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Summary

The Stevelduct is a new type of transport for containers, invented by Aad van den Ende. It combines the technique of the aqueduct and that of "stevelen" (Dutch), hence the name Stevelduct. Stevelen is a phenomenon that occurs on flowing waters, objects drifting on the surface of the water can achieve higher speeds than the water speed, because of the component of the object's weight acting in the direction of the slope, due to the gradient of the water.

The Stevelduct will consist of a channel with a small gradient, causing the water to flow about 5 km/h. In the channel unmanned, non-motorized pontoons are used to transport containers (2 TEU's), a lift is used to place a loaded pontoon in the channel every 30 seconds. The pontoons are driven by the momentum of the flowing water and extra speed will be gained by the effect of stevelen, achieving a total speed of about 6 km/h. The pontoons are guided by rails, where a surplus in buoyancy pushes the pontoons against the rails.

The main goal of this research is to analyze the technical feasibility of the Stevelduct, to check the viability of the project. The research is focused on the basal functioning of the Stevelduct, In order to do this, the concept is further elaborated, the main dimensions and the energy usage are determined. Different aspects of the concept will be addressed, such as the required gradient, the effect of stevelen, the transport loss factor (TLF), logistics and others. With the results found an analysis of a possible Stevelduct connection between the Maasvlakte and Roosendaal is made, after which conclusions about the technical feasibility of the Stevelduct can be drawn.

The channel cross-section shape has been analyzed with the help of Chezy's formula for uniform flow in open channels. The required channel gradient depending on four different channel shapes (triangular, rectangular, trapezoidal and circular) has been minimized for a constant water flow speed and cross-sectional area. This resulted in that the channel gradient is minimum for a semicircular shape.

The pontoons require a surplus in buoyancy, which needs to be as small as possible to reduce the rolling resistance of the guidance, but large enough to maintain contact with the rails and wheels. The required buoyancy surplus has been determined by the imbalance of uneven loaded containers and the distance between the guide rails.

With the buoyancy surplus, the maximum weight of the containers and the estimated weight of the pontoon, the pontoons have been dimensioned for the different channel shapes. The shapes of the cross-section of the pontoons have been chosen the same as the channel shape. Under the condition that a minimal channel cross-sectional area is required to allow flow around the pontoon, the semicircular shape performed the best, as the distance from pontoon to the channel wall is the largest and thus the effect of the channel walls on the water flow is the smallest. The minimum area requirement for the semicircular channel has resulted in an upper bound for the channel gradient of 0.24 m/km, as the gradient and cross-sectional area are related.

The stevel speed of the pontoons depends on the weight component due to the gradient of the channel (the stevel force), the rolling resistance, water drag of the pontoon and air resistance. By balancing the forces, a relation between the gradient and stevel speed was found. Maximum loaded

pontoons start to stevel at gradient of 0.10 m/km and a stevel speed of 1 km/h (total speed 6 km/h) is reached at a gradient of 0.15 m/km, which is the lower bound of the channel gradient. The effect of wind has a great influence on the speed of the pontoons, a 5 Bft frontal wind reduces the speed with about 75%.

Pontoons with low loads compared to the maximum load sail at lower speeds, as stevel force becomes smaller, while the rolling resistance increases. Since the mass of the containers varies, so will the speed of the pontoons. This can be preventing by ballasting the loaded pontoons to an equal weight, with the result that all pontoons have the same speed, which increases the predictability of the system.

The energy usage of the Stevelduct depends on the mass flow rate of the water, pontoons and load and the height of the channel. For a constant flow speed the energy usage decreases as the gradient increases, due to the relation between the cross-sectional area and channel gradient. The energy usage for the boundaries of 0.15 and 0.24 m/km are respectively 45 and 33 kW/km for non-ballasted pontoons and 47 and 37 kW/km for ballasted pontoons. Some additional power, between 13.7 and 31.0 kW, is required to accelerate the water and pontoons to the flow speed of the water.

The TLF of the ballasted pontoons varies between about 0.0060 and 0.0076 depending on the channel gradient, for non-ballasted pontoons this is about 10% lower. This is in the region of the TLF of trains and ships, which have the lowest TLF, but with the advantage that green electricity can be used.

A Stevelduct connection between the Maasvlakte and Roosendaal, which was proposed in the concept, has been analyzed with the previous found results. The usage of tunneled section was mentioned, but in the case a pump or lift fails, large volumes of water pontoons and containers are still inside the channel and keep flowing to the end of the channel. This would require sufficient drainage and buffers for the pontoons, containers and water, which could be problematic underground.

The results found in the analysis of the different aspect concerning the functioning of the Stevelduct and that of the Maasvlakte-Roosendaal connection are technically feasible, thus it can be concluded that the Stevelduct is technically feasible. However, wind and the varying mass of the containers can greatly influence the characteristics of the behavior of the pontoons, but the channel can be protected from wind and the mass can be equalized by ballasting the pontoons. Also problems could occur in case of equipment malfunction in tunneled sections of Stevelduct. Pump or lift failure could be problematic in tunneled sections as the drainage and storage of such large volumes of water, pontoons and containers is difficult underground.

All with all it can be concluded that the Stevelduct is technically feasible, but the pontoons should be protected from wind and the usage of tunneled sections could be technically infeasible.

Summary (in Dutch)

Het Stevelduct is een nieuw type transport voor containers, uitgevonden door Aad van den Ende. Het combineert de techniek van het aquaduct en die van stevelen, vandaar de naam Stevelduct. Stevelen is een fenomeen dat optreedt op stromend water, objecten drijvend op het wateroppervlak kunnen door de helling van het water hogere snelheden behalen dan dat van het stromende water.
Het Stevelduct zal bestaan uit een kanaal dat onder een kleine hoek staat, waardoor het water met ongeveer 5 km/h gaat stromen. In het kanaal worden onbemande, niet-gemotoriseerde pontons gebruikt voor het vervoer containers (2 TEU's per ponton), een lift plaatst iedere 30 seconden een beladen ponton in het kanaal. De pontons worden voortgestuwd door het momentum van het stromende water en extra snelheid wordt verkregen door het effect van stevelen, waardoor een totale snelheid van ongeveer 6 km/h wordt behaald. De pontons worden geleid door rails, waarbij een overschot aan drijfvermogen de wielen tegen de rails aan drukt.
Het belangrijkste doel van dit onderzoek is om de technische haalbaarheid van het Stevelduct te analyseren. Het onderzoek richt zich op de basale werking van het Stevelduct, hiervoor wordt het concept verder uitgewerkt, waarbij de belangrijkste afmetingen en het energieverbruik bepaald zullen worden. Verschillende aspecten van het concept komen aan de orde, zoals de vereiste helling, het stevelen, de transport loss factor (TLF), logistiek en anderen. Met de gevonden resultaten wordt een analyse van een mogelijke Stevelductverbinding tussen de Maasvlakte en Roosendaal gemaakt, waarna conclusies over de technische haalbaarheid van het Stevelduct kunnen worden getrokken.

De vorm van de kanaaldoorsnede is geanalyseerd met behulp van de Chezy's formule voor uniforme stroming in open kanalen. De vereiste helling van het kanaal, afhankelijk van vier verschillende kanalen vormen (driehoekig, rechthoekig, trapeziumvormig en cirkelvormig) is geminimaliseerd voor een constante stroomsnelheid en dwarsdoorsnede. Het resultaat is dat de helling van het kanaal minmaal is bij een kanaal met de vorm van een halve cirkel.
De pontons vereisen een surplus aan drijfvermogen, deze moet zo klein mogelijk zijn om de rolweerstand van de geleiding te minimaliseren, maar groot genoeg om contact tussen de rails en wielen te behouden. Het benodigde surplus aan drijfvermogen is bepaald door de onbalans van ongelijke geladen containers en de afstand tussen de geleiderails.
Met het surplus aan drijfvermogen, het maximale containergewicht en het geschatte gewicht van de pontons, zijn de pontons gedimensioneerd voor de verschillende kanalen vormen. De vorm van de ponton doorsneden zijn gelijk genomen aan de vormen van het kanaal. Onder de voorwaarde dat een minimale kanaaldoorsnede is nodig om stroming rond het ponton toe te staan, presteerd de halfronde vorm het best, omdat de afstand van ponton tot de kanaalwand het grootste is en dus het effect van de kanaalwand op waterstroom het kleinst is. Omdat de helling en dwarsdoorsnede gerelateerd zijn, leidt de eis van de minimale oppervlakte bij het halfronde kanaal tot een bovengrens voor helling van het kanaal van 0.24 m/km.
De stevelsnelheid van de pontons is afhankelijk van de gewichtscomponent van het ponton als gevolg van de helling van het kanaal (de stevelkracht), de rolweerstand, de weerstand van het water en de luchtweerstand.

Door het evenwicht van deze krachten op te stellen is een relatie tussen de helling en stevelsnelheid gevonden. Maximaal beladen pontons gaan stevelen bij helling van 0.10 m/m, een stevelsnelheid van 1 km/h (een totale snelheid van 6 km/h) wordt bereikt bij een helling van 0.15 m/km, dat is de ondergrens voor de helling van het kanaal. Het effect van wind heeft een grote invloed op de snelheid van de pontons, een frontale wind van 5 Bft vermindert de totale snelheid met ongeveer 75%.
Pontons met lage belastingen in vergelijking tot de maximale belasting varen met lagere snelheden, omdat de stevel kracht kleiner wordt, terwijl de rolweerstand toeneemt. Omdat de massa van de containers varieert, doet de snelheid van de pontons dat ook. Dit kan worden voorkomen door het ballasten van de beladen pontons tot een gelijk gewicht, als gevolg hebben alle pontons dezelfde snelheid, waardoor de voorspelbaarheid van het systeem vergroot wordt.
Het energieverbruik van het Stevelduct is afhankelijk van de massastroom van het water, pontons, lading en de hoogte van het kanaal. Voor een constante stroomsnelheid neemt het energieverbruik af naarmate de helling oploopt, dit als gevolg van de relatie tussen de dwarsdoorsnede en de helling van het kanaal. Het energieverbruik voor de grenzen van 0.15 en 0.24 m/km zijn respectievelijk 45 en 33 kW/km voor ongeballasteerde pontons en 47 en 37 kW/km voor geballasteerde pontons. Een extra vermogen, tussen 13.7 en 31.0 kW, is nodig om het water en de pontons aan het begin van het kanaal te versnellen tot de stroomsnelheid van het water.
De TLF van de geballasteerde pontons varieert, afhankelijk van de helling van het kanaal, ongeveer tussen 0.0060 en 0.0076, voor ongeballasteerd pontons is dit 10% lager. Dit is in de regionen van de TLF van treinen en schepen, die de laagste TLF hebben, met het voordeel dat groene stroom gebruikt kan worden, zodat er geen schadelijke emissies optreden.
Een Stevelduct verbinding tussen de Maasvlakte en Roosendaal, die werd voorgesteld in het concept, is geanalyseerd met de gevonden resultaten. Het gebruik van ondertunnelde gedeeltes was genoemd, maar dit zou onhaalbaar kunnen zijn, want als een pomp of lift uitvalt, zijn er nog grote hoeveelheden water pontons en containers in het kanaal en blijven naar het einde van het kanaal stromen. De benodigde afwatering en buffers voor de pontons, containers en het water zouden ondergronds tot problemen kunnen leiden.

De resultaten gevonden in de analyse van de verschillende aspecten met betrekking tot het functioneren van het Stevelduct en die van de Maasvlakte-Roosendaal-verbinding zijn technisch haalbaar. Echter, hebben wind en de variërende massa van de containers grote invloed op het gedrag van de pontons, maar het kanaal kan worden beschermd tegen wind en de massa kan worden gelijkgesteld door het ballasten van de pontons. Ook kunnen problemen optreden in geval van een storing in de apparatuur in ondertunnelde secties van Stevelduct. Het falen van een pomp of lift is problematisch in ondertunnelde secties, omdat ondergronds de afwatering en opslag van zulke grote volumes aan water, pontons en container moeilijk is.
Al met al kan worden geconcludeerd dat het Stevelduct technisch haalbaar is, maar de pontons moet worden beschermd tegen wind en het gebruik van ondertunnelde secties zou technisch onhaalbaar kunnen zijn.

List of symbols

f_t	= transport loss factor	[-]
g	= earth's gravitation	[m/s^2]
n	= roughness parameter	[-]
m	= mass	[kg]
y	= water depth	[m]
A	= area	[m^2]
B	= buoyancy	[kg]
C	= Chezy's constant	[m$^{1/2}$/s]
C_d	= air drag coefficient	[-]
C_{rr}	= coefficient of rolling resistance	[-]
C_t	= total drag coefficient	[-]
E	= energy	[J]
F_{air}	= air resistance	[N]
F_b	= buoyant force	[N]
F_{b+}	= surplus buoyant force	[N]
Fg	= gravity force	[N]
F_{rr}	= rolling resistance	[N]
F_s	= stevel force	[N]
F_{water}	= water drag	[N]
H	= height	[m]
L	= length	[m]
P	= wetted perimeter	[m]
P	= power	[W]
P_U	= power	[W]
Q	= volume flow	[m^3/s]
R_h	= hydraulic radius	[m]
S_0	= channel gradient	[-]
S	= wetted surface	[m^2]
U	= speed	[m/s]
W	= weight	[N]
α	= angle	[rad]
η	= efficiency	[-]
θ	= angle	[rad]
ρ	= density	[m^3/s]

Contents

1. Introduction

The Stevelduct is a new type of transport for containers, invented by Aad van den Ende. It combines two obsolete techniques, that of the aqueduct and a technique formerly used by skippers navigating on rivers named "stevelen" (Dutch), hence the name Stevelduct.

Stevelen is a phenomenon that occurs on flowing waters (rivers, channels), objects drifting on the surface of the water can achieve higher speeds than the water speed. This extra speed is gained by a component of the object's weight acting in the direction of the slope, due to the gradient of the water.

The Stevelduct will consist of a channel that has a small gradient, causing the water to flow. In the channel unmanned, non-motorized pontoons are used to transport containers. The pontoons are driven by the momentum of the flowing water and extra speed will be gained by the effect of stevelen.

The main goal of this research is to analyze the technical feasibility of the Stevelduct, to check the viability of the project. The research is focused on the basal functioning of the Stevelduct, In order to do this, the concept is further elaborated by determining the main dimensions and the energy usage. Different aspects of the concept will be addressed, such as the required gradient, the effect of stevelen, transport loss factor, logistics and others.

In chapter 2 the concept by Aad van den Ende is presented, here the working, capacity, environment, energy and possible scenarios for implementing the Stevelduct are addressed. From this concept a number of research questions are proposed. In chapters 3 to 7 the analysis is made, here the research questions are investigated and other aspects of interest are addressed. In chapter 3 the channel cross-section is analyzed, in chapter 4 the dimensions of the pontoons are examined, in chapter 5 the effect of stevelen and the behavior of the pontoons is researched, in chapter 6 an analysis of the energy requirements is made and in chapter 7 one of the scenario's proposed in the concept for the implementation of the Stevelduct is analyzed. The next chapter includes the conclusions drawn from analysis and the research questions are answered. And lastly recommendations for future research and concept improvements are given.

2. Stevelduct concept and research questions

In this chapter the concept is described as presented by Aad van den Ende.

2.1 Working

The concept of the Stevelduct consists of an aqueduct, where containers are transported in un-manned, non-motorized pontoons (see figure 1). The pontoons are driven by the momentum of the flowing water and the effect of stevelen. The water flow in the channel is driven by gravity, due to the gradient of the channel.

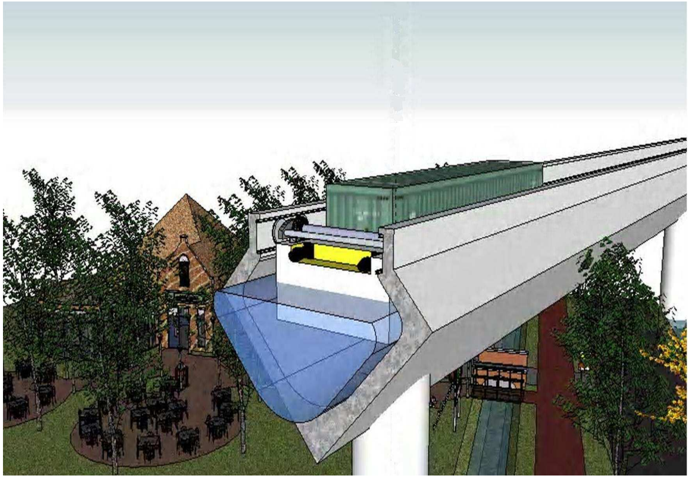


Figure 1: An impression of the Stevelduct (by A. v.d. Ende).

The pontoons used for the containers will be guided, to suppress unwanted motions of the vessels. This is achieved by attaching wheels to the pontoons that run underneath tracks which are attached to the channel structure. Contact between the wheels and tracks is achieved by pushing the wheels against the tracks by a surplus in buoyancy. This results in a rolling resistance of the upside-down driving pontoons that is inverse proportional to the load of the vessel.

Two channels are located next to each other, to support transport in both directions. At the start of the channel the water is elevated to the height of the channel by pumps, the water can be circulated between both channels. The loaded pontoons are placed in the channel by a rotating revolver-lift (see figure 2).

2.2 Logistics and capacity

The revolver-lift launches a pontoon in the channel every 30 seconds. The vessels will have a cruising speed of about 6 km/h, this would result in 2880 pontoons a day. A pontoon is able to carry 2 TEU's and possibly in the case of double stacked, 4 TEU's, this would add up to respectively 2.102.400 or 4.204.800 TEU's per year in one direction.

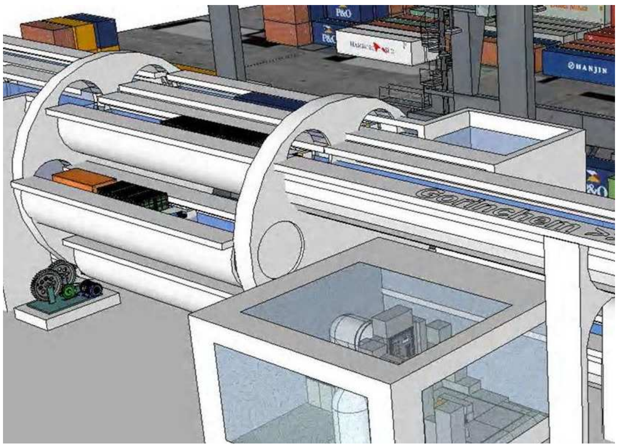


Figure 2: A revolver-lift, elevating the pontoons to the height of the channel (by A. v.d. Ende).

2.3 Environment and energy

The Stevelduct is a relatively simple continuous container transport system without the limitations and emissions associated with other types of transport. In contrast to road and water transport, energy can be fed continuously, since the required energy is required on fixed locations (pumps and lifts). This means that usage can be made of sustainable energy, with the result that there are no emissions of greenhouse gasses, particular matter and other pollutants.

2.4 Scenarios

In the concept 2 different kinds of scenarios are proposed, the outpost and the transition scenario.

The first is the outpost scenario and consists of outposts located outside the agglomeration of Rotterdam. By means of the Stevelduct containers are transported in a straight line between the seaport terminal and the outposts and vice versa. Further transport from and to the outpost is accommodated by other means of transport. In this way the pressure on the roads around and towards Rotterdam is relieved. Three possible locations are mentioned. The first is the Kijfhoek near Zwijndrecht, where the containers can be transported further by trains. Other mentioned locations are Haaglanden region and near Roosendaal in West-Brabant.

The second is the transit scenario and consists of a direct connection between Maasvlakte and Duisburg (Ruhr) in Germany. This connection could also be combined with the outpost of the Kijfhoek, since this is in the path of the transit connection.

The area surrounding the Maasvlakte consist of a lot of waterways and protected nature, in order to spare nature and cross waterways partial tunneling in all directions may be required.

2.5 Research questions

The viability of the concept has to be checked, an analysis of the concept has to be made to see if it is technical feasible. Since no research has been performed yet, the basal functioning of the Stevelduct has to be analyzed and the main dimensions and energy usage have to be determined.

The main research question is:
Is the Stevelduct technical feasible?

From this several sub-questions have been derived:
- What is the optimal shape of the channel cross-section?
- What will the dimensions of the pontoon be?
- What buoyancy surplus is required?
- At which gradient will stevelen take effect?
- What is the required channel gradient?
- What is the effect of wind?
- How will the pontoons behave during transport?
- How much power does the Stevelduct require?
- What is the transport loss factor of the Stevelduct?

First, the research questions concerning the technical feasibility will be analyzed. Based on the results found, an analysis of the Stevelduct connection Maasvlakte-Roosendaal of the outpost scenario is made, after which conclusions about the technical feasibility are drawn.

3. Channel cross-section analysis

The shape of the channel cross-section of the Stevelduct is one of the factors that have an influence on the water flow inside the channel. To be able to predict the channel dimensions, certain conditions have to be met. For open-channel flow, i.e. channel flow with a free surface, the condition is that the flow is uniform. A flow is uniform if the flow parameters remain constant over distance. Uniform flow thus occurs in long channels that are straight and have a constant gradient and channel cross-section. As can be seen from the scenario the Stevelduct will cover large distances in a straight line, in order to analyze the channel cross-section, the cross-section and gradient are assumed to be constant.

For uniform flow, a formula often used by engineers for approximating channel dimensions is Chezy's formula in combination with Manning's correlation for Chezy's coefficient [1]

$$U_{water} = CR_h^{1/2} S_0^{1/2} \qquad (1)$$

where C is Chezy's coefficient, U_{water} is the uniform water speed, R_h is the hydraulic radius, S_0 is the gradient of the channel. The hydraulic radius is

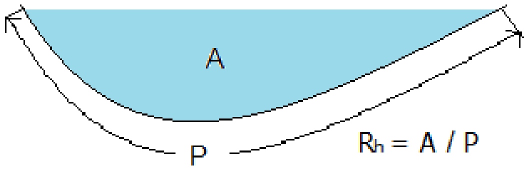


Figure 3: Parameters to calculate the hydraulic radius

$$R_h = \frac{A}{P} \qquad (2)$$

where A is the cross-sectional area, P is the wetted perimeter (see figure 3).
The channel gradient is

$$S_0 = \tan \alpha \qquad (3)$$

where α is the angle between the horizontal and the channel bottom.
Manning's correlation for Chezy's coefficient C is

$$C \approx \frac{R_h^{1/6}}{n} \qquad (4)$$

where n is a roughness parameter (for concrete n = 0.012 - 0.017 [2]).
Combining eq. 1 and 4 results in:

$$U_{water} \approx \frac{1}{n} R_h^{2/3} S_0^{1/2} \qquad (5)$$

Chezy's formulation enables the determination of the most efficient low resistance sections for given conditions. In this case S_0, the slope of the channel has to be minimized for a given flow area and velocity, this results in maximization of R_h. Since R_h = A / P, maximizing R_h for given A is the same as minimizing the wetted perimeter P.

Four different cross sections have been examined; a triangular, rectangular, trapezoidal and circular cross section.

3.1 Triangular section

For a triangular shape the cross-sectional area is given by

$$A = \frac{1}{2} by \qquad (6)$$

Where b is the width of the water surface and y is the water depth (see figure 4). The wetted perimeter is given by:

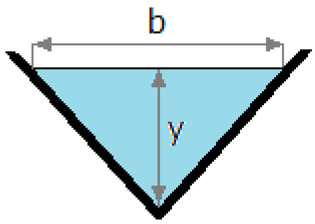


Figure 4: Triangular cross-section

$$P = \sqrt{b^2 + (2y)^2} \qquad (7)$$

By combining eq. 6 and 7, the wetted perimeter P can be rewritten in terms of A and y, the equation becomes:

$$P = \sqrt{\left(\frac{2A}{y}\right)^2 + (2y)^2} \qquad (8)$$

For the best hydraulic section the ratio of b and y, such that P is minimum for constant A has to be determined. Minimums and maximums can be found by setting $dP/dy = 0$. Differentiating the equation with respect to y and substituting $A = 1/2by$ results in

$$\frac{dP}{dy} = 2\frac{\left(y - \frac{b^2}{4y}\right)}{\sqrt{y^2 + \frac{b}{4}}} = 0 \quad \rightarrow \quad y = \frac{1}{2}b \qquad (9)$$

where the result found corresponds to a minimum wetted perimeter. Thus a triangular channel is most efficient when the flow depth is half the channel width, in other the words, the sides are inclined at 45°, this corresponds to a half square.

3.2 Rectangular section

For a rectangular shape the cross-sectional area is given by

$$A = by \qquad (10)$$

Where b is the width of the water surface and y is the water depth (see figure 5). The wetted perimeter is given by

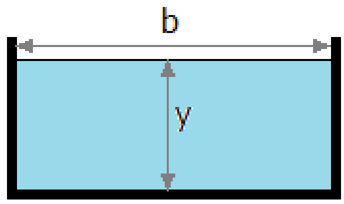


Figure 5: Rectangular cross-section

$$P = b + 2y \qquad (11)$$

P can now be rewritten in terms of A and y, the equation becomes

$$P = \frac{A}{y} + 2y \qquad (12)$$

Differentiating, setting $dP/dy = 0$ and substituting $A = by$ results in

$$\frac{dP}{dy} = 2y - b = 0 \quad \rightarrow \quad y = \frac{1}{2}b \qquad (13)$$

where the result found corresponds to a minimum wetted perimeter. Thus, a rectangular section is the most efficient when the flow depth is half the channel width, this corresponds to a half square.

3.3 Trapezoidal section

For a trapezoidal shape the cross-sectional area is given by

$$A = By + sy^2 \quad (14)$$

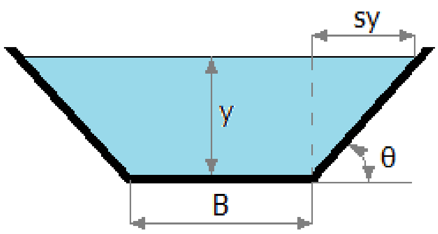


Figure 6: Trapezoidal cross-section

Where B is the width of the channel bottom, y is the water depth and s is the gradient of the side walls (see figure 6). The wetted perimeter is given by

$$P = B + 2y\sqrt{1+s^2} \quad (15)$$

Now the wetted perimeter can be rewritten in terms of A, s and y,

$$P = \frac{A}{y} + y(2\sqrt{1+s^2} - s) \quad (16)$$

Differentiating P with respect to s, for constant A and y yields,

$$\frac{dP}{ds} = \frac{2s}{\sqrt{1+s^2}} - 1 = 0 \;\rightarrow\; s = \frac{1}{\sqrt{3}} \text{ or } \theta = 60^\circ$$

Now P can be differentiated with respect to y, for constant A and substituting $A = by + sy^2$ and $s = 1/\sqrt{3}$, results in:

$$\frac{dP}{dy} = -\frac{B}{y} + 2\sqrt{1+s^2} - 2s = 0 \;\rightarrow\; B = \frac{2}{\sqrt{3}}y \quad (17)$$

where the result found correspond to a minimum wetted perimeter. Thus a trapezoidal cross-section is the most efficient when the sides are inclined at 60° and the channel-bottom width is 2/√3 the flow depth, this corresponds to half a hexagon.

3.4 Circular section

For a circular shape the cross-sectional area is given by

$$A = R^2\left(\theta - \frac{\sin 2\theta}{2}\right) \quad (18)$$

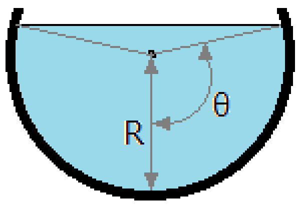


Figure 7: Circular cross-section

where R is radius of the channel and θ is the angle between the center and vertical (see figure 7). The wetted perimeter is

$$P = 2\theta R \quad (19)$$

Now the wetted perimeter can be rewritten in terms of A and θ

$$P = 2\theta\sqrt{\frac{2A}{2\theta - \sin 2\theta}} \quad (20)$$

Differentiating P with respect to θ for constant A results in

$$\frac{dP}{d\theta} = -\theta\left(\frac{1}{A} - \frac{\cos 2\theta}{A}\right)\left(\frac{\theta}{A} - \frac{\sin 2\theta}{2A}\right)^{-\frac{3}{2}} + 2\left(\frac{\theta}{A} - \frac{\sin 2\theta}{2A}\right)^{-\frac{1}{2}} = 0 \;\rightarrow\; \theta = \frac{\pi}{2}$$

where the result found corresponds to a minimum wetted perimeter. Thus a circular cross-section is most efficient at an angle of ½π, this is equal to a half circle.

3.5 Optimal cross-section

Now the optimal cross sections of the four shape types are known, they can be compared to find the most hydraulic type of cross section in relation to the cross section surface. In figure 8, the wetted perimeters are plotted versus the section surface. As can be seen, the least efficient of the analyzed channel cross-sections are the triangular and rectangular cross-sections, as they both have the largest wetted perimeters for a given cross-section surface. The trapezoidal cross-section performs a little better. The most efficient is the circular cross-section, and in fact is the most efficient of all possible shapes [1].

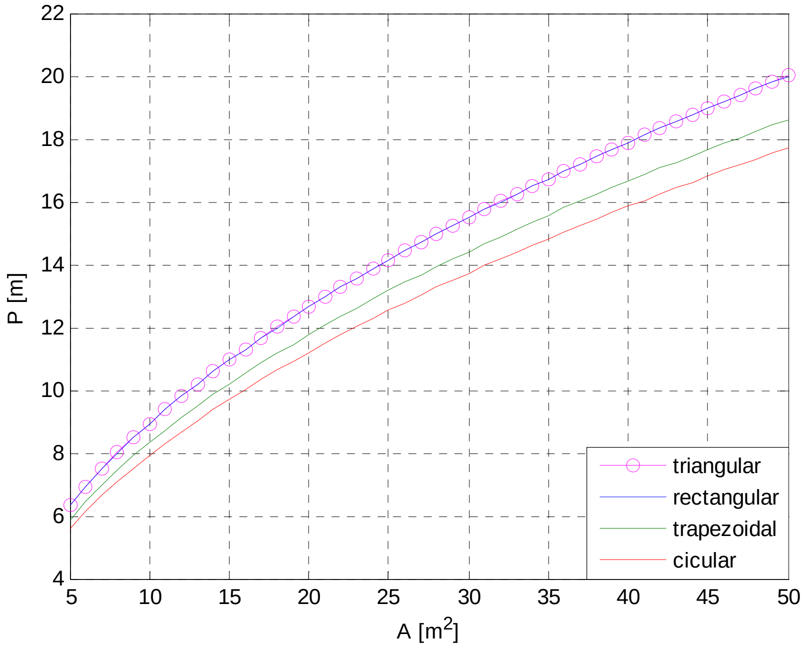


Figure 8: A comparison of the wetted perimeter of different channel shapes as a function of the cross-sectional surface area.

In order to calculate the relation between the channel cross-sectional area and the channel gradient, the uniform flow speed has to be known. In the concept a total speed of the pontoons of about 6 km/h is mentioned, this speed is equal to the sum of the speed of the water flow and the extra speed gained by stevelen. Since the stevel speed is not known yet, it is assumed to be small ± 1 km/h, this would result in a uniform flow speed of 5 km/h. The relation between the cross-sectional area and channel gradient is plotted in figure 9 and will be used later on.

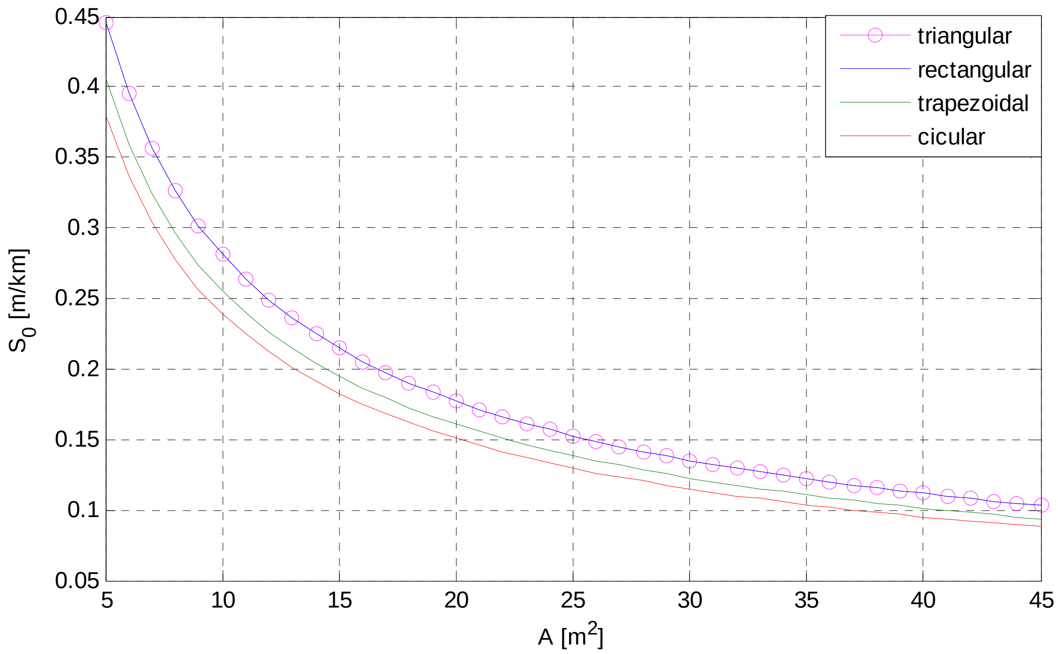


Figure 9: A comparison of the channel gradient of different channel shapes as a function of the cross-sectional surface area. U_{water} = 5 km/h, n = 0.013

4. Pontoon analysis

The pontoons will transport the containers through the channel and their motion is guided. In order to make further calculations the dimensions of the pontoons have to be analyzed.
The pontoons have to be dimensioned on the largest and heaviest containers they will transport. The maximum size will be that of a 45ft container, with a length of 13.72 m and a width of 2.44 m.

The required buoyancy depends on the maximum mass of the transported load, the mass of the pontoon and the required surplus in buoyancy for guidance. The maximum load consists of two fully loaded 20ft containers with a combined mass of 61 ton, the mass of the pontoon is assumed to be 12 ton. The surplus in buoyancy is determined in the next part.

The pontoons will be guided by rails, preventing unwanted motions like rolling, yawing and pitching. The required force of the wheels on the rails needs to be as low as possible to reduce the rolling resistance, but there are minimum requirements as rail-wheel contact needs to be maintained. The force is generated by a surplus in buoyancy, in other words, the pontoon is pushed down in the water. This extra force, the buoyant surplus force is

$$F_{b+} = F_{b1+} + F_{b2+} \qquad (21)$$

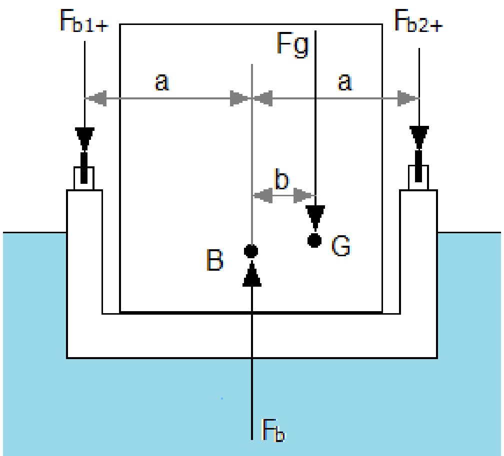


Figure 10: Acting forces on the pontoon to determine the required buoyancy surplus

Where F_{b1+} and F_{b2+} are the forces on the wheels on each side of the pontoon (see figure 10).
Ideally the center of gravity of the containers would lie in the center of the horizontal plane, but in reality its location varies. Contact between wheels and rails is maintained under the condition

$$F_{b1+} * a - Fg * b > 0 \qquad (22)$$

where a is half the distance between the wheels, Fg is the force by gravity of the load and b is distance between the center of gravity and center of the container (see figure 10).

A distance between the wheels of 3.5 m is taken, leaving some space for positioning the container on the pontoon, thus a = 1.75 m. The center of gravity of a fully loaded container is assumed to be maximum 30% out of the center or b = 0.366 m. The mass of two fully loaded 20ft containers is 61 ton. This results in a minimum surplus in buoyant force of

$$F_{b1+} = Fg * b / a$$

$$F_{b1+} = 61 * 10^3 * 9.81 * 0.366 / 1.75 = 125 * 10^3 N$$

This is about 13 ton or 13 m^3. This results in a total buoyancy of B_{total} = 61 + 12 + 13 = 86 ton, thus the total displaced volume will be 86 m^3. For pontoons with a length of 15 m (45ft container is 13.72 m) and a displaced volume of 86 m^3, the required frontal surface area of the pontoon will be 86 / 15 = 5.75 m^2.

4.1 Minimum channel cross-sectional area

The dimensions of the pontoons determine the minimum required cross-sectional area of the channel, as the pontoons have to fit in the channel. Also a minimal distance between the pontoon and channel walls is required minimize wall effects, i.e. the influence of the channel walls on the water speed in the vicinity of the walls is greatly affected, resulting in lower flow speeds near the walls. This distance is assumed to be 0.5 m and the shape of the pontoons is taken the same to that of the channel (see figure 11) to minimize the channel dimensions (condition 1). Another effect is that water needs to be displaced along the pontoon, since the pontoon travels faster than the water, i.e. the frontal surface area of the pontoon times the distance the pontoon travels relative to the water is equal to the volume of water that is displaced along the pontoon. From this it follows that minimal extra channel cross-sectional area is required to displace water, for this extra area a value of 4.25 m^2 is taken, resulting in a total area of 10 m^2 (condition 2).

Calculations for the minimum channel cross-sectional area under condition 1:
For a rectangular pontoon the width becomes 3.39 m, using eq. 10 and 13, resulting in a channel width of 4.4 m. The channel cross-sectional area then becomes 9.64 m^2.

For a trapezoidal pontoon the width becomes 4.21 m, using eq. 14 and 17, resulting in a channel width of 5.36 m. The channel cross-section then becomes 9.34 m^2.

For a circular pontoon the width becomes 3.83 m, using eq. 18 and $\theta = \frac{1}{2}\pi$, resulting in a channel width of 4.83 m. The channel cross-section then becomes 9.15 m^2.

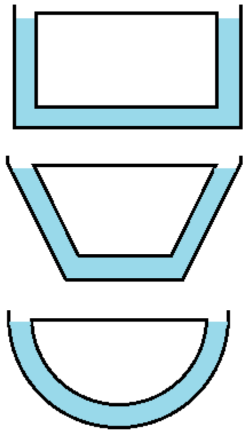


Figure 11: Channel and pontoon cross-sectional shapes

Since the cross-sectional areas of all shapes under condition 1 are smaller than the 10 m^2 specified in condition 2, the cross-sectional areas of all shapes become 10 m^2. However, under condition 1 the minimal required cross-sectional area for a circular channel is the smallest, implying that the distance between the pontoon and channel walls is the largest for circular channels based on an area 10 m^2. For a rectangular, trapezoidal and circular channel these distances become respectively 0.54, 0.58 and 0.61 m, thus a circular channel is most favorable. Taking this into account and the fact that the circular channel is most efficient of all shapes, all further calculations will be conducted for the circular channel only.

Thus a minimum cross-sectional area of 10 m^2 is required. From figure 9 it can be seen this require a gradient of 0.24 m/km, which is the maximum gradient, since the gradient decreases with an increasing cross-sectional area.

5. Stevel analysis

Stevelen is the phenomena of objects traveling faster than the speed of the water the object is drifting in. The water in rivers and channels flows from A to B, due to a difference in height between these points. The potential energy lost is transformed into kinetic energy and frictional losses. Since the potential energy of the water decreases, so does the height of the water surface. In other words, the surface of the water will have a gradient too. In uniform flow this will be equal to gradient between A and B.

The basis of stevelen is that the weight of the drifting object is directed vertically downwards, but the hydrostatic buoyancy force on the object is directed normal to planes of equal pressure, that is, normal to the free surface [3]. However, it appears that floating objects can only travel faster than the water they sample if they are large compared to the scale of the turbulent fluctuations transporting momentum downwards in the stream [4].

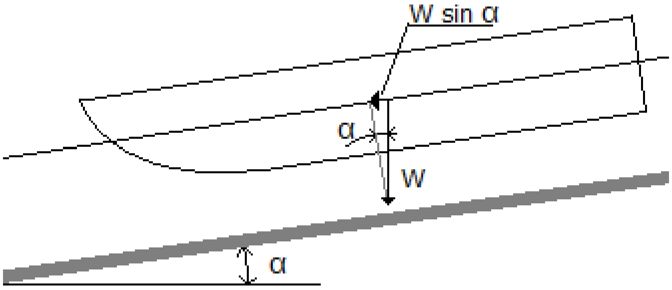


Figure 12: The stevel force is a component of the weight of the vessel.

Since the pontoons will be large compared to the depth of the channel, thus it can be concluded that stevelen will occur.

Because weight of the pontoon is directed downwards and the buoyancy is normal to the water surface, a component of the pontoon's weight acts in the direction of its path. This component, the stevel force is equal to [5]:

$$F_s = W \sin \alpha = mg \sin \alpha \qquad (23)$$

where W is the weight of object floating on the surface and α is the angle between the horizontal and the channel bottom, m is the mass of the object and g is earth's gravitation.

5.1 Stevel speed

The pontoons will reach higher speeds than that of the flowing water due to the gravity component of the loaded pontoon's weight called the stevel force, this force is balanced by three resistive forces. The first is the constant rolling resistance force, due to the contact between the wheels and guide rails. The second is the drag force of the water acting on the pontoon, due to the speed of the pontoon through the water. The last is the air resistance, due to the speed of the pontoon and the wind.

The final speed is reached when

$$F_s - F_{rr} - F_{air} - F_{water} = 0 \qquad (24)$$

where F_s is the stevel force, F_{rr} is the rolling resistance of the guidance, F_{air} is the air drag of the pontoon and containers and F_{water} is the water resistance of the pontoon. The stevel force is given by eq. 23. The rolling resistance of the guidance is [6]

$$F_{rr} = C_{rr} F_n = C_{rr}(F_b - mg) \qquad (25)$$

where C_{rr} is the coefficient of rolling resistance, F_n is force normal to the rails and F_b is the total buoyant force of the pontoon. The air drag of the pontoon and containers is [1]

$$F_{air} = 0.5\rho_{air} A C_d U_{air}{}^2 = 0.5\rho_{air} A C_d (U_{wind} + U_{water} + U_{stevel})^2 \qquad (26)$$

where ρ_{air} is the air density, A is the frontal area of the pontoon and load, C_d is the air drag coefficient, U_{air} is the air speed relative to the pontoon, U_{wind} is the wind speed, U_{water} is the water flow speed inside the channel and U_s is the stevel speed, which is the speed of the pontoon relative to the water. The resistance of the pontoon in the water is [7]

$$F_{water} = 0.5\rho_{water} S C_T U_{stevel}{}^2 \qquad (27)$$

where ρ_{water} is the water density, S is the wetted surface of the pontoon and C_t is the total drag coefficient of the pontoon.

From these relations it can be seen that F_s increases with the mass of the pontoon, while the rolling resistance decreases, because the surplus in buoyancy decreases with a larger mass. This means the highest speeds are reached when, the pontoon is fully loaded. This would reduce eq. 25 to

$$F_{rr} = C_{rr} F_{b+} \qquad (28)$$

where F_{b+} is the force of the buoyancy surplus.

5.2 Stevel speed calculations

In order to calculate at which speed the pontoon will stevel as a function of the channel gradient, some assumptions have to be made for the values of the required variables.

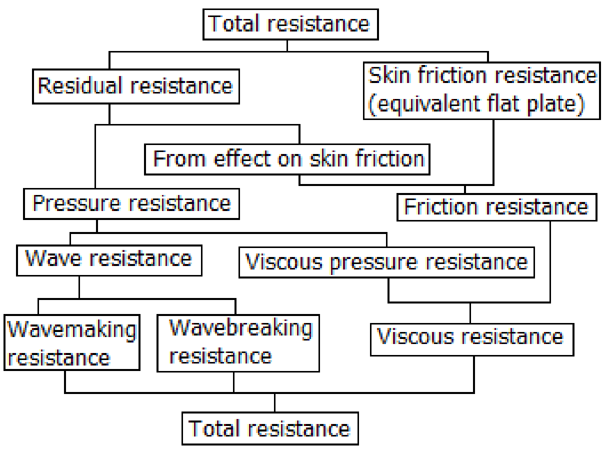


Figure 13: Ship resistance decomposition [7]

The value of the total drag coefficient C_T for pontoons (similar to barges) is in the order of 0.004 [8], however this value is based on much larger waters than that of the Stevelduct. As can been seen from figure 13 there is a complex relation between the different types of resistance that act on a ship. It is assumed that the presence of the bottom and walls of the Stevelduct channel in the vicinity of the pontoon will increase the value of C_T. For instance, wall effects may occur and the flow speed next to the pontoon will be larger than in open waters, as the displaced water has to pass through a relatively small area. For these reasons the value of C_T is doubled to 0.008.

The wetted surface for a circular shaped pontoon with a length of 15 m, a width of 3.83 m and draught of 1.92 m is estimated to be about 100 m^2, thus S ≈ 100 m^2.

The value of the air drag coefficient for objects with a square frontal surface is ± 1 [1]. The frontal surface area is assumed to be that of the container, thus A = 2.44 * 2.59 ≈ 6.5 m^2.

The values of the coefficient of rolling resistance for steel wheels on steel tracks vary with a factor of 5, from 0.0002 to 0.0010 [6]. An intermediate value of C_{rr} = 0.0005 is assumed.

Stevel force:

g	= 9.81	m/s^2	
m	= $73*10^3$	kg	(maximum load: a pontoon à 12 ton + 2 TEU'S à 30.5 ton)

Rolling resistance

C_{rr}	= 0.0005
F_{b+}	= $13*10^3$ * 9.81N

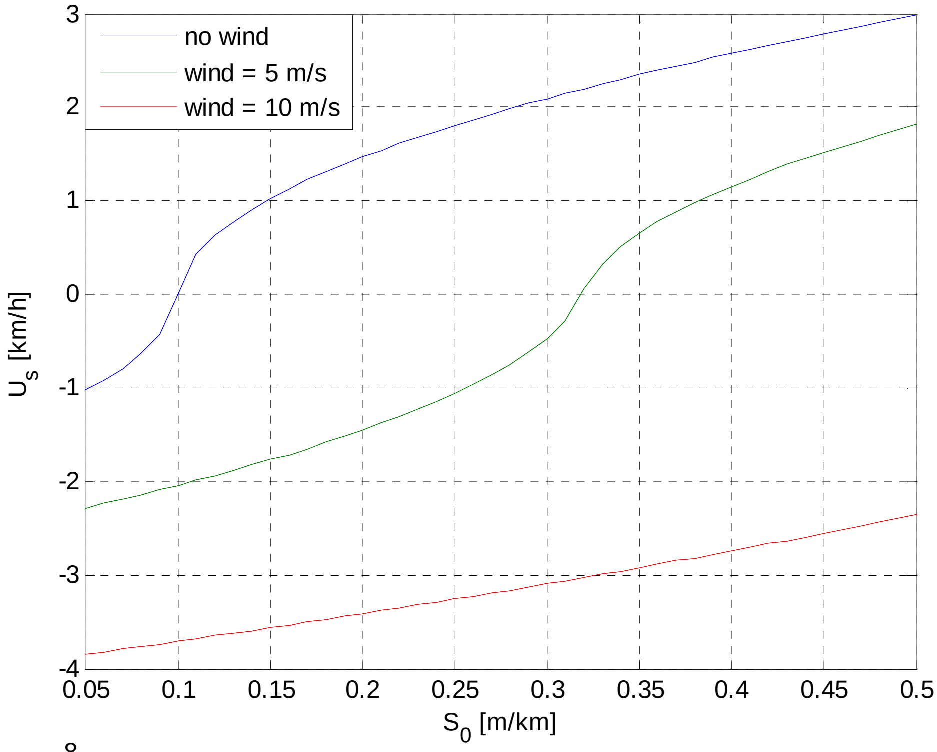
Air drag:

A	= 6.5	m^2
C_d	= 1	
ρ_{air}	= 1.24	kg/m^3

Water resistance

C_T	= 0.008	
S	= 100	m^2
ρ_{water}	= 1000	kg/m^3

With the above listed values the stevel speed of the pontoons depending on the channel gradient has been calculated and is plotted for different wind speeds in figure 14. The total speed of the pontoon is equal to the sum of the speed of the water flow and stevel speed.



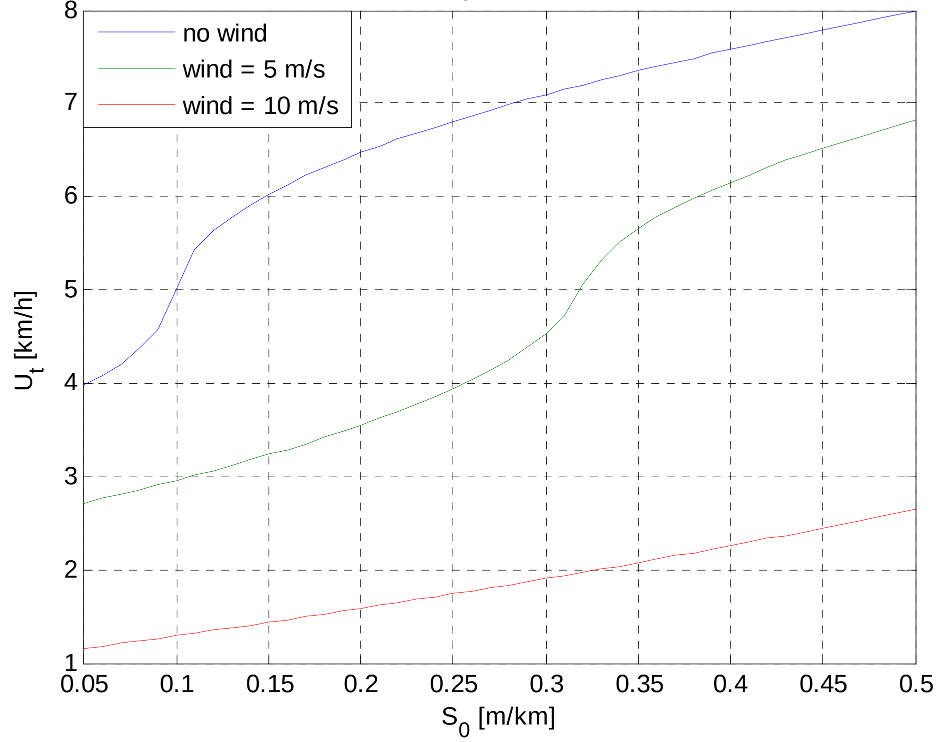


Figure 14: Above, the stevel speed is plotted for different frontal wind speeds. Under, the total speed is plotted for 3 different wind speeds. 5 m/s is 3 Bft and 10 m/s is 5 Bft.

From figure 14 it can be seen that without wind the pontoons will start to gain higher speeds that of the water flow at a gradient of 0.10 m/km. A total speed of 6 km/h, as mentioned in the concept, is reached at a gradient of 0.15 m/km. From figure 9 it can be seen that this would result in a circular cross-sectional area of 20 m^2. This results in that the cross-sectional area is bounded between 10 m^2 at a gradient of 0.24 m/km and a channel width of 5.1 m, and 20 m^2 at a gradient of 0.15 m/km and a channel width of 7.1 m.

The effect of wind on the speed of the pontoons is very large, a 5 Bft frontal wind reduces the speed with about 75%, stronger wind could even bring the pontoons to a standstill.

5.3 Pontoon behavior during transport

The pontoons are un-manned and non-motorized and thus not controlled during transport. In the previous sections, the possibility of ballasting the pontoons was mentioned. The advantage over non-ballasted pontoons was an increase in speed, due to a higher stevel force and a lower rolling resistance. This leads to two possibilities for the behavior of the pontoons during transport, one for non-ballasted and one for blasted pontoons.

For non-ballasted pontoons the mass can differ from one empty 40ft container to two fully loaded 20ft containers, respectively 3.8 and 61 ton. As a result of the difference in mass the speed will differ too, as can be seen in figure 15. The speed difference increases from 4.2 to 4.9 km/h at gradients of 0.15 to 0.24 m/km, which are the boundaries for the Stevelduct.

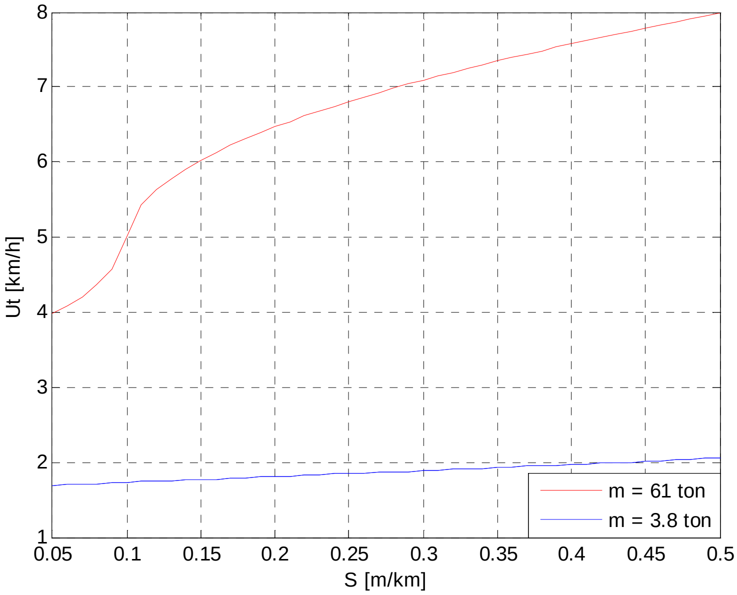


Figure 15: The total speed of the pontoon without wind, compared for empty and maximum loaded containers.

This difference in speed means that pontoons can bump in to each other. As the slowest pontoon sets the pace, pontoons can gather and form chains, which will make it harder to predict traveling times and require more of the equipment.

For ballasted pontoons there is no difference in mass. Thus theoretically the speed of the pontoons will be the same, as a result the pontoons won't form chains and the traveling time of the pontoons decreases and is the same for every pontoon, increasing the predictability of the system. In reality however, due to small differences in friction and mass, the speed of the pontoons may vary slightly, but this effect will be small compared to non-ballasted pontoons.

6. Energy analysis

6.1 Power

The power that is required to operate the Stevelduct depends on the mass of the water, pontoons and containers that need to be elevated to the height of the channel. The volume flow through the channel depends on its cross-sectional area, the speed of the water and the submerged volume of the pontoons. Since the Stevelduct is a continuous transport system the required power to run it depends on the length, the power per unit length is

$$\frac{\Delta P}{\Delta L} = \frac{1}{\eta}\left(\rho Q + \left\{\frac{m_{pontoon} + m_{load}}{\Delta t}\right\}\right) g S_0 \qquad (29)$$

where η is the efficiency of the total system, Q is the water flow rate, $m_{pontoon}$ is the total mass of the pontoon, m_{load} is the mass of the load, Δt is the time between pontoon launches, g is earth's gravitation and S_0 is the channel gradient. The term ρQ is equal to the mass flow of the water through the channel.

The flow rate of the water is a function of the channel gradient and is given by

$$Q(S_0) = U_{water} A(S_0) - \frac{B_{total}}{\rho \Delta t} \qquad (30)$$

where ρ is the density of water, Q is the water flow rate, U_{water} is the uniform water speed, A is the channel cross-sectional area, B_{total} is the total buoyancy of a pontoon.

Combining eq. 29 and 30 results in the power per unit length for non-ballasted pontoons:

$$\frac{\Delta P(S_0)}{\Delta L} = \frac{1}{\eta} g S_0 \left(\rho U_{water} A(S_0) - \left\{\frac{B_{total} - m_{pontoon} - m_{load}}{\Delta t}\right\}\right) \qquad (31)$$

For ballasted pontoons the term $B_{total} - m_{pontoon} - m_{load}$ can be replaced by the buoyancy surplus B_+, reducing eq. 31 to:

$$\frac{\Delta P(S_0)}{\Delta L} = \frac{1}{\eta} g S_0 \left(\rho U_{water} A(S_0) - \frac{B_+}{\Delta t}\right) \qquad (32)$$

Since the Stevelduct requires channels in both directions, a difference in height between the ends of the channel doesn't influence the total power consumption. If there is a height difference between the end points of the Stevelduct, the loss of potential energy in one direction is compensated by the gain in potential energy in the other direction. Since the pontoons and water are circulated the average energy consumption of both directions is the same, if there is a height difference between the end points or not.

The required power per km as a function of the circular channel cross-sectional area and as a function of the channel gradient is plotted in figure 16 and 17 for a water flow speed of 5 km/h, a roughness parameter of n = 0.013 and a system efficiency of 0.85 (85%). The average mass of a TEU, including empty containers is 9.6 ton [9] (2 TEUs per pontoon).

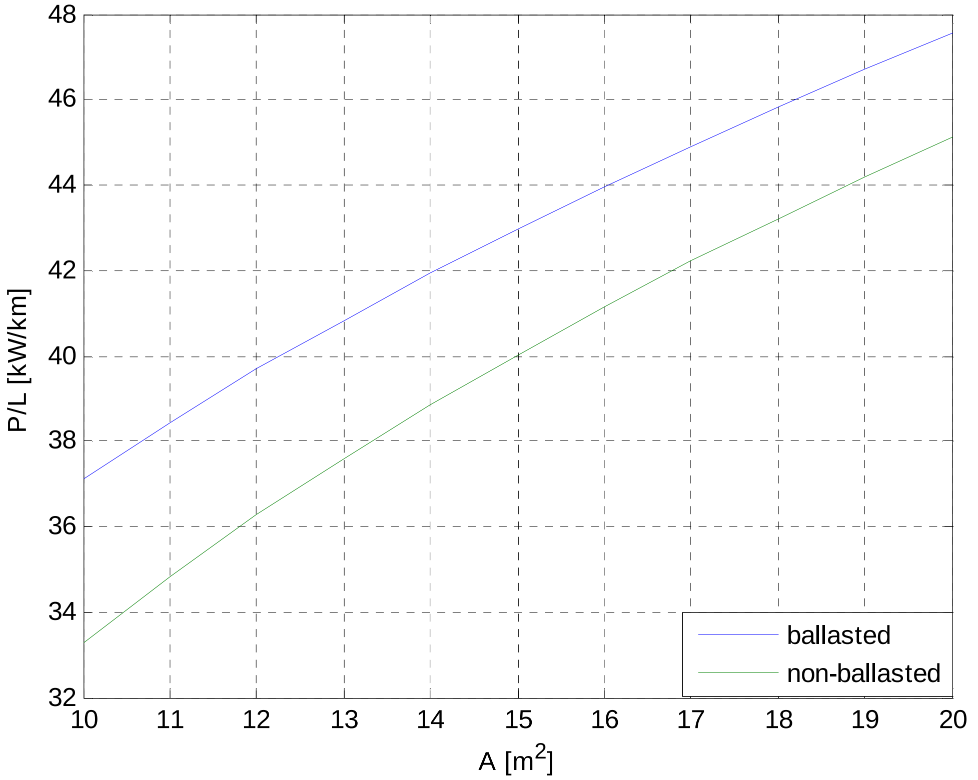


Figure 16: The required power for elevating the pontoons, load and water to height of the Stevelduct plotted as a function of the channel cross-sectional area.

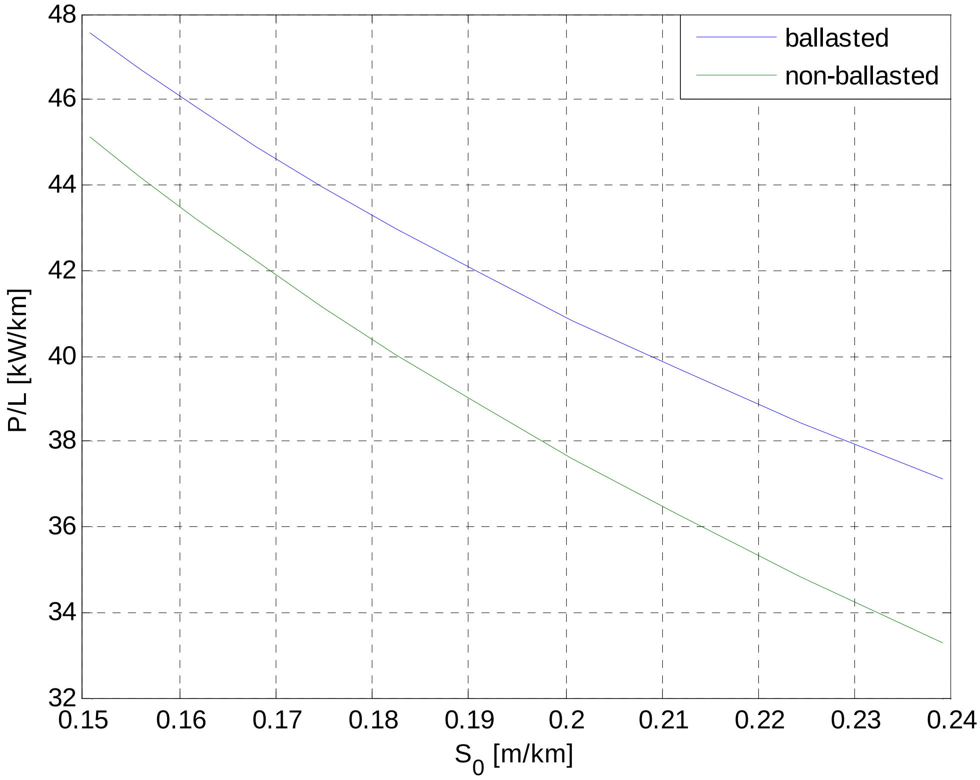


Figure 17: The required power for elevating the pontoons, load and water to height of the Stevelduct plotted as a function of the channel gradient.

Since the water flows under the action of gravity, time and distance are needed to accelerate the water and pontoons to the uniform flow speed. It might be wanted to reduce this distance, by mechanically accelerating the water flow and pontoons up to uniform flow speed of the water of 5 km/h, so the flow parameter remain constant over the entire length of the channel. The power required to do this is

$$P_U(S_0) = \frac{1}{\eta}\frac{1}{2}\left(\rho Q(S_0) + \left\{\frac{m_{pontoon} + m_{load}}{\Delta t}\right\}\right) U_{water}^{\;2} \tag{33}$$

where η is the efficiency of the system. By substituting eq. 30, eq. 33 for non-ballasted pontoons becomes:

$$P_U(S_0) = \frac{1}{\eta}\frac{1}{2}\left(\rho U_{water} A(S_0) - \left\{\frac{B_{total} - m_{pontoon} - m_{load}}{\Delta t}\right\}\right) U_{water}^{\;2} \tag{34}$$

For an efficiency of 0.85 the average power required to accelerate the non-ballasted pontoons and water up to the uniform flow speed varies between 13.7 and 29.5 kW for cross-sectional areas of respectively 10 and 20 m^2. For ballasted pontoons eq. 33 becomes:

$$P_U(S_0) = \frac{1}{\eta}\frac{1}{2}\left(\rho U_{water} A(S_0) - \frac{B_+}{\Delta t}\right) U_{water}^{\;2} \tag{35}$$

For an efficiency of 0.85 the power required to bring the ballasted pontoons and water up to speed varies between 15.3 and 31.0 kW for cross-sectional areas of respectively 10 and 20 m^2.

6.2 Transport loss factor

The transport loss factor (TLF) is used make the energy usage of transport types insightful and is defined as [10]

$$f_t = \frac{E}{WL} - \frac{H}{L} \tag{36}$$

where E is the total consumed mechanical energy during transport, W is the weight of the transported load, L is the length of the transport route and H is the height difference between the start and end of the transport. As can be seen from eq. 36, a low TLF means a low energy consumption per transported weight and thus a good energy performance.

Although potential energy is used to drive the system, if the Stevelduct is located on a horizontal surface there is no difference in height between the start and end point. Thus the height difference H is measured between the point where the pontoons and containers are lifted by the revolver-lift and the end point of the Stevelduct.

Because, as mentioned in the previous paragraph, the gain in potential energy in one direction is compensated by an equal loss in potential energy, this reduces eq. 35 to:

$$f_t = \frac{E}{WL} \tag{37}$$

For the Stevelduct E is equal to the added potential energy, thus that of the water flow together with the mass of the pontoon. W is equal to weight of two TEU's.

For a non-ballasted pontoon the consumed energy is

$$E(S_0) = \frac{1}{\eta} g S_0 (\rho U_{water} A(S_0)\Delta t - (B_{total} - m_{pontoon} - m_{load}))L \tag{38}$$

where g is earth's gravitation, S_0 is the gradient of the channel, ρ is the water density, Q is the water flow rate, Δt is the time interval between pontoon launches, B_{total} is the total buoyancy, $m_{pontoon}$ is the mass of the pontoon, m_{load} is the average mass of two TEU's and L is the length of the channel.

The weight of the transported load is

$$W = g * m_{load} \tag{39}$$

By substituting eq. 38 and 39 in eq. 37 the TLF for non-ballasted pontoons becomes:

$$f_t(S_0) = \frac{S_0(\rho U_{water} A(S_0)\Delta t - (B_{total} - m_{pontoon} - m_{load}))}{\eta m_{load}} \tag{40}$$

For a ballasted pontoon carrying 2 TEU's the required energy to run the Stevelduct becomes

$$E(S_0) = \frac{1}{\eta} g S_0 (\rho U_{water} A(S_0)\Delta t - B_+)L \tag{41}$$

where B_+ is the surplus in buoyancy. The TLF for ballasted pontoons then becomes:

$$f_t(S_0) = \frac{S_0(\rho U_{water} A(S_0)\Delta t - B_+)}{\eta m_{load}} \tag{42}$$

In these equations the power to accelerate the pontoons and water up to speed could not be incorporated, since this power relative to the power to operate the Stevelduct decreases with the length of the channel. As a result, it is not possible to calculate the TLF without knowing the length of the channel. Accelerating the flow and pontoons up to speed will increase the TLF but its influence will decrease as the length of the channel increases. The energy required to accelerate the water and pontoons to the speed of the water can be found by multiplying eq. 34 by Δt for non-ballasted pontoon carrying 2 TEU's and becomes:

$$E_U(S_0) = \frac{1}{\eta}\frac{1}{2}\left(\rho U_{water} A(S_0)\Delta t - \left(B_{total} - m_{pontoon} - m_{load}\right)\right) U_{water}{}^2 \tag{43}$$

For ballasted pontoons eq. 35 is multiplied by Δt, resulting in:

$$E_U(S_0) = \frac{1}{\eta}\frac{1}{2}\left(\rho U_{water} A(S_0)\Delta t - B_+\right) U_{water}{}^2 \tag{44}$$

To calculate the TLF, the total consumed energy of eq. 37 is the sum of eq. 38 and 43 for non-ballasted pontoon and the sum of eq. 41 and 44 for ballasted pontoons. For a channel length of 50 km the TLF for ballasted pontoons would increase by 0.8 and 1.3 % for cross-sectional areas of respectively 10 and 20 m^2. This increase is inverse proportional to the length of the channel, thus if the length is doubled than the increase is halved.

The TLF without the energy required to accelerate the pontoons and water up to speed for non-ballasted and ballasted pontoon is plotted as a function of the channel cross-sectional area and the channel gradient in figures 18 and 19.

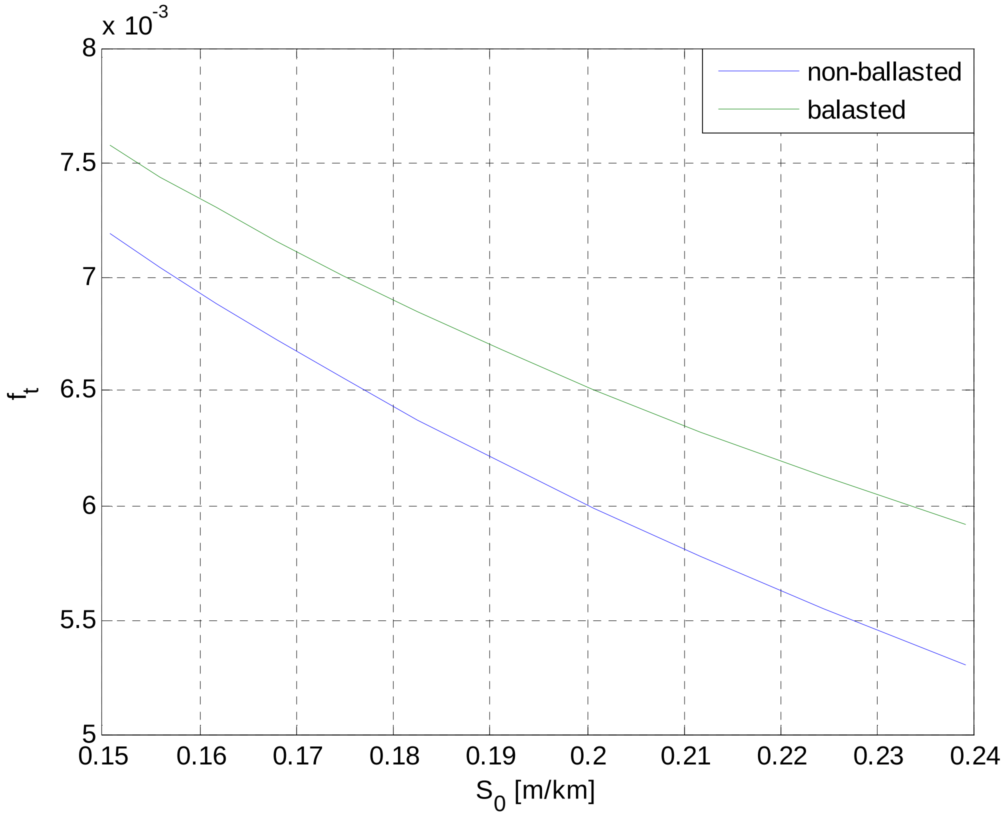


Figure 18: TLF as a function of the channel gradient.

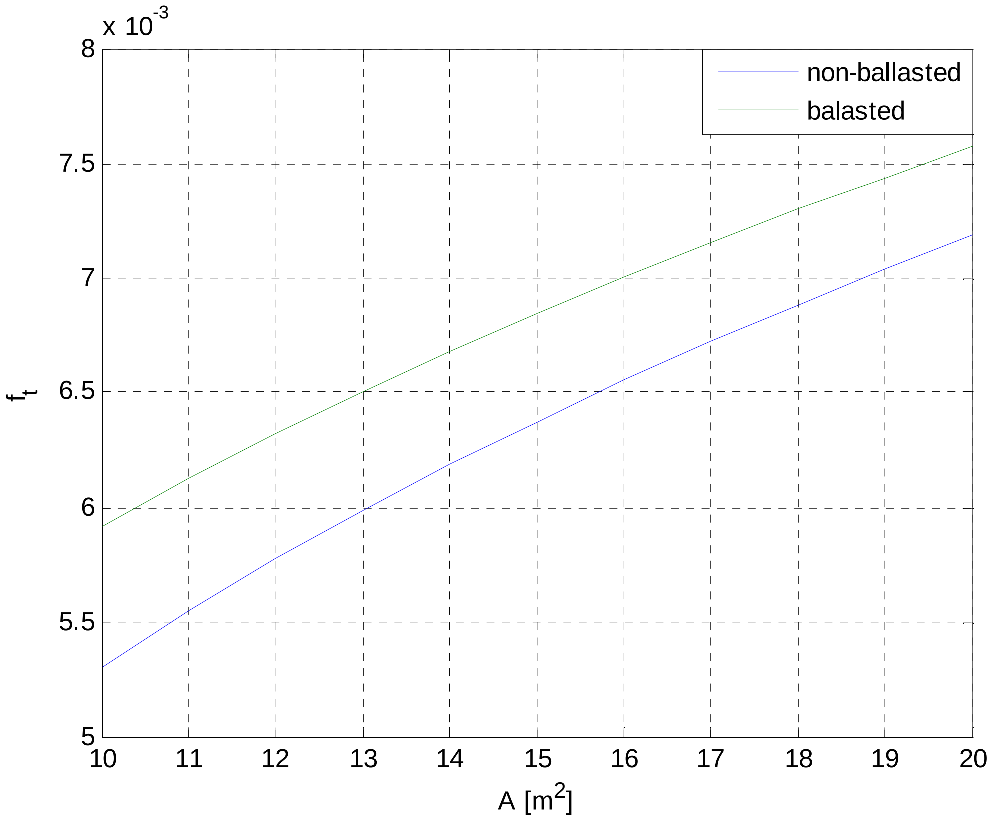


Figure 19: The TLF as a function of the channel cross-sectional area.

The TLF without acceleration is in the range of 0.0053 - 0.0072 for non-ballasted pontoons and 0.0059 - 0.0076 for ballasted pontoons. As can be seen from figure 20, this is in the region of ships and trains, which have the lowest TLF of all modalities. For ballasted pontoons with acceleration the TLF range increases slightly to 0.0060 – 0.0077.

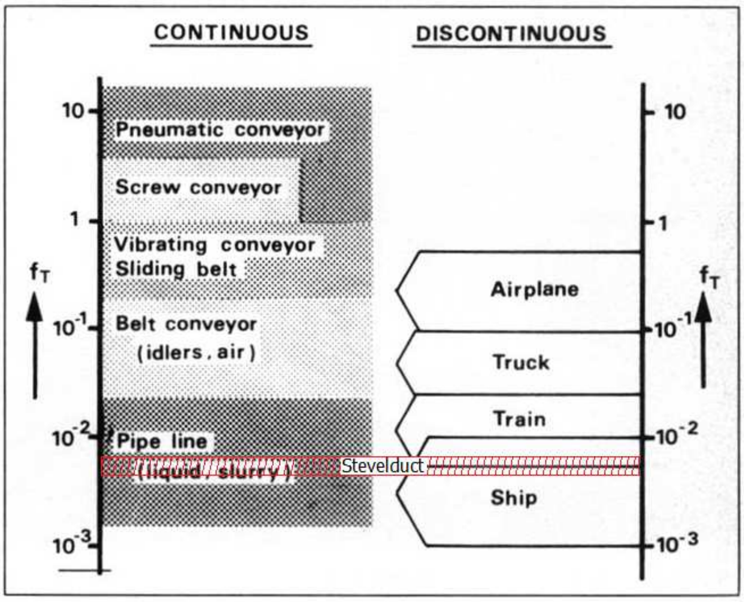


Figure 20: The TLF for different transport types [10].

6.3 Emissions

Since only electrical energy on fixed locations is required, use can be made of green electricity, with the result that greenhouse gasses, other pollutant gasses and particulate matter that result from the burning of fuel are not emitted. However, due to the wear of wheels and guide rails particulate matter is emitted, but these emissions are hard to predict and should be measured, but probably will be very low.

7. Scenario analysis

Figure 21: Stevelduct connection between Maasvlakte and Roosendaal

The outpost scenario consists of three outposts located around Rotterdam, one of those outposts located near Roosendaal. This outpost is connected with the Maasvlakte in a straight line, see figure 21. The distance between the Maasvlakte and Roosendaal is about 50 km.

7.1 Technical data

In figure 22 the technical data for the Maasvlakte-Roosendaal connection is shown for ballasted pontoons. This is done for the boundaries found in chapters 4 and 5, which restrict the domain in which the Stevelduct can operate.

Due to the required height of the Stevelduct it might be necessary to split it in half, which would reduce the height of the channel by half. The possibility of (partial) tunneling to pass waterways and nature was mentioned in the concept, in this way the height limit can be avoided.

Distance	50	km	50	km
Water speed	5	km/h	5	km/h
Cross-sectional area	10	m^2	20	m^2
Water flow rate	13.9	m^3/s	27.8	m^3/s
Water volume in channel	$423*10^3$	m^3	$914*10^3$	m^3
Pontoons in channel	896		1000	
Gradient	0.24	m/km	0.15	m/km
Height	12.0	m	7.5	m
Speed pontoons	6.7	km/h	6	km/h
Power	1.86	MW	2.38	MW
TLF (not accelerated)	0.00592		0.00757	
TLF (accelerated)	0.00596		0.00766	

Figure 22: Boundaries of the functional domain of the Stevelduct

7.2 Technical malfunction

The equipment that is susceptible to malfunctions are the water pumps required for the water flow and the revolver-lifts to elevate the pontoons to the height of the channel. If the pumps would stop working, between $423 * 10^3$ and $914 * 10^3$ m^3 water is still in the channel and will keep flowing towards the end of the channel. Drainage and buffers would be required to prevent local flooding. This could be problematic, especially in parts that are tunneled. Also measures should be taken to prevent derailment of the pontoon's guidance as the water level drops.

In the case of a pontoon lift malfunctions, where the Stevelduct connection split into multiple sections, there are still 896 to 1000 pontoons inside the channel. These pontoons and the containers they transport possibly can't be retained in the channel and need to be stalled in a buffer. This would require extra handling material and an area large enough to stall the pontoons and containers. This could be problematic in tunneled sections, where this problem also exists if the connection isn't split in multiple sections.

7.3 Capacity

At an interval of 30 seconds between launches the capacity in one direction is just over 2.1 million TEU's per year, thus in both directions over 4.2 million TEU's per year can be transported. In 2009 the total container traffic added up to 9.7 million TEU's and where equally divided over the incoming and outgoing TEU's [11]. The total number is expected to grow to 22 million TEU's in 2020 (Port Authority). This would mean a share of 19% of all container traffic of the Port of Rotterdam in 2020.

8. Conclusions

8.1 What is the optimal shape of the channel cross-section?

From the channel cross-section analysis it can be seen that a semicircular channel is the most efficient shape to transport water through an open channel. This because, the semicircular channel has the smallest wetted perimeter of all shapes if the cross-sectional area is held constant. This also means that the least amount of channel wall is required, implying that also the least amount of material is needed to build the channel, if the wall thickness is constant among the different shapes.

In addition, the semicircular channel has an advantage over other shapes, considering the pontoons. Since the distance between the pontoon and the channel walls is the largest of all, for a constant channel cross-sectional area and pontoon length. This is advantageous, because wall effects, having a negative effect on the pontoon's speed, decrease as the distance from the pontoon to the channel walls increases.

For these reasons it can be concluded that the optimal shape of the channel cross-section is semicircular.

8.2 What will be the dimensions of the pontoon?

Under the assumption that a surplus buoyancy of 13 ton and a total pontoon length of 15 m are required, the semicircular pontoons would have a diameter of 3.83 meter.

8.3 What buoyancy surplus is required?

A minimum buoyancy surplus of 13 ton is required to maintain contact with the guidance of the pontoon for containers where the center of gravity is maximum 30% out of the center and a distance between the guide rails of 3.5 m.

8.4 At which gradient will stevelen take effect?

Vessels on rivers start to stevel as soon as the water surface has a gradient, the pontoons in the Stevelduct do not. Since the pontoons are guided, the rolling resistance has to be overcome first before stevelen will take place. For the proposed assumptions this means that stevelen will start to occur at a gradient of about 0.1 m/km. At a gradient of 0.15 m/km the stevel speed will be 1 km/h, making the total speed (stevel + water speed) of the pontoon 6 km/h.

8.5 What is the required channel gradient?

The required channel gradient depends on the desired characteristics of the Stevelduct, but the channel gradient is bounded by the minimal gradient required to stevel and the minimal required channel cross-sectional area which restricts the gradient. The domain in which the Stevelduct can operate is bounded to 0.15 to 0.24 m/km. An optimal gradient can't be specified, because some parameters are more favorable at smaller gradients, while others are at larger gradients. At the largest gradient the required height of the Stevelduct is the largest, but the speed is the highest (6.7 km/h) and the cross-sectional area and the required power are the smallest. At the smallest gradient the required height of the Stevelduct is the smallest, but the speed is the lowest (6.0 km/h) and the cross-sectional area and the required power are the highest. Thus a gradient should be chosen depending on the desired characteristics.

8.6 What is the effect of wind?

The wind can greatly reduce the speed of the pontoons, at a strong wind of 10 m/s (5 Bft) the total speed is reduced to about 1.6 km/h. Stronger winds can bring the pontoons to a standstill or even reduce further to negative speeds, however measures are possible to reduce the effect of the wind, for example by a windbreak.

8.7 How much power does the Stevelduct require?

There is an interesting relation between the power and the channel gradient, the power decreases as the channel gradient increases. The domain of the power in which the Stevelduct can operate for one channel ranges from 37.1 kW/km at a gradient of 0.24 m/km to 47.2 kW/km for at a gradient of 0.15 m/km. If usage is made of pumps to accelerate the pontoons and water up to uniform flow speed at the start of a channel, an extra power of 15.3 to 31.0 kW is required per channel at gradients of respectively 0.24 and 0.15 m/km.

8.8 What is the transport loss factor of the Stevelduct?

The TLF of the Stevelduct is in the range of 0.0053 – 0.0072 for ballasted pontoons, for non-ballasted pontoons this is 0.0059 – 0.0076. This is in the range of the TLF of ships and trains, who have one of the lowest TLF of all transport types. An advantage of the Stevelduct compared to other transport types is that it can be powered by green electricity, thus no greenhouse gasses and pollutants will be emitted.

If the pontoons and water are accelerated up to uniform flow speed at the start of the channel the TLF will increase, but this influence will be small as the power to bring the flow up to speed is relatively small compared to the power to run the Stevelduct. For a channel length of 50 km the TLF for ballasted pontoons would increase by 0.8 and 1.3 % for cross-sectional areas of respectively 10 and 20 m^2 (gradients of 0.24 and 0.15 m/km).

8.9 How will the pontoons behave during transport?

The behavior of the pontoons can be unpredictable for non-ballasted pontoons, as the speed and the mass of the pontoons are related, since the mass of the containers can vary, so does their speed. But by ballasting the pontoons to an equal weight, the speed of the pontoons will equalize, which will increase the predictability of the system. Another advantage of ballasting is that the all pontoons will sail at their maximum speed, and thus the traveling time is decreased.

8.10 Is the Stevelduct technical feasible?

The results found in the analysis of the sub-questions and that of the Maasvlakte-Roosendaal connection of the outpost scenario are technically feasible. The Stevelduct has a good energy performance, as can be seen from the relatively low TLF, with the advantage that green electricity can be used. However, wind and the varying mass of the containers can greatly influence the characteristics of the behavior of the pontoons, but the channel can be protected from wind and the mass can be equalized by ballasting the pontoons.

Also problems could occur in case of equipment malfunction in tunneled sections of Stevelduct. If a pump fails, sufficient drainage and buffers would be required, as the channel still holds a large volume of water. In case of revolver-lift failure extra handling equipment and buffers to stall the pontoons and containers may be required. The storage and/or drainage of such large volumes of water, pontoons and containers is problematic underground.

Thus it can be concluded that the Stevelduct is technically feasible, but the pontoons should be protected from wind and the usage of tunneled sections could be technically infeasible.

9. Recommendations

The method used to calculate the speed of the pontoons does not take the effects of the restricted water of the channel into account. It seems very likely that wall effects will affect the pontoon's resistance, and thus its speed. There could also be an interaction between the restricted water and the pontoon's speed, in other words, the pontoon's speed will also influence the speed of the water. A computational fluid dynamics (CFD) or scale model could be made in order to show the effects of the channel walls in the vicinity of the pontoon on the speed of the pontoon and water flow.

The effect of wind on the speed of the pontoon is incorporated in the calculations, however its effect of wind on the behavior of the water flow is not. Strong winds could stow the water, depending on the wind direction this could result in lower or higher flow speeds, which consequentially could alter the water level inside the channel. This would affect the rolling resistance and could maybe result in a loss of guidance. However, since the effect of the wind without the effect of the wind on the flow is already large, it is advisable to protect the Stevelduct from wind.

The mass of the pontoons is positively related to its speed, because the mass of the transported containers varies, so will the speed of the pontoons. By ballasting the pontoons to the maximum load, their weight is equalized, as a result all pontoons will have the same speed. This will positively affect the logistics of the system, because this would results in a better predictability of the system and the average speed of the pontoons is higher compared to that of non-ballasted pontoons.

When the water enters the channel the water needs some distance to accelerate under the action of gravity to uniform flow speed. During this distance the flow is non-uniform, thus the parameters as speed, channel cross-sectional area and water depth change. The flow speed during this distance is lower than the uniform flow speed and the volume flow is the same, as a result the water depth is larger than that during uniform flow. This means that the rolling resistance is larger, if the distance between the rails and channel bottom is constant, which influences the behavior of the pontoons. By mechanically accelerating the pontoons and water to the uniform flow speed this influence is avoided, as the flow parameters remain constant during the total length of the channel.

References

[1] Fluid mechanics, 5th edition, Frank M. White, McGraw-Hill, 2003, ISBN 0-07-240217-2

[2] http://www.efm.leeds.ac.uk/CIVE/CIVE2400/OpenChannelHydraulics2.pdf

[3] The speed of drifting bodies in a stream, J.R.D. Francis, Imperial College, London, 1956

[4] A further note on the speed of drifting bodies in a stream, J.R.D. Francis, Imperial College, London, 1960

[5] Fundamentals of ship resistance and propulsion, Part A: resistance, ir. A.J.W. Lap, Publication No. 129a of the N.S.M.b.

[6] http://www.tribology-abc.com/abc/cof.htm

[7] Practical ship hydrodynamics, Volker Bertram, Butterworth-Heinemann, 2000, ISBN 0-7506-4851-1

[8] Scale effects in towed barge stability tests, Robert Latorre, Ocean Engng Vol.15 No. 4 pp.305-317, 1988

[9] Container hoogtemetingen, Rijkswaterstaat, Adviesdienst Verkeer en Vervoer, Rotterdam 1996

[10] The loss factor of transport, C.O. Jonkers, Transport und Umschlag, Nr. 2, 1981

[11] http://www.rotterdamportinfo.com/facts/table9.cfm