AquaFence sustain their leading position in flood defense.

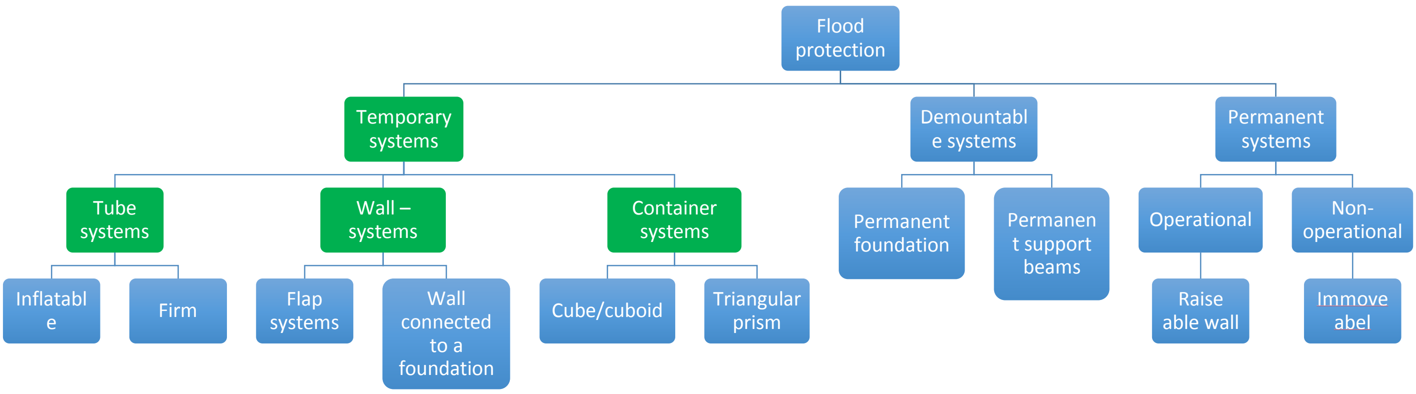


Figure 2 - Chart of different variants of flood protection systems. Inspired by the figure in [6]

1.3 Problem Formulation and objectives

The overall goal of this master project is to contribute to the development of an all-new flood protection system. This report gives an overview of existing flood protection systems to highlight smart solutions and possible weaknesses in the market. The existing solutions and the identified weaknesses were exploited in the process of developing concepts for novel temporary flood protection solutions. Using a systematic engineering design approach, the project identifies high-level requirements for the new solution and shows a number of early-stage product concepts that meet these requirements.

2 Existing temporary flood protection systems

2.1 Evaluative criteria for existing systems

There are many temporary flood protection systems on the market. Not every system delivers a satisfying solution, and they will therefore not be presented in this report. Unique solutions which provide the system with properties that gives advantages are valued. Rapid deployment, small storage volume, high provided height per volume material ratio and anchorage properties are qualities that are evaluated. The temporary flood protection systems presented in this chapter were chosen for a more thorough evaluation and compared in a PUGH-matrix. In the process of developing new solutions, the strengths and weaknesses in the existing systems must be identified. The Environment Agency in England have made a report showing a list of temporary flood protection systems on the market [6]. The systems from this report and additional solutions that I have found to be interesting is the base of this review.

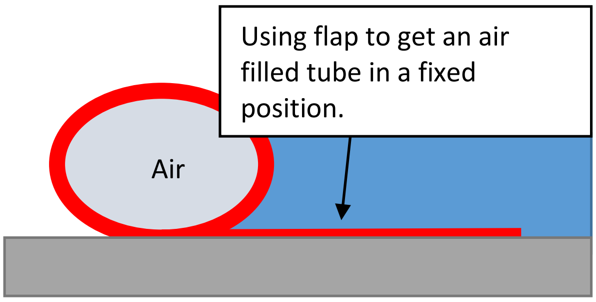
Examining the design of specific variants, strengths and weaknesses can be revealed. Chapter 2.2 – 2.5 present a selection of the temporary flood protection systems on the market. Other systems are left out because they delivered unsatisfying solutions or basically the same solutions as one of the presented protection systems.

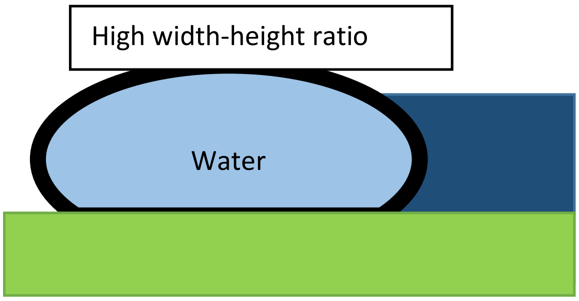
Several designs of temporary flood protection systems are available on the market, hereby referred to as tube systems, container systems, bag systems and free-standing barriers.

2.2 Tube systems

Tube systems can either be solid or filled with air or water. Solid tubes are filled with concrete or just have a solid shell and therefore doesn't fulfill the requirements that is important to temporary system, hence Chapter 0.

In this report the water- and air filled solutions are evaluated. These systems are presented in Figure 3). Figure 3 illustrates that the water filled system (Figure 3 (b)) has higher width-height ratio than the air filled (Figure 3 (c)), which is an effect resulting from the gravity forces of the water.





(a) *(b)*

Figure 3 – Cross section of an air filled tube system (a) and a water filled tube system (b).

Advantages and disadvantages in using air- and water filled systems are listed in Table 1.

Table 1 – Advantages and disadvantages for air- and water filled tube systems.

Air filled system	**Water filled system**
Advantages: • Light weight • Few people needed for installation • Quick installation • Easy to clean • Small storage space required	Advantages: • Can be used in uneven terrain • Small storage space required • Quick installation • Light weighted before use, and heavy during usage
Disadvantage: • Inflexible • Weakness to tearing • Exposed to vandalism • Need of a flat bedding surface	Disadvantages: • Has to be emptied and cleaned after used • Need water • The width is a lot bigger than the height.

Inflatable tube systems are easy to set-up, require few people and small storage volume compared to other systems.

Air filled tubes give other properties than water filled tubes. Figure 4 shows four tube systems that are already on the market. These four systems deliver four unique solutions which is why they were selected for a more thorough examination. NOAQ – TW Tubewall (Figure 4 (a)) is filled with air instead of water.

An air filled system is light weighted, and for that reason NOAQ – TW Tubewall needs a flap and external fasteners to be in a fixed position. The other systems from Figure 4 have high weight, since they are filled with water, and therefore they do not need external elements to be anchored to the ground. Use of air will also make a module much less flexible than a module filled with water, as an air-filled module does not have the possibility of making a turn. To turn an air-filled system, angled connectors between the modules are needed. Contrary, the flexibility of the water-filled tube systems can be regulated by the volume of water inside the tubes. Besides the physical differences, a system containing air instead of water is better for the environment after a flood because it does not have to discharge more water to the already water damaged environment.

(a) *(b)* *(c)* *(d)*

Figure 4 - Four different existing tube systems. All systems were found in [6]. (a) is NOAQ – TW Tubewall. (b) is Aquadam. (c) is Tigerdams. (d) is Waterwalls Type B.

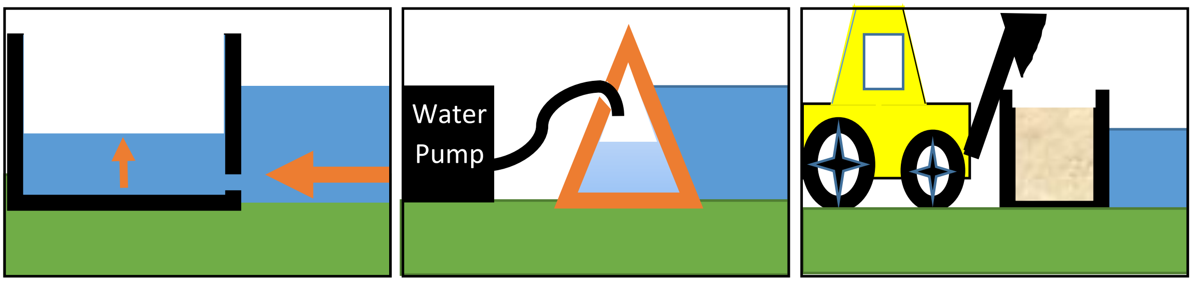
The three systems showed in Figure 4 (b), (c) and (d) are all containing water, but they have dissimilar physical structure. Aquadam (Figure 4 (b)) consists of modules creating a large tube, Tiger dams (Figure 4 (c)) is build out of stacked small tubes and Waterwall Type B (Figure 4 (d)) is constructed of three chambers which makes the system taller compared to Aquadam. There are two reasons to make several chambers within a tube, as in the Aquadam solution. Firstly, more chambers make it possible to use more water pumps, which leads to a faster setup. Secondly, more chambers will make the system less vulnerable to leakage. If one chamber starts leaking, the other chambers might still hold enough water to protect the system from failure.

Stacking of smaller tubes like Tigerdams gives the system a possibility to gain height with a smaller amount of water than Aquadam's system. The system from Aquadam and similar systems need a lot of water to gain height, as the gravity will always disperse water horizontally, leading to a system with larger width than height. A shape like Waterwalls Type B could also help the system to gain height, but it will need something to lean up to.

2.3 Container Systems

Container systems are light weighted before setup and use the filling material to get rigid, fixed and waterproof. Container systems vary in shape, flexibility, filling material and filling method. They can either be self-filling, filled by pumps or excavators, as illustrated in Figure 5.

Container systems like the ones in Figure 5 (b) and (c) are filled preceding a flood impact. Self-filling systems are filled with rising flood water during the flood.



(a) *(b)* *(c)*

Figure 5 – (a) shows the principle of a self-filling module. (b) shows a container system being filled by a pump (c). shows container system contain sand, rocks or other heavy things.

Advantages and disadvantages in using container systems and self-filling container systems are listed in Table 2.

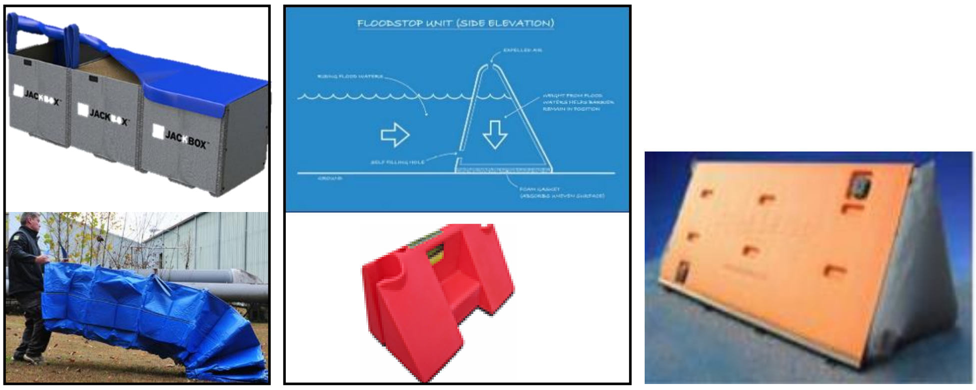
Table 2 - Shows advantages and disadvantages for container systems and self-filled container systems.

Self-filling container systems	**Container systems**
Advantages: • Light weighted before use and heavy during usage. • Easy to maneuver in small places • Height-width ratio close to 1 • Some system could be used in uneven terrain • Quick installation • Quick removal of the system • Need of few people during installation Disadvantages: • Can be clogged/blocked • Weakness to wind before flood • Some systems are not foldable, which leads to high storage space-barrier length ratio	Advantages: • Stackable • Light weighted before use and heavy during usage • Easy to maneuver in small places • Flexible • Height-width ratio close to 1 • Some system could be used in uneven terrain • Need of few people during installation Disadvantages: • Has to be emptied and cleaned after use • Slow installation • Slow removal of the system • Some systems are not foldable, which leads to high storage space-barrier length ratio • Need of external tools like pumps, excavators etc.

Figure 6 presents different container systems. Like all the other presented systems they comprise only a selection of the many systems one the marked. The three selected systems are chosen because they contain some qualities that are of interest for further investigation. The AquaLevee system (Figure 6 (a)) could also have been presented in the tube barrier presentation, but it has been chosen to be introduced among the container systems because the main part of the system is a triangular container. Using a triangular container is also what makes the system interesting. The AquaLevee container gives structural support, which makes them different from the tube systems presented in Figure 6 as they give the possibility of increased height relative to width.

Floodstop (Figure 6 (b)) and Aqua Levee (Figure 6 (a)) show some similar properties. Both systems have a triangular shape, and both are filled with water. While Aqua Levee needs a pump to be filled, Floodstop is self-filling. A self-filling barrier is the most time and cost efficient alternative, and it does not need a water pump like Aqua Levee. On the other hand, self-filling barriers could be clogged/blocked, and if the Floodstop system does not fill with water during the flood it could start floating or sliding, leading to failure. However, the possibility of heavy wind could be a reason to fill the barriers with water before a flood occurs. Strong wind could blow away the barriers, while filling a system with water makes it heavier and could be enough to make it resist the wind.

HESCO Jackbox (Figure 6 (a)) is one of the few systems that has a rapid deployment and is foldable at the same time, which are properties of interest. HESCO Jackbox is a system of connected foldable boxes which make the system easy to store. Each box is vertical hinged in the middle of the surface that faces the incoming water and the opposite surface, making the box foldable. The lower picture of HESCO Jackbox in Figure 6 (a) shows a man pulling the system out like a big accordion.



(a) (b) (c)

Figure 6 – Three container systems. (a) is HESCO Jackbox [11]. (b) is Floodstop. (c) is Aqua Levee. Both (b) and (c) were found in [6].

2.4 Bag systems – Flexible free standing barriers

The available bag systems are named so in this report because they consist of pockets which are filled with incoming water. Bag systems stand out from other temporary barriers because they use flexible fabric which shapes a V as illustrated in Figure 7. What is really interesting about bag systems is their ability to be rapidly installed. Bag systems are light weighted and utilize storage space in an efficient way. These properties give the possibility to store hundreds of meters of protection barrier within one crate, contributing to rapid deployment.

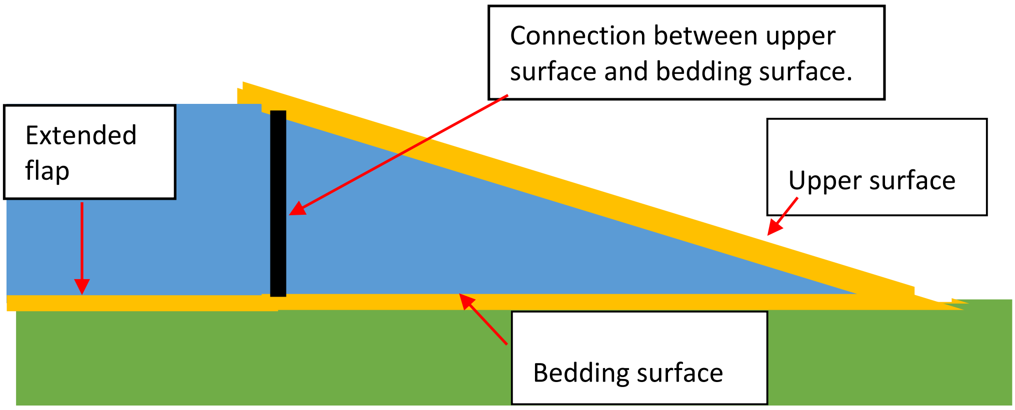


Figure 7 – Cross section of a bag system. The extended flap is added to the bedding surface to gain more weight from the flood water. The connection between the upper surface and bedding surface is what holding the systems together.

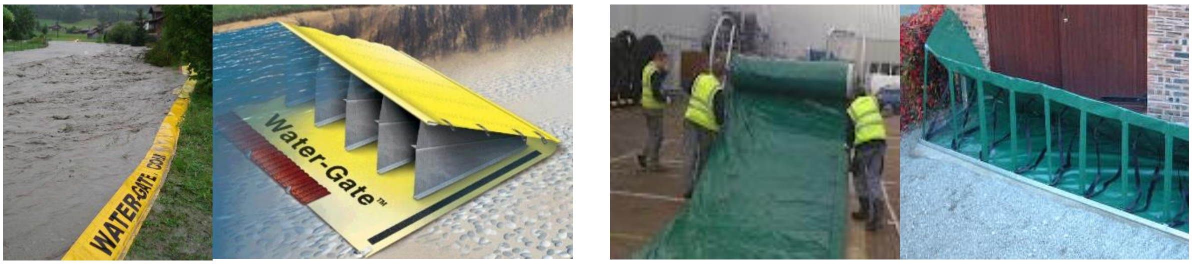
Figure 7 shows the principle of a bag system. The barrier has a flap and a connection between the upper surface and the bedding surface. The flap is just an extension of the bedding surface. The extension is to make sure that the system gains enough weight from the flood water to be in a fixed position. The connection between the surfaces is to make sure the system doesn't fail.

Advantages and disadvantages in using bag systems are listed in Table 3.

Table 3 - Advantages and disadvantages for bag systems.

Bag systems	
Advantages:	Disadvantage:
• Light weight	• Doesn’t look as safe as other systems
• Rapid installation, the fastest on the market	• Large floating objects could push down the upper surface which could lead to overtopping
• Could be used in uneven terrain	• Maximum height about 1.5 meters
• Few people need for installation	

Figure 8 present two existing bag systems. These two systems have different qualities in the connection between the upper surface and the bedding surface. As seen in Figure 8 (b), the Rapidam system has a connection between the surfaces which holds the upper- and bedding-surface apart. The Water-Gate system shown in Figure 8 (a) is folded prior to a flood and rises with rising water level. The upper surface contains a low-density material which allows it to float and rise with the increasing water height.



(a) *(b)*

Figure 8 – Two existing bag systems. (a) is Water-Gate. (b) is Rapidam. Both systems were found in [6].

2.5 Free-standing barriers

In the group of free-standing barriers are all the temporary flood protection systems that do not fit one of the previous presented system categories. Subcategories to free standing barriers are commercially called frame barriers and rigid free-standing barriers. There are various available systems belonging to this category of flood protection systems, and in this report, the systems presented in Figure 9 are given a closer look Portadam (Figure 9 (b)) is a frame barrier which means that the frame and protection surface are separated. As shown in Figure 9 (b), the protection surfaces are divided in many panels, which give the constructor the possibility to dimensioning/adapt the height of the system to resist the flood water.

NOAQ Boxwall (Figure 9 (a)) has the typical shape of a rigid free-standing barrier. The barrier system is modular with an L-shaped design. Modular, non-rigid free-standing barriers have the protection surface integrated with the rest of the module, while frame barriers have a rigid frame with the protection surface spanning between them.

(a)

(b)

Figure 9 – (a) shows NOAQ Boxwall which is a rigid free-standing barrier. (b) shows Portadam which is a frame barrier. Both (a) and (b) were found in [6].

Advantages and disadvantages in using rigid free-standing barriers and frame barriers are listed in Table 4.

Table 4- Advantages and disadvantages for free standing barriers.

Rigid free standing barriers	**Frame barriers**
Advantages: • Easy to install • Easy cleaned and reusable • Looks safe • Usually doesn't need machinery/tools to set-up	Advantages: • Easy to install • Easy cleaned and reusable • Usually doesn't need machinery/tools to set-up.
Disadvantages: • Uneven terrain could lead to seepage due to the support plate rigidity • Many systems are relatively heavy • Require large storage space	Disadvantages: • Uneven terrain could lead to seepage due to the support plate rigidity • Many systems are relatively heavy • Require large storage space

2.6 Pugh based matrix

A Pugh matrix is a concept screening based method. Usually a Pugh matrix is used to narrow the number of concepts and to improve them [7, p. 150]. In this chapter a Pugh based matrix were used to explore differences and weaknesses in the temporary flood protection market. The Pugh-matrix (Figure 10) contains all the presented systems in Chapter 2. Some requirements defined in Chapter 3 are derived from the Pugh matrix.

Concepts

	Selection Criteria	Weight	Tube systems			Bag systems		Reference system	Container systems			Free standing barriers	
			TW Tubewa	Aquadam	Tigerdams	Water-gate	Rapidam	Aquafence	Floodstop	HESCO Jackbox	Aqua Levee	IBS K systems	NOAQ Boxwall
Deployment	Time to deploy the system	0,13	0	-0,13	-0,13	0,13	0,13	0	0	0,13	-0,13	-0,13	0,13
	Weight before setup	0,1	0,1	0,1	0,1	0,1	0,1	0	0,1	0,1	0,1	0	0,1
	Intuitive setup	0,1	0	0	-0,1	0,1	0,1	0	0,1	0,1	0	0	0,1
Man power	Number of persons needed for installation	0,05	0,05	0,05	0,05	0,05	0,05	0	0,05	0,05	0,05	0,05	0,05
	Number of persons needed for carrying the system	0,05	-0,05	0,05	0,05	0,05	0,05	0	0,05	0,05	0,05	0,05	0,05
Flexibility	Maneuverability	0,05	-0,05	-0,05	-0,05	-0,05	-0,05	0	0	-0,05	-0,05	-0,05	0
	Height extension	0,01	0	0	0,01	0	0	0	0	0,01	0,01	0	0
	Possibility to open	0,05	-0,05	-0,05	-0,05	-0,05	-0,05	0	0	-0,05	0	0	0
Storability	Foldeable	0,15	0	0	0	0	0	0	-0,15	0	0	0	-0,15
	Space utilazation in folded state	0,1	0,1	0,1	0,1	0,1	0,1	0	-0,1	0	0	0	0
Appearence	Attractive design (looks safe)	0,1	-0,1	-0,1	-0,1	-0,1	-0,1	0	0	0	0	0	0
	Number of small part (bolts etc)	0,05	0,05	0,05	0,05	0,05	0,05	0	0,05	0,05	0,05	0	0,05
	Need of external tools (Pump, drills etc)	0,01	-0,01	-0,01	-0,01	0,01	0	0	0,01	-0,01	-0,01	0	0,01
	Protection height/width	0,05	-0,05	-0,05	-0,05	-0,05	-0,05	0	0	0	-0,05	0	-0,05
		Total	-0,01	-0,04	-0,13	0,34	0,33	0	0,11	0,38	0,02	-0,08	0,29

Figure 10- Shows the existing temporary flood protections systems. Aquafence is used as reference.

The Pugh matrix in Figure 10 compares the existing systems presented in Chapter 2.2-2.5. The systems were rated with respect to properties that will lead to rapid deployment, storability and flexibility amongst other factors.

AquaFence was used as a reference, with a neutral score. The other systems were scored in the negative- or positive direction, depending on their qualities compared to AquaFence's system. The systems with a lower total score than AquaFence's system are marked in red, while those with a higher total score are marked in green.

By comparing the different available solutions in this matrix, properties that are important for developing a new system were identified, such as rapid deployment. The matrix shows that there are four systems that are better than AquaFence regarding deployment time. These systems are Watergate, Rapidam, HESCO Jackbox and NOAQ Boxwall. The latter two are small systems with small protection height [8, 9]. The other two are bag systems which requires large width to obtain large protection height. This reveals that the market is in need of rapidly deployable systems that also provide large protection height.

3 IDENTIFICATION OF REQUIREMENTS

In terms of product development, requirements are functions or features defining the product. In order to make a detailed requirement list it is essential to identify the requirements and define to what extent they are met. The result will be a list of demands and wishes regarding the final product. Demands are requirements that must be fulfilled to meet the main objectives, for instance that a flood barrier should not leak water if the purpose is to keep one side dry. Wishes are requirements that not necessarily have to be met, but should be taken into consideration when possible. A wish should always give an advantage. When considering requirements categorized as wishes, a list with pros and cons should be made to evaluate the importance of the features relative to the associated inconveniences. Adding features or functions can increase the complexity and cost of the product. [10, pp. 146-147]

The competition in the flood protection market is increasing. To be in a leading technological position, it is important to be innovative and deliver a system with high standards. In order to design a temporary flood protection system in a satisfying way it is important to get an overview of demands and wishes.

A temporary flood protection system has only two absolute demands. Firstly, the system must be able to hold back water. Secondly, the system must have the ability to be moved. These two demands make up the basis for which properties the system must contain. There are many ways to fulfill these two demands, and to get a clearer view of how to proceed, the demands were divided into subdemands. For every defined subordinated category, a requirement gets more specified. In total, the primary, secondary and tertiary requirements give a clear view of what is demanded of a successful system [10, p. 170]. A list of wishes was developed, which includes properties that improve the system and gives it a competitive advantage. Besides the list of wishes and demands AquaFence have made a list of design requirements which was taken into consideration in the decision process that led to which requirements to examine.

AquaFence's list of design requirements:

- The system should be quick and easy to assemble in the field, and contain few small parts like bolts.
- Strong and lightweight materials
- Have an attractive, modern design that gives the system an identity and that the least possible extent "disturbs" the surroundings.
- Good maintainability
- Recyclable.
- Competitive (price, function, distribution) and adapted for industrialization and mass production

The design requirements from AquaFence in addition to demands and wishes obtained by evaluating strengths and weaknesses in the existing systems on the market are presented in the hierarchy list in Figure 11.

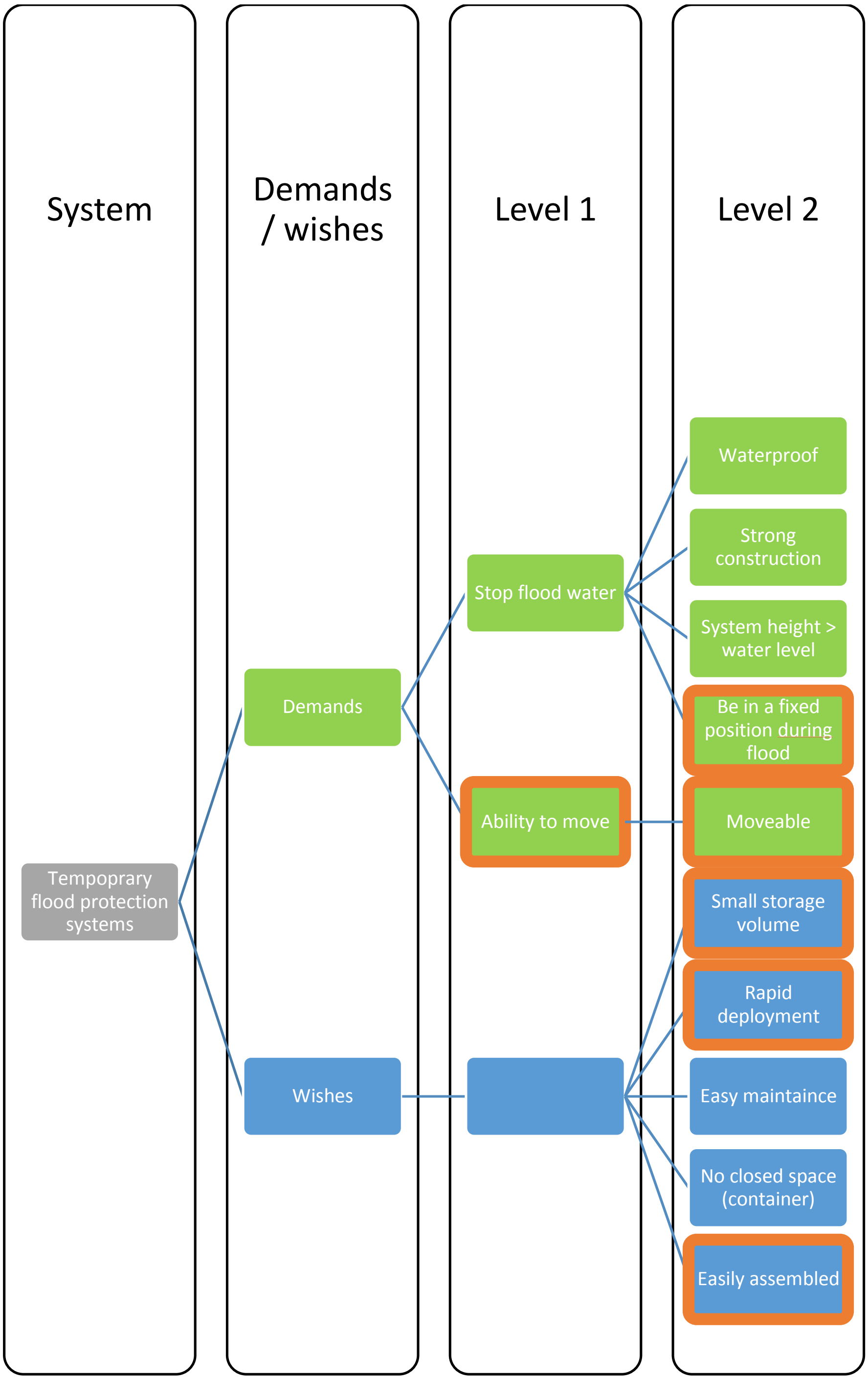


Figure 11 – A hierarchy list that shows demands and wishes for a temporary flood protection system. The green boxes present demands, and blue boxes present wishes. The boxes marked with an orange frame are the requirements that will be investigated in this project. The demands were chosen after a comprehensive evaluation of the flood protection market.

Deciding which requirements to investigate further in this report was done by studying the existing temporary flood protection market. The existing market was evaluated in a PUGH-matrix (). A market evaluation revealed strengths and weaknesses in existing products. Both strengths and weaknesses are worth knowing. The requirements that were chosen for further investigation are the boxes marked with a red frame in Figure 11. These requirements were further divided into subdemands which are listed in

Figure 12.

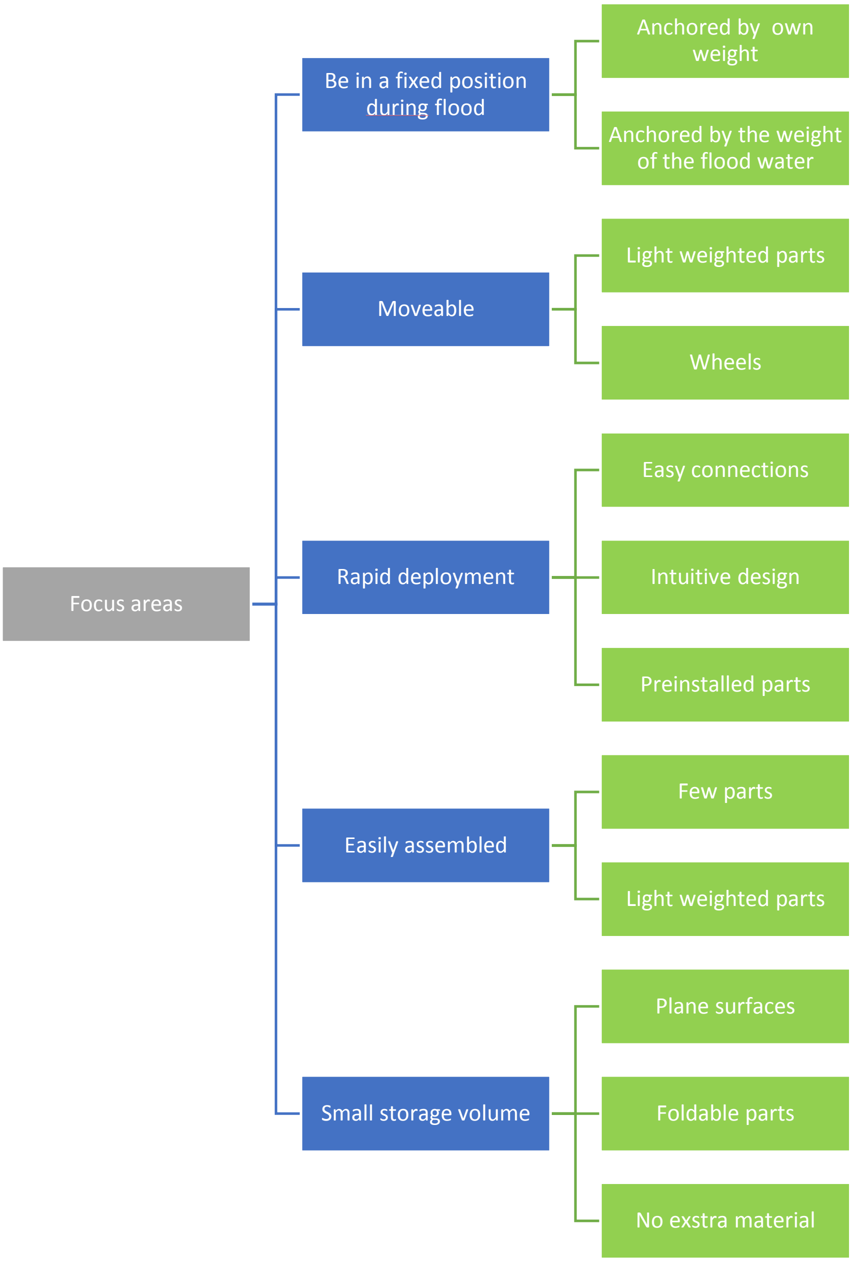


Figure 12 – A hierarchy list based on the boxes marked with red frames in Figure 11. The blue boxes are similar to the marked boxes in Figure 11 and they present the requirements that this project looks further into.

Solutions that led to system advantages were used when developing new concepts in Chapter 5. Exploring weaknesses in the flood protection market could reveal potential advantages for a new flood protection system. Identified weaknesses and strengths were defined as requirements which were examined in this thesis. The market analysis that was conducted in this project was performed by comparing all the systems that were found to be interesting in a PUGH-matrix (Chapter 2.6). Since there are many similar and cumbersome temporary flood protection systems available, a selection of systems with interesting properties were examined more closely. The systems of interest show some properties that give competitive advantages, like Aquafence's product which gets stronger with the rising flood water.

From the market analysis, certain weaknesses were revealed. In the temporary flood protection market today there are very few good solutions that meet the demands regarding rapid deployment and the ability to cope with high water levels. Therefore rapid deployment is one of the aspects that are examined in this project. Another weakness that was revealed is the utilization of material. In many systems, the ratio of protection area per material volume is too low. These systems are too large and heavy compared to the protection they provide.

Besides logic and user-friendly requirements there are requirements controlled by other factors. Many products have to give the buyers something besides the purpose it is meant to fulfill. Trends today show that people prefer products that are environmental friendly and are produced locally. This could mean that customers are likely to buy systems made in their own community, because it shows solidarity and renders the buyer with a feeling of contributing to the local community. Moreover, local products are often cheaper, because of the lower transportation expenses compared to imported systems. With this in mind, the designer should think of the possibility to let local firms assemble the system.

4 CONCEPTUAL DEVELOPMENT

4.1 Causes of Failure

During a flood, several causes of failure may occur related to the flood protection system. Failure types can be distinguished into five general topics [11, p. 4]:

- Sliding/rolling
- Seepage
- Leakage
- Tilting
- Collapse

Every flood protection system has the possibility of failure. Therefore, it is important to design the system in a way that minimizes the possibility to meet one or several failure types. Wind, floating elements, bad design, vandalism, and human failure are all factors that may cause failure of the flood protection system.

Obviously, it is important to try avoiding the mentioned failure types. During the design phase of a flood protection system, the engineers should consider the risk of failure and put it up against properties that the system should hold. For instance, large and heavy systems provide stability and robustness, but on the other hand they will be more difficult and expensive to produce, store and transport. Therefore, it is important to consider which strengths the flood protection system should get and which to neglect. There are many factors to evaluate, and often a system property becomes worse when another is improved.

Some systems have obvious weaknesses or strengths against some failure modes. Heavy weight and elastic fences like a tube filled with water will clearly have a reduced risk for seepage compared to a light fence built out of hard plastic boxes.

4.2 Geometric Shapes

4.2.1 The importance of suitable geometry

The geometric shape decides the base of which properties a system can contain. Meaning, whichever shape a system has it is chosen because it provides the system with advantageous properties. Boxes, triangular prims, cylinders, curved plates, angled plates, plane plates etc. provide different properties to a system. For instance a box system like the ones in Figure 14 (b) or (c) provides stability and the ability to contain water. Triangular prims, shown in Table 10, do the same with less material, but it can contain less amount of water or other fillers. Every compared shape has contradictions, which is why it is important to be aware of them and to learn to compensate for the potential disadvantage.

All the shapes mentioned in the section above can provide water protection, but the rule of thumb is that the projected area of a system should haven a constant height, and match the water level which is also constant. A constant height makes the projected area square or rectangular.

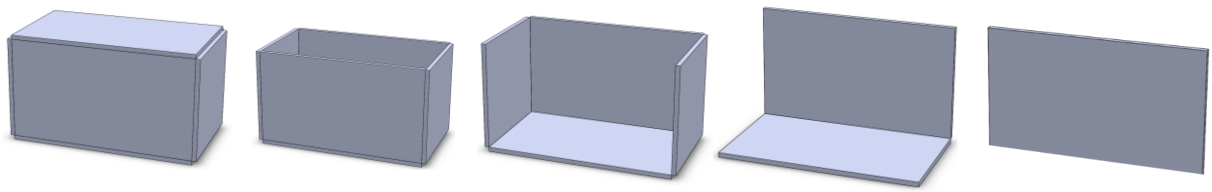
It is already established in the requirements chapter that a new system should be light weighted and space saving. With that in mind the designer wants the flood protection system to have minimum surface area which leads to minimum material volume. For instance, a cube has six surfaces, but it is only the side facing the flood that provides water protection. Considering the fact that only one side is used for flood protection, it is fair to say that six sides are too many if the purpose is to build something light weighted and small.

Ideally, a flood protection system only need the surface facing the water, but that will not be possible if the system should provide safety against failure causes like tilting, sliding or collapsing. A system can gain stability by for instance adding a foundation as shown in Figure 13 (d), or to make two plates support each other in a V-shape as shown in Figure 14 (d). Stability can also be obtained by support beams and fastenings.

4.2.2 Square/box:

Containers are used as fences because they can be filled with water, sand etc. to gain weight to the system after installation. Other reasons to use box-modules come of their stability and stacking properties. A closed container (Figure 13 (a)) has no advantageous properties that an open container (Figure 13 (b)) cannot provide. Since an open container has one less surface and therefore uses less material than a closed container, a system which is build out of containers should use open container modules. Figure 13 (c) shows a container which is further stripped into four plates, with two plates in an L-shape with sidewalls on each side. When additional plates are removed from the box system, a wall with a flap forming an L (Figure 13 (d)) or a free standing wall (Figure 13 (e)) remains.

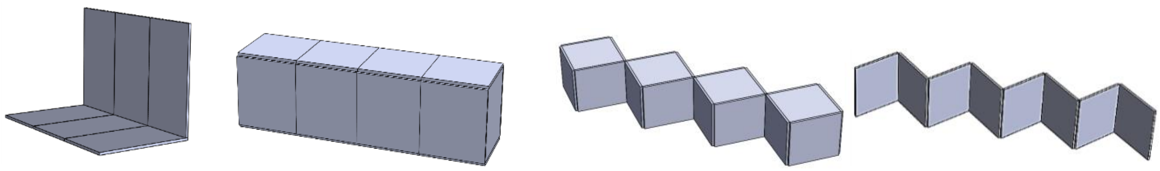
Boxes like those in Figure 13 (a) and (b) are not suited for water protection if the system should be as small and light weighted as possible. Figure 13 (d) shows the most efficient system because it uses lesser material.



(a) (b) (c) (d) (e)

Figure 13 – Shows a box stripped down to a wall. (a) is box, (b) is an open box, (c) is a wall with a flap and sides to support (d) is wall with a flap and (e) shows a free standing wall.

A barrier or fence is often imagined as a straight lined wall like the ones sketched in Figure 14 (a) or (b). It is natural in a person's mind to place cubic shapes in straight line because of the stability, stacking properties and the appearance. However, this is not the most efficient way to arrange boxes or perpendicular plates if the purpose is to get the biggest projected area. For instance, Figure 14 (b) and (c) show two rows containing four identical cubes. In the latter (Figure 14 (c)), the cubes are turned 45 degrees creating 90 degrees between the hinged plates. The row with these hinged corners provides bigger projected area than the row with cubes connected wall-to-wall (Figure 14 (b)). Figure 14 (d) shows a material-effective system where angled plates are hinged to support each other in a V-shape.



(a) (b) (c) (d)

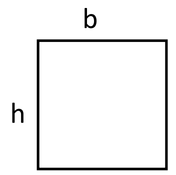
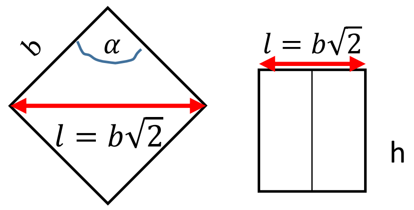
Figure 14 – (a) is a straight lined wall with flaps. (b) is a straight line of boxes. (c) is a row of box modules with hinged corners. (d) is a row of angled plates hinged together.

The equations in Table 5 show that the systems in Figure 14 (c) and (d) have a projected area that is $\sqrt{2}$ times bigger than those in Figure 14 (a) and (b), because the length per module is increased by $\sqrt{2}$. By chancing the angle, ∝, the length can be adjusted. The length will increase as the angle is approaching 180 degrees.

$$\propto \rightarrow 180^{o}: Projeced\ area\ increases$$

While the angle is changing, the center of mass is moving. The center of mass is an important factor to consider to prevent tilting. To sum up, considering fence length and stability, the most efficient way to use square surfaces is to build a barrier as sketched in Figure 14 (d). In Table 5, area properties for one module of the fence systems in Figure 14 are presented.

Table 5 – Area properties for one module from systems presented in Figure 14: Cubes. Row 1 shows the projected area of one module in Figure 14(a) or (b). Row 2 shows the projected are of one module in Figure 14 (c) or (d).

Projected area of one module, Figure 14 (a) or (b): $A_{projected} = (hb)$	 $A_{projected} = hb$
Projected area of one module, Figure 14 (c) or (d): $\alpha = 90^{o} \rightarrow l = b\sqrt{2}$ $A_{projected} = h(b\sqrt{2})$	

4.2.3 Cylinder

Besides the use of square surfaces it is common to use cylindrical modules in flood protection systems. Depending on the positions of the cylindrical figures they can be used as flood barriers. Table 7, Table 8 and Table 9 show the cylinders from Table 6 arranged in different positions making a flood fence.

Table 6 – Area properties of a cylinder, semi cylinder and quarter cylinder.

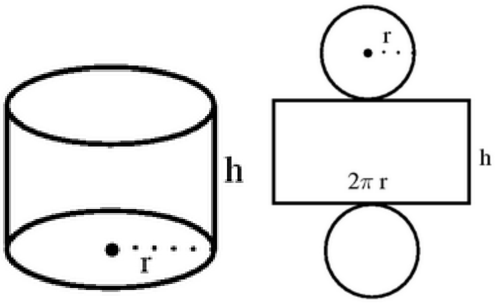
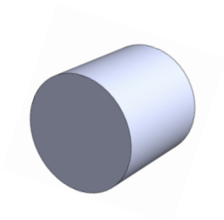
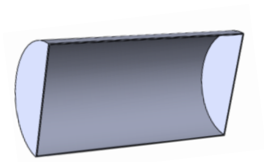
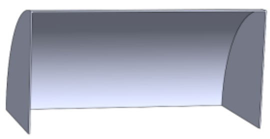
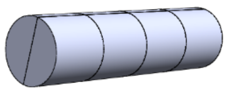
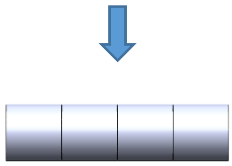
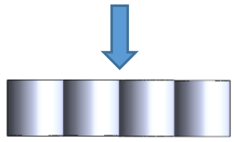
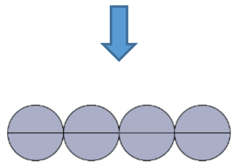
Cylinder surfaces:  [12]	
Cylinder with cap ends: $A_{total} = 2\pi r^2 + 2\pi rh = 2\pi r(r+h)$ $A_{projected} = 2rh$	
Semi cylinder: $A_{total} = \pi r^2 + \pi rh = \pi r(r+h)$ $A_{projected} = 2rh$	
Quarter cylinder: $A_{total} = \frac{\pi r^2 + \pi rh}{2}$ $A_{projected} = rh$	

Table 7 – Cylinder: Different assemblies and area properties:

Cylinder:	(a):	(b):	(c):
The illustrations (a), (b) and (c) show that there are three different ways to orient cylinders to make a barrier. Cylinders oriented like (c) will leave gaps in the barrier, shown in the projected view. Therefore, (c) will not provide safety from water without out external parts to fill the gaps. The barriers (a) and (b) are watertight and makes a square when projected. Projected area and total area for both of berries are equal. $n = number\ of\ modules, r = radius, h = hight\ or\ lenght\ of\ a\ cylinder$	 Projected view  $A_{projected} = 2rh * n$ $A_{total}\ (just\ wall) = 2rh\pi * n$	 Projected view  $A_{projected} = 2rhn$ $A_{total}\ (just\ wall) = 2rh\pi * n$	 Projected view  $A_{projected} = r^2\pi * n$ $A_{total} = (2rh + r^2)\pi * n$

The three barriers presented in Table 7 are all build out of cylinders. For each system, cylinders are placed in different positions, which gives different properties. From Table 7, (a) and (b) have another projected area than (c). Barrier (c) provides bigger projected area than (a) and (b) if:

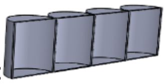
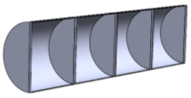
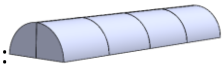
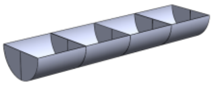
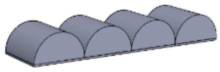
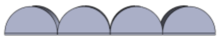
$$h < r * \frac{\pi}{2} \rightarrow (c)\ gets\ a\ greater\ projected\ area\ than\ (a)\ and\ (b).$$

$$h > r * \frac{\pi}{2} \rightarrow (a)\ and\ (b)\ gets\ a\ greater\ projected\ area\ than\ (c).$$

where $n = number\ of\ modules, r = radius, h = hight\ or\ lenght\ of\ a\ cylinder$

Barrier (c) need additional parts to be watertight. (a) needs support to prevent rolling.

Table 8 – Semi cylinder: Different assemblies and area properties:

Semi cylinder:	Column 1:	Column 2:	Column 3:
A semi cylinder is half of cylinder divided lengthwise. The columns to right show five different ways to place a semi cylinder to make a barrier. The columns are divided and determined by the project area from the figures. The figure in Column 3 needs external parts to get a uniform height, which is important to get an efficient flood fence. The barriers in Column 1 (b) and Column 2 (b) need external support to be stable.	(a):  (b):  Projected view  $A_{projected} = 2rh * n$ $A_{total} = r\pi(2h + r) * n$	(a):  (b):  Projected view  $A_{projected} = rh * n$ $A_{total} = r\pi(2h + r) * n$	(a):  Projected view  $A_{projected} = \left(\frac{r^2\pi}{2}\right) * n$ $A_{total} = r\pi(2h + r) * n$

In Table 8 five different ways to make a barrier from semi cylinders are presented in addition to their area properties. A comparison of the displayed barriers shows that the barriers from Column 1 have twice the area of the figures in Column 2.

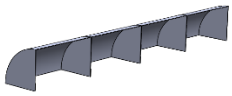
$$h < r * \pi \rightarrow The\ figure\ in\ Column\ 3\ gets\ a\ greater\ projected\ area\ than\ the\ other\ figures$$

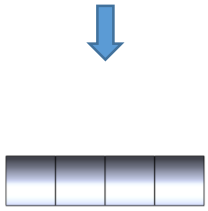
$$h > r * \pi \rightarrow Figures\ in\ Column\ 1\ gets\ a\ greater\ projected\ area\ than\ figures\ in\ Column\ 3$$

Table 9 – Quarter cylinder: Different assemblies and area properties

<table>
<tr>
<td>Quarter cylinder, Row 1:

The figure shows a barrier consisting of four quarter cylinders facing the flood with the inside of the cylinder. Each cylinder has ends to support the system.

$A_{total} = \frac{r\pi}{2}(2h + r) * n$</td>
<td></td>
<td rowspan="3">All the quarter cylinders have the same area and projected area properties.

Projected view


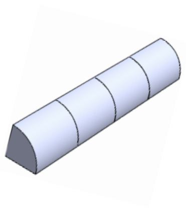
$A_{projected} = rh * n$

$A_{total} = \frac{r\pi}{2}(2h + r) * n$

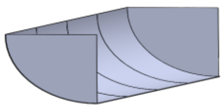
$n = number\ of\ modules, r = radius,$

$h = hight\ or\ lenght\ of\ a\ cylinder$</td>
</tr>
<tr>
<td>Quarter cylinder, Row 2:

This is a similar figure to figure shown in Row 1. The different is that this system faces the flood with the outside.

$A_{total} = \frac{r\pi}{2}(2h + r) * n$</td>
<td></td>
</tr>
<tr>
<td>Quarter cylinder, Row 3:

This barrier needs external support to be stable and is the figure in Table 8 Column 2 (b) divided lengthwise.

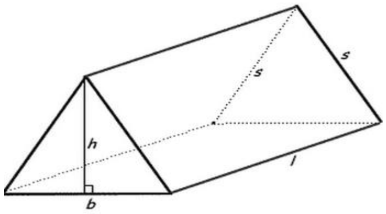
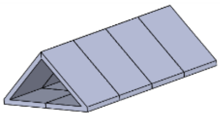
$A_{total} = \frac{r\pi}{2}(2h + r) * n$</td>
<td></td>
</tr>
</table>

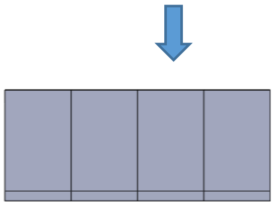
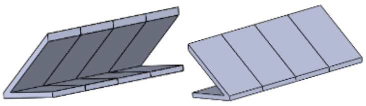
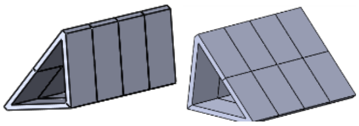
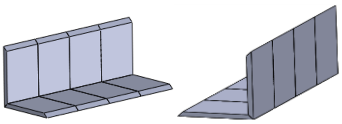
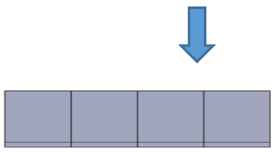
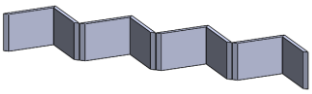
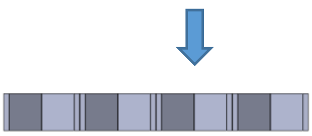
When comparing cylinders, semi cylinders and quarter cylinders the semi cylinder gets the biggest projected area if the total surface areas are equal. The quarter cylinder have the second greatest area with equal surface area, and a hole cylinder makes the smallest.

4.2.4 Triangular figures

Table 11 presents area properties of triangular shapes.

Table 10 – Area properties: Triangle, triangular prism

<table>
<tr><td>Triangular prism:
$$A_{projected} = lh * n$$
$$n = number\ of\ modules$$</td><td></td><td></td></tr>
<tr><td>Triangular prism:
$$A_{total} = l(b + 2s) * n$$</td><td></td><td rowspan="3">All of this triangular figures have the same projected view. The differences is number of surfaces and wich way they are facing the water.

Projected view

$$A_{projected} = lh * n$$</td></tr>
<tr><td>Semi triangular prism, the triangular prism divided along the h-axis:
$$A_{total} = l\left(s + \frac{b}{2}\right) * n$$</td><td></td></tr>
<tr><td>Semi triangular prism with ends:
$$A_{total} = l\left(s + \frac{b}{2} + h\right) * n$$</td><td></td></tr>
<tr><td>Semi triangular prism, without the base:
$$A_{total} = 2ls * n$$
$$A_{projected} = lh * n$$</td><td>
Projected view
</td><td>This semi triangular prisms are similar, the differents is which sureface that faces the flood. They have a shape simular to the box based barrier shown in Figure 14 (a).</td></tr>
<tr><td>Semi triangular prism, without the base and turn on the side:
$$A_{total} = 2ls * n$$
$$A_{projected} = lb\sqrt{2} * n$$</td><td>
Projected view
</td><td>This semi triangular prism a shape simular to the box based barrier shown in Figure 14 (d).</td></tr>
</table>

From Table 10 it can be determined that the semi triangular prism without base and turned on the side has the best projected area properties. This figure has a projected area $\sqrt{2}$ times bigger than the rest of the triangular shapes.

4.2.5 Comparing the geometric figures

In the last three subchapters, various square-, cylindrical- and triangular shapes have been presented. In Table 5 and Table 10 triangular and square shaped figures are presented. Both of these tables show that Figure 15 is the most efficient way to orient two surfaces considering the area properties.

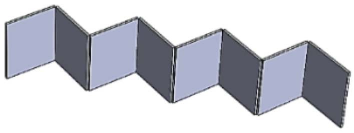
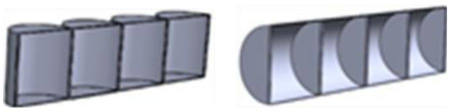


Figure 15 – Hinged plates

From the cylindrical figures it has been shown that semi cylindrical figures can proved the biggest projected area with smallest amount of surface area. Table 8 Column 1 shows two figures similar to the figures in Figure 16 (a) and (b).



(a) (b)

Figure 16 – Semi cylindrical figures

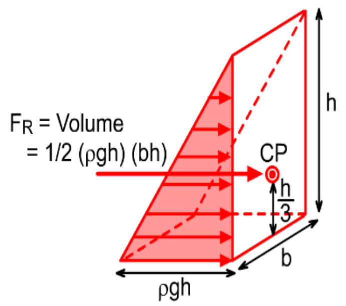
Area properties of the systems in Figure 15 and Figure 16 show that Figure 15 provides the largest projected area when the total area is equal. This means that from all the presented geometric shapes it is the V-formed shape in Figure 15 that provides the largest projected area, disregarding a plane plate like the one in Figure 13 (e), which will not be taken into consideration because of its lack of support.

The largest projected area is just one perimeter when deciding the design of the flood protection system. A flood barrier should also be intuitive and easy to set up, contain good transportation and storing qualities and other aspects, like design with respect to water pressure.

4.2.6 Forces during operation time

A flood protection system is often exposed to different forces during operation time. Floods tend to appear at the same time as stormy weather. Besides flood, strong winds derived from stormy weather often lead to complications during the installation process or worse like tilting and failure of the flood protection system during flood. Wind conditions are varying be geographical position and from one storm to another and it is therefore problematic to predict the magnitude of forces caused by winds. AquaFence's manual tells that a flood protections system should be able to operate in wind conditions up to 225 km/h [1]. For a system to operate in these extreme conditions it is necessary to anchor the system to the ground with fastenings or by heavy weight. The concepts presented in this report in Chapter 5 will not take wind condition into account, meaning it will not be presented aerodynamic shapes, coatings and forces caused by wind.

Flood protection systems have to handle pressure from water and hits by floating objects. The hydrostatic pressure is continues throughout the flood and the water pressure are distributed with minimum pressure at water surface and increasing towards the bottom, which leads to maximum pressure at the water bottom. Since hydrostatic water pressure increases equally through the depth it is easy to find the resulting force derived from the pressure. Water pressure vector is always perpendicular to the surface. The water pressure distribution and resultant force are shown together with equations and explanations in Figure 17.



Hydrostatic pressure:

$P = water\ pressure$

$F_R = Resultant\ force$

The resultant force always occurs at one third of the depth.

$P = \rho g h$

$$F_R = \frac{1}{2}(\rho g h)(bh)$$

Figure 17 – Hydrostatic pressure prism

It is important to design the flood protection system to deal with water pressure. If it is done incorrect it could lead to failure. Depending on the geometric shapes, pressure from water may give high stresses in critical parts, which may lead to failure or push and relocate modules and in that way reach failure. So, the two main failure types from water pressure are high stresses or sliding. There are several ways to deal with these problems, and the high stress problem could be dealt with by the design of the system. Figure 18 shows different section of modules and how the water pressure is distributed to the system.

Figure 18 displays seven different figures which indicate where the water pressure and moment applies. The biggest moments applies where the support plates are connected to the water protection plates. The geometric shapes in Figure 18 and Figure 19 are selected, because they have the geometric shape of existing barriers and are efficient solution to stop floodwater.

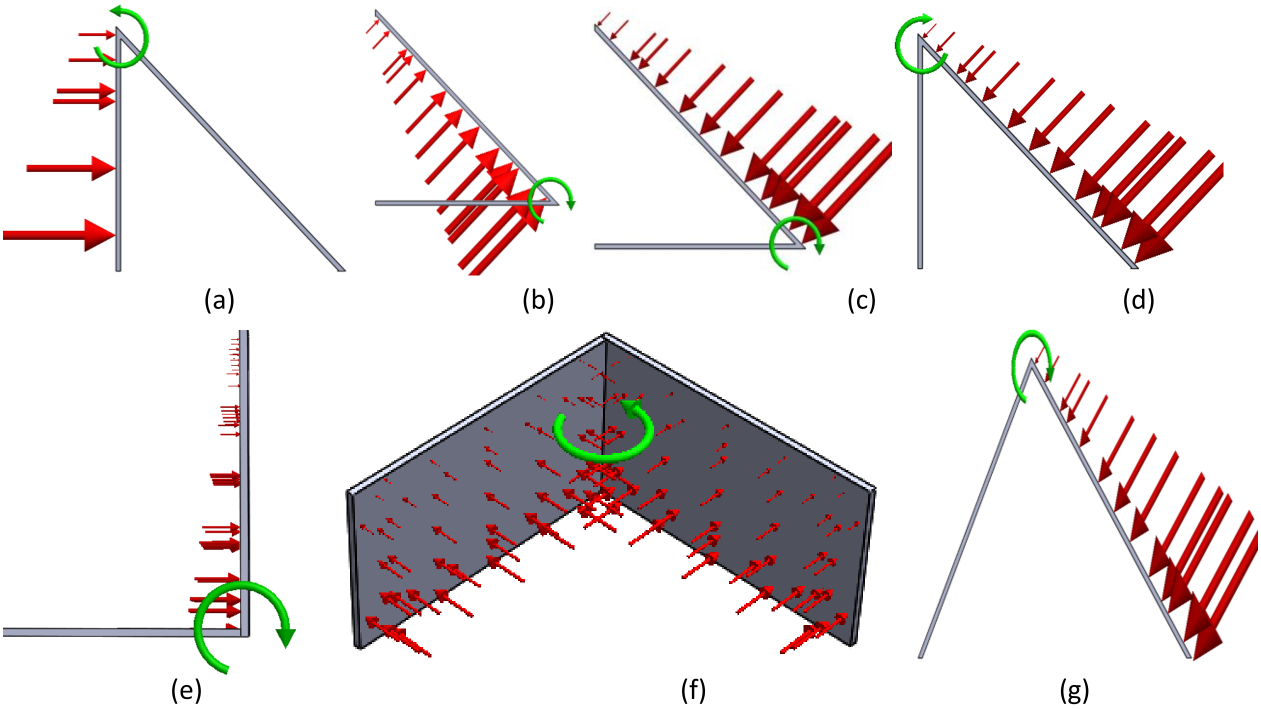


Figure 18 – Geometrical figures with applied water pressure (red vectors) and moment/torque (green vector). (a) – The protection plate is perpendicular to the water with a diagonal support plate. (b) – Diagonal protection plate with a supporting foundation. (c) – Diagonal protection plate and supporting foundation. (d) – Diagonal protection plate and a support plate perpendicular to the ground. (e) – Two perpendicular plates, the protection plate is parallel with the water depth. (f) – Two perpendicular plates, both plates are facing the water. (g) – Triangle, one plate facing the water.

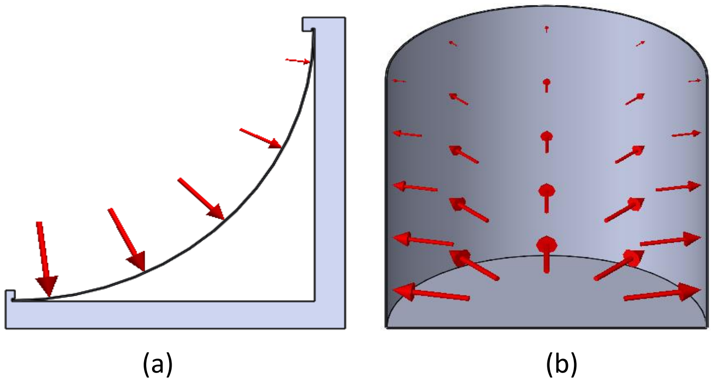


Figure 19 – A quarter of cylinder and a standing semi cylinder with water pressure applied. (a) – Quarter of cylinder supported by a flap. (b) – Semi cylinder.

When building a fence it is important to know the reason for why you are using plates perpendicular or angled to each other like the modules in Figure 18, or curved plates shown in Figure 19. Figure 18 (b), (c) and (e) have all a torqueing moment near the ground in joint connection between the plates. In Figure 18 (b) and (e) the water pressure is working to "open" or rip apart the surfaces. In Figure 18 (c) the water pressure is trying to collapse the module, by pushing the surfaces together. The red vectors represent water pressure and indicate on which side of the module the water is contained and the green vector represents the torque. Figure 18 (a), (d) and (g) have the torquing moment at the top of the module where the surfaces are connected. Figure 18 (a) and (d) have the same shape, but the difference is which plate is facing the water. Both Figure 18 (d) and (g) have a plate facing the water angled. Figure 18 (a) has the plate facing the water standing perpendicular to the ground.

4.3 Deployment – From box to flood protection

4.3.1 Fast set-up (deployment)

The deployment process is time consuming, and contains the unload phase and installation of the system. As known, time could be a critical factor during flood so it is important to make every step as quick as possible. The time spent in these phases are dependent on how the system is stored, in the meaning of sizes, numbers and weight of parts, stacking of parts and the connection between parts. If a system is made out of modules and the modules are handled by persons during the unload phase, the designers should pay attention to finding the optimal solution for unloading of the system. The optimal solution for the unloading -and installation process is the fastest one. To find the fastest way to unload and install the system you have to study many aspects because there are a lot of factors that comes in to play, and the fastest way to do something might vary between systems. Use of tracks, wheels, or rolls will in general be faster than lifting. Other solutions could be the use of light frames, which could be easily pulled out because of the light weight. HESCO Jackbox shown in Figure 6 (a) has these properties. If the system is handled and lifted by persons there are a lot of things to consider: size and number of parts, number of persons moving parts, number of persons installing the system, hinged parts or separated parts. Clearly, there are a lot of possibilities when unloading and installing the system.

The requirements identified in Chapter 0 tell that rapid deployment is important to get an improved system. There are few rapid and solid solutions in the market today. Rapid systems are either small or bigger and exposed for failure. On the other hand, tall and solid solutions are very time consuming compared to the small ones. Given a general system there are several ways to improve deployment time, by for example changing the number of parts, either by dividing the system into smaller or bigger parts. Using wheels or tracks could reduce set-up time and the number of people need for installation. Another way to reduce the set-up time is to improve module connections or makes the parts lighter. A good interaction between these improvements will lead to rapid deployment.

Properties that could lead to rapid deployment:

- Fast connections
- Sections of preconnected modules could be possible if the modules have:
    - Light frames
    - Wheels
    - Rails
    - Rolls

A row of hinged modules makes a section. An interaction between large parts, wheels and hinged module connections would lead to a rapid set-up. Preinstalled sections could be stored and ready to be pulled out. The time consuming phase in this imagined system would be the section connections. The same conditions apply if a system is either made of thin -or elastic parts. The system could be rolled-out from a roll.

An interaction between small parts and rapid connections between parts would also lead to a fast set-up. An imagined system like this would be most efficient if many people are working.

4.3.2 Storing of Modules and module interactions

Module connections are the links between two module's protection surfaces. The connection is important for the stability of the system, water tightness and the time it takes to deploy a system. In this report it was decided to emphasize the importance of the compatibility between module connections and quick system set-up using wheels and light frames. This has been done because there are no existing flood protection systems using wheels, and there are a few systems that use light frames in the deployment phase. The connections between modules should be compatible with use of wheels or light frames. To optimize the compatibility, the modules should be preinstalled in the storing box and connected in a way that makes it possible to trail a row of connected modules from the storing box. Another possible module connection would be a quick and easy click-connection like a seat belt buckle. Use of click-connections is much easier applied if a module is transported by wheels, since the modules will be in the same height. Since squared shapes have the most efficient geometry for storing, other geometric shapes will be neglected.

If a system consist of modules which have a quadratic shape when folded there are three different ways to store the modules. They are either stacked lying, standing or angled. Standing modules have two potential directions to be pulled out, either with the protection surfaces facing the moving direction, or the modules can be turned 90 degrees and be pulled out by the ends. Figure 20, Figure 21 and Figure 22 are illustrating invisible storing crates stored with standing modules. The red vector arrows are demonstrating the pulling direction. A cross section of an angled storing crate is shown (Figure 23).

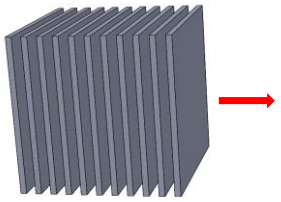


Figure 20 – Modules stored standing in a storage crate. The red arrows a direction vectors, showing the deployment direction.

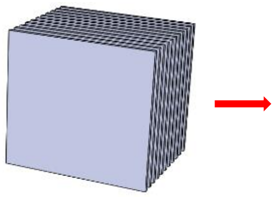


Figure 21 – Modules stored standing in a storage crate. The red arrows a direction vectors, showing the deployment direction.

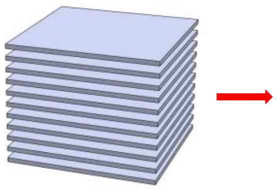


Figure 22 – Stacked modules. The red arrows a direction vectors, showing the deployment direction.

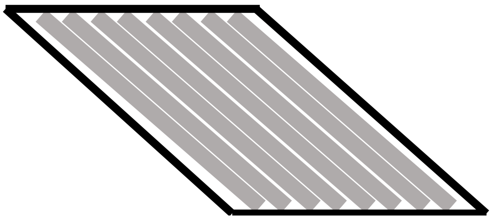
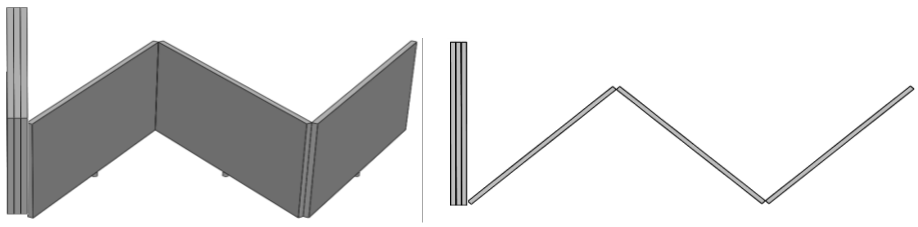


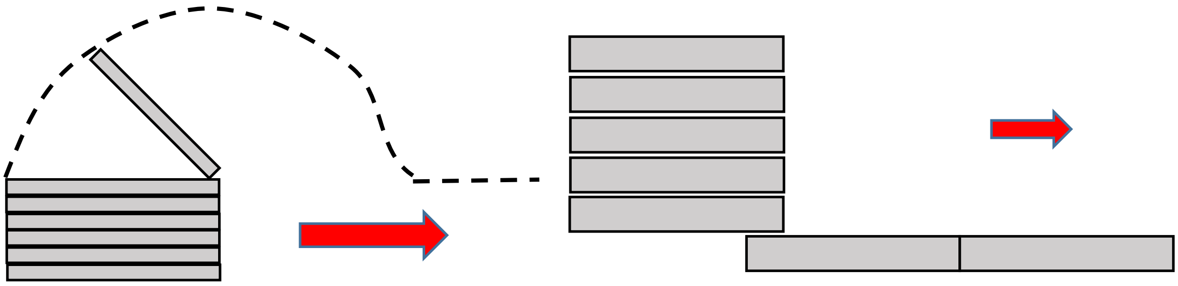
Figure 23 – Cross section view of an angled storing crate.

Figure 24, Figure 25, Figure 26 and Figure 27 illustrate different ways of pulling out hinged systems.



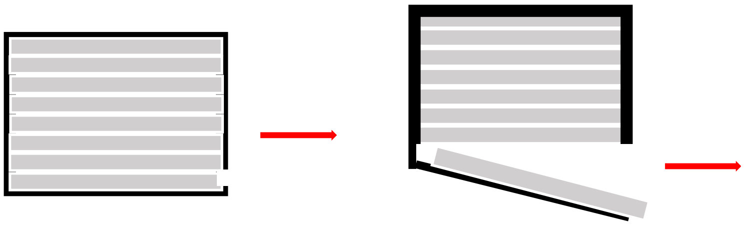
(a) (b)

Figure 24 – The figures are illustrating two potential ways to trail the system from a storing box like Figure 20. Figure (a) shows hinged modules dragged along the ground. The modules are hinged in the ends perpendicular to the ground. Figure (b) shows hinged modules dragged along the ground. The modules are hinged in the ends parallel to ground.



(a) (b)

Figure 25 – This figures show two ways to position modules from a storing box with the modules stacked like Figure 21. The figures (a) and (b) are viewed from above. The red arrows are direction vectors which shows the trail path. In figure the modules are hinged and pulled out from the side of the storing box. The modules need to be turned 180 degrees since the modules are hinged in the ends, this means that the system need some extra space to be positioned. This is shown by the stippled line. Figure (b) the modules would just be pulled out of the storing box. The modules could be connected by ropes or



(a) (b)

Figure 26 – This is a cross section view of a storage box filled with modules. The modules are lying similar to the modules in Figure 22. The red arrows are direction vectors, which show the direction of the module deployment. Figure (a) illustrates stacked modules inside a storing crate. The crate has an opening towards the ground where the modules are supposed to be dragged out. Figure (b) is also based on the arrangement in Figure 22. The bottom of the storing box are opened so the modules inside the box could slide out.

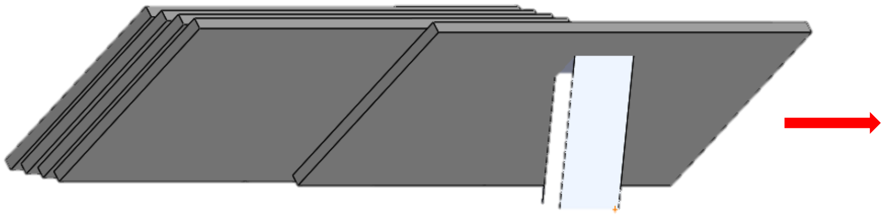


Figure 27 – Stored angled modules.

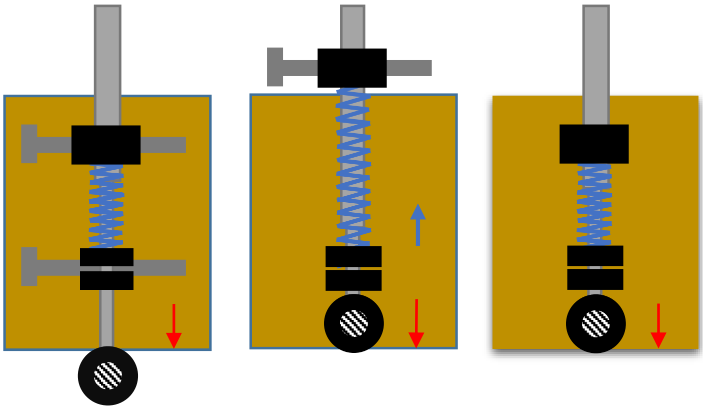
4.3.3 Wheels

The fastest way to transport objects is to pull, push or roll them. Being able to do that in an efficient way and without tearing parts the modules has to be designed with wheels, tracks, light frames, or in a cylindrical shape so it can be rolled.

Adding wheels to a system will increase the weight and it will lead to need of extra storage space. As showed in Chapter 4.2.6 the optimal way to store objects are to make them flat, with that in mind it is important that the wheels are affix to the system in a way that leads to little dead space between the modules. The wheels that are affixed to the system should not be too small. Small wheels will have problems rolling in uneven terrain, gravel and soft ground. Therefore should wheels be large enough to deal with the mentioned problems.

Besides the downgrade in storing properties, one other problem arise, the wheels that are affixed to the system have to be removed after deployment. For the reason that, the system should touch the bedding ground with as much area as possible to gain stability, water tightness and rigidity.

The effect of using wheels instead of carrying the system is best shown if parts and modules are connected. If many modules are connected it will be possible to do the fastest set up, because one person could deploy many modules just by pulling.



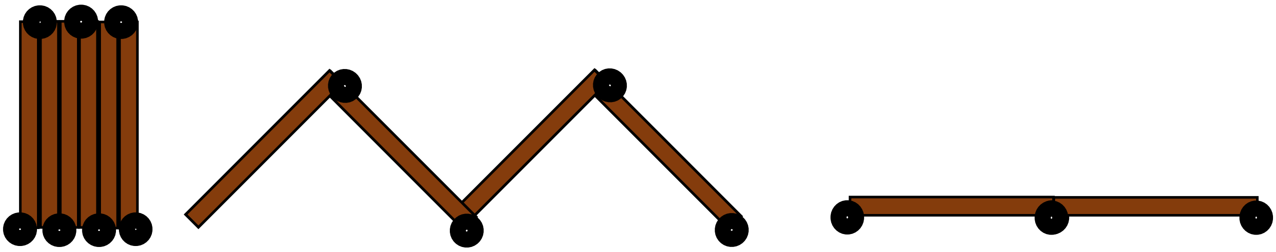
(a) (b) (c)

Figure 28 – Wheel suspension for a standing plate. The figures show how it could work from transportation to deployment. The black circular figures illustrate wheels, the blue figures illustrate springs, the horizontal grey lines are wedges, the black figures illustrate fasteners, the grey vertical lines are rods, the red vectors illustrate the gravity force and the blue illustrates the force from the spring. Illustration (a) shows the wheel sustention when it is ready to be transported. During transportation there are no forces applied to the spring, the gravity force are exerted to the fixed fastener

Figure 28 shows a possible solution for a wheel suspension. The lower black fasteners are fixed to the system. The upper black fastener are utilizing the energy from the blue spring and it is fixed to the rod. The red vectors indicate gravity, and the blue vector indicates the force from the spring.

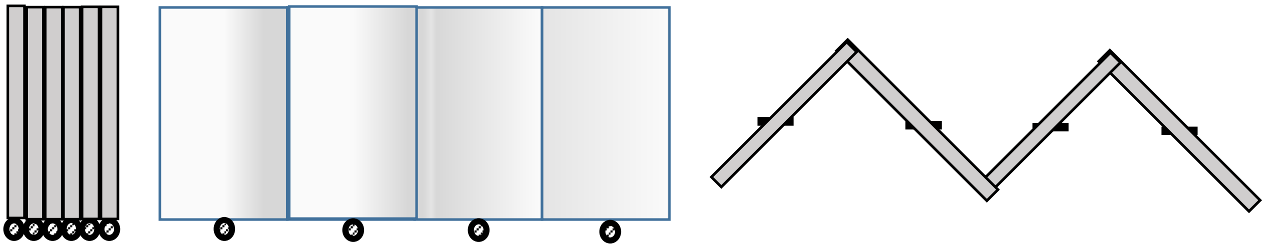
The first picture shows the wheel suspension ready for transportation, there is no force applied to the spring. The second picture is after deployment when the system reach the ground level. Gravity will force the system towards the ground when the wedge in the lower fastener are pulled out. The spring soften the fall. In picture two the spring has gained potential energy. This means that the spring tries to force the system upwards. The energy is released when the upper wedge is removed from the upper fastener, shown in picture three.

Figure 29 and Figure 30 show two possible methods to pull out hinged modules with wheels.



(a) (b) (c)

Figure 29 – Deployment of plates. Stored state (a), partly pulled out (b) and fully stretched (c).



(a) (b) (c)

Figure 30 – Deployment of plates. Stored state (a), pulled out as seen from the front the barrier (b) and top of the barrier (c)

4.4 Anchoring the system

4.4.1 Anchoring technics/possibilities

The anchoring of the whole system and the connection between modules are vital to make a flood defense system impermeable and rigid. During a flood, the flood protection fence should be fixed considering the possibility of failure when the fence moves. If the whole fence, or some of it moves, it might make the fence more fragile. It can be compared to an egg, which is hard to break when only squeezing it, but which will break easily if some part of it is corrupted before squeezing. Therefore, both anchoring and connection between modules are important to stability and robustness of the system.

With the use of fasteners the system can be fixed to the surroundings, in the means of walls, ground, curbs, lamp post, existing fence, hooks etc. Not all systems need additional fasting to be anchored, depending on the structure some system are fixed by the friction between the system and the ground. If a system is heavy, friction and weight might be enough to keep it in position.

Designing a flood protection system, anchoring is the most vital function besides stopping water. Anyone could build a wall, but the hard part is to design a system that does not move and doing that with as few and light parts as possible. Besides that, the system should be intuitive and easy to setup and take down. Because the anchoring has such vital function, it is fair to say that it has huge influence of the design.

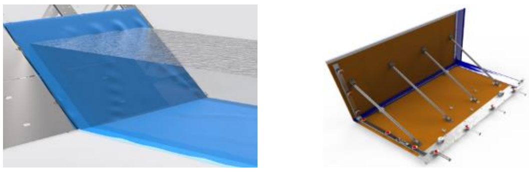
There are two ways to anchor a flood defense system: Weight and fasteners. Weight and fasteners are most common and it is used for many temporary flood system today.

4.4.2 Weight

Anchoring the system with weight could be a smart solution to get the system fixed to a position. Gaining weight to the system is always soluble and can be done by adding external loads or it can be done by dimensioning the system with more - or heavier materials. External load can be stones, sandbags, water etc. Using weight to anchor the system is a good alternative if there are any legally restrictions against damaging the ground.

Adding weight to the system by dimensioning gives a system containing large and heavy modules. High weight will provide stability and better anchoring. On the other hand, large and heavy parts could make the installation process more difficult because they are more unmanageable than light weighted small parts. A challenge for new temporary flood protection systems is to hold the ability given by heavy system, but doing that with light parts.

Flood protection systems that have a part or parts lying along the bedding ground, will exploit the weight from the flood water to get rigid. Flood protection systems which use flaps to gain weight from flood water to retain its position, gain stability and to be watertight. When a flap gets pressurized by flood water it will be force against the ground, making it impermeable for the flood water to leak through the system. Figure 31 show two systems which use flaps. The containers systems could be self-filled during flood or filled by persons before flood impact. Figure 32 shows three container systems. Figure 32 (a) and (b) is filled before flood impact with water and sand, Figure 32 (c) shows a conceptual drawing of a self-filling system which gets filled during flood by flood water.



(a) *(b)*

Figure 31 – Shows a fabric flap and hinged panels.(a) – Fabric flap used to waterproofing and utilization of flood water to gain weight to the system. (b) – Utilize water to gain weight and stabilization to the system.

(a) *(b)* *(c)*

Figure 32 – Shows different geometric figures containers external load. (a) - Triangle container filled with water. (b) - Mobile system. Using sand to stabilize. http://nyp-corp.com/fibc-bags-flood-control-emergency (c) is a conceptual drawing from a self-filling system.

5 Early-stage Product Concepts

In this chapter it will be described how the developing of concepts and different function are worked out, and a carefully description on all of them.

5.1 Concept 1 – Protection plate with vertical support beam

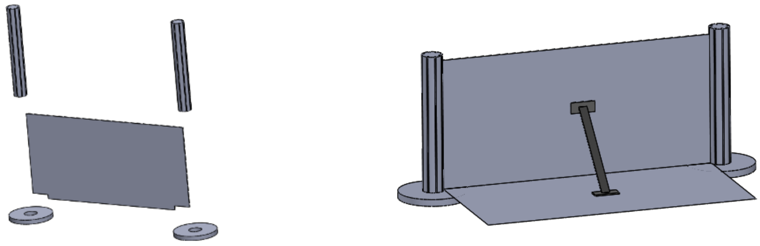
Concept highlights:

- Six separated parts
- No external tools

Modular concept. This is the only concept which is deployed by carrying the modules. One module consist of two vertical support beams, two anchor rings, protection plate with a canvas and support element from protection plate to canvas.

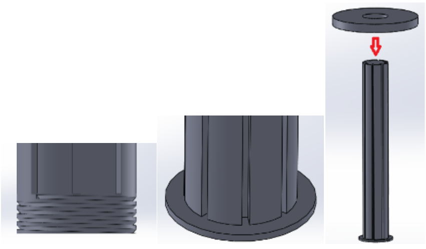
The canvas is a flap and is preconnected to the protection plate. The anchor rings are threaded through the support beams. The support beam are connected to the protection plate and canvas. The protection plate are connected to the support beams. Possible variations: the support beams could be tighten to the anchor rings or threaded the anchoring through support beams. The system is sketched in Figure 33, and different ways to connect the support beam are presented in Figure 34.

The full system consists of 6 parts. Two of the parts are used for the connection between two modules which give 4 new parts per module.



(a) *(b)*

Figure 33 – (a) Show an exploded view of the Concept 1 without the canvas. (b) Shows a fully deployed module of Concept 1.



(a) *(b)* *(c)*

Figure 34 – Show the variation of how to connect the support beam to the anchor ring. (a) The beam have threads,

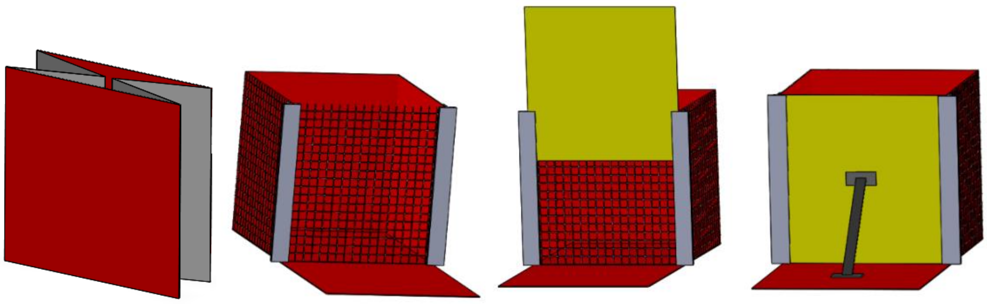
5.2 Concept 2 – Grid fence boxes (the sides are folded and the system is pulled out in a line)

Concept highlights:

- Light weight
- Preconnected modules
- Four separated parts
- No external tools
- Self-filled

This is a self-filled light weighted modular system. The system is stored as folded grid boxes with a waterproof canvas attached to the sides. The side supports (grey beams) are used to give the system stability and connect the protection plate to the box. The protection plate is solid and have an opening at the bottom so that the floodwater can fill the boxes during flood. The deployment of one single module is shown in Figure 35.

In a stored state the modules are connected and folded (Figure 35 (a)). The side connections are added and then the protection plate is added (Figure 35 (b) and (c)). After the protection plate is fastened a support beam from the protection plate to the flap is affixed (Figure 35 (d)). To deploy the system, hinged modules are pulled out from storage to make long barriers (Figure 36). This system is based on the technique used in HESCO Jackbox and HESCO Container (showed in Chapter 2.3 in Figure 6) [9, 13].



(a) (b) (c) (d)

Figure 35 – Shows the process of the deployment. (a) shows a module in a stored state. (b) shows a module after the side support is attached. (c) shows how a protection plate are fixed to a module. (d) Shows a fully installed module with connection between bedding canvas and protection plat .

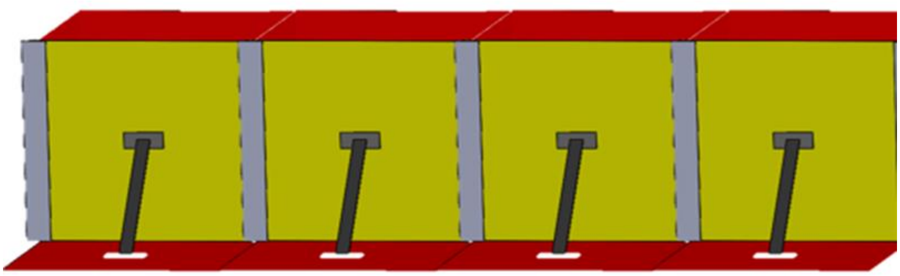


Figure 36 – Shows a fully installed section of modules.

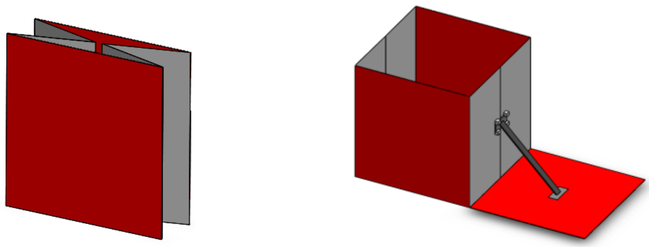
5.3 Concept 3 – Grid boxes

Concept highlights:

- Light weight
- Preconnected modules
- Two separated parts
- No external tools
- Self-filled

This is a self-filled light weighted modular system. The system is stored as folded grid boxes with a waterproof canvas attached to the sides. The grey side is made of a solid, non-elastic material. This is the protection plate, which has a connection system for a supporting beam. The red flap is elastic and it is packed and stored with the rest of the module. After the modules are pulled out, the support beam between the flap and protection plate is attached. The deployment of one single module is shown in Figure 37, and fully installed section is showed in Figure 38.

In a stored state the modules are connected and folded (Figure 37 (a)). The folded protection plate is fastened by the connection of a support beam from the connection point at this plate to the bedding canvas (Figure 37 (b)). To deploy the system, hinged modules are pulled out from storage to make long barriers Figure 38. This system is pulled out from storage with the side that is not folded, canvas and grid wall, in the pulled direction. This system is based on the technique used in HESCO Jackbox and HESCO Container (showed in Chapter 2.3 in Figure 6) [9, 13].



(a) *(b)*

Figure 37 – Shows the process of deployment. (a) a folded module. (b) fully installed module.

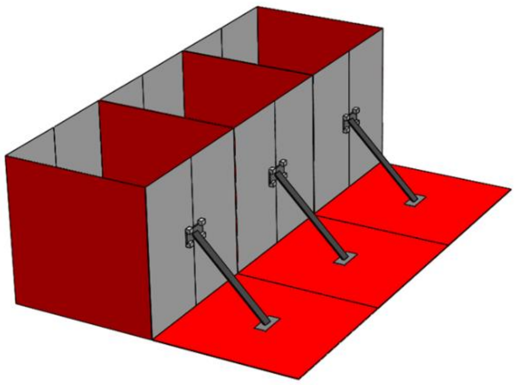


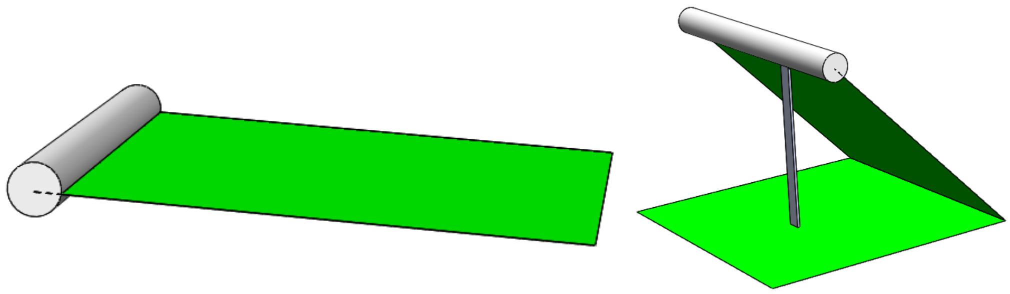
Figure 38 – A section of fully installed boxes.

5.4 Concept 4 – Flexible fabric system which uses the flood water to rise

Concept highlights:

- Fabric based
- All parts preconnected
- External floating objects

This system is inspired by the Water-gate [14] and Rapidam [15] principle, shown in Chapter 2.5 in Figure 8. The canvas are installed layerwise and with a floating cylinder at the end to give buoyancy (Figure 39 (a)). The support between the upper and lower surface is a wire (Figure 39 (b)). The wire is preinstalled and lying between the surfaces when stored. During flood the system will rise with rising water level. Figure 39 shows the system in a folded state before flood and as risen during flood. Every part is preinstalled.



(a) *(b)*

Figure 39- Shows a section of Concept 4. (a) shows the system in a folded state. (b) shows the system during flood.

5.5 Concept 5 – Flap system which use the flood water to rise

Concept highlights:

- Preconnected modules
- No external tools
- All parts preconnected

Concept 5 is inspired by the Water-gate [14] and Rapidam [15] principle, shown in Chapter 2.5 in Figure 8. Concept 5 uses a grid frame with a connected canvas. During deployment the system is pulled out as shown in Figure 40.

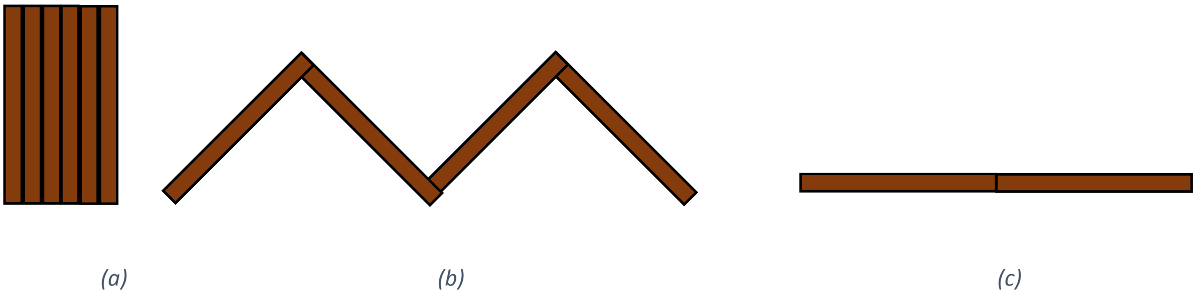


Figure 40 – Shows the deployment process. (a) folded state. (b) is during deployment. (c) is fully deployed

Concept 5 uses the same technique as Concept 4 to rise during a flood. The system is shown as folded and in functional state in Figure 41.

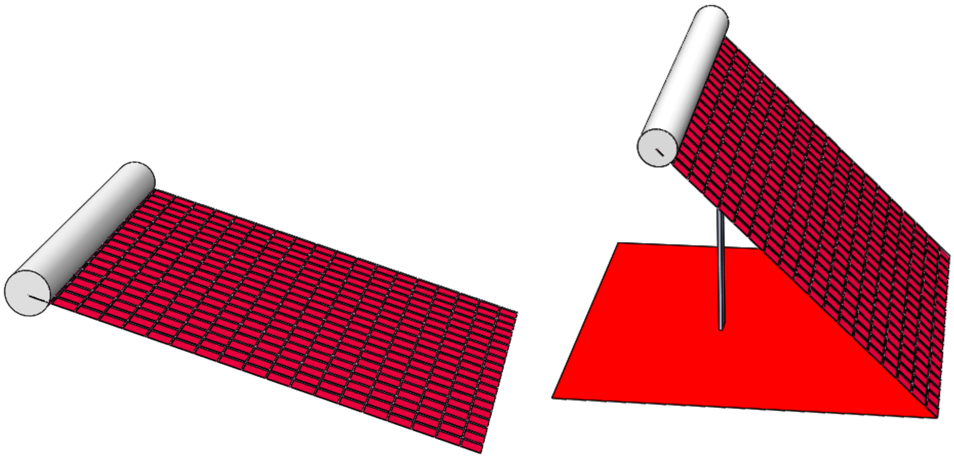


Figure 41 – Shows a section of Concept 5. (a) shows the system in a folded state. (b) shows the system during flood.

5.6 Concept 6– Modular flap system using wheels

Concept highlights:

- Use of wheels to deploy the system
- Removal of wheels after the system is positioned
- Support beam (pre connected)

Concept 6 is a modular system. The system is pulled out from preconnected modules as shown in Figure 29, and it is using wheels during deployment. This design is based on the design AquaFence [16] delivers today. Figure 42 shows a fully installed section of this system.

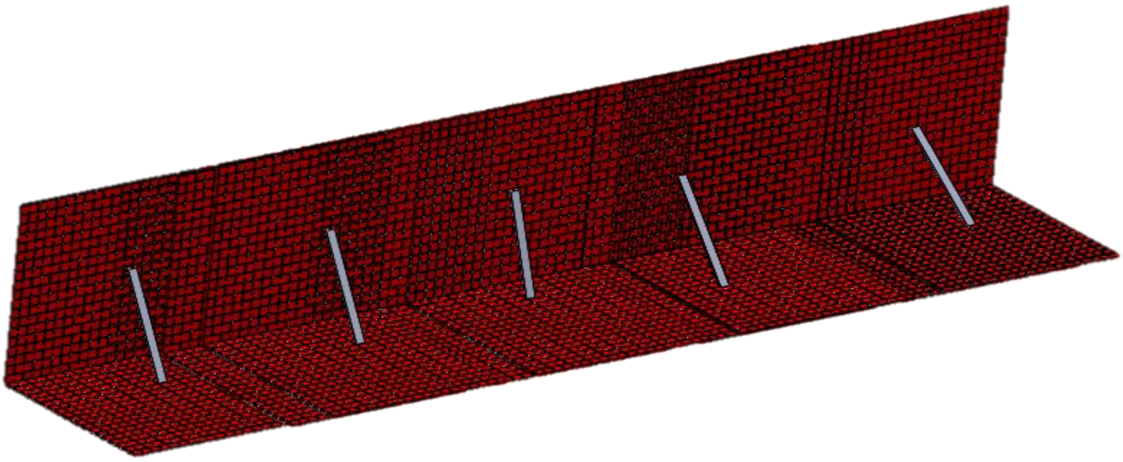


Figure 42 – A fully installed section of Concept 6.

5.7 Concepts with triangular geometrics (light weight and wheels)

5.7.1 Concept 7– V-fence

Concept highlights:

- Preconnected modules
- Large protection surface with little material
- Light weight

This is a V-shaped modular system. The system is pulled out of the storing crate as shown in Figure 43. The system in a folded state and after deployment is shown in Figure 44. In the PUGH-matrix in Chapter 5.8, this system was assumed to have support beams between the modules, contributing to the stiffness.

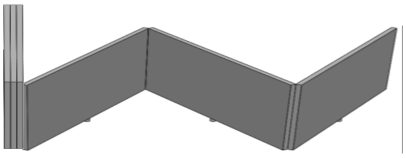
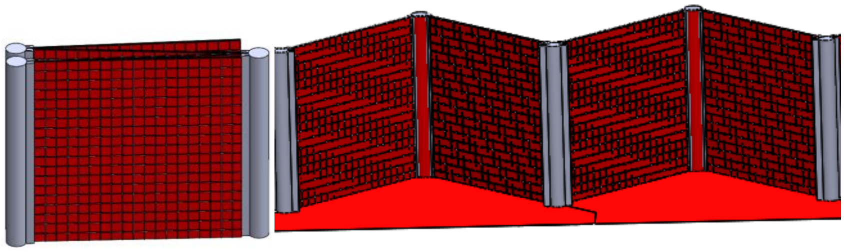


Figure 43 – The modules are preconnected and pulled out.



(a) *(b)*

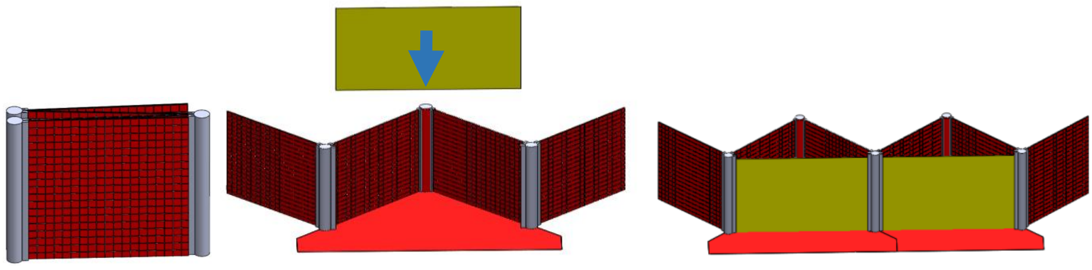
Figure 44 –(a) shows the system in folded state. (b) shows the system after deployment.

5.7.2 Concept 8 – V-fence with protection plate

Concept highlights:

- Preconnected modules
- Two separated parts (v-module and protection plate)
- No external tools
- Self-filled
- Light weight

Concept 8 is equal to Concept 7 except that Concept 8 have the ability to connect a protection plate, as shown in Figure 45. In the PUGH-matrix in Chapter 5.8, this system was assumed to have support beams between the modules and between the protection plates and the bedding flaps, contributing to the stiffness and stability.



(a) *(b)* *(c)*

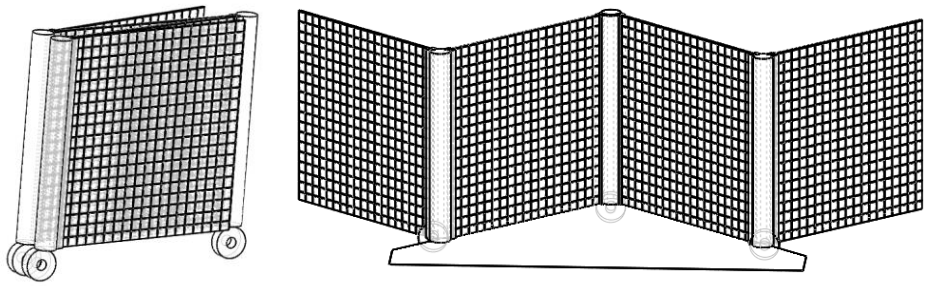
Figure 45 – (a) shows the Concept 8 in a folded state. (b) shows a section of the system partly deployed. (c) shows a section fully installed.

5.7.3 Concept 9– V-fence with wheels

Concept highlights:

- Preconnected modules
- No external tools
- Wheels (they have to be removed)

Concept 9 is a V-shaped modular system. The system is pulled out of the storing crate as shown in Figure 46. The parts are preconnected and the system have wheels attached. This system contains heavy plates and that is why the wheels are needed. To obtain watertight and stable barriers, the wheels must be removed for the system to be in a functional state. In the PUGH-matrix in Chapter 5.8, this system was assumed to have support beams between the modules, contributing to the stiffness.



(a) *(b)*

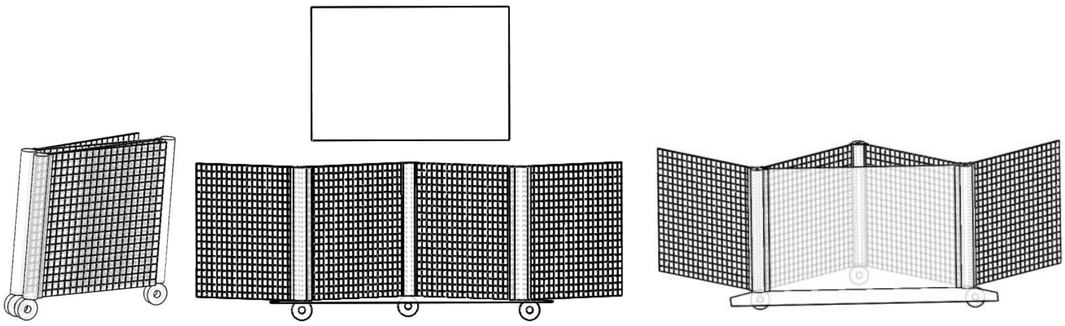
Figure 46 – (a) shows the system in a stored state. (b) shows the system after deployment.

5.7.4 Concept 10 – V-fence with protection plate and wheels

Concept highlights:

- Preconnected modules
- Two separated parts (box-module and protection plate)
- No external tools
- Wheels (they have to be removed)
- Self-filled

Concept 10 is equal to Concept 9 besides that Concept 10 uses a protection plate, as shown in Figure 47. In the PUGH-matrix in Chapter 5.8, this system was assumed to have support beams between the modules and between the protection plates and the bedding flaps, contributing to the stiffness and stability.



(a) *(b)* *(b)*

Figure 47 – (a) shows the system in a stored state.(b) shows the system before the protection plate is attached. (c) shows the system after deployment.

5.8 Concept scoring matrix

Criteria	Explanations	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8	Concept 9	Concept 10	*Weighting*
Maneuver ability		0,1	0,3	0,3	0,3	0,3	0,3	0,2	0,2	0,2	0,2	*0,10*
External tools	Drills, pumps, screw drivers etc.	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	*0,01*
Number of people needed		0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	*0,01*
Volum utilization	Storage volum	1,6	1,44	1,28	0,16	0,64	1,12	0,32	0,48	0,8	0,96	*0,16*
Bedding ground variations	Ground plate flexibility and module connection	0,3	0,2	0,2	0,1	0,2	0,4	0,2	0,2	0,2	0,2	*0,10*
Safety feel	Appearance	0,1	0,1	0,1	0,3	0,2	0,1	0,2	0,1	0,1	0,1	*0,10*
Intuitiv setup	Number of parts, different	0	0	0	0	0	0	0	0	0	0	*0,10*
Deploym ent time	Estimations	1,28	1,12	0,8	0,16	0,16	0,64	0,32	1,12	0,48	0,96	*0,16*
Light wetight	(Weightestimations)	0,2	0,15	0,1	0,05	0,05	0,2	0,05	0,1	0,2	0,25	*0,05*
Parts	Number of disconnected parts	0,25	0,2	0,1	0,05	0,05	0,15	0,1	0,2	0,1	0,15	*0,05*
Stability	Center of gravity(Weight and design) and where the force apply (vippe-moment)	0,64	0,32	0,48	0,96	0,96	0,8	0,8	0,32	0,48	0,16	*0,16*
Sum		4,49	3,85	3,38	2,1	2,58	3,73	2,21	2,74	2,58	3	

Figure 48 – Concept scoring matrix. Concept evaluation. The green areas are highlighted because these are the four best concepts.

The matrix in Figure 48 compares the various developed concepts with respect to properties that will lead to rapid deployment, stability and little unused space during storage (volume utilization), amongst other factors. The weighting column shows to what degree the different properties contribute to the total score of the concepts. The top four concepts are highlighted in green, and by the lowest total score it is shown that Concept 4 is the best solution. Of the completely new and innovative designs, Concept 7 meets the demands to a higher degree than the others.

5.9 Discussion

Strengths and weaknesses of the existing flood protection market were identified, explored and utilized as high-level requirements in the development of concepts for an all-new temporary flood protection system. A concept scoring matrix was made for the early stage concepts which gave an overview over the different solutions and was used to evaluate and compare their qualities. All the presented concepts have properties and principals that AquaFence's new system could benefit from. In the process of developing a new temporary flood protection system, it becomes evident that every property that is added to the system has a downside. Such contradictions make it difficult to develop a "perfect" system which fulfills all requirements without any form of sacrifice. In the process of finding the requirements that is important for a new temporary flood protection system, the temporary flood protection market was explored. A need for a rapid deployable and stable solution which provides a sufficient protection height was identified. To be able to provide these qualities to a new system, designs were investigated that could provide the system with more protection area using less material and still be stable. Examples of solutions are the possibility of using canvas instead of solid plates, the possibility to use preconnected parts, and facilitating for fast transportation of the system.

The concept scoring matrix for the developed concepts shows that the system which needs to be lifted takes longer time to deploy than the ones that can be pulled out. If a system has to be lifted, the modules cannot be preconnected because it will render the system too heavy and big to handle for the persons deploying it. When a system must be lifted, the individual parts should be as manageable as possible, making lighter and smaller parts more convenient. This is the main issue in making a system that should be lifted and carried by man force. If the size of the system is reduced, it loses protection height, which it is an unwanted consequence. This project first of all considers solutions that can provide a sufficient protection height, along with other mentioned properties. Reducing the module size will obviously make the system more manageable, but this was not an option as it is conflicting with the requirements that were chosen for the new system. Making a system with light parts is possible, and it is not conflicting with the requirements if the system has sufficient anchoring. However, if the system is designed with light parts its more tempting to try to deploy many modules simultaneously instead of one by one. If the system is light-weighted enough, several modules can be connected together and it will be possible to deploy many modules at the same time. Therefore it would we preferably for a temporary system to have the ability to be pulled out instead of being lifted and carried. To sum up, if a system that is deployed by lifting/carrying should get a fast deployment, the modules should either be smaller, lighter or both. Smaller systems do not fulfill the requirements that were set for the new system, and lighter systems are more efficient if it is pulled.

A light weighted system is worth discussing in contrast to a more heavy system. In general, a light-weighted system is easier for humans to handle than heavy systems, but this is unfortunately also the case for a flood. This contradiction forces the designer to add properties to compensate for either high - or low weight. From Chapter 5.8 where the V-barriers were presented, four concepts were developed. These concepts prove that one design can get different qualities by adding different functions. All four systems are based on the same design but the qualities and properties are quite different. In Concept 7 the walls are made of grids with a canvas attached, and the wall connections are thin. Concept 9, which looks quite similar to Concept 7, has solid walls, a massive wall connection, and wheels. The wheels were added so that the heavier system in Concept 9 could be transported as fast as the lighter system in Concept 7. The wheels solve the transportation problem for the system in Concept 9, but three new issues appear. Adding wheels increases the production cost and storage volume, and the wheels have to be removed to deploy the system. Though the system in Concept 7 is easy to transport and rapidly deployed, it is more fragile than Concept 9 because it uses lighter and more elastic parts.

This leads to another aspect which is not measurable by use of numbers, namely the appearance of the protection barriers. In research for this report, every searchable existing temporary flood protection system was evaluated. The result was remarkable, as many of the existing systems are oversized and clumsy with large potential for improvements. The unpractical appearances might be a result of an attempt to make systems that can deal with whatever condition the system is exposed to. There are large variations in floods and in the forces applied to the system, which might be a reason for why they are dimensioned with a high safety factor. From the customer’s point of view, it can be difficult to determine which system is the best, but by the first impression they can find the large systems attractive because it renders the costumer with a feeling of robustness, even though it might not be. Therefore, the appearance of the system could be important.

All the concepts that are presented in Chapter 5.1-5.9, except Concept 4, 5 and 6 have side support either by a support beam or a side wall. Side support helps a system to stiffen the modules and distribute the forces applied by the flood. Modules that do not have side support, but have the protection plates placed perpendicular to the flood water, like AquaFence’s existing systems, have all the water pressure applied to the connections between the bedding plate and protection plate. With side supports the stresses caused by the pressure are distributed to the side support, which relieve the pressure on the connections. The V-barrier design in Chapter 5.8 also distributes the stresses to the sides because the plates are angled. The angle between the plates makes the water pressure attack the plates in different directions, and therefore the stress is distributed to the sides. Figure 18 (f) shows the how the water pressure is applied to a V-barrier.

In Concept 2, 8, 10 a protection plate is added to systems that could function without the inclusion of protection plates. The protection plate is added for three reasons: primarily the protection plate gains stiffness to the system. Secondly it protects the side walls from streaming water and floating objects. Thirdly the protection plate moves the center of gravity away from the rear of the module, which makes the system less likely to tilt, especially before flood impact when strong winds can tilt the system. During a flood, the third point does not have much influence because these systems are filled with water.

6 Summary and Recommendations for Further Work

6.1 Limitations

The evaluations that are made are mostly based on assumptions. The PUGH-matrix in Chapter 2 is based on numbers given by the companies producing the systems, and I have not had the possibility to qualify them. The concept scoring matrix presented in Chapter 5 is based on the solutions presented in the Concept chapter. The concepts are not fully functioning system and therefore are evaluations based on estimations.

6.2 Recommendations for Further Work

Prototyping – Small scale models of temporary flood protection systems were made, but modeling in small scale was difficult as the systems are depending on the high weight from the flood water or own weight to be waterproof. If the models are too small it does not get the amount of water it needs to be waterproof or high enough own weight to tighten the barrier. In this project several small scale prototypes were built to inspect connection mechanisms. They were tested in a small plastic box, but they failed because of the lack weight to tighten the system. Models should therefore be made in large scale.

6.3 Conclusions

The work in this thesis contributes to AquaFence's process in developing an all-new temporary flood protection system. From a comprehensive study of the existing temporary flood protection systems on the market, strengths and weaknesses were identified, as well as areas not covered by the available products. The strengths and weaknesses were defined as requirements for the new system, and they were used in the development of early stage concepts that meet these demands. Important aspects in the development of new temporary flood protection systems are rapid deployment, large protection area relative to amount of material, and storage properties.

A comparison between the developed early stage concepts for a new temporary flood protection system was made, in which the V barrier proved to provide an innovative and novel design and met the identified requirements for an all-new system.

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