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Opportunities and limitations of network analysis for the Belgian multimodal transport of freight:

A case study analyzing the impact of the Brexit on the Belgian transport flows between 2018 and 2022

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Preface

It is with great pleasure that I present this thesis, which explores the usage of multimodal transport and seeks to provide a valuable tool to analyse the Belgian fright transport sector. This work could not have been realized without the guidance, support, and expertise from individuals and institutions that I received throughout the redaction.

The aim of this thesis is to develop an application that can be utilized by various stakeholders to analyze and assess the Belgian transport sector, thereby helping them in adjusting their policies accordingly. By leveraging the power of aggregated monthly transport data between 2018 and 2022, generously provided by Statbel, this application will help users to visualize, analyze, and interpret the intricate flows of transported freight through Belgium.

I would like to express my deepest gratitude to my supervisor, Prof. An Carbonez, and my co-supervisor, Febe Brackx, from KU Leuven for their support and guidance throughout the entire thesis journey. Their expertise and encouragement have been instrumental in shaping the research direction and refining the methodology employed.

I am also immensely grateful to my mentors, Kjell Jacobs and Steven Dubaere from Statbel. Their invaluable insights, suggestions, and technical expertise have enriched this thesis and helped transform ideas into reality. Their unwavering commitment to academic excellence and dedication to the field of transport analysis have been truly inspiring.

Additionally, I would like to extend my heartfelt appreciation to the entire faculty and staff at KU Leuven and Statbel for fostering an environment conducive to learning, innovation, and academic growth. The resources, facilities, and support provided have been vital in conducting this research and shaping the outcomes.

I cannot end this preface without thanking my friends and family. I could always rely on their support and encouragement to overcome the challenges along the way.

Summary

This research paper applies a network analysis on multimodal freight transport through Belgian ports, focusing on the impact of Brexit on the Belgian transport sector. This study uses a Shiny App to visualize, analyze and interpret the flows of freight. Initially applied on waterways, the application could be used for other modes of transportation like trains and road.

The research question focuses on exploring the opportunities and limitations of utilizing network graph analysis on the multimodal freight transport network by using Brexit as a case study. Given that Brexit has implications for trade and transportation, especially regarding the Irish border, the usage of network analysis becomes a valuable tool to interpret shifts in trade flows and identify important ports (nodes) or water segments (edges).

The literature review examines the usefulness of generating multimodal transport data and highlights the distinctions between multimodal and intermodal transport. The literature review also looks at research on the impact of Brexit on freight transportation and expresses that a network analysis on the freight transportation aspect of Brexit is needed. To address this need, this study uses aggregated monthly transport data from Statbel to construct a network graph representing the multimodal freight transport system. The methodology involves processing the data using the R programming language and relevant libraries for visualization and network analysis. Ports are represented as nodes, while connections between ports are represented as edges in the network graph. Metrics such as degree centrality and betweenness centrality are used to assess the importance of ports and segments within the transportation system.

The results section presents the findings of two case studies. The first case study examines the impact of Brexit on shipping through Belgian ports, by inspecting the number of ports, connections, and freight volumes between Belgian, Irish, and UK ports between 2018 and 2022. The second case study investigates the effects of removing a critical node in the network, revealing an alternative route and shift in the flow. The research concludes by emphasizing the potential of network graph analysis in comprehending multimodal freight transport networks and providing valuable insights for policymakers, stakeholders, and researchers. An extensive list of suggestions for furture research can also be found in the conclusion paired with the limitations of this study.

List of Abbreviations

BE	Belgium
CLMS	Copernicus Land Monitoring Service
IE	Ireland
RORO	Roll-on Roll-off
Statbel	The Belgian statistical office, Statistics Belgium
UK	United Kingdom
UN	United Nations

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1 Introduction

In recent years, multimodal and intermodal freight transport gained in momentum. Multimodal and intermodal freight transport both involve the use of multiple modes of transportation, such as road, rail, and sea, to move goods from their point of origin to their final destination [1]. Although the terms are often used interchangeably, there are subtle differences between them. Multimodal transport involves a single carrier responsible for the entire transportation process, whereas intermodal transport involves multiple carriers, each responsible for a different mode of transportation [1].

The interest in multimodality is reflected in several initiatives by federal and regional institutions like Statbel. The Belgian statistical office, Statistics Belgium (Statbel), is the official and national statistical institution of Belgium, operating within the Federal Public Service Economy. Statbel collects, processes, and distributes reliable and relevant figures about the Belgian economy, society, and territory. Federal institutions such as the Planning Bureau and the FPS Mobility are active users of Statbel's data for feeding all kinds of models, needed to support policy measures. The same goes for regional institutions in terms of designing policies in their areas of competence. For example, the Flemish government set up 'Multimodaal Vlaanderen', with the aim of helping to absorb the growth in freight transport predicted by the Federal Planning Bureau [2].

The interest in multimodal and intermodal transport already appeared in the European Commission's 2011 White Paper. This states that the European transport sector should become more sustainable: consuming less and cleaner energy and using more efficient transport networks [3]. Eurostat is now looking into the possibility of setting up a task force on intermodal transport to gain a better understanding of the transport chain [2] and drives towards a more competitive and sustainable transport system [3]. To reach this goal, they will need to possess information on all modes of transport and on their environmental impact. This particular attention from the European Commission is not a surprise because the transport sector has an economic importance but also a political and environmental one.

The multimodal chain is first and foremost an economic reality. The economic sector and individual companies like seaports need multimodal data to develop economic models and insights into new market opportunities. Railway companies, key players in the transition to a greener transport model, require such data for setting performance targets. Several major transport groups no longer operate purely within 1 transportation mode but offer their customers full multimodal handling of goods [2, 4].

The Irish case is particularly relevant in the context of Brexit's impact on the freight transportation sector due to the unique challenges it presents. As the only land border between the United Kingdom and the European Union, the Irish border has become a point for potential disruptions in the movement of goods [5].

Research question

The aim of this thesis on multimodal transport is to provide a tool that could be used by the different stakeholders to analyze the European transport sector and help them adjust their policy. Using aggregated monthly transport data for the 2018-2022 period provided by Stabel, an application will be built to help visualize, analyze, and interpret the flows of transported freight through Belgium. Using the R package "Shiny" a web application will generate graphs representing the flows of freight that pass through Belgium based on several properties like the type of goods of the transportation mode. Using a network analysis, the application will be able to give insights into the evolution of transport routes (edges) and the evolution in the importance of actors like ports or trading partners (nodes). The application will first be built using only the data for Belgian waterways but could be scaled using European data and data from other transport modes (train, aviation, pipeline).

To assess the opportunities and limitations of this tool, this study will use Brexit and a hypothetical disruption of the Albert Canal as case studies. The United Kingdom and Irland are among the biggest trading partners of Belgium, this thesis will try to measure what impact Brexit had on the Belgian Multimodal freight transport network.

A network graph is a visual representation of connections between objects (here ports), which are referred to as nodes or vertices, and the relationships between them, represented by lines or edges. They provide a powerful method of visualizing and analyzing complex relationships in data. They offer a means of breaking away from the constraints of tabular data, allowing us to comprehend the underlying structure and interconnectivity of the data. This analysis makes it possible to identify major nodes (ports) and major flows of freight and thus adjust policies accordingly. This analysis could for example measure that the flow of goods from the United Kingdom (UK) did not drop but partly has been replaced by Irish ports. Having now a greater cost when exporting goods to Belgium, companies could opt for cheaper transport modes and thus other routes. Being able to notice and interpret such shifts in routes could help adjust policy when developing new infrastructure.

2 Literature review

2.1 Statbel's prior analysis

The original idea for the topic of multimodal transportation stems from two internal documents produced by Statbel. At the start of 2018, Dubaere et al. wrote a document in which the team working around transportation and mobility would assess the feasibility of generating multimodal data and statistics. As Statbel already collects data from the different transportation modes (aviation, rail, road, and sea) and sends the aggregated data to Eurostat, they wanted to evaluate the potential to link these different data sources. Multimodal data is thus here the data of the different transportation modes linked together Multimodal statistics from their point of view are descriptive statistics measuring the proportion of goods passing through important actors like ports. In their report, Statbel's team lists which steps are needed to be able to link the data sources together and which quality aspects of the data should be improved [4].

A couple of months later, Statbel's team wrote a new report about the feasibility of producing multimodal statistics. In this report, they showed how the Belgian Sea transportation could easily be linked with the inland waterways as the same geographical nomenclature is used. As these two modes represent the biggest volume of goods being transported in Belgium, they proposed to have a first layer of multimodal water transport to which the other transportation modes could be added [2]. This report also shows extensively the opportunities for generating multimodal transport statistics and provides Statbel with a plan to analyze multimodal transport in Belgium.

2.2 Multimodal and intermodal freight transport

Multimodal transportation is often more expensive than intermodal transportation, but it provides an enclosed, all-inclusive solution where a single business addresses all the shipper's needs [6]. On the other hand, intermodal transportation allows shippers to optimize routing and total shipping costs by leveraging the individual expertise of multiple carriers [1]. As Statbel collects data from the ports and not from the carriers, there is no way to make the distinction between multimodal and intermodal freight transport in this research and the term multimodal will be used to refer to the usage of multiple modes of transportation.

Both intermodal and multimodal transport benefit from the most efficient combination of several means of transport, which optimizes lead times, reduces inventory costs, and keeps freight prices under control [7]. However, the adoption of multimodal and intermodal transport faces challenges such as inadequate infrastructure, regulatory barriers, and coordination issues among different transport stakeholders [8]. Therefore, it is essential to address these challenges to unlock the full potential of these transportation methods. Key literature in this area focuses on the advantages of these transportation methods, including reduced environmental impact, increased efficiency, and cost savings [1, 6]. Studies have also explored the role of logistics service providers, transport infrastructure, and policy in facilitating the growth of multimodal and intermodal transport [8].

2.3 Network graph analysis in transportation studies

Network graph analysis is a powerful tool used in transportation studies to model and analyze complex transportation systems. It involves the representation of transportation networks as graphs, with nodes representing locations and edges representing connections between them [9]. This method allows researchers to analyze and optimize various aspects of transportation systems, such as accessibility, robustness, efficiency, and vulnerability [10, 11].

Key literature in this area includes studies that apply network graph analysis to understand the structure and dynamics of transportation networks [12, 13, 14], as well as those that focus on the application of graph analysis to specific transportation modes, such as maritime [15] and rail [16]. In the context of freight transport, network graph analysis has been used to examine the structure and efficiency of transport networks, identify critical links and nodes, and evaluate the resilience of the networks to disruptions and uncertainties [13, 17].

Recent advancements in computational methods and data availability have allowed researchers to incorporate more complex and realistic features into their network graph models, such as multiple transport modes, time-varying demands, and stochastic disruptions [13, 12].

As summarized by He et al. in 2021 in their paper about the robustness of the Dutch multimodal freight transport network, researchers have been studying transportation networks under different scopes [18]. He et al. (2021) categorize a dozen papers based on the transportation mode they analyze the robustness metric and the perturbation type they use. Out of this summary, He et al. conclude that network analysis on transportation is less common for multimodal networks than for unimodal networks (2021) [18]. Therefore, He et al. (2021) proposed an approach on network modelling and robustness assessment for multimodal freight transport networks, where the nodes represent junctions, terminals, and crossings, and the links represent pathways. Freight can thus switch between different modalities at interconnected terminals. They also consider disruptions of infrastructure elements and capacity degradation of pathways as perturbations. They finally compute the node criticality, defined as the impact of a node removal on the total travel time. Taking this approach, He et al. were able to show that the Dutch multimodal freight transportation network is relatively robust against single random disruptions. They also claim that their research helps to schedule the maintenance of the transportation network by assigning priority to the critical infrastructure [18]. This research has a similar approach with the exception that the nodes only represent ports and not terminals as only transportation using ships is studied.

2.4 Previous research on Brexit's impact on the freight transportation sector

Brexit, the United Kingdom's decision to leave the European Union, has affected multiple sectors of activities. Previous research has for instance focused on the security aspect like Black et al. in 2017 [19] or the change in the labour market like Fetzer and Wang (2020) [20]. More specific to the freight transportation sector, the Irish case is being researched as the Irish border has become a focal point for potential disruptions in the movement of goods [5].

The Irish border's importance lies in its role as a critical link for cross-border trade and transportation between the UK and Ireland, as well as between Ireland and the rest of the EU. The potential for increased customs checks, regulatory barriers, and delays poses significant risks to the efficiency and reliability of freight transportation across the border [21]. Additionally, the Good Friday Agreement, a peace agreement between the UK and Ireland, further complicates the matter by mandating minimal disruption to the border's status [22]. As a result, understanding the potential impacts of Brexit on the Irish border and the freight transportation sector is crucial to develop adaptive strategies and maintaining smooth cross-border trade and transportation flows in the region.

Some research has explored the implications of Brexit on specific transport modes and corridors, such as the Channel Tunnel and the Irish border, highlighting the vulnerabilities of these critical links in the transport network [22, 21, 5]. A few studies have examined the post-Brexit reconfiguration of transport networks and the potential shifts in trade flows and logistics patterns [23, 24, 25]. These studies have provided valuable insights into the possible adaptations of the freight transportation sector in response to the new trade and regulatory environment.

The literature on Brexit's impact on the freight transportation sector remains limited and fragmented, with most studies focusing on specific aspects or case studies. Therefore, a comprehensive and systematic analysis of the post-Brexit changes in the freight transport networks, is needed.

3 Data

This research aims to analyze the multimodal freight transport network using Statbel's data, focusing on (sea)ports as nodes and connections between them as edges. The study incorporates data from the Copernicus Land Monitoring Service and the United Nations to generate a network of routes. The analysis explores the degree centrality, shortest paths, and other network properties to better understand the transport system. The impact of Brexit on the transport of freight between Ireland and Belgium will be used as a case study to assess the method's opportunities and limitations.

3.1 Data variables and sourcess

To gain a good understanding of the goods flows, it is essential to have a clear picture of them per transport mode. Thus, the first intent of multimodal statistics is not to track individual goods but to gain insight into the flow of goods to and from these economic poles, as explained by Jacobs et al. (2019) [2].

As a starting point, water transport is taken as exhaustive quality data sources are available. The starting point is the incoming sea tonnages since the final destination of the freight is known for the vast majority of them. For freight shipped by sea to other parts of the world, the final destination is sometimes still unknown on departure from Belgium. The goods are only sold on the ship and will only then know their final destination. The link between sea and inland navigation can be made quite easily as the final destination are for both coded in the same geographical nomenclature, namely the UN/LOCODE [2].

Description	Type
Source port	nominal
Destination port	nominal
Type of freight	categorical
Date	continuous
Gross weight in tonnes	continuous
Port coordinates	geometry point
Shortest route	geometry linestring
Degree centrality	continuous
Country	categorical
River/ Canal segment	nominal
Betweenness centrality	continuous
Length in meters	continuous
Passed tons	continuous
Type of waterway	categorical

Table 1: List of variables with their type

Statbel is already legally obliged by European regulations to produce several transport statistics on the different modes of transport: aviation, rail, road, maritime and inland waterways. All transport statistics are produced at their premises, including data collection and processing [4]. For this research, only the maritime and inland waterways are used because unfortunately the other modes of transport cannot be linked to the maritime and inland waterways data yet. Steps are taken by Statbel to resolve this issue. From Statbel we get access to aggregated monthly data about goods transported through Belgian (sea)ports. In Table 1, a description of the used variables can be found.

From Statbel we get access to aggregated monthly data about goods transported through Belgian (sea)ports. We thus already gathered the variables: Source port, Destination port, Type of freight, Date, and Gross weight of goods in tonnes. The port of departure and arrival are necessary to create the nodes of the network while the type of freight and tonnage are used to create the edges of the network. The dates will be used in an iterative process to track the evolution of importance of ports and routes. The type of freight is crucial as ports are specialized in specific markets, and consequently have facilities and infrastructure to transport the specific freight. Zeebrugge, for instance, is Europe's most important Roll-on Roll-off (RORO) port, partly due to its storage capacity for rolling stock and its ability to quickly move it deeper inland by rail. The port of Antwerp is strong in the petrochemicals market, among other things, partly due to the presence of large petrochemical facilities and its extensive pipeline network [2].

The coordinate of each port is necessary to be able to generate routes between (sea)ports. As Statbel uses United Nations' (UN) LOCODES to code the ports of origin and arrival for transported goods, we could easily find the coordinates for most ports trrough the UNLOCODE list. International trade relies heavily upon the clear identification of key data such as the traders involved, the goods being exchanged, and the locations related to the movement of the goods. The United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT) maintains and develops an unambiguous coding method to identify locations linked to international trade called the United Nations Code for Trade and Transport Locations (UN/LOCODE) [26].

This research used Copernicus Land Monitoring Service (CLMS) geofiles to help compute routes between two ports. The CLMS is a part of the European Union's Earth Observation Programme. CLMS offers essential geographical information on land cover, land use, vegetation state, water cycle, and earth surface energy variables. It serves a wide range of users in Europe and worldwide, particularly in the field of environmental terrestrial applications [27]. CLMS provides us with segments of all the waterways in the Rhine and Seine basins with their length and type (River, canal, or coast). From the network graph this research can compute the number of tons that passes through a waterway and what its betweenness is.

3.2 Time period

The study uses longitudinal data, making it possible to plot the evolution of connections for each desired (sea)port over time. The time period of the data is starting from January 2018 until March 2022 to cover both pre-Brexit and post-Brexit periods to assess the impact of Brexit on the Belgian Multimodal freight transport network. The Brexit official date is February first, 2020 and because this research uses monthly data, the end of the pre-Brexit is set to January 2020. Data from April 2022 to December 2022 is missing as Statbel's transport data is being collected, processed, controlled, and published per trimester with a delay of six months.

4 Method

4.1 Overview of the method

An R Markdown pipeline has been used to process and analyze the data. The code is developed using the R programming language, with libraries such as igraph, tidygraph, dplyr, ggplot2, leaflet, and shiny for graph theory and geospatial data processing. Custom functions are created to pre-process the data, generate nodes and edges, and analyze the networks. An interactive Shiny App is also developed to facilitate visualization, analysis, and interpretation of the results. A R Markdown script can be found in the appendix and on GitHub together with dummy data to test the Shiny App [28].

The data pre-processing and analysis steps involve cleaning, filtering, transforming, and analyzing the data to generate relevant network graphs and statistical measures. Data visualization techniques include geospatial visualization of the network using network graphs, heatmaps of betweenness centrality for edges, Sankey diagrams for descriptive tonnage, and scatterplots for evolution over time. The quality of the data pre-processed data is guaranteed by Statbel's rigorous quality-checking data pipeline in SAS. For the network analysis, the validation will be done with a case study assessing the impact of Brexit on the Belgian multimodal freight transport network. By describing the evolution of network properties (number of nodes, number of edges, importance of ports and routes) before and after Brexit, we hope to find results that match the literature around Brexit.

4.2 Building networks

Network graphs, also known as graph theory, are a fundamental part of data science and statistics. A network graph is a visual representation of connections between objects, which are referred to as nodes or vertices, and the relationships between them, represented by lines or edges. These can be used to represent a wide array of real-world systems, such as social networks, web pages, biological networks, and indeed, transportation systems [29].

4.3 A simple network as an example

Creating a network graph from a standard tabular dataset involves several steps. The first step is to identify the nodes, which are the individual entities in the system. The edges, or connections between nodes, are the interactions or relationships that exist between these entities. In the tabular dataset, each row usually represents an interaction, and it contains the identifiers of

Source	Destination	Type of freight	Tonnage
Southampton	Antwerp	RORO self-propelled	93122
Southampton	Zeebrugge	Container	113
Antwerp	Southampton	RORO self-propelled	4748
Zeebrugge	Southampton	Liquid bulk	4441

Table 2: Simple dataset with three ports

the interacting entities. With this information, we can construct a network graph where the nodes represent the unique entities, and the edges represent the relationships [30].

The adjacency matrix is a square matrix used to represent a finite graph. The elements of the matrix indicate whether pairs of vertices are adjacent or not in the graph [29]. In the case of a freight transportation network, an adjacency matrix can be used to represent which ports are directly connected by a route. Let's start with an example:

First, we create a list of the unique ports from Table 2 to serve as our nodes: Antwerp, Zeebrugge, and Southampton. The adjacency matrix is a square matrix where the size is equal to the number of nodes. In this case, it would be a 3x3 matrix. Each row and each column represent a port, and the intersection represents the connection (or edge) between them.

Initially, we fill the adjacency matrix with zeroes, assuming no connections. Then we iterate over our table data. Each row in the table represents an edge. For example, in the first row, we have a route from Southampton to Antwerp. We find the corresponding cell in the matrix and set the value to 1, indicating a direct connection. For undirected graphs (graphs for which the direction has no importance), the adjacency matrix would always be symmetrical.

From To	Antwerp	Zeebrugge	Southampton
Antwerp	0	0	1
Zeebrugge	0	0	1
Southampton	1	1	0

Table 3: Adjancy matrix simple dataset unweighted

Our adjacency matrix can be found in Table 3. This matrix forms the basis of our network graph. Nodes represent ports and edges represent direct connections between ports. In the case of a weighted network graph, such as ours where we have properties like the volume of freight and the type of freight, the adjacency matrix can be modified to contain these values instead of just ones. For example, replacing the 1 between Southampton and Antwerp with 93122 to represent the tonnage of freight transported from Southampton to Antwerp results in Table 4.

From To	Antwerp	Zeebrugge	Southampton
Antwerp	0	0	93122
Zeebrugge	0	0	113
Southampton	4748	4441	0

Table 4: Adjancy matrix simple dataset weighted

Now a network graph in Figure 1 can be built where nodes represent the ports themselves, while the edges represent the routes between these ports. The edge attributes are in this case the type of freight and the volume being transported along that route.

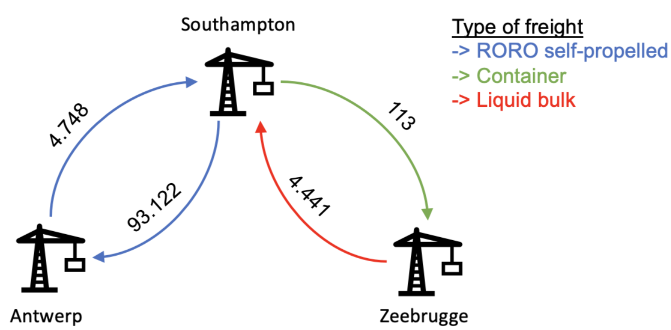

Figure 1: Network for simple dataset

This network clearly shows that we have a directed weighted graph with three nodes and four edges. The edges are weighted by using the tonnage of freight being transported and the type of freight is visualized with a specific color. By creating a network graph of this information, we gain a visual tool that allows for an intuitive understanding of the freight routes and their characteristics. We can immediately see which ports are directly connected, what type of freight is transported along which route, and the volume of freight that is being moved.

4.4 Three-step-process

This study follows a three-step process to generate an interactive multimodal transport network with routing for freight transport.

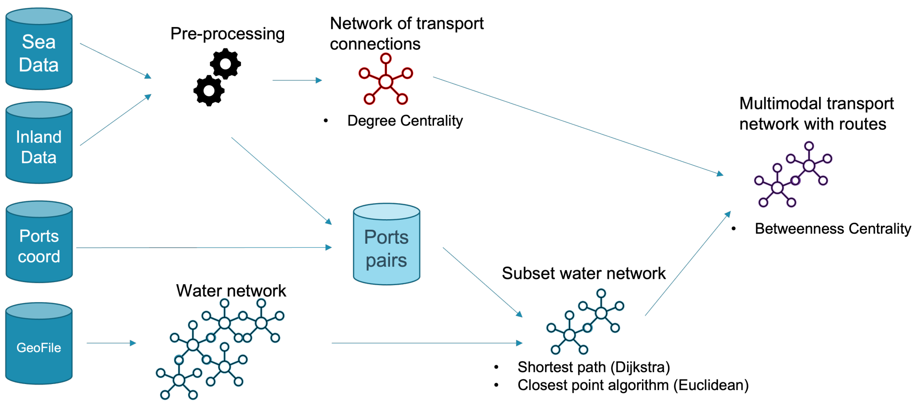

Figure 2: Pipeline

Step 1: Conversion of Statbel's data into a basic multimodal network of connections between ports In this step, the tabular dataset is transformed into a network graph, with ports as nodes and connections between them as edges. This network allows for the computation of informative metrics, such as degree centrality, which measures the number of edges or connections a node has, indicating its importance within the network. The number of edges is in this context the transport of a specific type of freight between a pair of ports [31]. This metric, therefore does not differentiate between the type of freight or the direction of the transport. The degree centrality could also be computed to differentiate between import and export or type of freight and also alternative formulas for the degree centrality like the weighted degree exist.

A port can have a large degree centrality by exporting and importing goods to and from many ports. The amount (tonnage), value, and frequency during the month is not relevant for this metric. However, the type of freight is important as each type of freight accounts for a different connection and increases the degree centrality by 1. The more types of freight are being transported through a port, the higher its degree centrality. The formula for the degree centrality used in this study is a simple version:

$$k_i = C_D(i) = \sum_{j}^{N} x_{ij}$$

where i is the focal node, j represents all other nodes, N is the total number of nodes, and x is the adjacency matrix, in which the cell x_{ij} is defined as 1 if node i is connected to node j, and 0 otherwise [32].When the adjacency matrix is weighted, x_{ij} can also be different from 1. In our case, each separate type of freight can count as a different edge meaning that the x_{ij} corresponds to the number of different freight types being transported between i and j.

By iterating the process for each month, an evolution in connections through time can be found. This helps the user to see similarities, disparities between ports in their evolution of the number of connections. For example, cyclical patterns due to seasonality were monitored by visual inspection. However, the importance of a port is not only depending on the number of connections. For example, the amount of tonnage being handled by a port also measures its importance. Another way of evaluating the importance would be by measuring how much freight is passing through a port or waterway. In 2021, the world saw how the obstruction of the Suez Canal by the Evergreen impacted the transportation of freight [33]. However, this network does not incorporate the routes freight are following.

To evaluate the importance of a waterway using this approach would require the computation of the betweenness centrality. The betweenness centrality is a measure that captures a completely different type of importance: the extent to which a certain vertex or edge lies on the shortest paths between other vertices. In other words, it helps identify individuals and route segments who play a "bridge spanning" role in a network." [34]

$$c_B(e) = \sum_{s,t \in V} \frac{\sigma(s,t|e)}{\sigma(s,t)}$$

where V is the set of nodes $\sigma(s,t)$, is the number of shortest (s,t)-paths, and $\sigma(s,t|e)$ is the number of those paths passing through edge e [35]. Note that this specific formula is the variant for compting edge betweenness as this is the one useful for this research.

As mentioned in the formula, the betweenness centrality needs shortest paths to be computed. In the current network, there are unfortunately no meaningful ways to compute (shortest)paths. In the current network, a route is a path using the edges between pairs of ports. For example, to go from Leuven to Mechelen, the current path goes through Antwerp because there are no connections between Leuven and Mechelen but there is a Leuven -Antwerp connection and a Mechelen-Antwerp connection. In other words, a path corresponds to a chain of connected ports and not to a navigable route between the ports. A second issue is that there is no actual value to compute the distance between two ports in the current network. The shortest path needs a metric to evaluate which route is the shortest. Shortest does not explicitly mean that the route should be the shortest in distance but it could also be the shortest in time or monetary cost. We thus need a new multimodal network for the transportation of freight that has information about routes and distances.

Step 2: Generation of a waterways network subset In step 2, using coordinates fetched from the United Nations, and Geofiles gathered from Copernicus, a waterways network is generated. The Rhine-basin and Seine-basin geofiles already had a network graph structure but each river and canal is cut into small segments resulting in a waterways network too big to make quick computations. It is thus imperative to reduce the amount of segments in the waterways network as pathfinding algorithms take a lot of time to compute.

Reducing the number of segments is achieved by first generating a list of all possible pairs of ports with their coordinates. Secondly, for each pair, the closest segment from the waterways network to each port is found by finding the segments with the smallest Euclidean distance to the port.

Once these two segments are found, the shortest path between these two segments (representing the two ports) is computed with Dijkstra's algorithm using the actual length as weights. In this research, the shortest path corresponds thus, with the route with the shortest distance while other approaches are possible like using time or cost. When this is done for all the possible pairs of ports, only the segments used at least once as on a shortest path are kept. Dijkstra's algorithm, named after the Dutch computer scientist Edsger Dijkstra, is a popular algorithm used in graph theory to find the shortest path between two nodes (or vertices) in a graph [36]. The Dijkstra algorithm is greedy as it makes the locally optimal choice at each stage with the hope that these local choices will lead to a global optimum [37].

Now that a smaller and computable subset of the waterways network is available 3, it is manageable to combine the first multimodal network of connections together with the waterways network in the following step. This process is only done once.

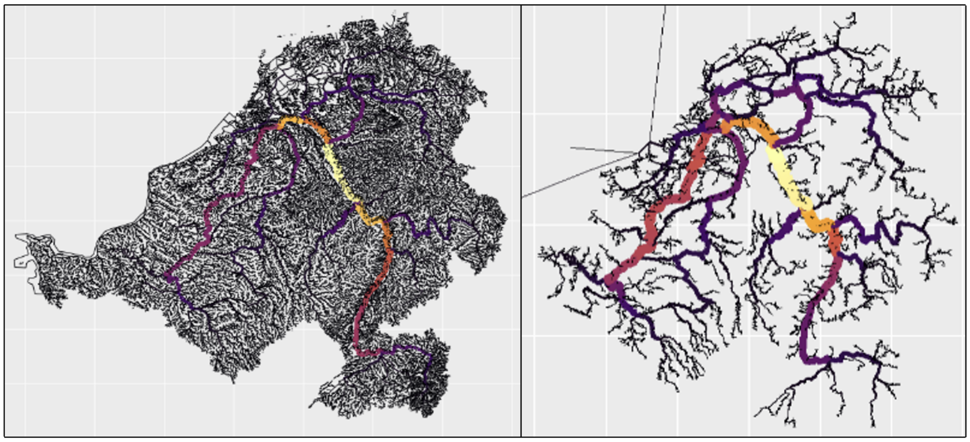

Figure 3: Underlying waterways network before and after step 2 colored with betweenness centrality for each segment

Step 3: Final multimodal freight transportation network with routes In step 3 we combine our first multimodal network with the waterways network to produce the final multimodal network containing the routes. This way, we get more insights into the importance of some ports and some water segments.

A first custom function takes the final waterways network from step 2 and changes the weights of route sections based on the user's choice. The user can change the weight of a port or waterways segment to be infinite such that the usage of this port or segment becomes impossible. It returns the new network graph with the new weights as well as the heatmap of betweenness for this new network. The color and size represent the betweenness value and higher values indicate more significant segments.

Another custom function combines the prepared data frame (step 1) together with the returned waterways network and returns a multimodal network graph containing the shortest route as well as the tonnage passing through each route segment.

5 Results

This section presents the findings of two distinct case studies: the initial one exploring Brexit's effect on freight transportation through Belgian ports, and the subsequent one analyzing the implications of node removal within the network.

5.1 Case Study 1: Brexit's impact on Belgian freight transportation

Brexit's influence permeates numerous sectors. This first case study meticulously examines its effect on the movement of freight through Belgian ports, specifically highlighting a subgraph that incorporates freight arriving from or delivered to Irish and UK ports. This focus stems from the anticipation of Ireland being significantly influenced by Brexit. It is possible to assess Brexit's impact in three ways. Because network graphs are generated for each month between January 2018 to March 2022, 1) an evolution can be seen in the whole network, and changes appear in the importance of 2) ports and 3) flows of freight.

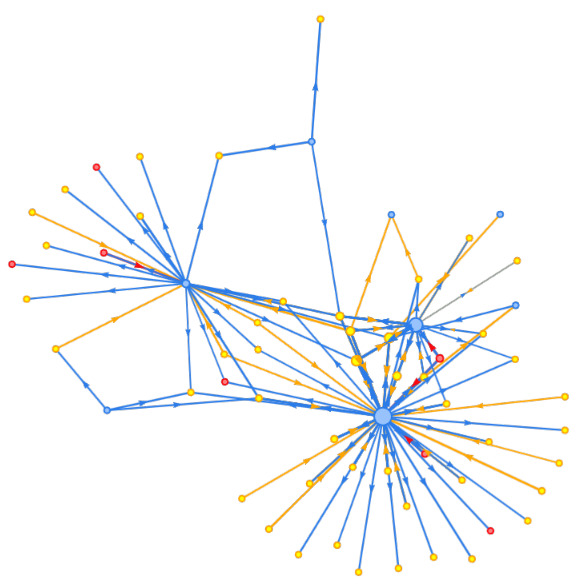

Figure 4: Network graph filtered with Irish and UK ports in January 2018 where blue, red, and yellow nodes represent respectively Belgian, Irish, and UK ports

A network graph containing only freight going through Belgian ports and filtered to keep Irish and UK ports can be seen in Figure 4. This specific network is generated using all types of freight in January 2018 and contains 62 nodes with 177 edges. The color of the edges corresponds with the color of the node of departure. In other words, a blue edge is a Belgian export. All 177 edges are not appearing as edges between the same pair of ports are lying on top of each other to increase the performance when rendering the graphs. Comparing 51 network graphs (January 2018 to March 2022) with each other is difficult and finding patterns or evolution would be tedious. Therefore, we can look at the centrality measures to gain more insights.

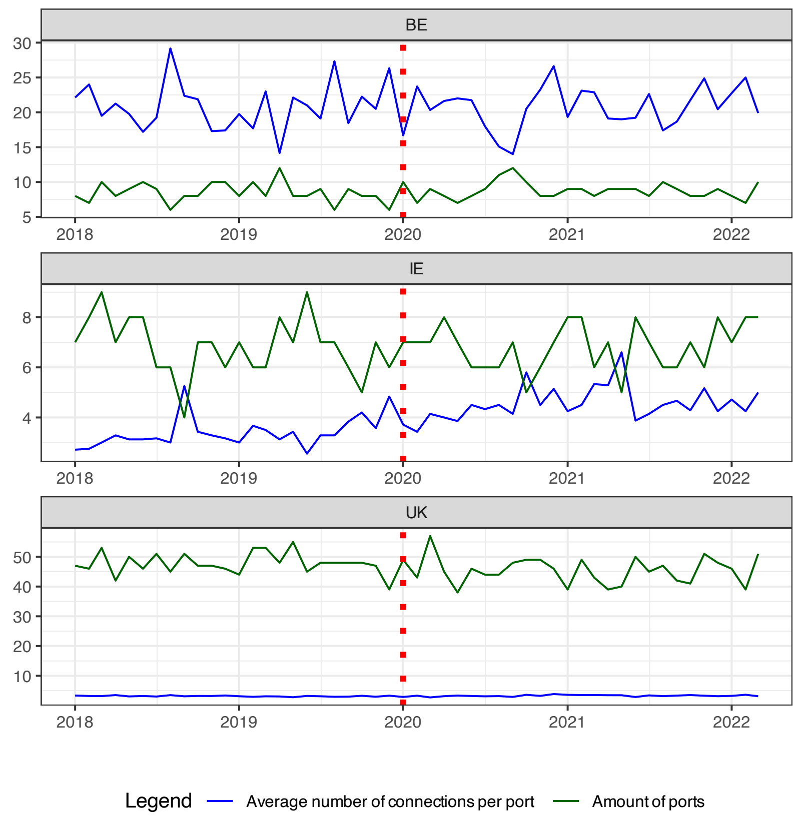

Figure 5: Evolution of amount of ports and average number of connections per port for Belgium, the UK, and Ireland

Figure 5 shows the evolution in the amount of Belgian, the UK, and Irish ports between 2018 and 2022 that appear in the network (green line). This corresponds with the number of nodes for each country in the network each month. The blue line shows the average number of connections per port for each country. This is measured by dividing the sum of the degree centrality for all the ports in the country appearing in the network by the number of ports for that country in the network. This figure helps understand Figure 4 when looking at January 2018. For instance, we only find 8 Belgian, 7 Irish, and 47 UK ports on the network graph for a total of 62. From Figure 5 we clearly see from the average number of connections for Belgium that the data only shows freight being transported through Belgium. If our dataset had contained all the transportation of freight between Belgium, Ireland, and the UK, there would also be connections between Irish and UK ports increasing their average number of connections per port.

Looking at the evolution across time in Figure 5, we can see that the number of ports is not constant. The fluctuation can be explained by large ports like the port of Antwerp or Zeebrugge for Belgium that appear each month while smaller ports are occasionally missing as they did not handle freight going to or arriving from Ireland and the UK. However, there does not seem to be a systematic increase or decrease in the number of ports during the selected period. The average of connections per port seems to behave differently in each country. In Belgium, we remark a highly fluctuating average of around 20 which is not surprising given that Belgium has half a dozen of important ports that have connections with many Irish and UK ports. In the UK, we find the opposite as we have a steady average for a large number of ports. The Irish average of connections per port is the most interesting as it appears to be increasing over time pointing to the fact that Irish ports are increasing their number of connections with Belgian ports. When alayzing all the freight types together, it appears that the line for the number of ports and the average number of connections are negatively correlated. When the number of ports increases, the average number of connections decreases and vice-versa. This means that the ports that are being added to account for the increase have fewer connections than the average number of connections for that country which results in a decrease. As the number of connections represents the number of freight types, we can conclude that these fluctuations are due to freight-specific fluctuations.

Appendices A, B, and C show the average number of connections and the number of ports for respectively Liquid bulk, RORO self-propelled, and RORO non-self-propelled. These three freight types show a similar pattern post-Brexit. The average number of connections and the number of ports for Belgium stays stable while the amount of UK ports decreases slowly after Brexit. This decrease already appeared prior to Brexit for RORO self-propelled and RORO non-self-propelled. For Ireland, we find different results. For Liquid bulk, we can see the apparition of a third port and the average number of connections does not drastically change. For RORO self-propelled and RORO non-self-propelled, the average number of connections increased while keeping the same number of ports, meaning that Irish ports made new connections with Belgian ports. This should be visible when looking at the average number of connections in Belgium but given that the amount of UK ports decreased, while keeping the same average of connections with Belgium, this effect is being masked.

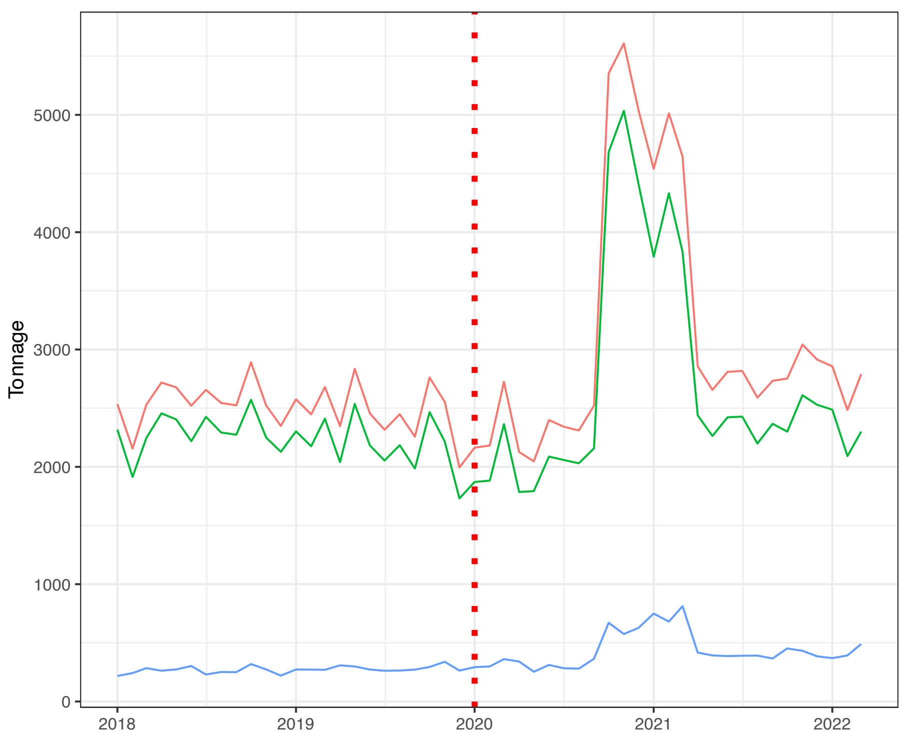

Figure 6: Evolution of amount of tons (in thousands) handled by Belgium (red), the UK (green), and Ireland (blue)

For the volume in tonnage in Figure 6 being handled by the Belgian, Irish, and UK ports, a similar pattern appears for all the freight types. A sudden increase in tonnage occurs between August 2020 and March 2021. However, this increase cannot be explained by a specific type of freight as it appears in each freight type. Next to this increase, the figure also shows a relative and absolute increase in volume handled by Irish ports meaning that Irish ports not only made new connections, but also transported more freight.

Instead of analyzing the countries, it is also possible to analyze the ports. Appendices D, E, and F show the number of connections Belgian, Irish and UK ports have. Note that the linear model and confidence interval and small ports are removed from the graphs to improve readability. In Belgium, only the port of Antwerp has an increase of connections that is accounted by an increase of Dry Bulk and RORO non-self-propelled connections.

In Ireland, a surprising increase in connections appears for the port of Cork that are explained by the investments made to enlarge the port and create new trading routes [38, 39]. These investments were used to develop the RORO self-propelled and non-self-propelled terminals and are also visible in Figure 11 , displaying the number of connections for the RORO freight types.

In the UK, the most interesting insight is that the ports of London, Southampton, Felixstowe, and Forth have an increase in their number of connections at the same time as the sudden increase of tonnage found between August 2020 and March 2021. This increase in connections paired with the increase in tonnage helps explain the reason for the sudden increase. Looking at the different types of freight in Appendix G it appears that the port of London had an increase in its volume of Containers while the port of Southampton saw an increase in the volume of Liquid Bulk in that same period. The port of Felixstowe and Forth both increased their volume in RORO and respectively handled more Liquid Bulk and Dry Bulk. The reason for the sudden increase in tonnage found between August 2020 and March 2021 is not explained by this method but strangely the origin of this phenomenon is different across the three countries. In Belgium, the increase of tonnage mostly appears in the ports of Antwerp and Zeebrugge where Zeebrugge handled the increase in RORO and Antwerp handled the increase in the other freight types. In Ireland, all the ports measured an increase in tonnage while UK ports showed a similar pattern as in Belgium, where ports that are specialized in a type of freight accounted for the increase in that freight.

Using Brexit as a case study, shifts in freight transportation flows could be detected. However, this study could analyze potential route alterations due to the model's limitation to inland routes. Looking at the routes in January 2018 and January 2022 where the color of the segments corresponds with the tonnage passing through the segment, it appears that more tonnage is coming from Ireland in January 2022. But changes in routes are not visible as both networks are using the same underlying network of waterways. For analyzing the impact of changing the underlying network of waterways a second case study is necessary.

5.2 Case Study 2: Node removal and its network Impact

The subsequent case study investigated the effects of eliminating a critical node from the network. The study focussed on a subgraph centered around the port of Genk in Belgium, chosen due to its proximity to the Albert Canal and the Maas River. The node identified for removal is located between the Kwaadmechelen and Hasselt canal locks, selected in light of the usage threats posed by recent summers droughts.

Flow Shifts and Alternative Routes

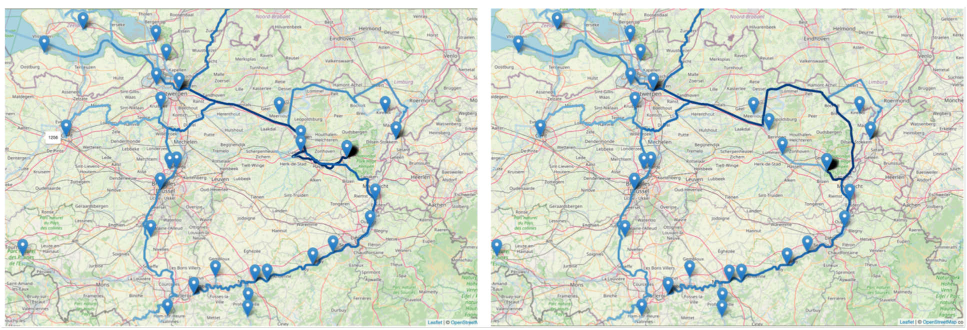

Figure 7: Routes before and after node removal

The node removal led to the discovery of an alternative route using other canals (Zuid-Willemsvaart & Bocholt-Herentals canal) and a visible shift in flow. Additionally, the predicted tonnage passing through different canal segments under the new network configuration was calculated increasing the tonnage from 15.000 tons to about 150.000 tons. The betweenness of the canal and river segments were altered. The segments of the Albert Canal that are not being used anymore, now have a betweenness of zero while the segments of the new route have a betweenness different from zero as they are being used. Other segments were left mostly unimpacted as the only change occurs due to the increased number of nodes in the segment (the new route passes through more nodes).

The betweenness is an interesting measure when looking at the whole network but this second case study shows that the tonnage passing through a segment is more interesting when looking at a specific case. A second insight from this case study is that the coordinates of the ports should be improved as the port of Genk is being localized in the city center and not next to the canal, resulting in an incorrect route utilizing a small river.

6 Discussion and Conclusion

In summary, this research demonstrates the potential of using network graph analysis to examine multimodal freight transport networks and unravel the impact of significant events like Brexit on cross-country transport flows. By combining data from reputable sources such as Statbel, Copernicus, and the United Nations, and employing network graph analysis techniques, a holistic perspective of the transport network and its intrinsic characteristics is obtained.

The findings of this research carry several implications for policymakers, industry stakeholders, and researchers. Armed with a tool to comprehend the repercussions of pivotal geopolitical events such as Brexit on multimodal freight transport networks, policymakers, and industry stakeholders are empowered to make well-informed decisions aimed at optimizing transport flows, mitigating disruptions, and fortifying the resilience of the transport network. Furthermore, the method developed in this research can be applied to other research contexts, providing a valuable tool for exploring the intricate interplay between diverse modes of transport in the context of global trade and commerce. Additionally, the research highlights the importance of incorporating network graph analysis in the study of multimodal freight transport networks. This approach allows researchers to gain a deeper understanding of the underlying structural attributes of transport networks, enabling the identification of critical nodes and edges susceptible to disruptions or necessitating further investment.

Despite the findings of this study, there are certain limitations that underscore the necessity for further research. Firstly, the research concentrates on the Belgian transport network, thereby introducing a limitation in terms of geographical generalizability. The distinct and unique characteristics of the Belgian network may limit the extrapolation of the findings to other countries or regions. Secondly, the methodological approach assumes that the degree centrality corresponds to the number of connections a port possesses within the dataset, which may not fully capture the complexity of the transport network. Furthermore, the analysis solely included ship transportation, neglecting the possibility of freight diversion to road or train routes in case of canal route inaccessibility. Routing predictions in the study were also based on the shortest distance principle, potentially overlooking the most cost-effective or time-efficient routes. Additionally, the study lacks inclusivity of all modes of transportation - notably road, rail, and air transport - thereby limiting its ability to accurately predict shifts in transportation patterns. Lastly, an improvement requirement was identified for enhancing the geographical precision of port localization within the model, illustrated by the inaccurate positioning of the port of Genk next to a small river instead of the canal.

As a proposition for future studies, researchers could attempt to extend the methodological approach to different countries or regions, thereby testing its applicability and generalizability in diverse contexts. This would provide valuable insight into whether the method holds robustness in different environments. Additionally, integrating more comprehensive network analysis metrics and techniques, such as clustering coefficients, modularity, and community detection, could help gain a more nuanced understanding of the transport network. Moreover, delving into the influence of environmental and economic factors on the multimodal transport network could prove crucial. For instance, investigating the potential effects of climate change, fluctuating fuel prices, or the impact of new regulations could offer deeper insights. Finally, expanding the scope to include other modes of transportation like road, rail, and air transport, would greatly enhance the predictive accuracy of transportation pattern shifts, making the study more comprehensive and universally applicable.

In sum, both case studies delivered insightful revelations about the structure and dynamics of the freight transportation network, while also signaling significant opportunities for further research to refine the understanding and modeling of these intricate systems. This research contributes to the understanding of the Belgian multimodal freight transport network and its response to significant geopolitical events such as Brexit. The proposed method offers valuable insights and can serve as a foundation for future research in this field. Network graphs provide a powerful method of visualizing and analyzing complex relationships in data. They offer a means of breaking away from the constraints of tabular data, allowing us to comprehend the underlying structure and interconnectivity of the data.

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Appendices

A Evolution of amount of ports and average number of connections Liquid bulk per port for Belgium, the UK, and Ireland

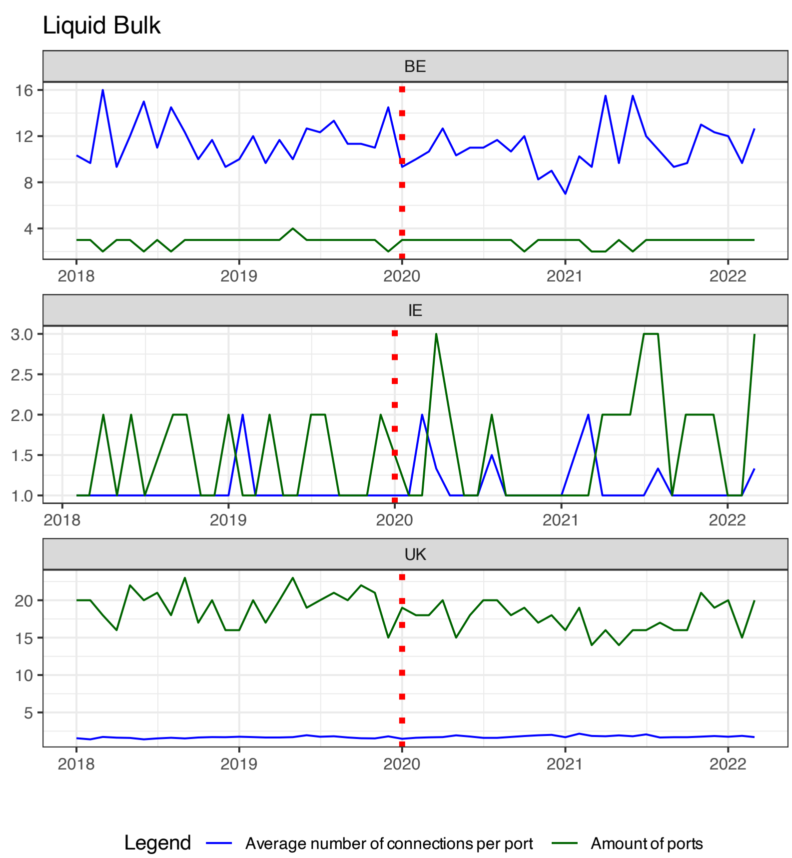

Figure 8: Evolution of amount of ports and average number of connections Liquid bulk per port for Belgium, the UK, and Ireland

B Evolution of amount of ports and average number of connections RORO self-propelled per port for Belgium, the UK, and Ireland

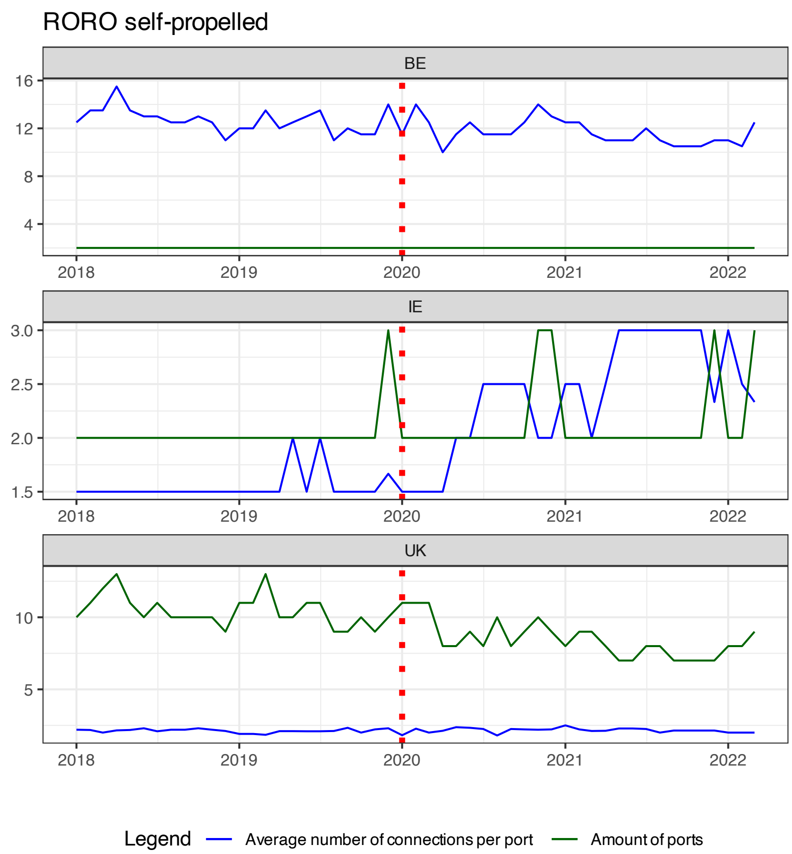

Figure 9: Evolution of amount of ports and average number of connections RORO self-propelled per port for Belgium, the UK, and Ireland

C Evolution of amount of ports and average number of connections RORO non-self-propelled per port for Belgium, the UK, and Ireland

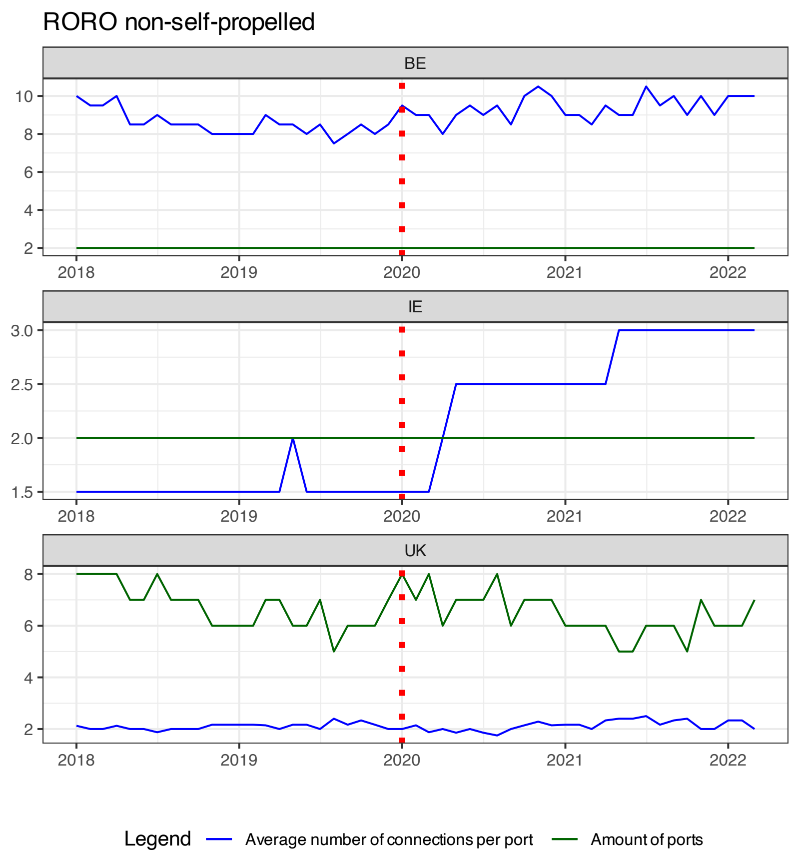

Figure 10: Evolution of amount of ports and average number of connections RORO non-self-propelled per port for Belgium, the UK, and Ireland

D Evolution of amount of ports and average number of connections for Belgium ports

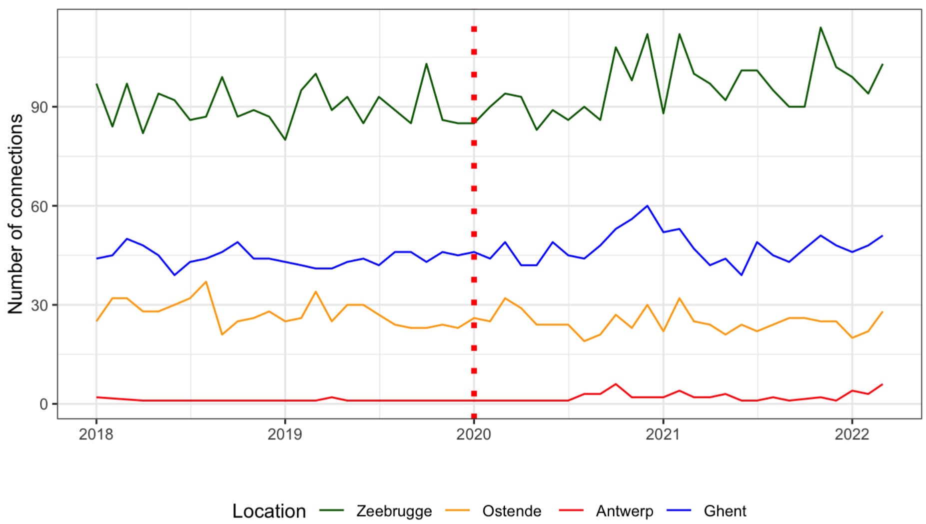

Figure 11: Evolution of amount of ports and average number of connections for Belgium ports

E Evolution of amount of ports and average number of connections for Irish ports

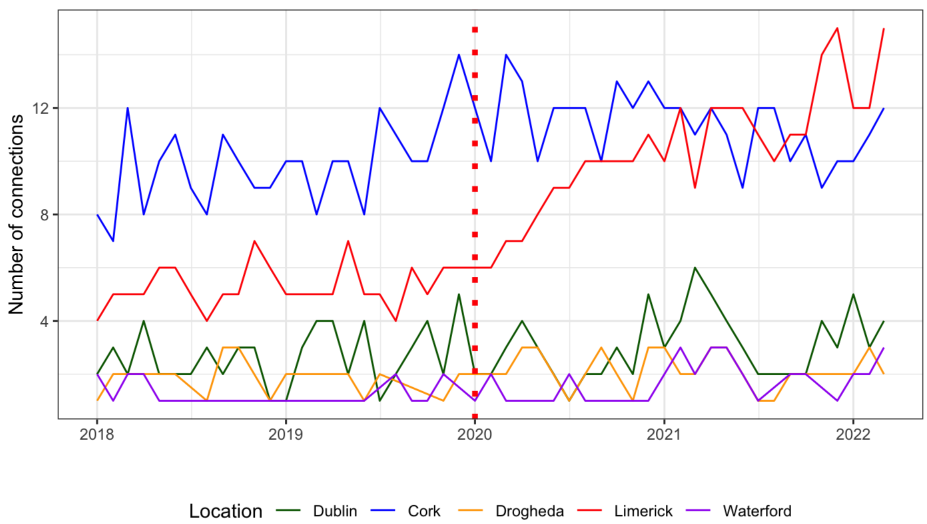

Figure 12: Evolution of amount of ports and average number of connections for Irish ports

F Evolution of amount of ports and average number of connections for UK ports

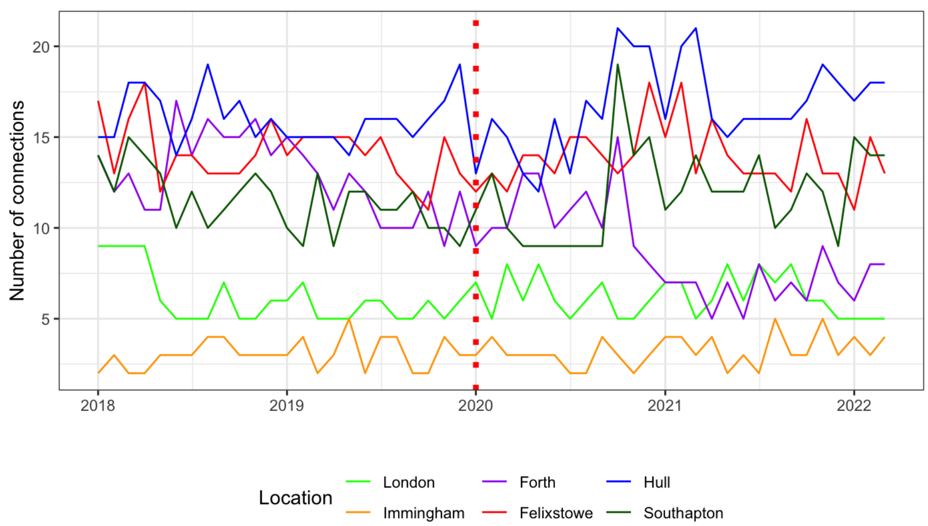

Figure 13: Evolution of amount of ports and average number of connections for UK ports

G Evolution of amount of tonnage (in thousands) for UK ports

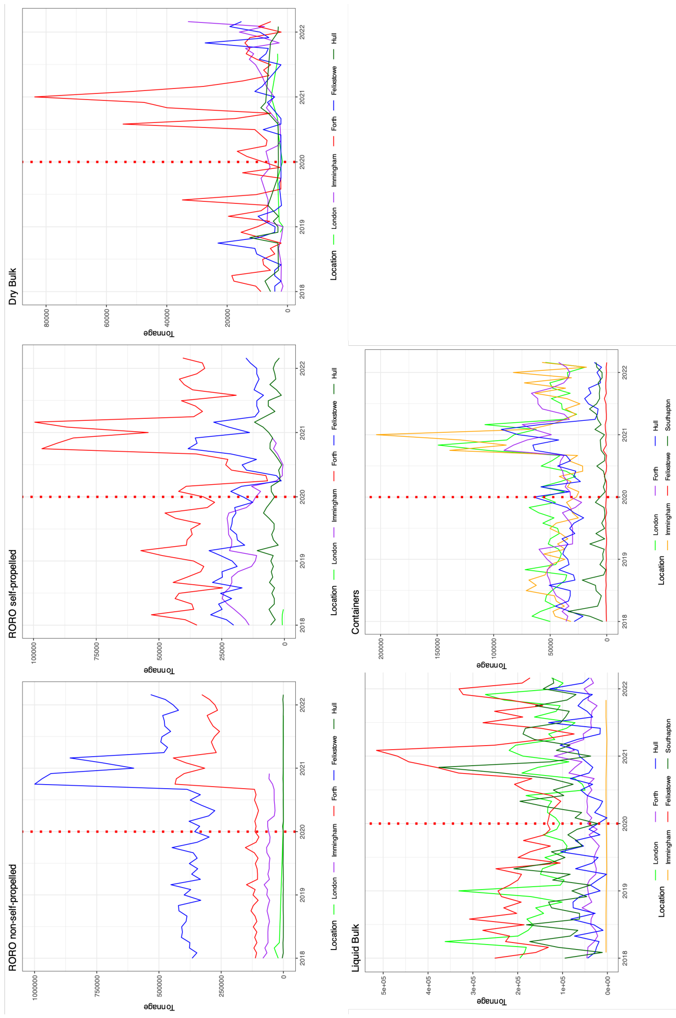

Figure 14: Evolution of amount of tonnage (in thousands) for UK ports

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