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“Multi-Objective Optimization for Transportation Network Design: A Linear Programming Approach”

“Konstantinos Papoulias”

Supervisor: “Michail Geranios”

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“Konstantinos Papoulias”

Supervising Committee

Supervisor:

“Michail Geranios”

“Hellenic Open University”

Co-Supervisor:

“Alexandros Diamantidis”

“Hellenic Open University”

Patras, Greece, September 2023

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Abstract

This dissertation proposes a linear programming (LP) model for multi-objective optimization of transportation network design. For global manufacturing companies minimizing the cost is a primary goal for the growth and sustainability of the company. Moreover, their service levels need to be high and punctual but due to the recent developments in global supply chain networks and methodologies, ~~the~~ Just-In-Time (JIT) logistics and lean manufacturing are creating bottlenecks and, more importantly, risks in the make-to-order supply chains. Lastly, there are new regulations in place by global or local authorities that aim to minimize carbon emissions as the world shifts towards a net zero state in regards to fossil fuels and greenhouse gas (GHG) emissions. The primary aim of this thesis is to provide a tool that efficiently supports the logistics sector and transportation network design obtain long term sustainable transport solutions. In academic literature, the subject of reducing carbon emissions along the supply chain is rising fast and plenty of methodologies have been used so far analyzing the fuel emission factor of various modes of transport. The transportation network is a critical part of the supply chain, and its optimization is essential for companies to remain competitive in today's globalized marketplace. The proposed research project aims to contribute to the existing literature on transportation network design by developing a linear programming model that can effectively balance cost, service time, and Environmental, Social and Governance (ESG) objectives. This will enable logistics and supply chain managers to make informed decisions regarding the design of transportation networks that can meet their company's goals and objectives along with the adaptability they need to address continuous risks and disruptions. The data obtained and used in this dissertation belong to a global manufacturer of various edible preparations. The LP model provides valuable insights and optimizes 40% of the cases in either cost, GHG emissions or service time, with an exceptional 12% of the cases being improved in all aspects. Future endeavors can consider more complex planning parameters such as IHC, global trade regulations such as FTA and PCOO.

Keywords

Linear Programming, Dijkstra’s Algorithm, Logistics, Carbon Emissions, Cost, Transit Time, Optimal Path, Network Design, Transportation Routing.

“Βελτιστοποίηση πολλαπλών στόχων για σχεδιασμό δικτύου μεταφορών: Μια προσέγγιση γραμμικού προγραμματισμού.”

“Κωνσταντίνος Παπούλιας”

Περίληψη

Η παρούσα διατριβή προτείνει ένα μοντέλο γραμμικού προγραμματισμού (ΓΠ) για την πολυκριτηριακή βελτιστοποίηση του σχεδιασμού δικτύων μεταφορών. Για τις παγκόσμιες κατασκευαστικές εταιρείες, η ελαχιστοποίηση του κόστους αποτελεί πρωταρχικό στόχο για την ανάπτυξη και τη βιωσιμότητα της εταιρείας. Επιπλέον, τα επίπεδα υπηρεσιών τους πρέπει να είναι υψηλά και ακριβή, αλλά λόγω των πρόσφατων εξελίξεων στα παγκόσμια δίκτυα και μεθοδολογίες εφοδιαστικής αλυσίδας, η εφοδιαστική Just-In-Time (JIT) και η λιτή κατασκευή δημιουργούν σημεία συμφόρησης και, το πιο σημαντικό, κίνδυνο στις αλυσίδες εφοδιασμού κατά παραγγελία. Τέλος, υπάρχουν νέοι κανονισμοί από παγκόσμιες ή τοπικές αρχές που στοχεύουν στην ελαχιστοποίηση των εκπομπών διοξειδίου του άνθρακα καθώς ο κόσμος μετατοπίζεται προς μια καθαρή μηδενική κατάσταση όσον αφορά τα ορυκτά καύσιμα και τις εκπομπές αερίων του θερμοκηπίου. Ο πρωταρχικός στόχος της διατριβής είναι να παρέχει ένα εργαλείο που υποστηρίζει αποτελεσματικά τον τομέα των logistics και το σχεδιασμό του δικτύου μεταφορών να αποκτήσουν μακροπρόθεσμες βιώσιμες λύσεις μεταφορών. Στην ακαδημαϊκή βιβλιογραφία, το θέμα της μείωσης, των εκπομπών διοξειδίου του άνθρακα κατά μήκος της αλυσίδας εφοδιασμού αυξάνεται γρήγορα και πολλές μεθοδολογίες έχουν χρησιμοποιηθεί μέχρι στιγμής, αναλύοντας τον συντελεστή εκπομπών καυσίμων διαφόρων τρόπων μεταφοράς. Το δίκτυο μεταφορών είναι ένα κρίσιμο μέρος της αλυσίδας εφοδιασμού και η βελτιστοποίησή του είναι απαραίτητη για τις εταιρείες να παραμείνουν ανταγωνιστικές στη σημερινή παγκοσμιοποιημένη αγορά.

Το προτεινόμενο ερευνητικό έργο στοχεύει να συμβάλει στην υπάρχουσα βιβλιογραφία σχετικά με το σχεδιασμό δικτύων μεταφορών αναπτύσσοντας ένα γραμμικό μοντέλο προγραμματισμού που μπορεί να εξισορροπήσει αποτελεσματικά το κόστος, τον χρόνο εξυπηρέτησης και τους περιβαλλοντικούς, κοινωνικούς και διακυβερνητικούς στόχους (ESG). Αυτό θα επιτρέψει στους διαχειριστές εφοδιαστικής και εφοδιαστικής αλυσίδας να λαμβάνουν τεκμηριωμένες αποφάσεις σχετικά με το σχεδιασμό δικτύων μεταφορών που μπορούν να επιτύχουν τους στόχους και τους στόχους της εταιρείας τους, μαζί με την προσαρμοστικότητα που χρειάζονται για την αντιμετώπιση συνεχών κινδύνων και διαταραχών. Τα δεδομένα που λαμβάνονται και χρησιμοποιούνται σε αυτή τη διατριβή ανήκουν σε έναν παγκόσμιο κατασκευαστή διαφόρων βρώσιμων παρασκευασμάτων. Το μοντέλο ΓΠ παρέχει πολύτιμες πληροφορίες και βελτιστοποιεί το 40% των περιπτώσεων είτε σε κόστος, εκπομπές αερίων του θερμοκηπίου ή χρόνο υπηρεσίας, με ένα εξαιρετικό 12% των περιπτώσεων να βελτιώνεται σε όλες τις πτυχές. Οι μελλοντικές προσπάθειες μπορούν να λάβουν υπόψη πιο σύνθετες παραμέτρους σχεδιασμού όπως ο IHC, οι κανονισμοί του παγκόσμιου εμπορίου όπως η FTA και η PCOO.

Λέξεις – Κλειδιά

Γραμμικός Προγραμματισμός, Αλγόριθμος Dijkstra, Logistics, Εκπομπές Άνθρακα, Κόστος, Χρόνος Διέλευσης, Βέλτιστη Διαδρομή, Σχεδιασμός Δικτύου, Δρομολόγηση Μεταφορών

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List of Abbreviations & Acronyms

3PL	3rd Party Logistics
4PL	4th Party Logistics
AGV	Automated Guided Vehicle
BCP	Border Control Post
CEFIC	European Chemical Industry Council
CVRP	Capacitated Vehicle Routing Problem
DAF	Distance Adjustment Factor
DC	Distribution Center
EOQ	Economic Order Quantity
ESG	Environmental and Sustainability Governance
FMCG	Fast-Moving Consumer Goods
FTA	Free Trade Agreement
FTL	Full Truck Load
GCD	Great-Circle Distance
GHG	Greenhouse Gas Emissions
GLEC	Global Logistics Emissions Council
GPS	Global Positioning System
GRG	Generalized Reduced Gradient
IHC	Inventory Holding Costs
JIT	Just in Time
LTL	Less than (full) Truck Load
PCOO	Preferential Country of Origin
POAO	Products of Animal Origin

SFP	Shortest Feasible Path
SKU	Stock Keeping Unit
TEU	Transport Equivalent Unit
TSP	Travelling Salesman Problem
UK	United Kingdom

1. Introduction

In today's dynamic and interconnected business environment, the effective management of supply chains stands as a paramount challenge and a strategic imperative. Within the expansive domain of supply chain management, logistics emerges as a pivotal component, encompassing a diverse array of activities, from warehousing to transportation. Transportation, in particular, commands special attention due to its substantial financial impact and profound influence on market competitiveness. As transportation costs often soar to a staggering 25% of an item's value, they not only weigh heavily on corporate budgets but also drive up consumer prices, compelling companies to seek innovative approaches for cost containment (Christopher, 2016). The logistics sector consists of multiple aspects with warehousing and transportation being the main categories. In the United States in 2019 the transportation costs constituted 65% of the total logistics cost and subsequently road transportation was 64% of that amount (APICS, 2022a).

On top of that, the global trade teams which are usually independent and separated from the operational teams have further altering characteristics that would eventually impact the outcomes of any transport. The teams which usually contain the duties, taxes, customs and documentation requirements of the physical movement typically fall under independent structures and organizations but their reach has a far greater impact. A paramount value that impacts costs and responsibilities are the incoterm agreements between each buyer and seller which ultimately define who bears the cost of transportation, warehousing, customs, and all handlings along the transaction. On average, a global door to door movement would include approximately 25 different stakeholders aligning together including all the work that they should individually generate, like documents, handling etc. (Dicken, 2011). Such types of movements are harder to execute in practice and sourcing products abroad is not a simple decision, which is why the majority of such flows are orchestrated by 3PL and 4PL companies who hold immense expertise in global and local markets.

The majority of carbon emissions emitted from transportation stems from road transportation, where we also observe the highest amount of emissions, a mode of transport relying heavily in fossil fuels even though quite a few alternative types of fuel have now emerged (Uherek et al., 2010). For instance in the United Kingdom the CO2 emissions from road transportation have increased dramatically over the last decades and the Department for Transport is projecting a constant increase of a rate between 5% to 10% (Warren, 2007). The graph below indicates CO2 emissions from fossil fuel combustion for medium and heavy freight trucks, depicted as blue and green respectively. The vertical axis indicates Mt CO2 while the horizontal years, calculated as estimates from the GEC model. Heavy freight trucks emit almost a quarter of the total emissions even though they only possess 2% of the road traffic (Transport & Environment, 2023).

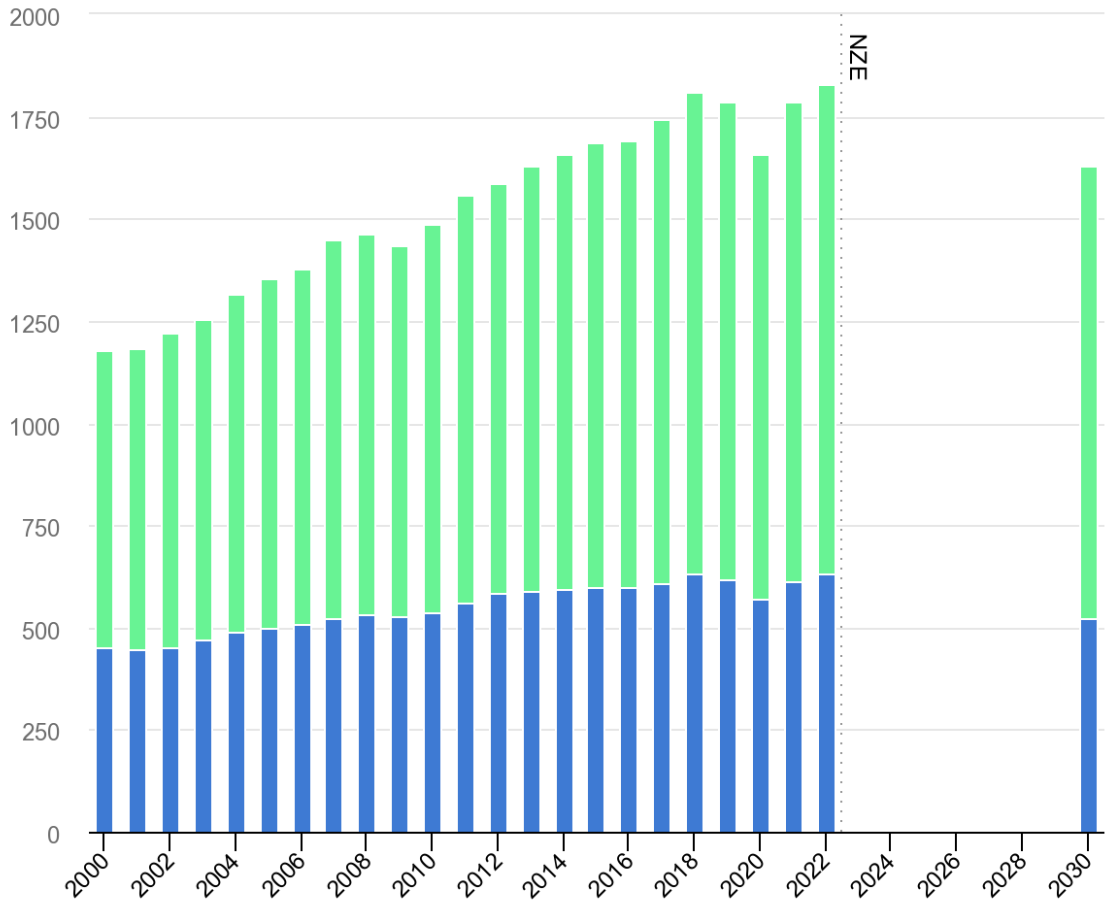

Chart 1: Global CO2 emissions from trucks and buses in the Net Zero Scenario, 2000-2030 (Source:(International Energy Agency, 2023))

The volatile nature of fuel prices, coupled with increasing concerns over environmental sustainability, has propelled the quest for alternative transportation. This is particularly pertinent as the rise in fuel costs directly affects transportation expenses, prompting companies to explore more efficient and environmentally friendly alternatives.

Fortunately, the evolution of inter-modality, which advocates the seamless integration of multiple transportation modes within supply chains, offers a promising avenue for cost reduction and sustainability. By judiciously combining road, rail, sea, and air transportation modes, businesses can enhance their operational flexibility, reduce transportation costs, and mitigate environmental impact. In turn, the inter-modality is increasing the complexity of modern supply chains as more and more actors of the supply chain need to coordinate and align, which again leads to an increase in technological investments in search for solutions.

However, it is crucial to acknowledge that transportation is not solely a financial concern; it also wields a significant environmental footprint. The transportation sector contributes approximately 15% of global greenhouse gas emissions, a statistic that underscores its central role in the sustainability discourse (Guo et al., 2018). Subsequently as reported by the Smart Freight Centre, freight transportation contributes between 8% and 10% of the global GHG emissions (Ehrler et al., 2023). Further analysis shows that predominantly the road freight transportation contributes 44% of the total CHG even though it only comprises 15% of the total freight activity (International Transport Forum, 2023). The same report surprisingly uncovers that road urban deliveries and global maritime shipping have the same amount of carbon emissions even though maritime shipping holds 70% of the total freight market movements. As global and local authorities enact increasingly stringent regulations aimed at curbing carbon emissions, the transportation industry is confronted with a profound transformation imperative. This transformation aligns with the global commitment to achieving a net-zero state concerning fossil fuels and emissions, a shift that necessitates a fundamental reevaluation of transportation network design and operation (UNFCCC, 2021).

The primary focus of this thesis is directed towards freight services and business transportation; however, it is essential to acknowledge that urban transportation is encountering similar challenges, challenges that encompassing high operational costs, the imperative of punctuality, and the increasingly pressing goal of achieving net-zero greenhouse gas (GHG) emissions, being pivotal considerations in the broader context of transportation systems. These challenges are intricately interwoven in the fabric of urban transit systems.

A substantial body of research has been dedicated to unraveling the complexities of public transportation, with a specific emphasis on transforming this sector into an environmentally friendly and sustainable mode of commuting. Scholars and experts have delved into various aspects of urban transportation, employing diverse methodologies to develop models that prioritize the reduction of GHG emissions and the overall sustainability of transportation networks, while privatizing the sector is also efficiently addressing the matter by employing best business practices and continuous improvement methodologies. Among the notable contributors in this field, the following authors among others have created linear programming (LP) models as a strategic tool. The objective of these LP models is twofold: firstly, to curtail GHG emissions associated with urban transportation, and secondly, to establish a resilient and sustainable transportation infrastructure (Günay et al., 2021). In regards to infrastructure and operational efficiency, Zhong et al. have developed a model using Dijkstra's algorithm to define the best strategy for charging stations while Wang et al. investigated potential synergies between the accessibility based planning for public transportation and the urban freight services (Y. Wang et al., 2023; Zhong et al., 2022). Within the same scope Qin et al. developed a reliable routing path for electric vehicles using Dijkstra's algorithm (Qin et al., 2022). For more references in regards to Dijkstra's algorithm and MILP model in smart and sustainable city logistics development see(Keramati et al., 2024; J. Wang et al., 2023; Zhou et al., 2023).

The application of LP models provides a systematic approach to optimizing resource allocation, route planning, and operational logistics within the urban transportation framework, thereby contributing to the overarching goal of environmental conservation by drawing meaningful insights that may inform policy decisions, industry practices, and academic pursuits, ultimately steering urban transportation towards a greener and more resilient future.

The most common is Carbon Dioxide but there are more GHG emissions that are often overlooked. An overview of these below as provided by the Smart Freight Centre:

CO_2 - Carbon Dioxide

CH_4 - Methane

CFCs - Chlorofluorocarbons

HFCs - Hydrofluorocarbons

NF_3 - Nitrogen trifluoride

N_2O - Nitrous oxide

PFCs - Perfluorocarbon

SF_6 - Sulphur Hexafluoride

SO_2F_2 - Sulfuryl Fluoride

Of course, it is a necessity to mention at this moment the Global Logistics Emissions Council (GLEC) and their immense work on decarbonizing freight transportation in the logistics sector. Purpose of the GLEC Framework is to support companies in calculating and reporting GHG and get compliant and certified for ISO 14083, the ISO certificate who validates the quantification and reporting of GHG emissions occurring from Transport Chain Operations. The chart below indicates the global CO_2 emissions by sector, showing the overall transportation emissions to reach 15%.

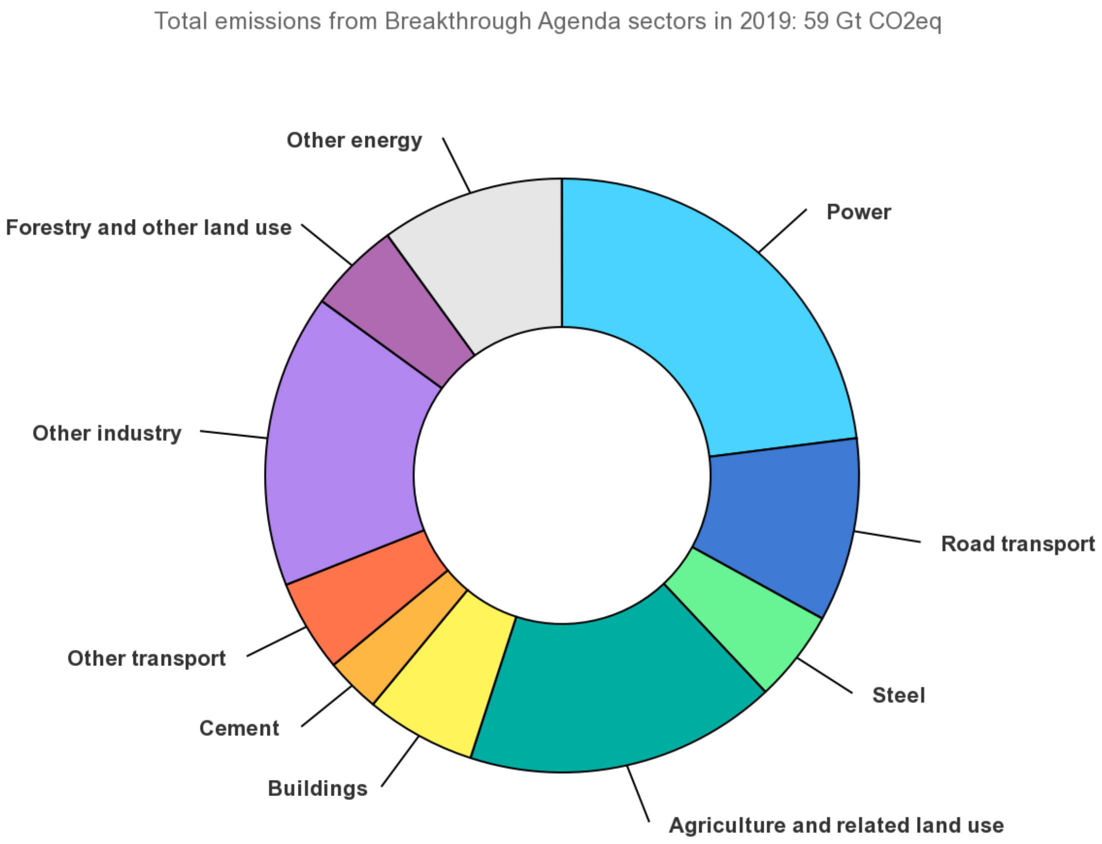

Chart 2: Greenhouse gas emissions by sector, 2019 (Source: (International Energy Agency, 2019))

In response to these environmental imperatives, an expanding body of literature has emerged, dedicated to mitigating carbon emissions across the supply chain. Researchers have developed diverse methodologies for analyzing the fuel emission factors associated with various modes of transport. These endeavors underscore the urgency of adopting eco-conscious transportation solutions that resonate with the environmental objectives of an increasingly conscientious world.

The transportation network, a critical artery within the broader supply chain ecosystem, stands at the crossroads of these multifaceted challenges and opportunities. Its optimization represents the linchpin of a delicate equilibrium, one that simultaneously considers cost efficiency, punctual service delivery, and the imperative to curtail carbon emissions. In today's hypercompetitive global marketplace, where borders blur, and competition knows no bounds, the capacity to craft a meticulously optimized transportation network is tantamount to organizational resilience and success.

This thesis embarks on a journey to contribute to the ongoing discourse on transportation network design. Through the presentation of a Linear Programming model, it navigates the intricate terrain of multi-objective optimization, offering a robust framework for decision-makers to balance cost, service times, and ESG objectives. The model equips logistics and supply chain managers with the analytical tools necessary to make judicious decisions regarding transportation network design, thereby enhancing corporate competitiveness and sustainability while contributing towards achieving long term strategies and goals. Importantly, the empirical foundation of this study rests on real-world data obtained from a globally recognized manufacturer specializing in various edible preparations, underscoring the practical relevance and applicability of this research.

1.1 Literature Review

This research represents a significant contribution to the value of the supply chain by introducing innovative approaches to optimization. The goal of every modern supply chain manager is to increase the value add of the supply chain by either reducing costs along the chain or increasing the operational quality (Badri et al., 2017), the latter being translated either as service time or sustainability development. In modern supply chains, transportation cost is no longer seen independently but supply chain management takes a more holistic approach examining all related factors and considering the total landed logistics cost before taking decisions (APICS, 2022a). Through the development of a robust linear programming model that balances cost, service time, and environmental objectives, this study equips supply chain managers with a powerful tool to enhance the efficiency and sustainability of their operations. Ultimately, this study contributes to the value of the supply chain by fostering operational excellence, sustainability, and competitiveness in today's dynamic and interconnected global marketplace. Moreover, the three factors examined in this thesis represent exactly half of the main factors that are being developed while examining geographies of supply chains as indicated in the book by

Watson et al. The authors present the below six aspects as drivers for the main tradeoffs (Watson et al., 2017):

1. Transportation Cost
2. Service Level
3. Risk
4. Local Labor, Skills, Materials, Utilities
5. Taxes
6. Carbon Emissions

Before proceeding further, the importance of the network must be defined which holds two aspects, also supporting the further statements made for the purpose of this work. The first aspect is the connectivity of the physical infrastructure, a framework of locations linked together by routes (Rodrigue et al., 2006). APICS further define logistics infrastructure to consist of ports and terminals, railway lines and road conditions with their main characteristics being size, quality and availability (APICS, 2022b). In a broader concept the networks are also seen as an assembly of relations that are aligned in provide a common outcome or result (Parker & Doak, 2012). As a term though this is much broader and does not reflect the company's identity. This is where the second definition of a network comes in and as per Martin Christopher is "A confederation of mutually complementary competencies and capabilities" (Christopher, 2016). Christopher, in his book, clearly places the company in a center of a network with all integrated and interdependent stakeholders forming the unique identity of that network and the company eventually allowing the corporation to compete against similar network scale companies. This is further supported by Dicken who describes corporations operating in multiple geographies as "networks within networks", elaborating that what seems to be a single organization is actually a set of subnetworks operating in synchronization (Dicken, 2011).

One of the most common problems solved with Integer LP is the Travelling Salesman Problem (TSP). The problem is comprised as a salesman needing to visit a number of cities and trying to identify which route is the most efficient to follow. The applications of TSP's formulation have various uses in transportation planning and logistics and more specifically in milk-run customer deliveries. Such deliveries are low quantity (LTL shipments most often) that get consolidated in a Distribution Center (DC) and are then subsequently delivered to multiple customers across various destinations.

From the factors examined in this thesis cost is the most important aspect of a company's financial image along with its operational sustainability and is as mentioned above low costs are a critical factor of survivability as well. In regards to this research, academia has proven multiple times that linear programming can be used to optimize costs along a distribution channel. The following research takes into account distance and cost in order to optimize rice distribution in Indonesia considering the network's 12 distribution centers and 22 destination provinces (Nurprihatin et al., 2021). The authors using the Capacitated Vehicle Routing Problem (CVRP) model as well managed to efficiently distribute the product in reduced cost validating the accuracy and capabilities of such tools. Moreover, as the paper states as concluding remarks the results are proposed as a policy to the local government, authorities, or stakeholders and this further facilitates that using such network design techniques is more than a mathematical calculation.

A sizeable portion of research focuses on transportation planning at capacity and cost, quite often using fuzzy methodology to formulate and solve such problems. The following research uses Linear Programming to plan supply and transportation using six constraints, two fuzzy and four known variables (Liang, 2008). More importantly the author is considering transit times along production and transportation cost which allows them to provide significant findings of such an application. Lastly, this research is applied in an industry of Fast-Moving Consumer Goods (FMCG) in Taiwan.

The below table illustrates examples of such uses to optimize cost in supply chains. Moreover, additional factors that are as either input or output and considered in this thesis are also demonstrated on the below papers along with the methodology used to calculate the output and the system and algorithm of choice for the below researchers.

Author(s)	Method	System / Solver	Input			Output	
			Cost	Capacity	Lead Time	Cost	ESG
(Kabak & Ülengin, 2011)	LP / PLP	GAMS / CPLEX	x	x		x	

(García et al., 2013)	LP	/ GLPSOL	x		x	x	
(Baller et al., 2022)	MILP	Excel /	x			x	x
(Nurprihatin et al., 2021)	MILP	CVRP	x			x	
(Saffar et al., 2014)	LP	/ NSGA	x			x	x
(Lamba et al., 2019)	MINLP		x	x		x	x
(Sadegheih et al., 2011)	MILP		x	x		x	x
(Elhedhli & Merrick, 2012)	MILP		x	x		x	x

Table 1: Relevant publications using LP to minimize cost in supply chains (Table Source: Author).

There are two obvious possible uses of such a tool in academia or the business environment. The first objective is for supply chain managers to take decisions and the second is to bring change and help drive continuous improvement. The first objective is to design according to the existing possibilities, the company's strategy and it's reflects, a long-term goal and incentive for logistics optimization. The second objective is a solution to current market trends and temporal inefficiencies. Therefore, such a tool is not restricted to a single use but is rather flexible and adaptable.

In the dynamic landscape of supply chain management, optimizing the routing of transportation has emerged as a focal point, with a growing emphasis on sustainability, particularly in the realms of green logistics and reverse logistics. This trajectory aligns with a broader trend among companies, who have increasingly recognized the significance of these dimensions in recent years. The asset holders and pioneers of the industry have additionally incorporated this mentality into their plans and strategies. We can see that vessel owners acting on such endeavors and in 2022, even though the number of vessels has increased 20% over the past 5 years, the average number of emissions per sea freight lane is maintained constant and even reduced in comparison to 2021 (Smart Freight Center, 2023).

Green logistics, also known as eco-logistics or sustainable logistics, revolves around minimizing the environmental impact of transportation operations while maintaining efficiency and cost-effectiveness. Strategies such as adopting fuel-efficient vehicles, optimizing route planning, and reducing emissions have garnered significant attention. These endeavors are in response to global environmental concerns and regulations aimed at mitigating carbon emissions. The growing body of literature in this area underscores the importance of integrating sustainability into transportation decisions, promoting eco-conscious practices, and reducing the carbon footprint of supply chain operations. Reverse logistics, on the other hand, addresses the movement of goods from the final destination back to the manufacturer or reseller for purposes like returns, recycling, or remanufacturing. As businesses become increasingly aware of the economic and environmental implications of waste and returned products, reverse logistics has gained traction. This area of research delves into efficient strategies for managing the reverse flow of goods, reducing waste, and recapturing value from returned products. The following authors used a Physical Linear Programming model in order to effectively identify ideal locations to be used as collection centers (Pochampally & Gupta, 2012). This model allows the researcher the declaration of preference for each of the contributing values of the algorithm.

There is a vast library of measuring tools and algorithms in the market that can support in identifying the optimal paths among a physical distribution channel. Such models include possibilistic approaches, mixed-integer approaches, and relevant modes such as Dijkstra’s algorithm meant to calculate the shortest path in a network or Monte Carlo simulation. In simulations, along Dijkstra’s Algorithm there are also D’Esporo’s and Moore’s algorithms (Van Vliet, 1978). Dijkstra’s algorithm is often used for alternative solutions to logistics as well and quite often to design and route Automated Guided Vehicles (AGV). This impacts the scheduling and prioritization of the warehouse activities of the logistics sector and on premise optimization. For detailed work the following authors have provided extensive research on AGV automation (Hu et al., 2022; Manafi et al., 2022). While warehousing is an important aspect of logistics so is transportation which is also the primary sector under study in this thesis. Dijkstra’s algorithm has also been used in research to identify shortest path problems. Shi et al. used the algorithm to identify shortest path and lower carbon emissions on a three-stage optimization model for intelligent scheduling (Shi et al., 2022). Dijkstra’s algorithm analysis in maritime shipping has already been extensively researched and has a notable contribution to multiple fields of study. Wang et al developed a model that suggested waypoints and optimal speed for vessel voyages while Liu et al used the same algorithm to address chokepoints and disruption mitigation on maritime transport (Liu et al., 2024; H. Wang et al., 2019).

In this thesis a combination of approaches will occur with the primary approach being linear programming optimization on a network. The network itself though will be defined using Dijkstra's Algorithm. While primarily being used in internet network routing problems, there are plenty of cases in academia where Dijkstra's algorithm has been used to identify shortest paths in logistics distribution models. Authors like Lusiani et al., used Dijkstra's work to identify the network shortest path, other authors like Rosita et al. combined multiple into a single value before applying the algorithm to find the overall best solution to a distribution problem (Lusiani et al., 2021; Rosita et al., 2019). Additionally, this method is increasingly popular in last-mile and city logistics with the increasing volumes occurring from the rise of e-commerce (Zou & Henan-Ligong-Daxue, 2010). The paper above demonstrates how external factors, such as the weather conditions, would affect the outcome of a routing problem demonstrating cases where the shortest geographical path is not the fastest path. The distance between nodes and their connectedness with a narrowed scope is also a reason why such theorems are applied mostly in city logistics and last-mile logistics. The reason of choosing to examine the whole structure of the geographical network is so that we can also identify alternative routings since there are constant disruptions in supply chains now even more than in the past since globalization has reached peak levels.

Application of Mixed-Integer Linear Programming (MILP) has emerged as a powerful tool in optimizing transportation logistics. A notable example is the recent research by Baller et al., who applied MILP techniques to optimize the inbound logistics of an automotive company (Baller et al., 2022). Such mathematical modeling approaches enable businesses to solve complex transportation optimization problems, balancing multiple objectives while considering constraints, ultimately leading to more efficient and cost-effective supply chain operations. Additionally, the research by Saffar et al., also represents a notable example of using LP methodology to optimize both cost and carbon emissions in a very holistic supply chain perspective ~~and~~ as the authors claim (Saffar et al., 2014). Sadegheih et al., also published a complete approach to Supply Chain network design using a Mixed-Integer Programming (MIP) model in order to optimize costs, capacity and carbon emissions (Sadegheih et al., 2011). The author's approach was to convert all factors to cost and then estimate the alternative solutions to a transportation network. A similar approach has been tested again for designing a supply chain network (Elhedhli & Merrick, 2012). Converting GHG emissions to cost is a common practice in the field of operational research. Latest reports indicate that carbon price for the month of December 2023 is equivalent to 80 euros per tonne of CO2 (Gryn, 2023). As part of this thesis we will not be converting the emissions to cost as we want to examine direction emissions per mode of transport rather than their cost equivalent. Future research may use the conversion if we plan to calculate total landed cost per route, in which case converting emissions to a monetary value has more applications. The research from the following authors has also been extremely insightful on transportation network design where they are using a MILP model to improve cost and travel time on a network of existing modes while considering new possible nodes as well (Luathep et al., 2011).

Measurement of carbon emissions plays an integral role in addressing environmental concerns within supply chain transportation. The approach mentioned involves calculating emissions on a specific route by considering the respective equipment's fuel factor and fuel consumption over the distance. This method aligns with broader efforts to accurately quantify and track carbon emissions, providing the foundation for targeted emissions reduction strategies. The most typical approaches to emissions calculation include the payload, distance, and emission factor, as the formula below indicates.

$$GHG = Distance\ (KM) * Weight\ (Tonnes) * Emission\ Factor\ (EF)$$

There are numerous cases in academia where the distances have been calculated as Euclidean distances in the absence of data. In contrast, we have been able to calculate the actual distances, often referred to as Metropolitan. In accordance with the GLEC Framework there is an ISO compliant way to measure distance. The Shortest Feasible Path (SFD) is the shortest operating path between two nodes. The Great-Circle Distance (GCD) distance which is the direct distance on a straight line taking into account the earth's curvature, which is currently only use in air freight movements (Ehrler et al., 2023). The Framework allows the use of actual distance if available but with the application of a Distance Adjustment Factor (DAF) based on the mode of transport.

In regards to the Emission Factor (EF), many institutions have provided different estimates with significant differences. The difference may lie in the unavailability of data in regards to specific engine types. In this thesis we will be using the European's Chemical Industry Council (CEFIC) data presented in collaboration with the Smart Freight Center in 2021 (Smart Freight Center & CEFIC, 2021). Table 2 below presents the main difference on average EF from the Smart Freight Center (SFC), GLEC framework in partnership with CEFIC and the European Chemical Transport Association (ECTA), CEFIC provision (ECTA & CEFIC, 2011; Smart Freight Center & CEFIC, 2021). The specific table indicates the developments that took place in tracking carbon emissions by comparing the 2011 and 2021 measurements of CEFIC, data presented by the same organization a decade apart. Additionally, we notice and allocate the observed improvements on engine types and consumption and consider these developments as improvements.

Mode	ECTA/CEFIC 2011	SFC/CEFIC 2021	Absolute Difference	Difference %
Truck	62	63	1	1.60%
Barge	31	20	11	43.14%
Rail	22	19	3	14.63%
Short Sea	16	12	4	28.57%
Air	602	629	27	4.39%
Deep Sea	8	5.7	2.3	33.58%

Table 2: Differences on average EF according to SFC and ECTA (Source: Author).

In summary, the literature reflects a growing commitment to sustainability in transportation logistics. Researchers and practitioners are exploring innovative solutions to optimize routing, reduce costs, maintain low lead times, and track and reduce carbon emissions. These efforts align with the evolving priorities of businesses seeking to harmonize economic efficiency, environmental stewardship, and operational excellence in an increasingly interconnected and conscious world.

1.2 Importance and Rationale

This chapter provides a comprehensive overview of the importance and rationale behind the research conducted in this thesis. It delves into the critical role of transportation network optimization in the context of supply chain management and elucidates the factors that underscore the significance of this study within the academic landscape.

Supply chain management is a complex and ever-evolving domain that plays a pivotal role in the success and sustainability of modern businesses. Within this multifaceted field, logistics, encompassing activities such as warehousing and transportation, holds a central position. Among these logistical facets, transportation network optimization stands as a critical endeavor.

The transportation network serves as the circulatory system of the supply chain, facilitating the movement of goods and materials from suppliers to manufacturers, from manufacturers to distributors, and ultimately to end consumers. In this intricate web of operations, the efficient design and operation of the transportation network are paramount. It directly impacts a company's bottom line, customer satisfaction, and its contribution to environmental sustainability.

Three fundamental dimensions guide the research conducted in this thesis: cost, service time, and lower GHG emissions. These dimensions represent the triad upon which modern logistics and supply chain management pivot. Cost is a relentless determinant of profitability. Efficient transportation network design can significantly reduce operational expenses, enhancing a company's competitive position. Service time is equally critical in today's consumer-driven market. Timely delivery not only meets customer expectations but also influences customer loyalty. Swift and accurate deliveries are integral to maintaining a competitive edge. The transportation lead time also gives has a sense of how much control companies have on their stock while it is in transit. As mentioned in the first chapter of the thesis there are numerous disruptions that constantly affect the delivery schedules and stock availability. For instance the recent events and escalations in the Red Sea have increased EU delivery time by an average of 11 days which in some case is even up to 50% increase in Deep Sea freight movements (Levine, 2024). Environmental objectives are increasingly vital due to mounting concerns over climate change and the environmental impact of business operations. Supply chains are under scrutiny, and organizations are challenged to reduce their carbon footprint. The transportation network, as a significant contributor to emissions, is a focal point for environmentally sustainable practices.

The rationale behind this research is multifaceted, encompassing both practical and theoretical dimensions. This research project holds immediate and practical relevance for businesses operating in the globalized marketplace. It addresses the pressing need for transportation network optimization by offering a novel approach that balances cost, service time, and ESG objectives. Logistics managers can employ the proposed linear programming model as a practical tool for informed decision-making in the design of transportation networks. Within the academic landscape, this research contributes to the burgeoning literature on transportation network design by advancing the understanding of how cost, service time, and environmental considerations can be simultaneously optimized. By doing so, it enriches the knowledge base of supply chain management, logistics, and operations research. Additionally, the study adds depth to the existing body of literature concerning the use of linear programming models in transportation optimization.

This research serves as a bridge between theoretical concepts and practical applications. While theoretical models and algorithms have been proposed in academia, their application in real-world scenarios often presents challenges. This study takes a practical approach by grounding the research in the operational context of a global manufacturer, enhancing the feasibility and applicability of the proposed model. In summary, the research conducted in this thesis explores the vital domain of transportation network optimization within the supply chain. It offers a balanced approach that considers cost, service time, and ESG objectives, catering to both practical and academic dimensions. By doing so, this research contributes to the evolving field of logistics, provides valuable insights for businesses, and enriches the academic discourse on transportation network design.

1.2.1 Academic Relevance

The proposed research project is relevant to several supply chain functions, not limited to and including Transportation Systems Management, Distribution Systems, Supply Chain Strategies and Risk Management. The primary contribution of this thesis lies within the network design section of supply chain as the tool will allow companies to design more resilient and adaptable networks according to individual goals. Moreover, academic research takes place exploring the benefits and past usages of Linear Programming (LP) models and applications of Dijkstra's algorithm in logistics network design. The thesis addresses a critical challenge in transportation network design that is central to effective supply chain management. By developing a multi-objective optimization model that incorporates cost, service time, and carbon emissions, the project will provide insights into how transportation networks can be designed to achieve optimal performance providing more efficient flows altogether. Additionally, the LP model of this thesis addresses the main aspects of a logistics networks, as mentioned above, and several additional factors such as network capacity and contract validity across multiple teams.

The research in logistics and supply chain management plays a pivotal role in the broader context of global trade optimization. By delving into topics such as efficient transportation networks, cost reduction strategies, sustainability measures, and risk management, this research equips businesses and policymakers with the knowledge and tools needed to enhance the effectiveness and efficiency of global or regional trade operations. Whether it is through the development of advanced route optimization algorithms, the promotion of eco-friendly supply chain practices, or the mitigation of supply chain risks, the findings from logistics and supply chain research directly contribute to the optimization of global trade, achieved also by looking into item composition and compliance and regulatory costs. In an era of increasing interconnectedness and international commerce, this research serves as a crucial guidepost, fostering economic growth and trade facilitation while addressing the complexities and challenges inherent in the global marketplace.

Lastly, we implement the model in a case study to further validate and explore the outcome and reasoning behind this design. Part of the case study research is also to further validate whether additional efficiency can be achieved by increasing cross-functional collaboration or centralization of process and routines as it is often observed that working in silos does not yield the maximum results.

2. Research Methodology

2.1 Methodology

Linear Programming (LP) is distinguished by its mathematical rigor and precision. It operates within the framework of linear relationships between decision variables, constraints, and objectives. This mathematical foundation ensures that LP models are well-defined, and solutions are obtained through systematic mathematical optimization techniques. The transparency and precision of LP make it particularly appealing for academic research, as it allows for the clear formulation and evaluation of supply chain network optimization problems.

LP's versatility is a key factor in its widespread acceptance in academia. It can be adapted to address a wide array of supply chain network design scenarios. Whether the goal is to minimize costs, maximize profits, optimize resource allocation, or balance multiple objectives simultaneously, LP can accommodate the specific requirements of the problem. This adaptability makes it suitable for exploring a broad spectrum of research questions and practical challenges within the realm of supply chain management.

A generic Linear Programming (LP) formulation involves defining decision variables, an objective function, and a set of linear constraints. For instance, x1, x2 etc would represent the decision variables, and the objective function Z be a linear combination of these variables, and the coefficients, for example c1, c2 etc. The constraints are represented as linear inequalities and non-negativity constraints are imposed on the decision variables. The primary objective is to maximize or minimize the objective function Z subject to these constraints, and linear programming algorithms, such as the simplex method or interior-point methods, are employed to find the optimal values of the decision variables that satisfy the constraints and optimize the objective function. A basic formula of the objective function of a LP model follows:

$$Z = c_1 * x_1 + c_2 * x_2 + \cdots + c_n * x_n$$

In academic research, efficiency is a paramount consideration, especially when dealing with complex supply chain network optimization models. LP enjoys a reputation for computational efficiency, particularly when handling problems with many decision variables and constraints. Modern LP solvers employ advanced algorithms that can efficiently explore solution spaces, delivering results within a reasonable time-frame. This efficiency is crucial for conducting extensive sensitivity analyses, scenario testing, and Monte Carlo simulations often required in academic research. A concise literature review has been conducted and provided in the chapter above which illustrates multiple uses and researches in the field of logistics and operational research.

The interpretability of LP solutions is a valuable asset for both researchers and practitioners. LP models produce clear and understandable results, making it easier for decision-makers to comprehend and implement the findings in real-world supply chain operations. This practical relevance ensures that the insights gained from academic research using LP are more readily applicable in industry settings. Additionally in this thesis the results are cross-verified against a case study providing credibility against the model as the data can be verified and referenced against actual occurrences.

Linear Programming models are inherently convex, which means they possess a unique and globally optimal solution. This property is particularly advantageous when the aim is to find the best possible solution without the risk of getting trapped in local optima. The assurance of global optimality provides academic researchers with confidence in the validity of their findings, reinforcing the credibility of LP as a research method. This is also a more favorable approach to supply chain networks where finding the lowest total landed cost is more favorable that segmented improvements and efficiencies.

LP seamlessly integrates with a variety of interdisciplinary tools and methodologies commonly employed in supply chain research. This integration allows researchers to combine LP with other modeling techniques, data analytics, simulation, and optimization methods, creating comprehensive analytical frameworks for studying complex supply chain network optimization problems. While the model itself is a mathematical formula, an algorithm, that runs its course until the optimal outcome is identified, the model itself is very modular and can be independently modified according to the project's needs and goals.

In conclusion, Linear Programming is a respected and valid research method in academia due to its mathematical rigor, versatility, computational efficiency, interpretability, and convexity. Its well-established principles and practical relevance make it an indispensable tool for addressing the multifaceted challenges and opportunities in supply chain network optimization. Researchers value LP for its ability to provide rigorous, actionable, and globally optimal solutions, contributing significantly to the advancement of knowledge in the field of supply chain management.

2.2 Case Study

The data to be used in this thesis will be obtained from a global food manufacturer. The company has engaged in operations across multiple markets for various edible meals and preparations. The corporation operates multiple factories and warehouses with support from 3PL and 4PL companies along with a group of external factories that support the high demand of the goods. Similarly, the company employees thousands of people who are located either on site, centralized or remotely. The data have been obtained from multiple teams working in conjunction for the European Supply Chain portfolio from rates and tenders performed within 12 months between December 2022 and November 2023. For this food manufacturer it is important to state that the products have a stable and long shelf life which eventually allows more time for planning and execution. Nevertheless, like most companies the purpose is to have as low inventory holding costs as possible along with high case fill rate.

The manufacturer is also performing under lean six sigma principles in manufacturing and logistics process with plenty of influences from JIT and Agile methodologies in execution. Most of the order planning happens as per make-to-stock policies for intra and inter-company movements while customer orders have a mixed make-to-stock and make-to-order approach.

The data provided by the company has undergone changes in order to protect their confidentiality and data protection regulations. Using active contracted rates are protected by non-disclosure agreements that the companies usually are hesitant to disclose, therefore all data in the thesis are normalized. The locations used have been coded for data privacy.

In this particular case study, the types of movements have been stratified into three tiers explained below:

Tier 1: This tier contains the movements of goods classified as raw materials and packaging ingredients needed in order to produce finished goods.

Tier 2: This tier contains the movement of finished and semi-finished goods from the place of manufacture to the warehouse, repack site or distribution center.

Tier 3: This tier includes transport that deliver goods to final customers.

In this thesis the transports examined are only related to finished goods movements so that would include tier 2 and 3 from the above list. At the same time if there are potential synergies with tier 1 movements that can contribute to the optimal result they will be considered. Additionally, in the thesis all calculations will consider FTL shipments as a standard which is also in line with what the case study is considering in terms of planning a pricing for all three tiers.

In regards to global trade the manufacturer has individual teams responsible for the trade related matters which also fall under different supervision and financial structure. In this particular study the impact of such parameters will be examined especially considering the company's geographical structure which has plenty of interaction between EU manufactured products and the United Kingdom, which since Jan 2021 is not considered EU territory and is subject of further trade activities, such as customs filings, veterinary inspection and new sets of documentation.

Moreover, in this particular case study, the incoterms that will be considered as active are EXW whenever the company is the buyer and DDP when the company is the seller. There are actually a few more incoterms in use from this specific corporation but their impact is minimized as most transports under this scope is considered either intra-company or inter-company with minimal effect on the financial stability of the possible outcomes. In reality, this isn't a limitation of the LP model that is developed but there will be insufficient data to validate across besides having a grey area of responsibility as intra-company movements, therefore specific incoterms are excluded from the study.

In terms of ESG governance and GHG emissions the company and scope of this case study falls under the scope 3 category emissions in regards to reporting and accounting as indicated in the GLEC Framework (Ehrler et al., 2023). Scope 3 emissions include all direct and indirect emissions produced from the suppliers to the reporting company and from the reporting company to the final customers. This scope includes the value chain activities and products and should be a cross-functional activity.

2.3 Methodology Approach

The research methodology of the thesis involves two main steps, the model development and the solution approach.

In regards to the model development, the linear programming model will be developed based on the expected data and flow of the transportation model, existing literature on transportation network design, and the three key objectives of the proposed model. These include operating cost, expected service time (lead time) and carbon emissions of supplier/route of choice. The model will be formulated as a mixed-integer linear program that can be solved using Microsoft's Excel or other software with relevant capabilities. Software MATLAB also is another tool that is commonly used to solve complex distribution problems (Ding & Zou, 2016; Lusiani et al., 2021). Microsoft's Excel has three types of solvers namely the simplex LP, the GRG nonlinear and the Evolutionary

Type. The model of this thesis will be using the Simplex LP solver since we do not face uncertainties and non-linearities therefore the Simplex LP is a suitable solver. Moreover, there is evidently large amounts of research using this linear model which is also deemed efficient for this type of research, transportation network design, and has demonstrated historically success.

In this particular study the model used resembles significantly Dijkstra's algorithm as the structure used sets the physical infrastructure as the network examined on top of which we plug in the rates provided by the global manufacturer. In practice this means that we explore more than just direct connections as contracted by the company which is under study in this thesis. If there are synergies within the network, Dijkstra's algorithm will support in identifying them in case they are sensible towards the objective. The reason for selecting this approach is because, as we mentioned above, this tool aims to "design" rather than "execute" in business terminology. The objective of this tool is to provide Supply Chain Managers and respective Network Design teams the options to analyze transportation beyond the traditional "direct shipment" approach and the ability to do that on a much larger, strategic scale and not to be used in the daily planning and operational activities. Moreover, this approach aims to address the segmented nature of logistics procurement since several rates and routes that are used in the model, that belong to different business units and scopes. As described above in chapter 2.2, there are multiple different organizational structures contributing in the results of this model further contributing to proving how cross-functional collaboration can improve the performance of the logistics flow of a company.

The data requirements for this thesis can be categorized into the below groups and subgroups:

1. Commercial Data
    a. Exchange Rates
    b. Benchmarked Rates
    c. Contracted Rates
2. Network Data
    a. Geographical Regions (Service)
    b. Factories/Warehouses (Locations)
    c. Transport Modes
    d. Lead Times
    e. Node Distances

3. Strategic Data
    a. Company Policy
    b. Company Targets
    c. Vendor Service Level Agreements
    d. Scope Split

The table below indicates additional details on these requirements, further explaining what the contribution to the thesis and the LP model is.

Category	Data Type	Comments
Commercial Data	Exchange Rates	The currency exchange rates used to convert all currencies to USD
	Benchmarked Rates	Rates provisioned during tenders but not awarded
	Constracted Rates	Active contracted rates with vendors
Network Data	Geographical Regions	Structure of involved countries
	Factories/Warehouse	Sites where the company operates and performs activities
	Transport Modes	Mode and equipment type of transport
	Lead Times	Transit Times between nodes
	Node Distances	Distance between nodes of the network
Strategic Data	Company Policy	A basic ruleset of what is considered permitted and valid

	Company Targets	Expected performance and validations of the model
	Vendor SLA	Active vendor agreement targets (in regards to capacity and transit time)
	Scope Split	Breakdown and combinations of data according to company structure

Table 3: Relevant data types and descriptions (Source: Author)

The below image illustrates the required data and presenting their synergies into achieving the optimal flow.

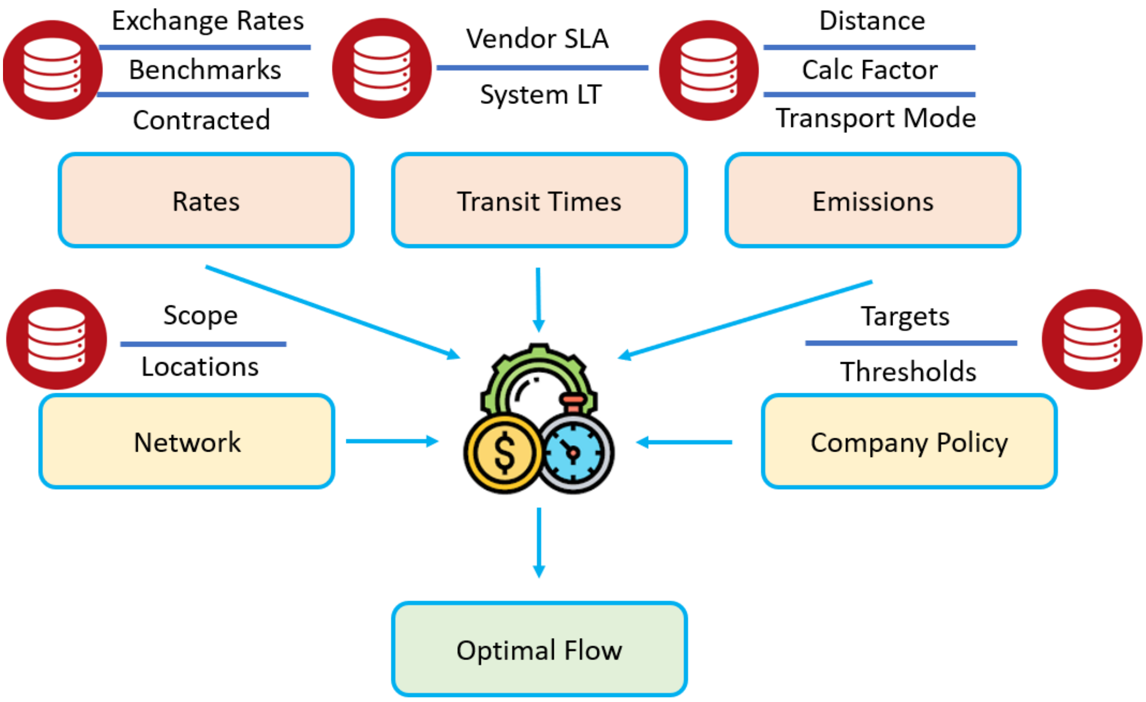

Figure 1: Data Structure of suggested Model (Source: Author)

The data will be organized into tables eventually creating unique entries that the algorithm can read and assess. In the image above we can see highlighted in red the three objectives of this algorithm with the required data above the boxes. The boxes with yellow highlights indicate the long-term company related structural data, altogether leading to the green highlight box which would hold the optimal outcome. The data will be structured in multiple tables which will hold either geographical data (Network nodes, transshipments, indirect or direct paths), service data (carriers and transit times) or costs (Contracted and Expected).

Distance calculation is also of paramount importance for the thesis especially since we want to calculate emissions but also because the examined company has distance and time-based rates for a few suppliers of transportation. Distances have been obtained from various sources which include available selective GPS tracking data, average of data movements, estimated sea freight mileage and in certain cases external websites providing distances which have been cross verified afterwards (for instance Google Maps, Cargopedia.net, Searates.com).

In regards to GHG emission calculations, the selected formula is suggested by the GLEC Framework and is indicated below:

$$GHG = Distance\ (KM) * Weight\ (Tonnes) * Emission\ Factor\ (EF) * DAF$$

This formula incorporates the DAF, where if actual distances are applicable then there will be an adjustment factor. This is used for sea movements and is set by the authors of the GLEC framework at a ratio of 1.15 per movement for short sea and deep sea voyages (Ehrler et al., 2023).

The solution approach of the model will include two main aspects, existing optimal solution and suggested optimal solution. The first indicates the optimal path based on the existing rates and options that the company under examination can handle while the second solution indicates a better path considering the three aspects that may not be immediately possible for the company to follow. Such inability could possibly be a result of insufficient network capacity, planning constraints or missing contracts. The expected solution will be validated by comparing the model's output to real-world data and assessing its accuracy and reliability, should this data be available.

The following parameters are our model's input data all of which are defined per lane, per unique combination of origin and destination, the carrier performing the operation and the mode of transport.

- Carbon emissions
- Transit Time
- Freight Cost
- Applicable Surcharges
- Connectedness of nodes
- Contracted/Available Capacity

Despite the input parameters there are only three outputs as optimization goals, cost, transit time and GHG emissions.

The increase in the number of handlings is referred to as the number of legs and represents an increase in the complexity of the supply chain. The more the excess number of legs along a route, the more the number of independent bookings and information that need to flow and coordinate. Each company, reader or research may interpret this complexity differently and there are various approaches into resolving and simplifying high complex cases occurring from this state.

3. Results and Findings

The current model runs LP over an interconnected network of nodes as defined by Dijkstra's algorithm. The limitation of this approach is that we can run a single optimization and analysis at a time due to the numerous constraints set by the network connectedness. By removing this constraint, the tool could run heavier in load calculations but would only consider direct connections between origin and destination. Alternatively, we can run sequentially the two algorithms, first, the Dijkstra's approach to define all possible routes and then the LP optimization to allocate capacity based on minimal cost.

For the comparison of the results, we have run the algorithm for 60 cases which include Actual (A) and Suggested (B) rates and for distinct cases where we are transporting Products of Animal Origin (POAO) and cases where we do not. It is noted that B type rates include A type rates but A type rates do not include B type.

3.1 General Results

In general implementation of the LP model, we designed was a success in all parts and by success we identify the efficient tracking of the shortest path while optimizing the main objectives of the LP model.

The main concepts that have been analyzed are listed below:

1. Network Design Functionality
2. Complexity
3. Cost
4. Capacity
5. Transit Time
6. Greenhouse Gas Emissions

Opportunities for the company under examination have been identified in all parts whereas it involves improving cost, emissions or lead time and in certain few cases both. Overall, out of 60 cases we notice improvements in 24 of them which represent 40% of the total use cases. The majority of these observations originate from the United Kingdom and have destinations within the European Union (EU). This may be a result of individual inconsistencies that member-states if the EU have in regards to customs activities and processes in different Border Control Posts (BCP). While it may be true in some a deep-dive into the results shows another perspective. Local haulage in the United Kingdom is procured in lower costs if procured locally by the business unit or independently as an individual leg. It is a sensible activity for a shipper to examine the pre-carriage and on-carriage costs of procured transport contracts as often there are opportunities or costs hidden on the dray legs.

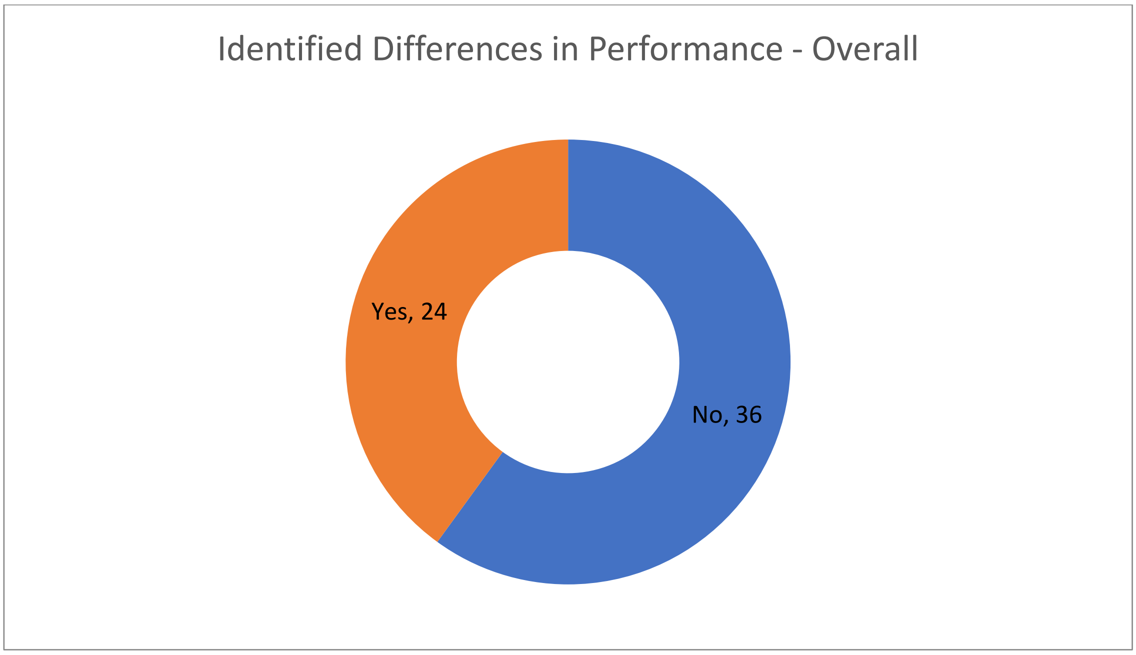

Figure 2: Identified lanes with potential improvements in either Cost, TT or GHG's out of data sample (Source: Author).

In exceptional cases we notice simultaneous improvements in all aspects of the model. This occurs six times during our observations, four of which correspond to lanes with origin or transit in/through The Netherlands. For instance, the flow from The Netherlands to Japan as a D/P service (DAP Incoterm) has been heavily enhanced to reduce cost, transit time to and GHGs to a staggering 12% drop in cost, 10% reduction in transit time and 0.7% in GHG emissions.

The above points will be explained in detail below, in the respective sub-chapters.

The rest of the results, 36 other use-cases in total, have shown no improvement potential using this model in any of the optimization goals. This means they are already optimized in full with the current data that we possess at this time. In the future a new terminal, or a new carrier or even the development of new equipment can change this outcome either positively or negatively. Therefore, it should be mentioned at this point, that running this algorithm should be a recurring exercise, rather than a one-off activity, for all supply chain managers and decision makers to ensure that the data sources and outputs are fully optimized and up-to-date.

As part of the analysis the Simplex LP model run in the thesis is generating three reports for each individual run, the answer report, sensibility report and limits report. Part of the sensibility report, is the allowed increase or decrease of the values that would alter the outcome of the model, they are therefore determining the allowable range for the coefficients of the objective function. These should be seen as ranges within which the coefficients can change without affecting the optimality of the current solution. This information will be particularly useful for decision-makers as it would provide additional visibility and flexibility. A few reports will follow in the Appendix B at the end of the thesis for visibility purposes.

3.1.1 Network Design Functionality & Complexity – Dijkstra's Algorithm

In regards to network design, it is evident from the results that Dijkstra's Algorithm was able to navigate and connect all paths of the network while identifying the shortest route, in our case defined by cost. Shortest paths were defined with up to a maximum of three legs, each being a separate booking with either the same or a different carrier/vendor. The current thesis aims to analyze the results of the network design output as "complexity". In this case, complexity increases as the individual number of bookings are increasing. The reasoning behind this logic lies with the fact that more handlings on an individual booking requires additional resources from the company to be provided. Resources can be subjectively interpreted uniquely for every company and reader as either human resources, software investment or any other form of capital expense, as they see fit. In this particular study, 36% of all analyzed routings, and specifically 92% of the improved routes, indicate an increase in the handlings therefore subsequently increasing the complexity factor. The same data sample indicates that 37,5 % of all identified positive results required twice as much complexity as they contain 3 individual legs per booking.

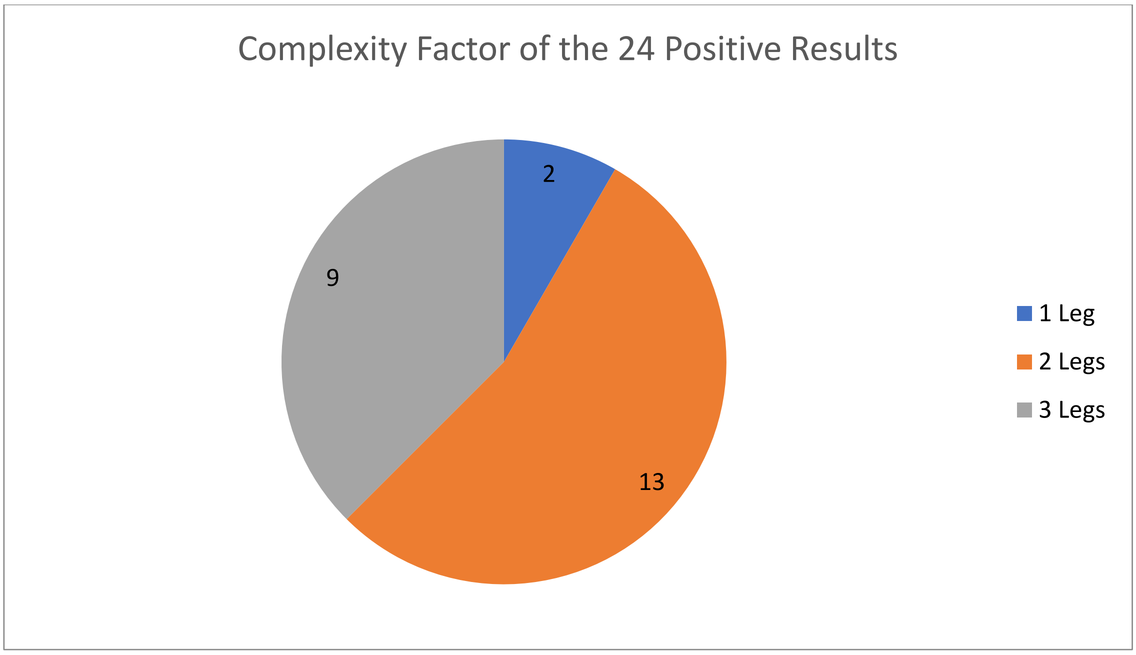

Figure 3: Pie chart indicating the complexity factor of the data sample containing improvements (Source: Author).

Results indicate in certain cases the network is already optimized as the returning results provide similar planning designs as the company is currently following. This corresponds mostly intra EU movements rather than inter-continental flows. This may be caused due to the fact that there is little to no visibility on the pre-carriage and on-carriage costs and modes that are being used in global transports. Based on this outcome is is also evident that functional centralization or cross-team collaboration can yield better results in the logistics network of this company and possibly can be applied broadly.

3.1.2 Cost

Cost is the most important outcome of this LP model as it ensures the company is sustainable enough in terms of logistics expenditure. There are only a handful of cases where the cost can be improved though and the main outliers in this case have been identified in the Polish flows, inbound and outbound to/from Poland. The main reason current expenditure is high is that at the moment the company is using road transportation to transport the goods from either the Polish factory or to the Polish warehouse. The developed model in this thesis is proposing alternative modes of transport mostly by using sea freight and the shuttling services from the ports of Poland to the company's premises. In certain cases, this results in amounts up to 40% reduction in cost and 28% reduction in emissions. Unfortunately, this result comes with the downside of doubling up on the transit time on this particular route which subsequently affects more departments within the company such as customer service and supply planning.

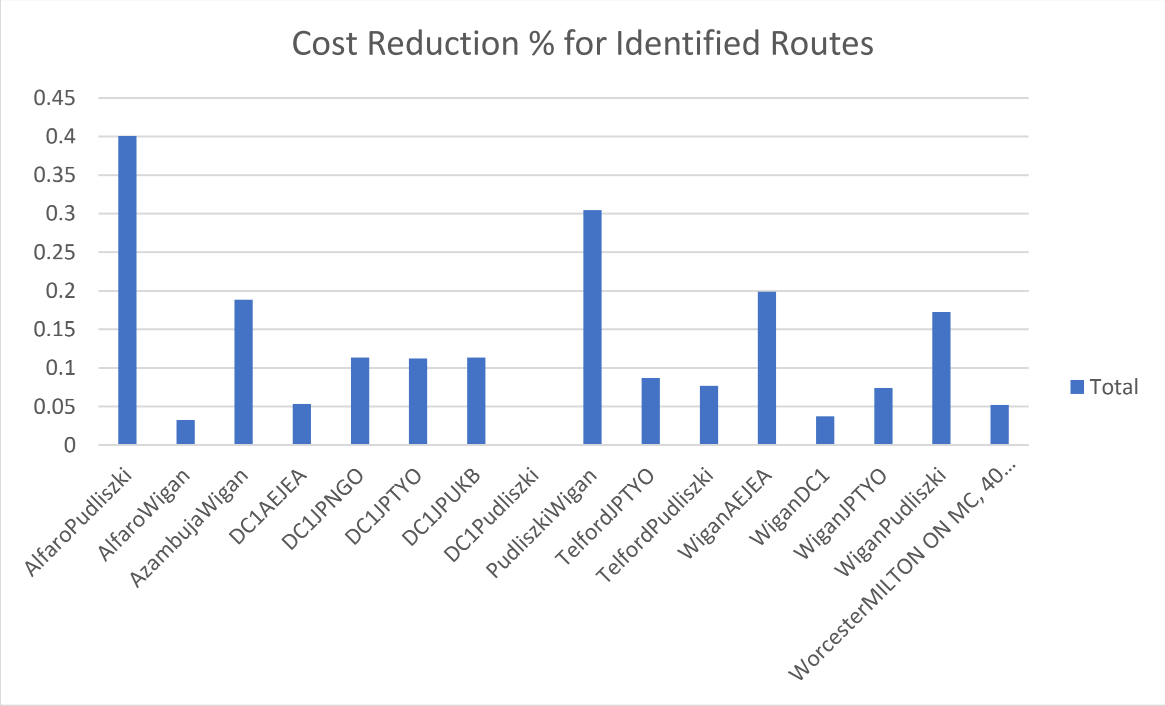

Figure 4: Percentage of reduced cost as identified in selected routes by this LP model (Source: Author).

Changing modes of transport is necessary in order to achieve most of the intra-EU reductions in cost but there are more risks related to such changes. For example, road transportation has a completely different capacity and availability pool for equipment and while sea freight networks rely in container pools sailing schedules will affect all movements increasing risk in case of a missed cut-off.

In certain cases, for example from Spain into the United Kingdom the individual cost reduction occurred from this model is 2% while complexity is increased from a single booking to 3 bookings. In combination with the missed sailing risk, it may be inefficient for the company to implement this change. In contrast, the route from Portugal into United Kingdom can have an 18% cost reduction and simultaneously reduce all other examined factors as well which is a reasonable investment for the company.

In principle we have only considered the basic cost types in this LP model which are the freight costs, customs and documentation cost and terminal handling charges. There are additional costs to be considered in subsequent researches which could be for example the inventory handling cost (IHC). Moreover, an important aspect of intermodal networks is the container pool and the container repositioning fees, which are not considered in this thesis. Subsequently this would increase the operating costs of the company unless viable options are identified. As viable options we would consider cases where flows are connected or handled by vendors or carriers who are active in both inbound and outbound flows. Alternatively, a 4PL could manage such flows for the company under study but that would also signify an increase in the operating costs. While more suggestions take place in the next chapter it is safe to state that the primary costs have been considered and the results can be deemed accurate and valid.

3.1.3 Transit Time

Out of all our results, transit time is the least promising in terms of improvements. The company of this case study has already achieved high utilization of the delivery times and in most cases, they seem to be as low as possible considering each mode of transport.

As mentioned above, there is an increased risk for changing the selected equipment type per route. In correlation with all other factors though lead time still plays an important role in this analysis. An increase in lead time could reduce the aforementioned IHC, therefore the results of this thesis can be used to further examine total landed cost impact by a change in the lead time. Out of the 24 identified possible improvements, 7 have increased lead times, 4 remain the same and the rest show a reduction.

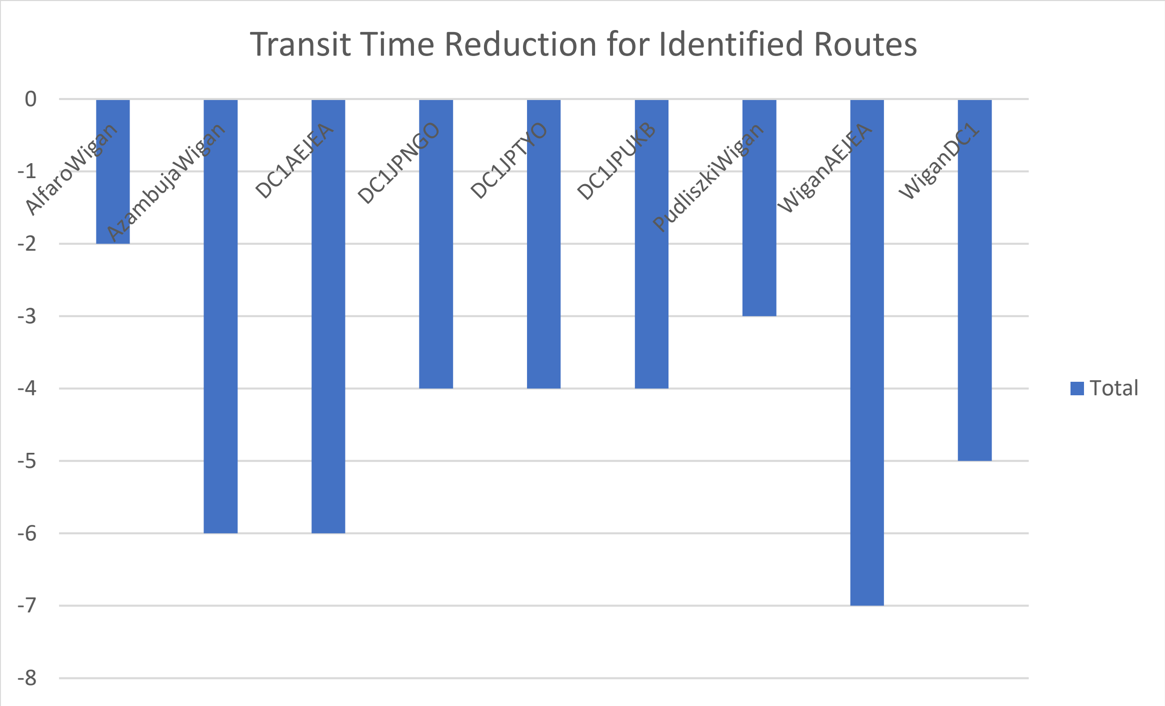

Figure 5: Transit Time Reduction in Days for Identified Routes (Source: Author)

Evidently, as inter-modality and the respective number of bookings per shipment increases so does the possibility of delay since more factors become increasingly important, for example the terminal cut-off types and quite often customs submission cut-off time. Such factors are applicable regardless if we use air freight, sea freight or rail.

3.1.4 GHG

In regards to GHGs in combination with the company's current modal shift we can observe that little to no enhancements can be made considering the volume and traffic the company is handling. Again, examining the 24 positive outcomes from the LP model we can observe that 14 distinct lanes have a change in the GHG emissions after running the LP model which represents 23% of all data analyzed. Out of these results 9 routes indicate a negative change in GHGs (Reduction of emissions) while 5 show a positive result indicating an increase in GHGs emissions to achieve a reduction in cost. Given the fact that all data analyzed are representing weekly values it is estimated that the company under examination can achieve a reduction of 14.6 thousand euros per week and a reduction in emissions of 16.7 tons. Should the company choose to only reduce GHGs then a 24.7 tons of emissions per week can be achieved per week for a reduction in cost of 7 thousand euro.

The following two graphs, figure 6 and figure 7, illustrate these results.

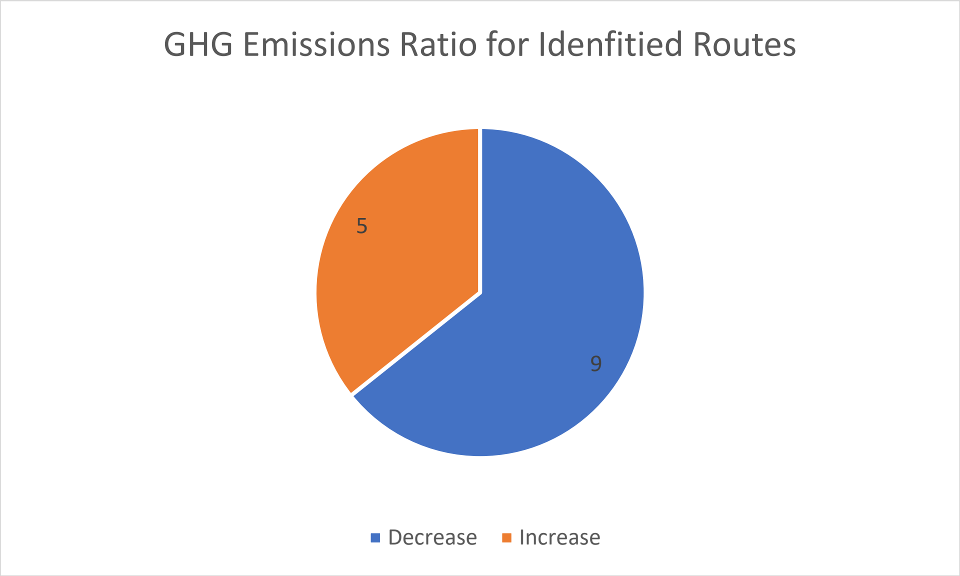

Figure 6: GHGs Changes in Identified Routes (Source: Author)

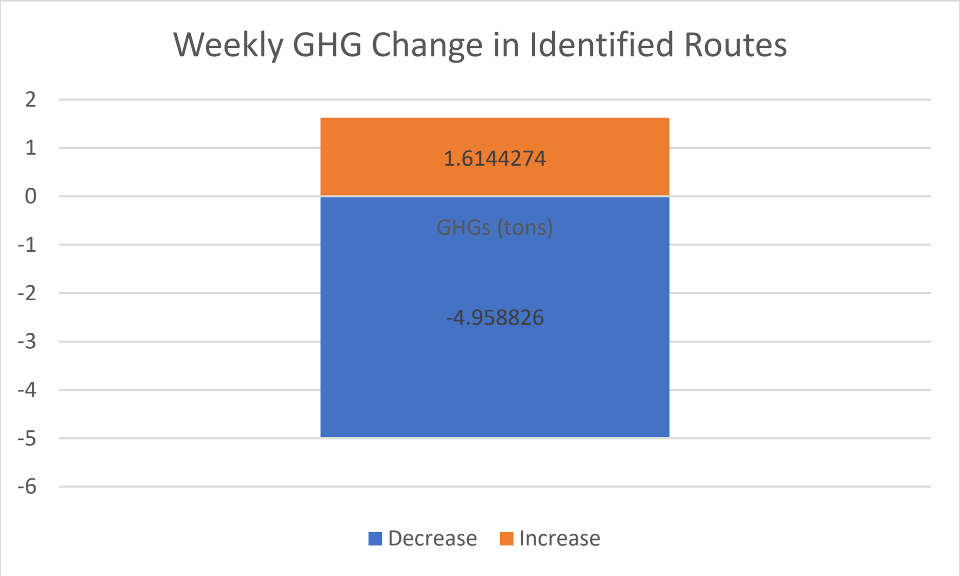

Figure 7: Sum of Weekly GHGs Change in Identified Lanes (Source: Author)

The above graph illustrated the overall weekly change in GHGs should the full model be used. In this case the company would achieve maximum cost savings while reducing emissions by 16.7 tons per week only on these specific routes.

It is noted in the results that the flows going into Poland mark very high yield in terms of emission reduction. From the UK into Poland, we notice a 41% and 52% reduction from two origin sites and we also observe from two other EU origin countries a 27% and a 62%

reduction in emissions. These results can be interpreted from the changing of the equipment type and mode of transport from road transportation to intermodal transportation. It is also stated in this point that the company does not have to completely switch modes of transports in case the risks are deemed too much, even though the increase in transit time is 1 and 2 days respectively with the exception of origin Spain, but they can rather have a slower approach where they convert for example 20% or 25% of the volume to intermodal.

3.1.5 Capacity

In terms of capacity, it is noticed that in all cases capacity constraints have been met. This is due to the fact that there is a sea freight option available for all lanes which satisfies the criteria at all times. We used the average number of shipments per week, which is 5 containers, equivalent to 11.25 TEU. Additionally, even in exceptions among certain lanes where the average number of containers is 120 per week all criteria have still been satisfied. Without the sea freight options there are constraints occurring for intra EU movements in certain flows that require non-containerized transport with transport modes such as Tautliner trucks and Box trailers. Additionally, we are now only examining a standard flow of 5 shipments per week per route but there are cases where the weekly flow is less or more. If we analyze routes with 100 shipments per week it is expected to run into more constraints in regards to capacity. In cases like this, the docking capacity of each individual site would also play a significant role and even though it is not examined as part of this LP model it would make a great addition for future research as mentioned in the following chapter. For the average number of 5 shipments per route per day the constraints are met for all sites as they have approximately 6 docks with 1 hour timeslots and operate on at least 12 hours per day, therefore each site can load and dispatch 72 shipments per day. Quite a few slots are reserved for domestic movements and reallocations which is not part of the scope of the thesis.

Evidently there are some changes suggested by the LP model in conjunction with Dijkstra's algorithm where in certain flows that currently utilize trailers it is efficient to change equipment types to containers. The suggestion in this case is to further expand the research and include IHC cost so that the financial impact of switching modes of transport can be evaluated.

As a concluding remark in regards to capacity it should be noted that there is great connectivity to the intermodal network for the company under this case study. The connections to ports and terminals and the number of different vendors providing services of various transportation modes reduces the risk of running into capacity issues.

The LP model that we defined in this thesis can be easily modified by allowing a user to run optimization on different parameters, namely one of the three objectives of the model, which are transit time, cost and GHGs. With the reliance on Dijkstra's algorithm, we run the benefit of using alternative routing options and whilst more complex the independent planning of each leg allows for optimizing most of the expected targets.

4. Conclusions and Recommendations

The central contribution of this thesis to the academic community lies in the validation and credibility it offers to the application of the linear programming model for optimal route problems in logistics. This validation is pivotal for both academia and industry, as it reaffirms the effectiveness and applicability of mathematical optimization techniques in solving complex transportation network design challenges. In regards to the industry, chapter 3 illustrates the results of our model which have been produced and verified. Valid outputs have been generated which the company under this case study can implement to achieve optimization across multiple logistics constraints. The chapter above analyzes in detail how the tool optimized 40% of all test scenarios in either of the three main pillars, cost, lead time and GHG emissions.

To enhance the validation process, future research could focus on conducting comparative studies between different optimization models, such as Linear Programming (LP), Mixed-Integer Linear Programming (MILP), and other heuristic approaches. By benchmarking these models against real-world scenarios, researchers can provide a comprehensive assessment of their strengths and weaknesses, further validating the effectiveness of linear programming in optimizing transportation networks.

The utilization of real data and structures from a global food manufacturer bolsters the credibility of the proposed model. Real-world data inherently reflects the complexities and nuances of supply chain operations, thus increasing the relevance and applicability of the research findings. For instance, a lead time corrector can be implemented where past data and real time events can affect the transit time between two points or a port congestion feature can also be implemented. Analyzing port capacity and congestion also contributes significantly more if we do an holistic analysis of the data as Dijkstra's algorithm is expected to route heavier volumes of TEUs through certain ports increasing the handling load and potentially affecting the transit time or capacity of these ports.

To build upon this valuable foundation, future research endeavors could expand the scope of data collection and analysis. This may involve collaborations with additional companies across diverse industries, allowing for the exploration of sector-specific challenges and requirements. A broader dataset can provide more comprehensive insights into the adaptability and robustness of the proposed model across various business contexts. For instance, by incorporating tier 1 movements of raw materials and packaging materials we hope to utilize more synergies that greatly improve the outcome of the developed LP model.

In the pursuit of continuous improvement, there are several avenues for enhancing the developed model. These potential enhancements can extend its capabilities and relevance in addressing the evolving dynamics of logistics and supply chain management. As mentioned in the literature review the model of this thesis is missing three out of six factors considered valuable tradeoffs in logistics as presented by the book of Watson et al. These factors are labor costs, risk and taxes. All three of them further elaborated on as part of the thesis conclusion below.

To align transportation decisions with a company's financial goals, future iterations of the model can incorporate additional checks against provided rates to ensure strict compliance with the respective company's budgeting plan. This would enable logistics managers to make decisions that not only optimize routes but also adhere to financial constraints, enhancing cost control and financial sustainability.

Transportation decisions are not solely influenced by immediate needs but are also guided by long-term strategic plans and the company's direction. Future research can integrate long-term strategic considerations into the model. By factoring in the company's growth trajectory, market expansion, and evolving transportation requirements, the model can provide insights into transportation network designs that align with broader corporate strategies. Additionally, supply chain managers and future researchers can use such a tool to decide what the ideal location is rather than finding the best route. This would use the network to find the ideal site rather than using the sites to find the ideal network. For instance, manager A wants to identify which country or location is best, to source a new raw material, then plugs in the details and with a few tweaks in the model, manager A obtains as a result the country/location where the total landed logistics cost will be the least.

The imperative to reduce carbon emissions along the supply chain is paramount. Future iterations of the model can incorporate mechanisms for carbon emissions offsetting and in-setting. This would involve quantifying emissions and exploring strategies to mitigate them, such as carbon offset projects or investments in sustainable transportation modes. Such an approach aligns with environmental objectives and contributes to a more sustainable supply chain.

One crucial aspect often overlooked is the composition of items within shipments. Crossing borders can introduce complexities, especially when items contain Products of Animal Origin (POAO) or other regulated goods such as alcohol, tobacco and medicine. Future enhancements to the model can include item composition considerations, accounting for potential additional checks, delays, and costs associated with specific types of goods. This level of granularity ensures that transportation network designs are sensitive to the diverse nature of goods being transported.

It is important to emphasize that the possibilities for model adjustments and enhancements are not limited to the recommendations above. The proposed model can be tailored to meet the specific design and operational requirements of individual corporations. Customization allows for a more precise alignment of the model with the unique characteristics and objectives of each company, thereby maximizing its utility and impact. Additionally, it is proposed for future endeavors on improving this model to consider the total landed cost of manufactured items by including their manufacturing costs, which would include utilities and manpower, and potentially convert each variable into a common denominator, for example cost, where it would be easier to optimize the entire supply chain process while running a single optimizing tool. Lastly, since the model can consume large amount of disconnected data, and using Dijkstra's algorithm create a network of networks, applications can exist that aid network design for humanitarian logistics. By combining data from multiple sources, within a secure environment, a larger network of possibilities can unfold, providing the range and speed that is often needed either for disaster control incidents or humanitarian aid.

In conclusion, the recommendations put forth aim to guide future research endeavors in the field of transportation network optimization. These enhancements and refinements will not only strengthen the academic validation of the linear programming model but also contribute to the practical relevance and applicability of transportation network design solutions across diverse industries and contexts.

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Appendix A: “Conversion Rates”

Distance		
From	To	Rate
m	km	*1000
mi	km	*1.6
nmi	km	*1.825
m	ft	*0.3048

Table 4: Distance Conversion Rates

Weight		
From	To	Rate
gm	kg	*1000
kg	ton	*1000
lb	kg	*0.4536

Table 5: Weight Conversion Rates

TEU Conversion	
Container Type	TEU Equivalent
20ft	1
40ft	2
45ft	2.5

Table 6: Container Size Conversion Rates

Appendix B: “Reports”

Sensitivity Report: Portugal to United Kingdom

Report Generated: 18/01/2024, Output changed for the protection of sensitive data.

Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
K8	3GB Go	0	0	2006.75983	5.9323035	434.3779665
K9	5GB Go	0	828.962091	3228.880855	1.63E+30	828.962091
K10	7GB Go	0	634.3761548	2570.148955	1.63E+30	634.3761548
K11	8GB Go	0	0	2454.00412	38.13711	572.8367272
K12	PPL5 Go	0	0	701.2027725	434.3779665	5.9323035
K13	3GB Go	0	1159.368144	2855.695615	1.63E+30	1159.368144
K14	5GB Go	0	0	2089.486405	106.5238823	5.9323035
K15	6GB Go	0	0	1742.785405	9.96765375	106.5238823
K16	7GB Go	0	1374.236089	2999.57653	1.63E+30	1374.236089
K17	PPL5 Go	0	2816.213837	3206.98425	1.63E+30	2816.213837
K18	DNL225 Go	0	0	684.734475	5.9323035	434.3779665
K19	5GB Go	0	0	2521.14382	622.5352642	948.9736935
K20	27PL Go	0	622.5352642	712.5572303	1.63E+30	622.5352642
K21	WGB3 Go	0	0	957.4148115	5.9323035	106.5238823
K22	WGB8 Go	0	9.96765375	830.002194	1.63E+30	9.96765375
K23	TGB9 Go	0	0	830.002194	106.5238823	1237.72257
K24	41IT Go	0	1064.37207	1064.37207	1.63E+30	1064.37207
K25	27PL Go	0	0	2449.442565	1.63E+30	6529.411905
K26	WGB3 Go	1	0	564.2558775	106.5238823	5.9323035
K27	WGB8 Go	0	656.1316425	1083.007249	1.63E+30	656.1316425

K28	TGB9 Go	0	364.03605	800.87931	1.63E+30	364.03605
K29	WGB3 Go	0	153.8485687	1064.805446	1.63E+30	153.8485687
K30	WGB8 Go	0	0	773.5766063	9.96765375	1509.882855
K31	27PL Go	0	2837.111659	752.690805	1.63E+30	2837.111659
K32	TGB9 Go	0	106.5238823	890.0681423	1.63E+30	106.5238823
K33	2NL Go	0	2936.292391	1310.95195	1.63E+30	2936.292391
K34	BDE143 Go	0	565.2879528	1469.863095	1.63E+30	565.2879528
K35	WGB3 Go	0	0	1028.401841	364.03605	556.3684298
K36	WGB8 Go	0	483.2145187	1374.236089	1.63E+30	483.2145187
K37	132FR Go	0	0	2418.24518	1.63E+30	5589.140293
K38	TGB9 Go	0	364.03605	1265.025274	1.63E+30	364.03605
K39	38ES Go	0	948.9736935	1031.435475	1.63E+30	948.9736935
K40	BDE143 Go	0	0	3044.03478	5.9323035	434.3779665
K41	CIT144 Go	0	0	3619.55844	512.3856915	1.63E+30
K42	LFR4 Go	0	5.9323035	2480.645655	1.63E+30	5.9323035
K43	PIT145 Go	0	0	2395.70391	434.3779665	369.236565
K44	TBE146 Go	0	0	2719.869345	617.12778	8.667525
K45	WGB3 Go	0	1086.787341	4254.64882	1.63E+30	1086.787341
K46	PPL5 Go	0	3229.519815	4134.409425	1.63E+30	3229.519815
K47	DNL225 Go	0	1469.010523	2667.864195	1.63E+30	1469.010523
K48	ENL100 Go	0	1838.247088	2693.86677	1.63E+30	1838.247088
K49	5GB Go	1	0	2600.2575	735.8728725	1.63E+30
K50	APT11 Go	0	793.598589	793.598589	1.63E+30	793.598589
K51	WGB3 Go	0	735.8728725	3900.38625	1.63E+30	735.8728725
K52	BDE143 Go	0	0	2621.05956	617.12778	1.63E+30
K53	LFR4 Go	0	1573.020823	3624.758955	1.63E+30	1573.020823
K54	TBE146 Go	0	617.12778	2914.021905	1.63E+30	617.12778

K55	WGB3 Go	0	2104.354776	4849.241035	1.63E+30	2104.354776
K56	PPL5 Go	0	1908.589005	2390.503395	1.63E+30	1908.589005
K57	DNL225 Go	0	2136.409948	2912.2884	1.63E+30	2136.409948
K58	ENL100 Go	0	2516.047543	2948.692005	1.63E+30	2516.047543
K59	WGB3 Go	0	0	3765.17286	1.63E+30	1.63E+30
K60	PPL5 Go	0	0	1232.522055	1.63E+30	1.63E+30
K61	WGB3 Go	0	0	5989.887325	1.63E+30	1.63E+30
K62	WGB3 Go	0	0	4475.27095	1.63E+30	1.63E+30
K63	BDE143 Go	0	0	4656.19443	1630.226489	1.63E+30
K64	PPL5 Go	0	2614.12554	5131.1748	1.63E+30	2614.12554
K65	DNL225 Go	0	1630.226489	4441.23981	1.63E+30	1630.226489
K66	ENL100 Go	0	1637.160509	4104.93984	1.63E+30	1637.160509
K67	PPL5 Go	0	0	2442.632425	1.63E+30	11694.2297
K68	AES6 Go	0	5694.563925	4191.61509	1.63E+30	5694.563925
K69	BDE143 Go	0	0	1541.085945	663.932415	1.63E+30
K70	CIT144 Go	0	1287.994215	3404.60382	1.63E+30	1287.994215
K71	LFR4 Go	0	1876.384198	2848.148715	1.63E+30	1876.384198
K72	PIT145 Go	0	1587.89058	2480.645655	1.63E+30	1587.89058
K73	TBE146 Go	0	663.932415	1880.852925	1.63E+30	663.932415
K74	WGB3 Go	0	2894.833056	4559.7457	1.63E+30	2894.833056
K75	DNL225 Go	0	2108.673868	1804.578705	1.63E+30	2108.673868
K76	ENL100 Go	0	2503.913009	1856.583855	1.63E+30	2503.913009
K77	ENL100 Go	0	0	745.40715	1.63E+30	1.63E+30
K78	PPL5 Go	0	0	1667.63181	1.63E+30	1.63E+30
K79	BDE143 Go	0	369.236565	4446.440325	1.63E+30	369.236565
K80	LFR4 Go	0	683.7327585	4191.61509	1.63E+30	683.7327585
K81	PIT145 Go	0	0	3428.87289	369.236565	1.63E+30

K82	WGB3 Go	0	819.827571	5020.85803	1.63E+30	819.827571
K83	PPL5 Go	0	3465.276495	5403.335085	1.63E+30	3465.276495
K84	DNL225 Go	0	2231.752723	4463.775375	1.63E+30	2231.752723
K85	ENL100 Go	0	2729.268658	4618.05732	1.63E+30	2729.268658
K86	8GB Go	0	2661.329932	3114.00253	1.63E+30	2661.329932
K87	AES6 Go	0	4422.171255	2217.152895	1.63E+30	4422.171255
K88	BDE143 Go	0	8.667525	847.683945	1.63E+30	8.667525
K89	DIE147 Go	0	1479.411553	3267.656925	1.63E+30	1479.411553
K90	TBE146 Go	0	0	514.850985	8.667525	1.63E+30
K91	WGB3 Go	0	2367.847536	3330.690655	1.63E+30	2367.847536
K92	PPL5 Go	0	2836.01418	1535.88543	1.63E+30	2836.01418
K93	DNL225 Go	0	1820.912038	814.74735	1.63E+30	1820.912038
K94	ENL100 Go	0	2164.146028	814.74735	1.63E+30	2164.146028
K95	BDE143 Go	0	0	3591.82236	1721.370465	1.63E+30
K96	WGB3 Go	0	1830.460986	5546.110045	1.63E+30	1830.460986
K97	PPL5 Go	0	1721.370465	3174.047655	1.63E+30	1721.370465
K98	DNL225 Go	0	2368.699619	4115.34087	1.63E+30	2368.699619
K99	ENL100 Go	0	2129.475929	3532.88319	1.63E+30	2129.475929
K100	3GB Go	0	1660.004388	830.002194	1.63E+30	1660.004388
K101	5GB Go	0	1237.72257	800.87931	1.63E+30	1237.72257
K102	6GB Go	0	1673.612402	890.0681422	1.63E+30	1673.612402
K103	7GB Go	0	1663.731424	762.7422	1.63E+30	1663.731424
K104	8GB Go	0	1647.783178	1265.025274	1.63E+30	1647.783178
K105	AES6 Go	0	5586.974438	2546.525576	1.63E+30	5586.974438
K106	BDE143 Go	0	1422.939551	1426.52547	1.63E+30	1422.939551
K107	CIT144 Go	0	2750.804381	3329.91396	1.63E+30	2750.804381
K108	LFR4 Go	0	2263.995835	1698.260325	1.63E+30	2263.995835

K109	NGB18 Go	0	11694.2297	7116.038025	1.63E+30	11694.2297
K110	PIT145 Go	0	2688.398202	2043.65325	1.63E+30	2688.398202
K111	PPL5 Go	0	4770.610731	2635.05148	1.63E+30	4770.610731
K112	DNL225 Go	0	4095.190206	2253.595016	1.63E+30	4095.190206
K113	ENL100 Go	0	4438.424196	2253.595016	1.63E+30	4438.424196
K114	WGB3 Go	0	0	5123.134825	1.63E+30	1.63E+30
K115	18PL Go	0	4262.693767	1298.519125	1.63E+30	4262.693767
K116	3GB Go	0	1850.169887	892.755075	1.63E+30	1850.169887
K117	5GB Go	0	1128.511755	564.2558775	1.63E+30	1128.511755
K118	6GB Go	0	1905.295345	994.338468	1.63E+30	1905.295345
K119	7GB Go	0	2056.803683	1028.401841	1.63E+30	2056.803683
K120	8GB Go	0	1593.17777	1083.007249	1.63E+30	1593.17777
K121	AES6 Go	0	5714.387055	2546.525576	1.63E+30	5714.387055
K122	BDE143 Go	0	1593.689794	1469.863095	1.63E+30	1593.689794
K123	CIT144 Go	0	2980.493794	3432.190755	1.63E+30	2980.493794
K124	DIE147 Go	0	1529.060213	2354.462465	1.63E+30	1529.060213
K125	LFR4 Go	0	2729.441928	2036.2938	1.63E+30	2729.441928
K126	PIT145 Go	0	2815.810819	2043.65325	1.63E+30	2815.810819
K127	TBE146 Go	0	1493.295649	1045.303515	1.63E+30	1493.295649
K128	PPL5 Go	0	4667.467184	2404.495315	1.63E+30	4667.467184
K129	130GB Go	0	0	953.42775	1.63E+30	1.63E+30
K130	DNL225 Go	0	4453.158989	2484.151181	1.63E+30	4453.158989
K131	ENL100 Go	0	4378.618274	2066.376476	1.63E+30	4378.618274
K132	3GB Go	0	1650.036734	830.002194	1.63E+30	1650.036734
K133	42IT Go	0	6529.411905	1221.97188	1.63E+30	6529.411905
K134	5GB Go	0	1509.882855	1083.007249	1.63E+30	1509.882855
K135	6GB Go	0	1547.153213	773.5766063	1.63E+30	1547.153213

K136	7GB Go	0	2265.257659	1374.236089	1.63E+30	2265.257659
K137	8GB Go	0	1692.420932	1319.630681	1.63E+30	1692.420932
K138	AES6 Go	0	5577.006784	2546.525576	1.63E+30	5577.006784
K139	BDE143 Go	0	1671.264143	1684.817715	1.63E+30	1671.264143
K140	LFR4 Go	0	2250.561171	1694.793315	1.63E+30	2250.561171
K141	PIT145 Go	0	2678.430548	2043.65325	1.63E+30	2678.430548
K142	131GB Go	0	0	1326.131325	1.63E+30	1.63E+30
K143	DNL225 Go	0	4528.999832	2697.372296	1.63E+30	4528.999832
K144	WGB3 Go	0	0	3072.38374	1.63E+30	1.63E+30
K145	18PL Go	0	1402.405545	701.2027725	1.63E+30	1402.405545
K146	AES6 Go	0	5438.005185	4533.115575	1.63E+30	5438.005185
K147	BDE143 Go	0	0	2139.14517	434.3779665	5.9323035
K148	CIT144 Go	0	670.866435	3385.535265	1.63E+30	670.866435
K149	LFR4 Go	0	1959.592438	3529.41618	1.63E+30	1959.592438
K150	PIT145 Go	0	1211.719995	2702.534295	1.63E+30	1211.719995
K151	TBE146 Go	0	875.420025	2690.39976	1.63E+30	875.420025
K152	WGB3 Go	0	3007.977876	5270.949745	1.63E+30	3007.977876
K153	27PL Go	0	1464.811725	732.4058625	1.63E+30	1464.811725
K154	DNL225 Go	0	2181.481079	2475.44514	1.63E+30	2181.481079
K155	ENL100 Go	0	2519.514553	2470.244625	1.63E+30	2519.514553
K156	3GB Go	0	0	1256.791125	1.63E+30	1.63E+30
K157	2NL Go	0	1265.45865	580.724175	1.63E+30	1265.45865
K158	38ES Go	0	3023.24739	1906.8555	1.63E+30	3023.24739
K159	AES6 Go	0	3731.504477	2532.650805	1.63E+30	3731.504477
K160	CIT144 Go	0	512.3856915	2933.09046	1.63E+30	512.3856915
K161	DIE147 Go	0	0	2794.41006	1479.411553	1.63E+30
K162	LFR4 Go	0	0	1275.85968	5.9323035	1.63E+30

K163	PIT145 Go	0	434.3779665	1631.228205	1.63E+30	434.3779665
K164	WGB3 Go	0	910.9568775	2879.964685	1.63E+30	910.9568775
K165	PPL5 Go	0	1509.151067	1215.187005	1.63E+30	1509.151067
K166	ENL100 Go	0	686.46798	343.23399	1.63E+30	686.46798
K167	AES6 Go	0	5589.140293	1031.435475	1.63E+30	5589.140293
K168	3GB Go	0	670.866435	2708.829355	1.63E+30	670.866435
K169	5GB Go	0	615.740976	3046.86283	1.63E+30	615.740976
K170	7GB Go	0	556.3684298	2523.34432	1.63E+30	556.3684298
K171	8GB Go	0	38.13711	2523.34432	1.63E+30	38.13711
K172	PPL5 Go	0	0	732.4058625	38.13711	622.5352642
K173	WGB3 Go	0	572.8367272	1083.007249	1.63E+30	572.8367272
K174	WGB8 Go	0	946.840431	1319.630681	1.63E+30	946.840431
K175	TGB9 Go	0	882.2673697	1265.025274	1.63E+30	882.2673697
K176	WGB3 Go	0	567.7228875	2879.964685	1.63E+30	567.7228875
K177	DNL225 Go	0	0	343.23399	567.7228875	686.46798
K178	WGB3 Go	0	0	5270.949745	1.63E+30	1.63E+30
K179	5GB Go	0	0	6036.69196	1.63E+30	1.63E+30
K180	Go	0	0	0	1.63E+30	0
K181	Go	0	0	0	1.63E+30	0
K182	Go	0	0	0	1.63E+30	0
K183	Go	0	0	0	1.63E+30	0
K184	Go	0	0	0	1.63E+30	0
K185	Go	0	0	0	1.63E+30	0
K186	Go	0	0	0	1.63E+30	0
K187	Go	0	0	0	1.63E+30	0
K188	Go	0	0	0	1.63E+30	0
K189	Go	0	0	0	1.63E+30	0

K190	Go	0	0	0	1.63E+30	0
K191	Go	0	0	0	1.63E+30	0
K192	Go	0	0	0	1.63E+30	0
K193	Go	0	0	0	1.63E+30	0
K194	Go	0	0	0	1.63E+30	0
K195	Go	0	0	0	1.63E+30	0
K196	Go	0	0	0	1.63E+30	0
K197	Go	0	0	0	1.63E+30	0
K198	Go	0	0	0	1.63E+30	0
K199	Go	0	0	0	1.63E+30	0
K200	Go	0	0	0	1.63E+30	0
K201	Go	0	0	0	1.63E+30	0

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
B8	18PL Constraints	0	4152.925695	0	0	0
B9	2NL Constraints	0	3842.493336	0	1.63E+30	0
B10	38ES Constraints	0	4274.150751	0	0	0
B11	3GB Constraints	0	2146.165865	0	0	0
B12	41IT Constraints	0	0	0	0	1.63E+30
B13	42IT Constraints	0	6633.57135	0	0	0
B14	5GB Constraints	0	1753.006931	0	0	0
B15	6GB Constraints	0	2099.707931	0	1.63E+30	0
B16	7GB Constraints	0	2217.152895	0	0	0
B17	AES6 Constraints	0	4356.612533	0	0	0
B18	APT11 Constraints	1	4353.264431	1	0	0

B19	CIT12 Constraints	0	3933.637313	0	0	0
B20	EDE13 Constraints	0	4953.923914	0	0	0
B21	HDE14 Constraints	0	4684.244978	0	0	0
B22	LIT15 Constraints	0	7178.638379	0	0	0
B23	LPL16 Constraints	0	5664.022004	0	0	0
B24	MES17 Constraints	0	5968.772183	0	0	0
B25	NGB18 Constraints	0	5894.355348	0	0	0
B26	PIT222 Constraints	0	2853.663698	0	0	0
B27	QDE223 Constraints	0	4246.400001	0	0	0
B28	RBE20 Constraints	0	5119.354733	0	0	0
B29	SES22 Constraints	0	5389.781513	0	0	0
B30	SFR1 Constraints	0	2151.594173	0	0	0
B31	SIT21 Constraints	0	4904.400113	0	0	0
B32	TGB9 Constraints	0	1316.163671	0	0	0
B33	TIT23 Constraints	0	6311.885879	0	0	0
B34	WGB3 Constraints	-1	1188.751054	-1	0	0
B35	WGB8 Constraints	0	1326.131325	0	1.63E+30	0
B36	ZNL25 Constraints	0	4261.134794	0	0	0
B37	PPL5 Constraints	0	3451.722923	0	0	0
B38	CGB77 Constraints	0	3402.95699	0	0	0
B39	DNL225 Constraints	0	3157.758861	0	0	0
B40	132FR Constraints	0	-201.092285	0	0	0
B41	27PL Constraints	0	4184.128785	0	0	0
B42	8GB Constraints	0	1698.921575	0	0	0
B43	ENL100 Constraints	0	3500.992851	0	0	0
B44	ZPL67 Constraints	0	6459.700799	0	0	0
B45	20IT Constraints	0	7789.698891	0	0	0

B46	BDE143 Constraints	0	1312.577753	0	0	0
B47	CIT144 Constraints	0	737.0540928	0	0	0
B48	LFR4 Constraints	0	1881.899181	0	0	0
B49	PIT145 Constraints	0	1960.908623	0	0	0
B50	TBE146 Constraints	0	1636.743188	0	0	0
B51	DIE147 Constraints	0	363.3488013	0	0	0
B52	130GB Constraints	0	235.3233038	0	0	0
B53	131GB Constraints	0	0	0	0	1.63E+30
B54	Constraints	0	0	0	0	1.63E+30
B55	Constraints	0	0	0	0	1.63E+30
B56	Constraints	0	0	0	0	1.63E+30
B57	Constraints	0	0	0	0	1.63E+30
B58	Constraints	0	0	0	0	1.63E+30
B59	Constraints	0	0	0	0	1.63E+30
B60	Constraints	0	0	0	0	1.63E+30
B61	Constraints	0	0	0	0	1.63E+30
B62	Constraints	0	0	0	0	1.63E+30

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