A Discrete Event Simulation to Measure the Resilience of Freight Systems During Drought Disruption

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Abstract

The Netherlands was faced with drought disruption within their Inland Waterways (IWT) in the past few years. The drought of 2018 was so severe that the disruption caused economic losses. As the topic of drought disruption is new, little strategies have been developed to reduce the economic loss due drought disruption. One concept has gained growing attention in the literature for potentially reduces such losses - namely, Synchromodal transport. Synchromodal transport - also called Synchromodality - consists of allowing freight forwards to select a transport modality until the last moment, instead of planning far before as is done now. In our paper we research to what extent Synchromodal transport can increase the resilience of the Dutch freight transport system during drought disruptions. Our rational for this research is the absence of insights for policy makers on how to reduce economic losses during drought disruption. Our research developed a Discrete Event Simulation to measure the performance of Road, Rail and IWT during droughts. We further developed a resilience Framework which identified five resilience metrics. We embedded the results of the simulation model within these metrics to evaluate the impact of Synchromodal transport for different penetration rates. Our results show that Synchromodal transport is able to avoid drought disruptions but only at penetration rates above 55% - which is seen as high. However, even when disruptions were still present, synchromodal transport helped reduced the damages done by big margins during the disruptions - event at low penetration rates. This suggests that any effort to adopt synchromodality can be useful against drought disruptions.

Keywords: Drought Disruption, Resilience, Synchromodality, Simulation, Inland Waterways

1 Introduction

The Netherlands faced a sever drought during the summer of 2018 which caused a disruption in the transportation of goods on inland waterways (IWT) [**?**]. During droughts, barges are unable to navigate with full cargo as the ships will navigate too close to the river bed. As all barges in the fleet are affected by this, the IWT sector as a whole is subject to a loss of capacity.The loss of transport capacity became too big in 2018 that goods were transported with delays. The latter can have great consequences for industries which are dependent on the arrival of these goods. This is what happened in 2018 where the drought disruption is linked to economic losses [**?**].

The economic loss for 2018 due to the drought disruption is estimated to be around 345 million euros [**?**]. To put this figure into perspective, the Dutch Ministry of Infrastructure & Environment had an annual budget of 8,4 billion for that year. Keep in mind that the loss due to droughts only occurs on a limited number of days through the year - whereas the budget figure is annual. Rijkswaterstaat estimated that 21 days in 2018 led to disruptions within IWT [**?**]. The message we want to conceive is that drought disruptions are unwanted as they harm the national economy.

Policy makers are therefore keen to ensure that drought disruption will have less negative economic impact in the future - a concern which seems justified as droughts are expect to become more frequent and more severe over the next decades [**?**] [**?**]. To reduce the impact of a drought disruption policy makers will have to develop a resilient transport system.

With this paper, we want to research how a transport system can become more resilient to drought disruptions. The added value of this research is that it will help reduce negative economic losses. Furthermore, we believe it to be justified to do a new research as little research has been done on this topic.

We are of the opinion that additional research must be conducted, to properly investigate this topic. Firstly, we found little papers who investigated the impact of droughts on the supply chain. Second, those that did put little emphasis on the multi-modal aspect of a supply chain - which we believe is interesting to investigate. Third, we would like to link to embed the findings of such a study in a resilience framework.

With that said, we want to evaluate the impact of a given strategy during a drought. The strategy which we selected is that of *Synchromodality.* Synchromodality is a relatively new concept in the literature in which shippers can select a transport mode at the last minute, instead of planning in advance. The belief is that synchromodal transport would make the supply chain more resilient as a portion of the goods initially intended for IWT could use the road or rail. We formulate our research question as follows:

> ”To what extent can Synchromodal transport in the Netherlands improve the resilience of multimodal transport against drought disruptions?”

1.1 Research Deliverables

The goal of this research is to evaluate the resilience of synchromodal transport. To do so, we will develop a tool which allows us to measure it. We do so because we are unsatisfied with the current models and approaches to evaluate the performance of different strategies.

We provide a conceptual diagram in figure 1 showing what this research will create. The figure is composed of two elements - a Simulation Model and a Resilience Analysis. The goal of the simulation model is to output the performance - e.g. throughput, queuing cargo - of the transport system for different drought scenarios and under different strategies. The goal of the Resilience Analysis to interpreter and measure the output of the simulation model. We provide a framework to explain how the system behaves, and have an analysis tool to quantitatively measure the resilience.

Within the Simulation Model one can observe three items - *Demand model*, *Supply model* and *Hydrological model.* These represent the modules - or sub models - of the simulation model. We explain in greater length in section 3 how each item is computed. They work together to produce the output of the simulation model. The Demand model is tasked with simulating the demand of goods to go from location A to location B with a specific transport mode. The Supply model is tasked

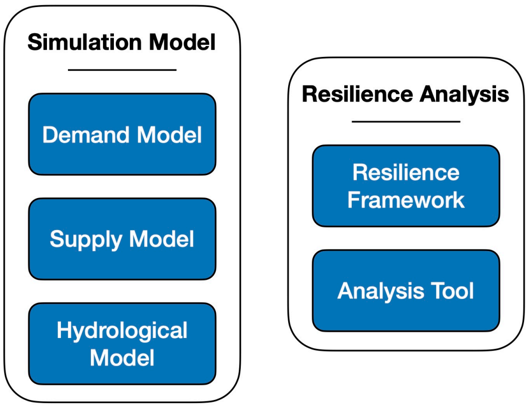

Figure 1: The Toolbox to Measure the Resilience of a National Freight System

with simulating the availability of transport capacity. Whilst the horological model simulated the water level.

The resilience analysis is composed of a Resilience Framework and an Analysis Tool. The framework explains the different time phases drought disruptions go through, and identifies a few metric to measure the resilience of the system. The analysis tool is a script which allows to measure the frameworks metric from the simulation model output.

1.2 Structure of Paper

This paper has a simple structure. The next chapter will briefly discuss the literature on the topic of drought disruption and resilience. The chapters after that describe the Resilience Analysis framework we developed, and the Simulation model. Section 5 provides the results before we discuss our research in the final chapter.

2 Background

This section is used to describe the background on of resilience within transport system. We first describe the concept of resilience, and then name transport related studies.

2.1 Resilience of Transport Systems

General Overview of Resilience

Resilience is a concept which is described in multiple domains, which is why there are multiple definitions of it. The concept failed to have a universal definition At has gotten to the point that [?] said that Resilience has lost its meaning through over use. He classifies four concept of the term - notably (1) Resilience as Rebound, (2) Resilience as Robustness, (3) Resilience as Graceful Extensibility and (4) Resilience as Sustained Adaptability -, and states the importance of defining which concept is used within the study. This analysis is shared by other scholars [?].

Definition of Resilience this paper
To that extent, our work defines resilience as:*the ability of a supply chain to return to its original state, or a new one* by [?]. We selected this definition because of the *or a new one* aspect - which is the concept behind synchromodal transport.

The differentiation between Robustness and Resilience
It's important to distinguish resilience from robustness. Where resilience represents the ability of a system to recover from a disruption, but robustness represents the ability to resist that disruption.

Different Domains for Resilience
Hosseini [?] studied the different domains in which resilience is present and classified four domains, namely: organizational, social, economic and engineering. Transport resilience is said to be part of the engineering domain, and two key elements of engineering resilience are 1) reliability of the system, and (2) the restoration of the system according to [?].

2.2 Frameworks on Resilience

The literature proposes a few resilience framework on which we can build forth on. We will explain two concepts present within the literature which are the *System Resilience as a Function of Time* developed by Henry & Ramirez-Marquez and the *Resilience Triangle* developed by Tierney & Bruneau.

System Resilience as a function of time by Henry & Ramirez-Marquez
Henry and Ramirez-Marquez [?] developed a time based metric to evaluate resilience - shown in figure 2. Their framework conceptualizes different stages of a system during a disruption. They distinguish a System Disruption phase & a System Recovery one and define three states, table Original State (SOS), Disrupted State (DS) and Stable Recovery State (SRS). Note how there is a difference in performance between the Stable Recover State and the Stable Original State.

Henry and Ramirez-Marquez define a disruption as an event which affect the system in a way that its performance is changed. Their framework describes a Resilience Action as *one that restores the system to a stable recovered state* S_f. Therefore, their framework must be interpreted that until S_f no resilient strategy or system reaction implemented.

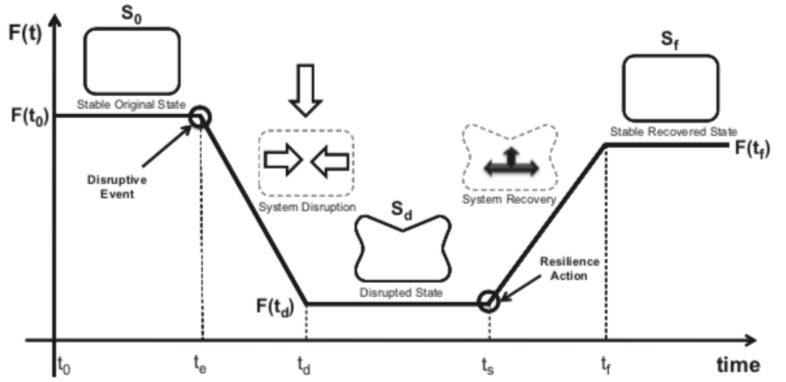

Figure 2: System Resilience as a Function of Time from Henry & Ramirez-Marquez [**?**]

The Resilience Triangle by Tierney & Bruneau
Tierney and Bruneau [**?**] offer their framework entitled R4 Framework, which developed the notion of a Resilience Triangle. The trianfle represents the surfacebetween the pre and post disruption. We show the concept in figure 3. Signifying that a large area is a bad resilience, and a small area a good resilience.

Their R4 framework is composed of four attributes of resilience. Namely, (1) Robustness, (2) Redundancy, (3) Resourcefulness and (4) Rapidity.

- Robustness: the ability of systems, system elements, and other units of analysis to withstand disaster forces without significant degradation or loss of performance.
- Rapidity: the capacity to restore functionality in a timely way, containing losses and avoiding disruptions.
- Resourcefulness: the ability to diagnose and prioritize problems and to initiate solutions by identifying and mobilizing material, monetary, informational, technological, and human resources.
- Redundancy: the extent to which systems, system elements, or other units are substitutable, that is, capable of satisfying functional requirements, if significant degradation or loss of functionality occurs.

The concepts of *resourcefulness* and *Redundancy* are considered two means by which resilience can be increased. Where the former looks at prior disruption strategies, and the latter at *post-hoc* strategies. As a side note, this thesis studies the redundancy.

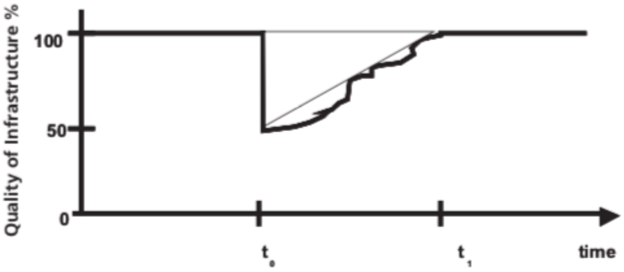

Figure 3: The Resilience Triangle from [?]

2.3 Studies on Transport Resilience

There are some papers which have developed resilience measures on disruptions. See for example the work of Chen & Miller-Hooks [?] or Desquesnes *et al* [?]. Unfortunately, their work was not ideal for our research as Chen & Miller-Hooks metrics are extremely aggregated and provide little information for policy makers as the the consequence of the disruption. And the work from Desquesnes *et al* focused on measuring the required water level to navigate without disruption.

Other studies studies such as Hayes *et al* [?] focused on the adaptability of a system, instead of creating resilience at infrastructure level whilst[?] studied the case of post-disaster recovery activities - e.g. emergency response. Here they investigated the case of earthquakes. Unfortunately, recovery activities do not uphold for drought disruptions as it is an external factor.

Some papers tried to quantitatively capture the resilience and proposed some measures - see [?] and [?]. However, we found that their measures offer no insights for policy makers with no specialization in mathematics. Indeed, their metrics is very abstract and difficult to interpret. This is problematic because resilience is a subjective connotation to it[?] [?][?] , and therefore the interpretation and understanding of the measure is important

Effect of Disruption
We found studies such as [?] and [?] which looked at the economic impact of a disruption in greater depth. For the case of [?], the disruption lasted one year. Whilst [?] simulated an inland port closure. Although their work is interesting, it did not simulate the transport performance or study the impact of a strategy.

What we observed in the literature is that work has been done on the topic of transport resilience, but the metrics offered by those studies do not fulfill our wish to measure the impact of transport policy in a simple manner.

We think its justified to perform our study because there are few papers who measure the performance of multimodal transport and embed these findings within a resilience framework. On top of that, we propose an evaluation of synchromodal transport as a strategy against drought disruptions.

The Concept of Synchromodality

The transport concept Synchromodality was first introduced in 2011, and proposed a concept in which shippers would select a transport modality based on live transport performance. This would mean that make a decision at the very last moment instead of planning ahead. Scholars point out this synchromodal transport offers the possibility to better cope with disruptions - see for example [**?**], [**?**], [**?**], [**?**] and [**?**]. However, there are some limitations to the concept of synchromodal transport. Critics state that there is a lack of real time data and that stakeholders will be reluctant to share information with their competitors. On top of that, the current approach requires parties to sign contracts - this would hinder the use of synchromodality. Nonetheless, the novelty of the concept makes an interesting case to study its impact for drought disruptions.

We noticed that the studies on synchromodal transport were mostly of qualitative nature and used to describe the concept, or make a case for it. Some studies have created simulations models to quantitatively measure the performance of synchromodal transport[**?**] [**?**]. Amongst their recommendations was the incorporation of dynamic agent behaviour.

3 Measuring Resilience

3.1 The Resilience Framework

The framework in figure 4 describes the system performance over time during a disruption. The x-axis represents the time, whilst the y-axis represent the performance for any chosen metric - here the throughput. The black line represents the system performance at any given moment in time.

The framework denotes events in time, and denotes time segments. The former represents a discrete event representing a single time stamp, whereby the latter is a time segments between two events and represents a system state.

The framework shows how the system performance starts at a normal performance but loses performance after a disruption (annotated as ’d’). The phase right until the disruption is referred to as the *Stable Original State.* After the disruption, the performance will be below normal level and worsen before it starts recovering. We note the *bottom performance* (annotated as ’b’) as the lowest performance point achieved during the disruption. The phase during the disruption where the performance worsens is called *System Disruption.* After this phase, the system remains disrupted but the rate of disruption is reduced. This phase is refereed to as the *System Recovery* phases and lasts until the the system performance is back at a normal level (annotated as ’n’). After this point, the system enters a new phases named *System Compensation* in which the performance level of the system is above the normal level as a reaction to recover the lost performance during the *Harmful Disruption.*

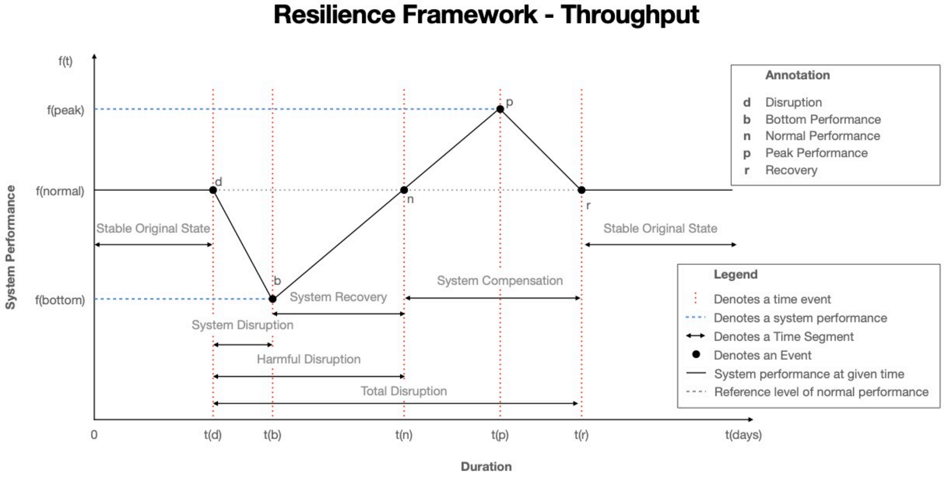

Figure 4: The Resilience Framework

Definitions of Events & Time Segments
In the following list we provide the definitions of the five events which are identified in the resilience framework.

- **Disruption**: The first day the system is disrupted.
- **Bottom Performance**: The day of the lowest performing performance of the system.
- **Normal Performance**: The first day after the Disruption event for which the system performance is at normal level.
- **Peak Performance**: The day of the best performing performance of the system occurring after the Disruption event.
- **Recovery**:The first day after the Peak Performance event for which the system performance is at normal level.

3.2 Metrics to Measure the Resilience

We are interested in measuring three aspects of the system behaviour. These are (1) the reaction of the system to the disruption, (2) the harm done to the system during the disruption, and (3) How well the system recovers from the disruption. We created a few metrics based of the resilience framework which would allow us to quantitatively measure these three aspects. We provide the definition of these metrics below and highlighted these aspects in figure 5.

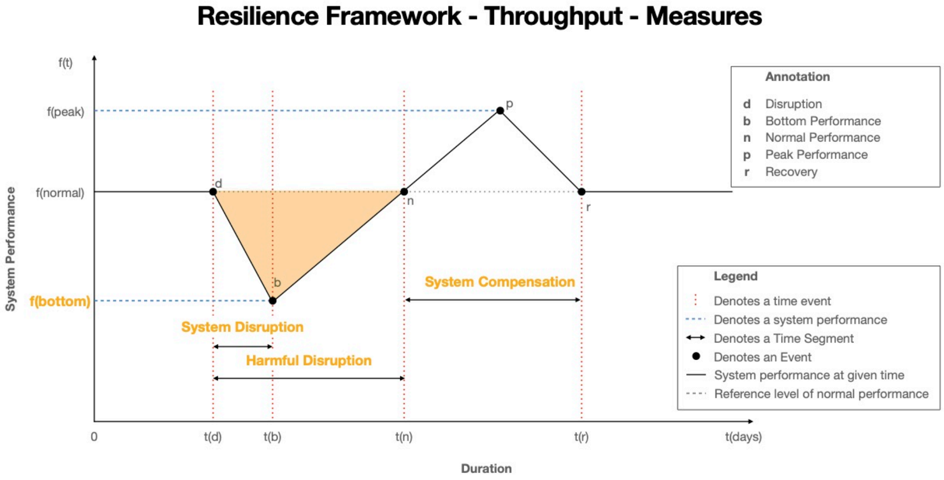

Figure 5: The Selected Measures of the Resilience Framework

Duration of System Disruption - *Reaction of the System*
The duration of the system disruption corresponds to the time between the *Disruption* and the *Bottom Performance*. Hence this measure gives an indication on the time before the system starts to recover.

Interpretation of measure: A low duration indicates a high resilience.

Bottom Performance - *Losses of the System*
The level of the *Bottom Performance* indicates how bad the system performance can get. This metric indicates the robustness of the system as it indicates how much damage can be inflicted. We provide the performance as a percentage of the *Normal Performance* as this provides the reader with

Interpretation of measure: A high performance indicates a high robustness.

Duration Harmful Disruption - *Reaction of the System*
The duration of the harmful disruption provides policy makers a tangible measure on the disruption of the drought. By tangible we mean that the measure can easy be understood and place in context - we will see with the surface of harmful disruption that this is not always the case.

Interpretation of measure: A small duration indicates the system can recover quickly.

Surface Harmful Disruption - *Losses of the System*
The surface of the harmful disruption adds a dimension to the *duration of harmful disruption* as it now considers to system performance too.

Interpretation of measure: A small surface indicates the system can limit loss.

Ratio Compensation to Harmful Duration - *Recovery of the System*
The ratio ratio of System Compensation of Harmful Disruption indicates the ability of the system to recover.

The idea behind this metric is to measure how well the system can compensate for losses. As the amount to recover is dependent on the losses faced, we took the the duration of the *System Compensation* relative to the duration of the *Harmful Disruption*.

Interpretation of measure: A low ratio indicates the system can compensation for loss quickly.

3.3 Analysing Simulation Output

We developed a resilience analysis tool which measures the resilience metrics for each simulation scenario. For this we need to provide a definition of each time event. These are the following:

Definitions of the Events
The algorithm is tasked with finding the five events which are described in the resilience framework (figure 4). For this we provide some definitions. The most important definitions are those for the *Disruption Date* and *Normal Performance Date* as these are provided with some constraints. These are the definitions.

- **Definition Disruption Date**: Six consecutive days below *Normal Performance.*
- **Definition Bottom Performance Date**: Lowest throughput.
- **Definition Normal Performance Date**: Ten consecutive days after the *Bottom Performance Date* to be on or above the *Normal Performance.*
- **Definition Peak Performance Date**: Highest performance after the *Normal Performance Date.*
- **Definition Recovery Date**: First date after the *Peak Performance Date* within the *Normal Performance.*

Notice how these events refer to the *Normal Performance.* This corresponds to the performance in the *Stable Original State* segment. Unfortunately we do not exactly know which dates fall within this segment. As such, we define the *Normal Performance* as the median the throughput before the *Bottom Performance Date.* We use the bottom performance as a reference point because we can compute this event at all times. Using the median guarantees that the performance will be within the the *Stable Performance State* segment.

We go on step further by creating a range of values which are consider the *Normal Performance.* We take ±2% of range from the median. All throughput values within this score are considered normal. We found the 2% value by trial and error. Furthermore, the analysis on the throughput is performance on a moving average throughput of seven days. Doing so takes away noise

4 Simulation Model - Computing the Throughput

The Model Narrative
The goal of the simulation model is to output the throughput of goods in tonnes/day. The model does this by simulating the demand of goods, and the supply of transport entities. We thus have two type of entities in the model.

The narrative of the model is that freight entities get generated and are provided with a destination they want to go to. The freight entities then select a modality they want to do this with. The model then verifies if sufficient capacity is available. If this is the case, the freight entity will get transported, otherwise it will have to wait for the next day.

The simulation model is tasked with outputting the daily throughput of goods over an entire year. The model simulates the throughput by computing the demand of goods to go from A to B with a given modality and also accounts for the availability of transport entities. Meaning that goods have to queue before being transported. Hence, the throughput we simulate is dependent on the modeling of freight demand, and transport supply. It is for this reason that figure 1 showed a demand model and supply model.

4.1 Demand Model

Goal of the Model: The goal of the demand model is to simulate the demand for the three modalities in tonnes/day.

By the means of a demand model we simulate the demand of goods to be transported with a given modality to their desired location. The narrative is that when demand entities are generated, they are randomly attributed a *Destination* and *Freight Classification*, but are still to select which modality they travel with.

Freight entities select their modality by the means of a Choice Model. A choice model is an algorithm which attributed a probability of choosing an alternative based on the performance of that alternative. In our model, the alternatives are the transport modes - road, rail and barge - and the performance metrics of these alternatives are *Travel Cost*, *Travel Time* and *Travel Reliability.* Our choice model uses the live travel time of the simulation model. Meaning that when queues get large, the travel time goes up.

The demand model accounts for queuing times in the total travel time. However, as assumed that freight entities accounted for some queuing time, and we are therefore interested in the delayed queuing time. We provide the equation for the Queuing Time in equation 1 and that of Queuing Delay in equation 2.

$$Queuing\ Time = \frac{Number\ of\ Entities\ Queuing}{Maximum\ Throughput\ of\ Terminal} \tag{1}$$

$$Queuing\ Delay = Queuing\ Time - Expected\ Queuing\ Time \tag{2}$$

Model Diagram

In figure 6 we show the model diagram for the demand model.

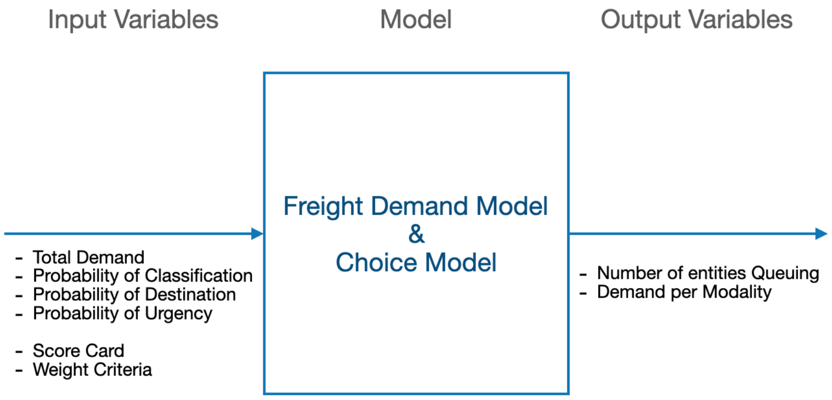

Figure 6: The Model Diagram for Freight Demand

4.2 Supply Model

Goal of the Model: The goal of the supply model is to provide capacity constraints on the supply side.

The supply model computes based on the demand for each modality, whether there is sufficient capacity to transport the goods. We show the equation to compute the number of trips needed in equation 3. The equation computes two things - (1) How many trips can a fleet provide, (2) How many trips re needed for the demand. The equation selects the lowest of these two values.

$$Number\ of\ Trips = Min\left(\frac{Fleet\ Size}{Cycle\ Time}; \frac{Demand}{Transport\ Capacity}\right) \tag{3}$$

- Fleet Size = Input Variable
- Cycle Time = Input Variable
- Demand = Computed by the Freight Demand Module
- Transport Capacity Road & Rail = Input Variable
- Transport Capacity Barges = Computed by equation 5

The interesting dynamic to equation 3 is that the capacity of barges is dependent on the water level. Therefore, the supply model computes the *load factor* for each barge using equation

5. Using the load factor the supply model can compute the updated *transport capacity of barges* using equation 4. This can then be used in equation 3 to know the capacity of the entire fleet.

$$Transport\ Capacity\ of\ Barges = Vessel\ Capacity * Load\ Factor \tag{4}$$

$$Load\ Factor = \frac{1 - 0,05}{Draught_{Loaded} - Draught_{Unloaded}} * (Water\ Depth - Draught_{Unloaded}) \tag{5}$$

Model Diagram of Supply Model
In figure 7 we show the model diagram for the Supply model. Notice how one of the input values *Demand per Modality* is taken from the Demand model.

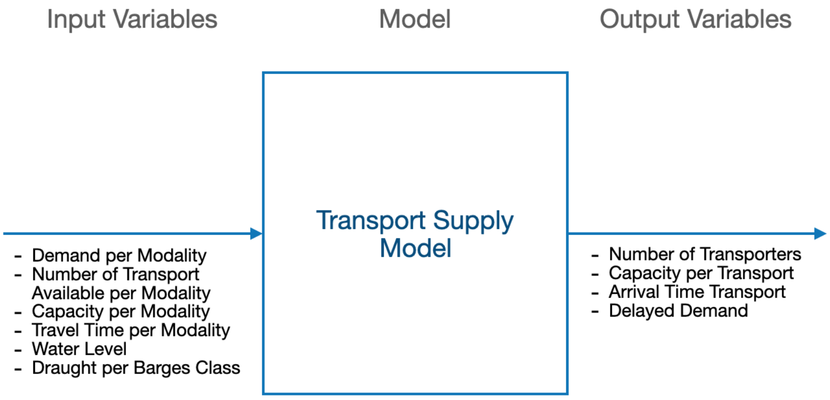

Figure 7: The Model Diagram for Transport Supply

4.3 Hydrological Model

Goal: The goal of the Hydrological Model is to generated a water level in meters for every day of the year.

The hydrological model provides the daily water level which is used in equation 5 to compute the load factor of barges. We developed our own method to generate drought scenarios. We have done this in a simple Excel model. The hydrological model produces daily water levels using a simple input setting. The modeller is only required to allocate each month with a drought level shown in table 1. The Excel model then computes a model stochasticly.

4.3.1 Steps of the Model

This approach allows for a quick and simple approach to create an infinity of controlled scenarios. This allows the research to test to greater lengths to impact of droughts on the supply chain. Below we explain the four steps of the Excel model.

Table 1: The four classification of water height

Drought Level	Water Height (meters)
None	10
Light	5
Medium	3,5
Severe	1,25

1. **Monthly Drought Level**: The first step consists of allocation a drought level on a month basis. These are the levels shown in table 1. We then project the associated water level to each day of that month.
2. **Daily Water Height**: The second step creates variance between the days by using a normal distribution on the water level allocated in step 1. We use the monthly water level as mean, and a standard deviation extrapolated from the water drought in 1976.
3. **Constraining Water Differences**: The third steps reduces the variance between consecutive days by adding constraints to the water heights generated in step 2. These constraints are:
    - Constraint 1: Water Levels have a maximum value of 15 meter - Higher water levels are possible but not relevant for our research.
    - Constraint 2: Water Levels have a minimum value of 1 meter - Lower water levels would signify that the river is dry.
    - Constraint 3: The difference between two days can be no greater than 0,5 meters - Greater differences were not found in the historic data set from 1976.
4. **Smoothing the Water Scenario**: The last test consists of applying a moving average of ten days on the water levels generated in the previous step. The moving average creates a much smoother and realistic water level.

4.3.2 Weather Scenarios

For this simulation we decided to create four scenario which are distinguished by their Severity - *Severe* or *Medium* - and their duration - *Long* or *Short*. We show the input values for each scenario in table 2. On top of that, each scenario has three varieties marked A,B or C. This means that the simulation model runs e.g. Severe Long A as weather scenario. We do so to account for sensitivity and variability of the weather scenario.

The Resilience Analysis tool measures the resilience for each weather scenario variety and then averages the scores of the three varieties. As such, the average score for e.g. Severe Long A, Severe Long B and Severe Long C provide the resilience for weather scenario Severe Long.

Table 2: The Four Water Scenarios used for Simulation

Month	**Severe Long**	**Severe Short**	**Medium Long**	**Medium Short**
January	None	None	None	None
February	None	None	None	None
March	Light	Light	Light	Light
April	Medium	Medium	Medium	Medium
May	Medium	Medium	Medium	Medium
June	Severe	Severe	Medium	Medium
July	Severe	Severe	Severe	Medium
August	Severe	Severe	Medium	Medium
September	Medium	Medium	Medium	Medium
October	Medium	Light	Light	Light
November	Light	None	Light	Light
December	None	None	None	None

5 Results

To answer our research question we must measure two aspects: first the performance of the transport system without Synchromodal transport. Second, the performance with synchromodal transport. We measure the impact of synchromodal transport for different synchromodality penetration rates. The penetration rate represents the percentage of freight goods which are allowed to make a modal choice at the last moment. All other freights entities must stick to their original choice.

5.1 Resilience of the current system

Figure 8 provides the daily throughput of goods for road, rail and barge transportation over an entire year for the weather scenario Severe Long. We can visually inspect from the figure that there is disruption from June to September, and a compensation from September to January.

Ff we provide the same graph for the other weather scenario we can visual observe a difference in performance. Table 3 provides the quantitative values for the resilience metrics. There we can confirm the the duration and surface is far higher for the most severe weather scenario.

Our first conclusion is that the system is able to withstand minor droughts but fails at more severe ones. On top of that, when disruptions are caused, they are long and cause for severe dames - see for example the surface and bottom value in table 3.

Table 3: The resilience metrics for different weather scenario, when synchromodal transport is zero.

Weather Scenario	Duration Harmful Disruption (Days)	Surface Harmful Disruption (Tonnes)	Duration System Disruption (Days)	Bottom Performance (%)	Ratio Compensation
Severe Long	87,11	1.505.640	33,6	85,16	1,427
Severe Short	56,6	1.010.438	22	86,04	1,346
Medium Long	26,3	315.387	8	88,85	1,825
Medium Short	0	0	0	100	0

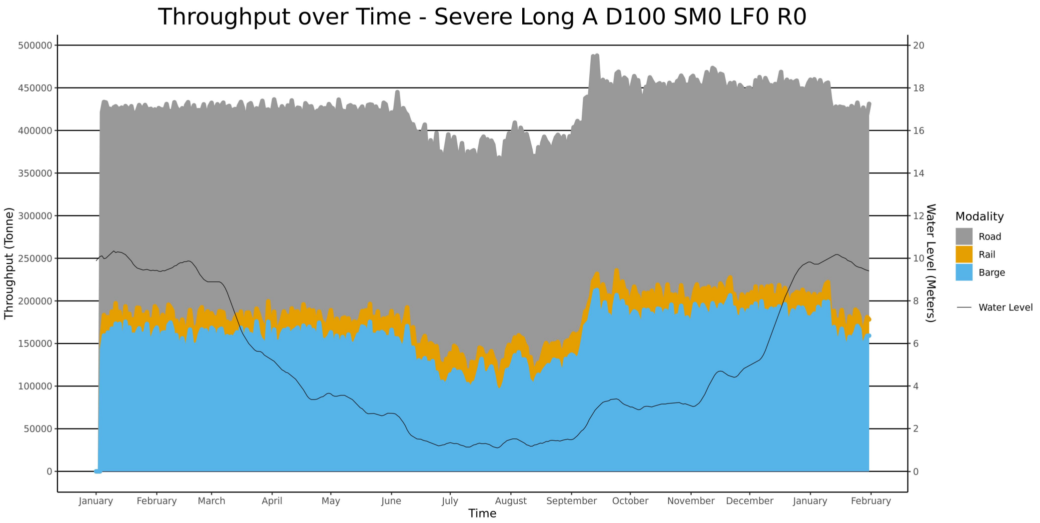
Throughput over Time - Severe Long A D100 SM0 LF0 R0

Figure 8: The Surface of the Harmful Disruption

5.2 Impact of Synchromodality

When discussing the impact of Synchromodality we are interested in two aspects. We want to know (1) at which level one can expect to see no disruption, and (2) how much improvement can we per additional penetration rate.

Differences in Duration
Figure 9 shows the Duration of the Harmful disruption for four Weather Scenarios - *Severe Long*, *Severe Short*, *Medium Long* and *Medium Short* - and for Synchromodal penetration rates ranging from 0% to 75% with a 5 point increase.

From figure 9 one can observe the significant differences in duration between weather scenarios. The *Medium Short* scenario showed to cause no disruption for all penetration rates. Whereas the most extreme drought scenario of *Severe Long* is confronted with a long disruption, and remains disrupted until the 55% synchromodal penetration rate.

This shows that synchromodality is eventually able to avoid disruptions in all scenarios, but we are skeptical if 55% penetration rate can be achieved. Hence we are inclined to say that synchromodal transport offers limited improvements for reducing the period of disruption. However, the reader must keep in mind that the duration tells nothing on the severity of the disruption.

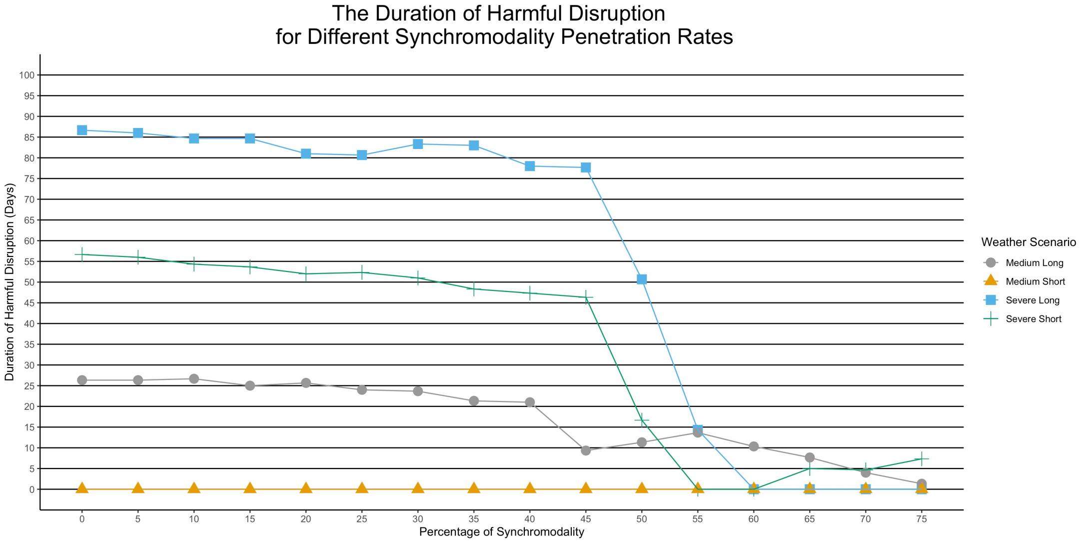

Figure 9: The Duration of the Harmful Disruption

Important Reduction in Surface

Figure 10 provides the surface from the harmful disruption for four Weather Scenarios - *Severe Long*, *Severe Short*, *Medium Long* and *Medium Short* - and for Synchromodal penetration rates ranging from 0% to 75% with a 5 point increase.

The first disclaimer we provide for the surface of the harmful disruption is the relation with the duration of the harmful disruption shown in figure 9. As the surface is dependent on the duration of that segment, there will be a strong correlation between the two. This is shown again in the difference between weather scenarios.

The positive message from figure 10 is the direct reduction in surface seen in the scenarios *Severe Long* and *Medium Long*. Its a sharper contrast compared with the improvements seen in the duration where improvements were only seen at high penetration rates. Here it is obvious that synchromodality helps to reduce the delays for severe drought.

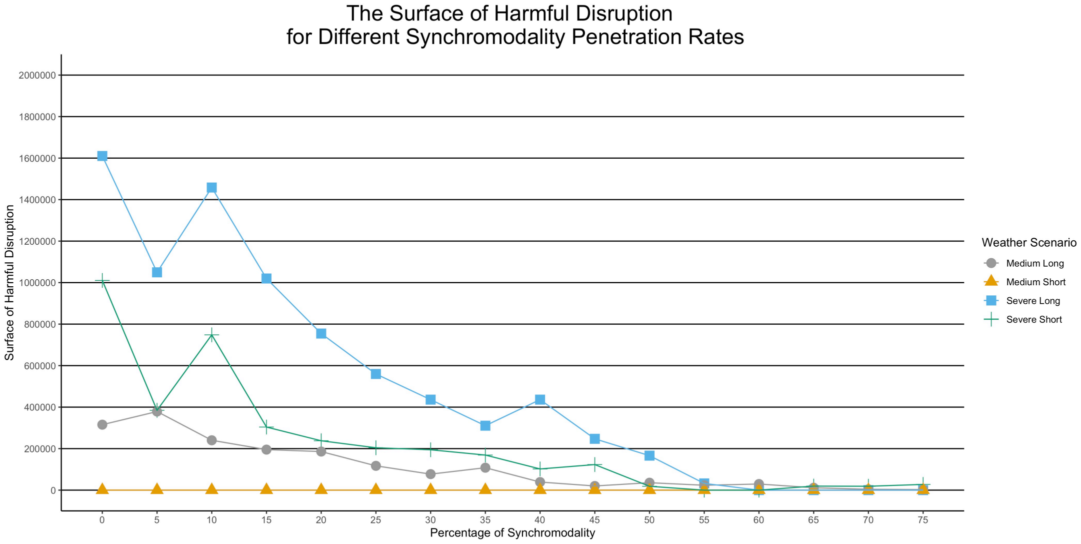

Figure 10: The Surface of the Harmful Disruption

6 Discussion & Results

6.1 Impact of Synchromodal Transport on Resilience

The research investigated the impact of Synchromodal transport during drought disruption. We measure the resilience for different penetration levels within freight goods. Our findings show that the benefit of synchromodal transport is to reduce the impact of a drought, but that the disruption requires a high level of synchromodal penetration. Furthermore, we found that the severity of the disruption is linked to the severity of the disruption, and that the transport system can handle minor disruptions.

On the Plausibility of Synchromodal Transport However, we would like to iterate that the adoption of Synchromodal transport is disputed. First of all, its current adoption is very limited - which can be linked to the novelty of the concept. On top of this, there are technological as well as collaboration barriers to overcome. For example, a great deal of live-data data is needed, and the infrastructure the measure this must still be installed [**?**]. Furthermore, stakeholders must be willing to share this data but many companies are reluctant to share this data with their competitors [**?**]. Interestingly, a recent case study on the success and failure factor pointed out the gap between the optimism of academics and the pessimism of stakeholders on the transport concept [**?**]. This supports our skepticism of its wide spread adaption.

6.2 Limitations of findings

There are a few limitations to these findings.

The major limitation is the high level of abstraction that our model took. Indeed, our model always assumes that if capacity is free, it will be available. On top of that, freight is able to select a transport modality very late which makes the effect benefit of synchromodal transport higher.

Next to the biases towards synchromodal transport, our findings offer no insights on the bottlenecks within the supply chain, or relevant information to policy makers as to how synchromodal transport can be improved. As such, these results should be seen as an indication as to what synchromodality can do. Here we showed that it will most likely not avoid the disruption, but it can limit the impact it has.

6.3 Future Research

We suggest that future research on synchromodal transport should focus on how it can be implemented and less on showing the benefits of the concept. We make this suggestion as there is a gap between between the literature being fund of this concept, but the industry disputing it because of contractual barriers. Hence the knowledge gap lies less on the potential benefit, but on how to make it work. Doing so would require an understanding of which stakeholders would be interested in using the concept and then investigating their barriers or bottlenecks.