AN APPLIED OPTIMIZATION MODEL FOR FREIGHT DELIVERY IN A PHYSICAL INTERNET SUPPLY CHAIN

by

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ABSTRACT

The Physical Internet (PI) is a recent infrastructure in the supply chain, which allows transformation of the current logistics system into a universally interconnected system. It aims at tackling the issues of economic, environmental, and social sustainability in conventional logistics, allowing improvement of unsustainable freight transportation. In analogy to Digital Internet (DI), the key concept of PI is an open interconnected logistics system with a collaborative distribution network of PI hubs. PI offers a common operating framework for different companies in which physical products can be transported seamlessly in standard modularised π-containers similar to data packets in a DI.

This thesis is a study of the PI and the conventional logistic system. The main objective of the thesis is to compare the 3 different models, PI system (P), standard system (S), and hybrid (H). From a system-wide cost perspective, it is shown that Model H performs better than the others.

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LIST OF ABBREVIATIONS USED

4IR: Fourth Industrial Revolution

BLP: Binary Linear Programming

CO: Conventional logistics network

CVRP: Capacitated Vehicle Routing Problem

DC: Distribution Centers

DI : Digital Internet

GDP: Gross Domestic Product

GHG: Green House Gasses

GLW: Global Logistics Web

IoT: Internet of Things

KPIs: Key Performance Indicators

MBLP: Mixed Binary Linear Programming

MILP: Mixed Integer Linear Programming

OEMs: Original Equipment Manufacturers

OLI: Open Logistics Interconnection

OSI: Open System Interconnection

OSW: Open Supply Web

P2P: point-to-point

PI: Physical Internet

PSN: Private Supply Networks

RFID: Radio Frequency Identification

SSW: Shared Supply Webs

VRP: Vehicle Routing Problem

WEF: World Economic Forum

π-container: Physical Internet containers

π-hubs : Physical Internet containers

π-movers : Physical Internet movers

π-nodes : Physical Internet nodes

ACKNOWLEDGMENT

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CHAPTER 1 INTRODUCTION

A supply chain is a set of facilities, suppliers, customers, products, and methods of controlling inventory, purchasing, and distribution. The chain links suppliers and customers, beginning with the production of raw material by a supplier, and ending with the consumption of a product by the customer. Logistics is the flow of goods or materials between suppliers and customers passing through several echelons in a supply chain, and each echelon may consist of many facilities. Logistics activities typically include inbound and outbound transportation management, fleet management, warehousing, materials handling, order fulfillment, logistics network design, inventory management, supply-and-demand planning, and management of third-party logistics services providers.

Generally, research and practice in supply chain logistics focus mainly on key factors of maintaining relations and coordination between suppliers and customers to achieve a more profitable outcome. The main emphasis is on customer response, inventory planning and management, supply, transportation, and warehousing. Even though these attributes are substantially important value addition, the current logistics system in implementation throughout the world is not sustainable economically, environmentally, and socially (Ballot et al., 2012). In Montreuil, B. (2011), thirteen unsustainability symptoms (Figure 1) were identified, providing the evidence to the previous assertion. From an economic perspective, the contribution of transportation to the economy is a measure of its contribution to Gross Domestic Product (GDP), which includes investments made, and transportation goods and services consumed. As per the statistics from the 2015 Department of Transportation reports U.S. Department of transportation (2017), transportation accounts for 9% of GDP (roughly $1,477.9 billion) and employs over 13.0 million people in a variety of roles, from driving buses to manufacturing cars to building and maintaining ports and railroads.

	Unsustainability symptoms	Economical	Environmental	Societal
1	We are shipping air and packaging	X	X	
2	Empty travel is the norm rather than the exception.	X	X	
3	Truckers have become the modern cowboys.	X		X
4	Products mostly sit idle, stored where unneeded, yet so often unavailable fast where needed.	X		X
5	Production and storage facilities are poorly used.	X	X	
6	So many products are never sold, never used.	X	X	X
7	Products do not reach those who need them the most.	X	X	X
8	Fast and reliable intermodal transport is still a dream or a joke.	X	X	
9	Getting products in, through, and out of cities is a nightmare	X	X	X
10	Products unnecessarily move, crisscrossing the world.	X	X	X
11	Networks are neither secure nor robust.	X		X
12	Smart automation and technology are hard to justify.	X		X
13	Innovation is strangled.	X	X	X

Figure 1 Unsustainability symptoms, source: Montreuil (2011)

From an environment perspective, Study by transport Canada Transport Canada (2019), shows that out of overall transport mediums (aviation, railways, etc.), road transport maintains its high among other mediums since 2005 to 2015 (Figure 2). Despite fuel efficiency improvements, emissions from road transportation, which represents 21% of total Canadian greenhouse gas emissions in 2016, have increased by 12% from 2005 to 2016.

From a social perspective, the U.S. Department of Transportation (2017) reported that from 2000 to 2015, road transportation (via trucks) had the highest percentage of fatalities, which raises the very critical issue of social sustainability (Figure 3). Another social sustainability concern is the number of hours drivers have to spend away from home, even if they have sufficient rest time during their trips.

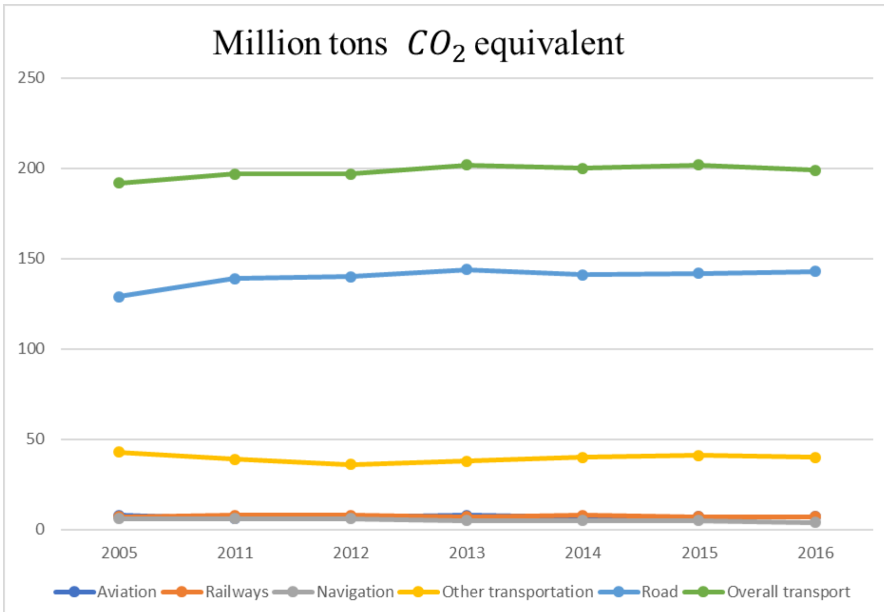


Figure 2 Million tons of CO_2 equivalent, source : U.S. Department of Transportation (2017)

As per Transport Canada (2019), the transportation sector grew by 3.2% in 2017, which is almost 1.4 times the growth rate of all other industries. In 2018, 920,800 employees (including self-employed people) were employed in the transportation and warehousing sector, demonstrating the growth of 2.7% from 2017. These growing trends in the transportation sector indicate that the demand for resources in the future will be substantially high. This also raises the concern for environmental and social sustainability.

Table 6-1 Fatalities by Freight Transportation Mode: 2000, 2010, and 2013–2015

	2000	2010	2013	2014	2015
Total transportation fatalities	**44,276**	**35,039**	**34,685**	**34,638**	**36,973**
Total highway fatalities	**41,945**	**32,999**	**32,894**	**32,744**	**35,092**
Total freight transportation fatalities	**6,079**	**4,287**	**4,558**	**4,523**	**4,631**
Freight as a share of total fatalities	**13.7%**	**12.2%**	**13.1%**	**13.1%**	**12.5%**
Highway[1]	**5,282**	**3,686**	**3,981**	**3,902**	**4,067**
Large-truck occupants	754	530	695	656	667
Others killed in crashes involving large trucks	4,528	3,156	3,286	3,246	3,400
Railroad	**717**	**520**	**505**	**552**	**502**
Train accidents	8	4	6	2	1
Highway-rail grade crossing[2]	353	187	157	203	155
Trespassers	328	310	317	325	302
Other incidents	28	19	25	22	44
Waterborne[3]	**42**	**62**	**64**	**50**	**52**
Freight	NA	22	19	18	40
Industrial/other	NA	40	45	32	12
Pipeline	**38**	**19**	**8**	**19**	**10**
Hazardous liquid pipeline	1	1	1	0	1
Gas pipeline	37	18	7	19	9

Figure 3 Fatalities by various freight transportation modes from 2000 to 2016, source: U.S. Department of Transportation (2017)

Various new innovative paradigms in logistics and supply chains can be observed in the literature, which tends to solve these sustainability issues by the integration of novel technological advancements. Organizations such as Airbnb and Uber are the prime example of the Fourth Industrial Revolution (4IR), which has developed a notion of shared economy and asset sharing (Barber, 2018). 4IR represents a series of significant shifts in values related to the emergence of new technologies that encompasses the digital, physical, and biological worlds (Philbeck & Davis, 2019). The World Economic Forum (WEF) has provided five themes related to 4IR for enhancement of the supply chain logistics and making them more sustainable. Themes include information services, logistics services, delivery capabilities, circular economy, and sustainability. The concept of 4IR is often confused with Industry 4.0. Industry 4.0 conceals the technological developments in manufacturing and production systems by focussing on relationships between digitization, organizational transformation, and productivity enhancement. It focuses on the vision of modular and efficient manufacturing systems for future production. In Lasi et al. (2014), authors also list the fundamental concept of smart factory, cyber-physical systems, self organizations, new systems in distribution and procurement, new systems in the development of products and services, adaptation to human needs, Corporate Social Responsibility. Another innovative are of research is Internet of Things (IoT). Sun (2012) defines IoT as "The radio frequency identification (RFID), infrared sensors, global positioning systems, laser scanners and other information sensing device, according to the agreed protocol, to any article connected to the Internet up to information exchange and communication, in order to achieve intelligent identify, locate, track, monitor and manage a network". IoT facilitates in managing a company's logistic architecture and helps in supervising the circulation in supply chain and share information.

Recently, there has been an intense wave of innovative change in business models generated by a new infrastructure called Physical Internet (PI) or "π". The PI is a novel concept in supply chain logistics with the potential of modernizing material handling, logistics, and facilities design aiming to enhance economic, environmental, and societal efficiency. PI is a vision for moving physical objects via a set of processes, procedures, systems, and mechanisms from an origin point to the desired destination in a way like how digital Internet moves packets of information from a host computer to another computer. PI thus emphasizes on following (1) Digital Internet exploitation, (2) seamless interconnectivity of logistics services, and (3) the magnitude expected for changes that are required (Montreuil et al., 2013). The framework of PI is based on standard and smart modular PI containers or π-containers that can be transported by all means (e.g., planes, trucks, barges, drones, and private cars) with ease (Crainic & Montreuil, 2015). PI containers are modularly sized from small parcels to large maritime containers that are moved through multimodal, distributed transportation networks in which the transit sites consolidate containers from various origins to optimize the loading on the upcoming level. PI is an open interconnected network that includes open logistics facilities such as open semi-trailer transit centers, open cross-docking hubs, and open warehouses, which enables a Global Logistics Web (GLW) (Montreuil et al., 2013).

Logistics Web	
1. Mobility Web	**2 Distribution Web**
1.1 Unimodal transport	2.1 Distribution Center
1.2 Multimodal transport	2.2 Warehouse
1.3 Transport management	2.3 Inventory control
1.4 Innovation	2.4 Innovation
3 Realization Web	**4 Service Web**
3.1 Production center (open fabs)	4.1 Legal framework
3.2 Production module	4.2 Access rules & structure
3.3 Demand management	4.3 Security
3.4 Innovation	

Figure 4 Logistics web attributes, source: Fergani et al. (2019).

In Fergani et al. (2019), a clustering strategy is provided to classify the literature dedicated to PI paradigm. This paper reviews scientific articles presented in the field of PI and categorise them on the basis of three factors: logistics web, organization, and resources. Figure 4 presents the attributes of the logistics web addressed in the literature.

As observed from the survey conducted by Fergani et al. (2019), there are a very limited number of publications on the transport management concerning route planning and cost determination in PI, specifically multimodal transport is more addressed in the literature compared to the unimodal one. This gap provides supports the motivation for this thesis.

The problem statement in this thesis consists of optimizing the transportation cost for unimodal freight delivery in a supply chain consisting of a multiple suppliers and multiple buyers/customers in what we term as a "π-Supply Chain" (π-SC). Figure 5 depicts the conceptual model of π-SC.

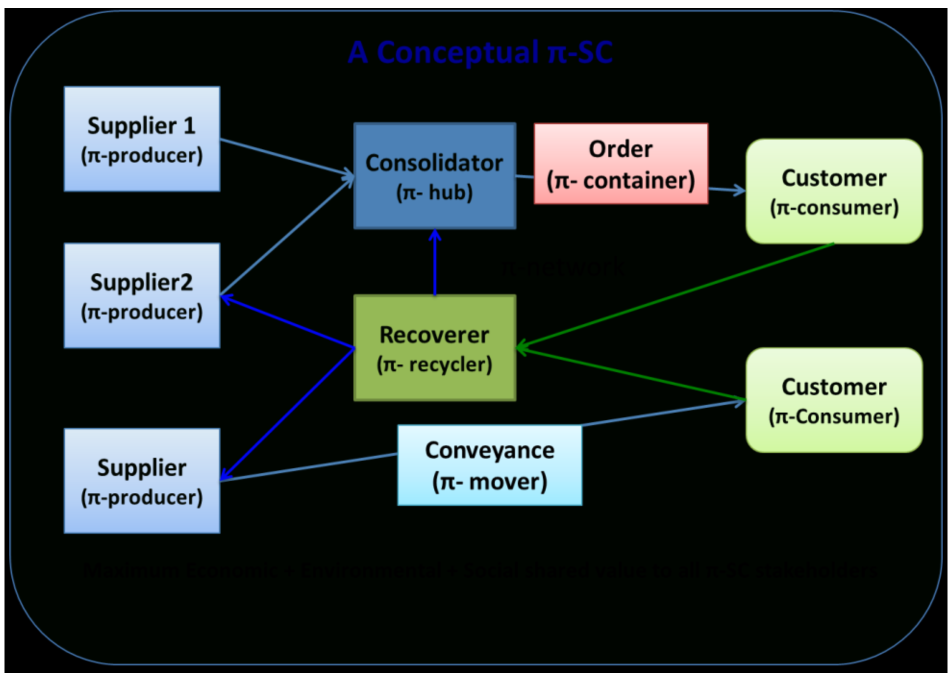
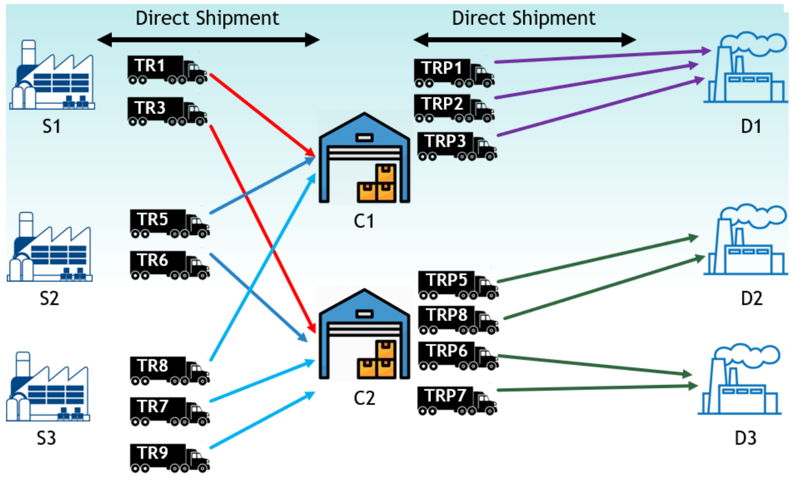


Figure 5 A conceptual π-Supply Chain, source: Ülkü, M.A. (2019)

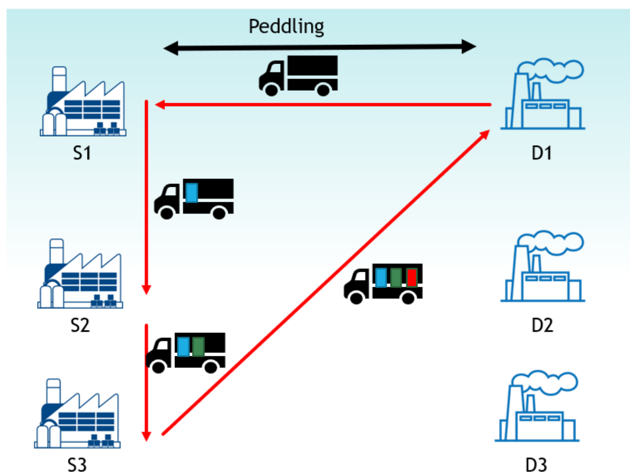
Ülkü, M.A. (2019) states that "A Physical Internet Supply Chain (PI- or π-SC) is a collective set of suppliers, customers, and value-recovery (e.g., reverse logistics) companies with the common goal of achieving sustainable production, delivery and consumption, by maximizing economic, environmental, and social shared-value of their business eco-system on a global scale, and by collaboratively devising and utilizing smart technologies, modular resources (e.g., π-containers, π-movers) and infrastructures (e.g., π-nodes) on a π-network." π-SC management, poised to a paradigm shift, probes the concept of business-as usual, brings about implementable disruptive innovations to SC infrastructure, operations, and leadership.

This research presents a comparison analysis based on freight transportation cost between the three models shown in Figure 6. The first model is a Binary Linear Programming (BLP) model for the PI supply chain configuration with size constraint of π-containers, with the configuration name Model P. The π-containers with varying sizes as per the orders (combination of products manufactured/assembled at a supplier) are delivered to the buyers as per their demands from specific suppliers through a network of uncapacitated π-hubs. In contrast to the PI system, which includes a multiple π-hub network, this configuration consists of 2-echelons. The first leg of the network comprises of set of suppliers delivering the π-containers on a set trucks owned by the supplier to the selected π-hubs as direct shipments, this selection is based on the minimum transportation cost and size constraints of π-containers. The second leg of the network comprises of a set of π-hubs, similar to the one in first leg and a set of buyers. Here, the fleet of trucks are owned by the π-hubs and they deliver to the buyers as per their demands on the routes as direct shipments, selected by the mathematical model based on minimum transportation cost.

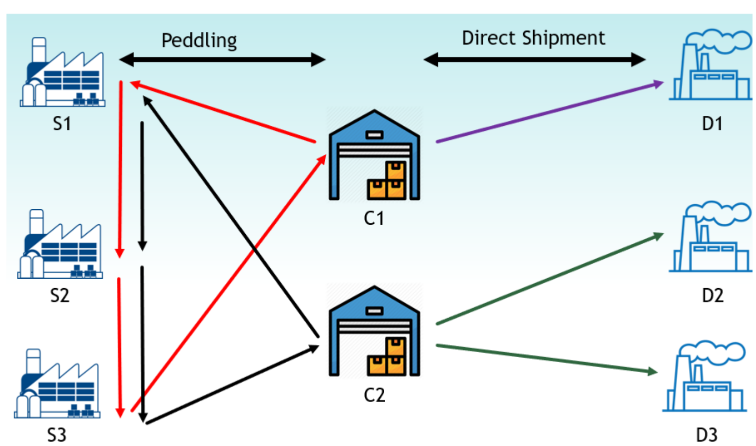
The second model is a standard transportation model; we call it Model S. As observed in literature, Model S is analogous to peddling, which a transportation configuration in which fleet of trucks is owned by the buyers, pick up products at one or



(a)



(b)



(c)

Figure 6 (a) Model P (b) Model S (c) Model H several suppliers and deliver them to one or several plants. Peddling does not involve any hubs or cross-docking centres, which increases the distance travelled by a single truck, as it has to travel larger distance without any consolidation point/center. For our problem, this configuration falls under the category of Capacitated Vehicle Routing Problem (CVRP), which is a subcase of Vehicle Routing Problem (VRP). A CVRP consists of a fleet of identical vehicles located at a depot (buyers in our case) with a known capacity. There are buyers have a known demand to be fulfilled by the suppliers and the cost of transportation between any pair of suppliers, or between any supplier and the buyer, is also known. The objective is to find the minimum transportation cost for the freight delivery routes, each route starting and ending at the buyer. Mathematical model of CVRP ensures that each supplier is visited by only one truck and no truck exceeds its capacity. The third model is a hybrid model, so the name Model H. This configuration integrates the concepts of Model P and Model S in the transportation network. Model P has greater influence on this configuration as it follows majorly the PI framework with a network of π-hubs in contrast to Model S. The supply chain network here is 2-echelon as well, but with the integration of peddling on the first leg, in which the fleet of trucks owned by the π-hubs pick up π-containers from one or several suppliers and deliver them back to the respective π-hub. For the second leg, the fleet of trucks owned by the π-hubs deliver to the buyers as per their demands in as direct shipment. Further, we compare these three models based on their system wide optimization of minimum total transportation cost and study the results based on a case study of Mexican automotive supply chain consisting of tier 1 suppliers and Original Equipment Manufacturers (OEMs).

Through this research, we contribute to the literature by conducting a performance analysis based on systemwide transportation cost between the Models P, S, and H on the basis of the following KPIs: fuel, labor, and truck cost. Our hybrid model (H) aims to bring together the logistical benefits of both peddling (via Model S) and PI (via Model P). As an illustrative example, we test our models based on the logistics data obtained from an automotive supply chain in Mexico. The optimality results showcased that Model H may outperform Models S and P, total systemwide transportation cost, which is a function of vehicle capacity utilization, total distance travelled (loaded or empty), among others.

Remainder of the thesis is arranged as follows. In chapter 2, a literature review related to PI paradigm is conducted, which includes the research conducted in introduction, design and implementation of PI infrastructure with the application of novel technologies that enable the PI. The proposed methodologies for all three configurations are described in chapter 3. In this chapter we present the mathematical formulations and heuristics used to develop the three models (Model P, Model S, and Model H). Chapter 4 focuses on the computational experimentation and analysis between the proposed systems based on a case study of Mexican automotive industry. This chapter discusses the approach adopted for data collection and selection of parameters, with the static optimization results obtained by implementation of the proposed models in chapter 3. In addition, we also define the Key Performance Indicators (KPIs) and based on these KPIs we compare the three supply chain networks. Finally, conclusions and future research directions are discussed in chapter 5.

CHAPTER 2 LITERATURE REVIEW

In this chapter we focus on the literature review on Physical Internet. The Term Physical Internet (PI) was first introduced as a big headline on the front page of The Economist in June 2006. The issue consisted of a logistics survey, with supply chain and logistics articles. Apart from the headline, the term PI was not emphasized until Montreuil (2011). Its capabilities, key features, comparison with Digital Internet have led to the main question: "Why would the world need a Physical Internet?" The answer to the latter question became vivid after the thirteen bold unsustainability symptoms presented by Montreuil (2011). The rest of the curiosities led to the definition of PI vision through 13 characteristics, briefly shown in Figure 7.

S.No	Thirteen characteristics defining the Physical Internet vision
1	Encapsulation merchandises in world standard smart green modular containers
2	Aiming towards universal interconnectivity
3	Evolve from material to π-containers handling and storage systems
4	Exploit smart networked containers embedding smart objects
5	Evolve from point to point hub and spoke transport to distributed multi-segment intermodal transport
6	Embrace a unified multi-tier conceptual framework
7	Activate and exploit an Open Global Supply Web
8	Design products fitting containers with minimal space waste
9	Minimize physical moves and storages by digitally transmitting knowledge and materializing objects as locally as possible
10	Deploy open performance monitoring and capability certifications
11	Prioritize webbed reliability and resilience of networks
12	Stimulate business model innovation
13	Enable open infrastructural innovation

Figure 7 Thirteen characteristics defining the Physical Internet vision, source: Montreuil (2011)

An overview of key elements of PI, which are the foundation of PI paradigm, is provided in Montreuil et al. (2010). These elements are classified into three main categories: containers, movers and nodes.

In Ballot et al. (2012), design approach for interconnected logistic services using open hub network is introduced through encapsulation of materials/goods in PI container or π-containers to tackles the sustainability issues in fragmented supply chains. This paper explains that PI enables users to contemplate and act in terms of open global mobility web and supply web, which helps in transforming logistics towards seamless and efficient interconnections of all logistics network.

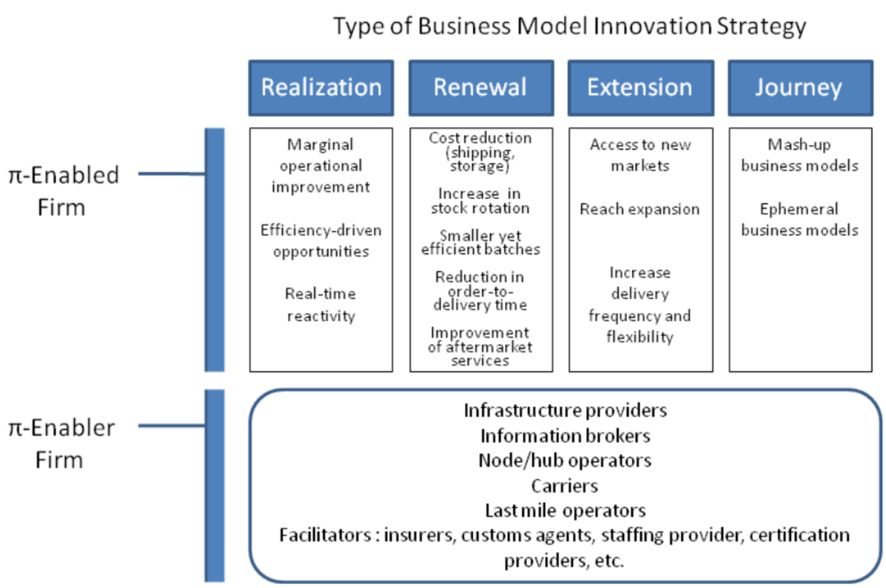


Figure 8 Implications of different types of business model innovation strategies for π-Enablers and π-Enabled firms, source: Montreuil et al. (2012)

Potential impacts of PI on business model innovation were the main focus of Montreuil et al. (2012). This paper classifies firms into two categories: π-enablers and π-enabled. The π-enablers are those firms that provide the infrastructural tools for the implementation purpose and π-enabled firms are the ones that exploit those tools for value creation. Figure 8 shows the relationship between π-enablers and π-enabled firms.

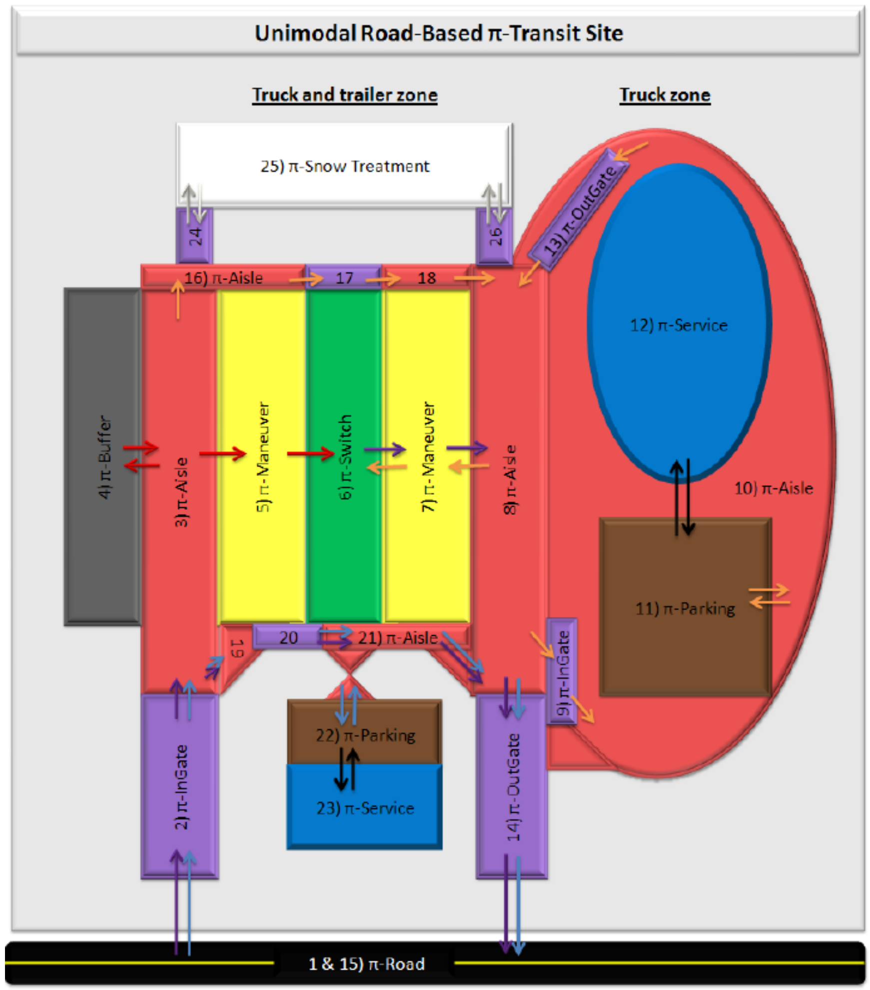


Figure 9 Block Layout for the Proposed Functional Design, source: Meller et al. (2012).

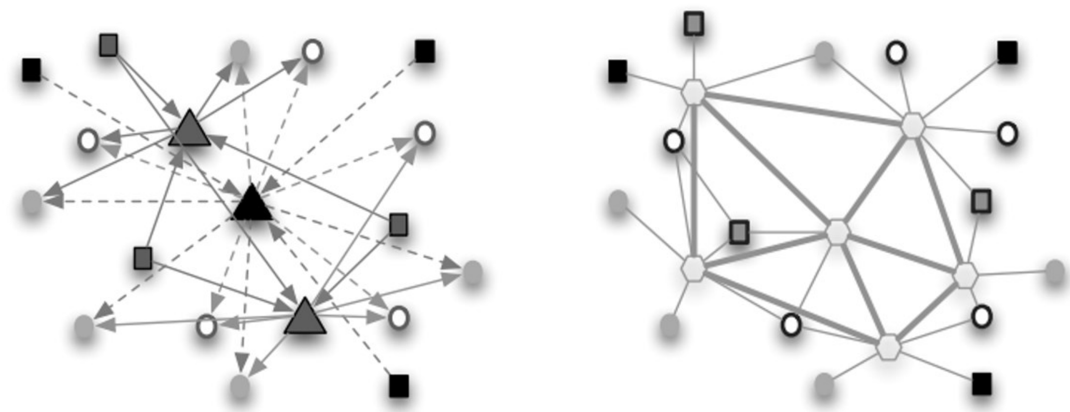
In Meller et al. (2012), functional design of road-based PI facilities needed for the operation of PI is provided as shown in Figure 9. Essentially, PI facilities are π-transit centres that facilitate the transfer of π-carriers from inbound to outbound destinations. It provides the method of transferring π-trailers from one truck to other but with a notion of considering the uncertainties involved due to arrival times of driver-trailer pairs. This paper also discusses two KPIs with the perspective of customers of the π-transit centre and the operators.

In Sohrabi et al. (2012), scenario-based distribution network design model is introduced which involves rigorous assessment of economic performance potentials of PI. This paper adopts an optimization-based approach to develop a generic distribution design network and adapts the model for existing closed and collaborative distribution systems, as well as for open distribution web, a key constituent of logistics web in PI (Montreuil, 2011). Research conducted in Sohrabi et al. (2012) also characterises three key drivers of distribution network design, which are available capacity, market-demand, and network cost. Also, it describes the future shaping variables that depend on time, location of distribution network resources, and product type for the future business environments.

Table 1 Layers of OSI, Internet and OLI models, source: Fontane et al. (2012)

Layer	OSI model: Digital Internet	TCP/IP model: Digital Internet	OLI model: Physical Internet
1	*Physical*	*Physical*	*Physical*
2	*Data Link*	*Data Link*	*Link*
3	*Network*	*Network*	*Network*
4	*Transport*	*Transport*	*Routing*
5	*Session*	*Application*	*Shipping*
6	*Presentation*		*Encapsulation*
7	*Application*		*Logistics Web*

A seven layered Open Logistics Interconnection (OLI) model and five layered TCP/IP model (Digital Internet) is describes and illustrated in Fontane et al. (2012). Similar to Open System Interconnection (OSI) model and Digital Internet (DI), which has structured layers that facilitates interconnections between digital counterparts, an OLI model is proposed in contrast to enable the interconnections of logistic services globally in PI (Table 1).



a) **b)**

Figure 10 a) Overlapping but disconnected logistics network;

b) Interconnected logistics network, source: Fontane et al. (2012)

Figure 10 depicts two different logistic network topologies, overlapping yet disconnected and interconnected to justify the radical impacts on logistics structuring, operations and performance as well as on the business models of Physical Internet users (retailers, distributors, manufacturers, etc.) proposed by Montreuil (2011).

Meller et al. (2012) introduced a first formal definition of PI as "An open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols." This paper provides an insight to the foundations of PI introduced by Montreuil (2011) and explains eight foundations of PI, shown in Figure 11. The design and development methodology of a mobility web simulator is proposed in Montreuil et al. (2013) to study and quantify the effect of evolving from current logistics system to PI on economical, environmental, and social efficiencies with a case study in France. This paper adapts the three-level approach defined in Montreuil et al. (2010) to provide a general architecture for developing a mobility web simulator. The approach is to capture the complexity and dynamicity of logistics contexts by mapping software agents with real world decision-making actors or systems.

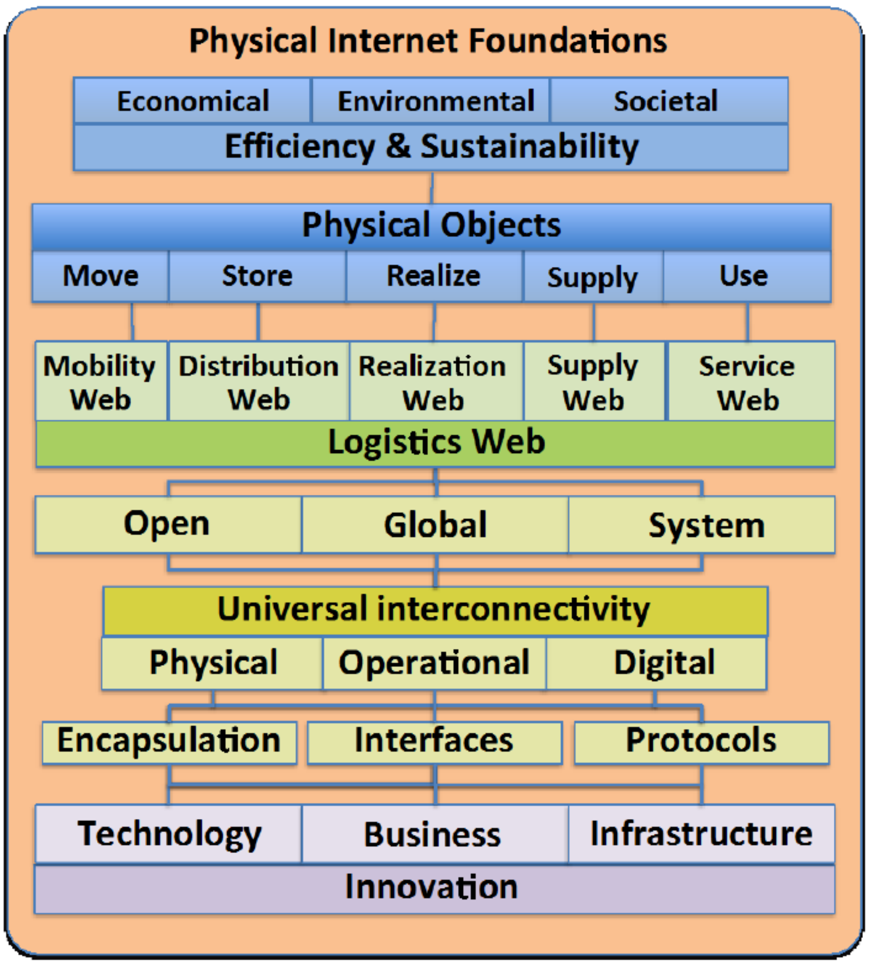


Figure 11 Physical Internet foundations framework, source: Montreuil et al. (2013)

In Sohrabi & Montreuil (2014), an interconnected distribution-planning framework is proposed exploiting the open distribution web in PI. The framework is structured through four layers: network, distribution, deployment, and delivery, which facilitate businesses to distribute its products across global markets, utilizing the currently open Distribution Centers (DC) that are operated by other businesses. In addition, this paper also proposes the distribution policy for a mid term planning horizon (e.g. season, month) and parameterize the policy for each product at each open DC in regard to the market served.

Table 2 Analogy between computing network and physical network, source: Sarraj et al. (2014)

Network	Internet	Physical Internet	Interconnection function
Flow	Datagram	π-Container	Encapsulation of merchandise
Node	Router	Hub	Place of orientation (sorting), change of mode, service provider
	Host (unique address)	Supplier or consumer	Place of containerisation and de-containerisation
Arc	Wire or wave connection	Transport services	Punctual or regular transport between two hubs

Sarraj et al. (2014) presents analogy between DI and novel logistics service networks based on PI, due to the strong similarities in both the networks (Table 2). Even though the type of object being transported differs. The proposed analogy is based on three vital characteristics: the definition of interconnection, the structure of the networks and the routing of objects through these networks.

In Tremblay et al. (2015), a synthesis of transformation of goods encapsulation by implementation of π-containers is proposed with introduction of three-tier structural characterization of π-containers. Figure 12 depicts the general characteristics of π-containers, presented in the paper. The three tiers modular design of π-containers consist of transport containers (T-containers), handling containers (H-containers) and packaging containers (P-containers).

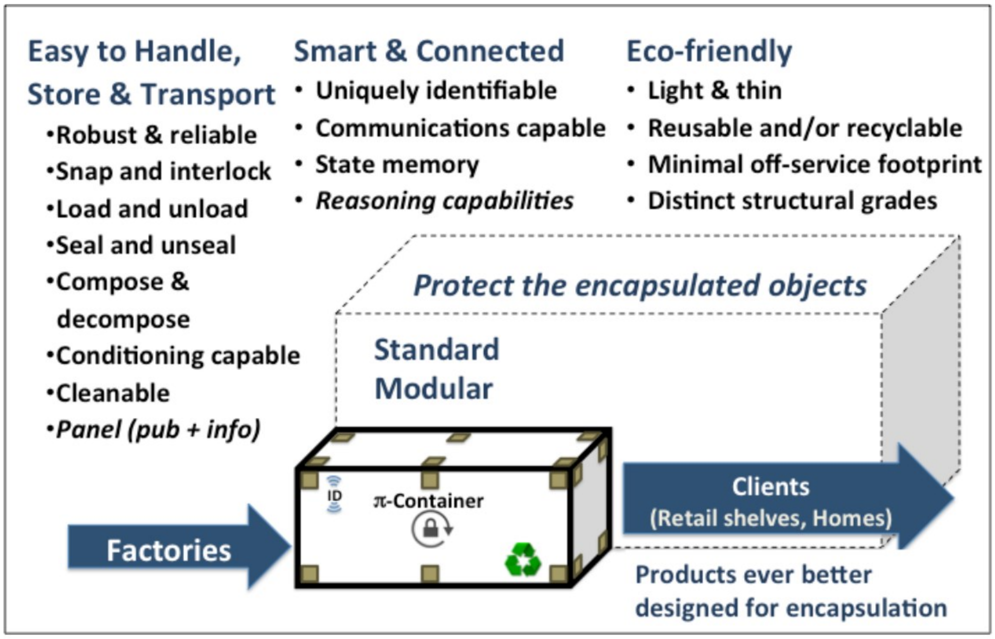


Figure 12 General characteristics of π-containers, source: Tremblay et al. (2015)

Table 3 Contrasting characteristics of existing private supply networks and shared supply networks, source: Sohrabi & Montreuil (2011).

Supply Network design	Decision making level	Facility utilization	Geographical extension	Customer service level
PSN	Strategic	Poor as facilities are utilized by a single company through long-term contracts	Constrained to the single company's network	Compromised by location and capacity of single company's facilities
SSW	Strategic	Improved relative to PSN but still constrained to partnering companies and long-term commitments	Constrained to the shared web of partnering companies	Compromised by location and capacity of partnering companies' facilities
OSW	Tactical, Operational	Improved by opening available space to other companies within short-term contracts	Globally extended	Fast and reliable by exploiting globally dispersed open facilities

In Sohrabi & Montreuil (2011), an exploratory study is conducted to assess the potential benefits of evolving from current supply network design, typically Private Supply Networks (PSN) and Shared Supply Webs (SSW) to PI enabled Open Supply Web (OSW). This research provides the contrasting characteristics of existing PSN and SSW with the proposed OSW on the basis of facility utilization, geographical extension, and customer service level as depicted in Table 3.

In Peng et al. (2019), a multi-objective mixed integer linear programming model is proposed to explore the sustainability performance of PI in an integrated production-inventory-distribution system. This paper adopted the approach of augmented ε-constraint method to solve the model and compared the sustainability performance of PI system with that of traditional and horizontal collaboration networks covering all the three dimensions of sustainability: economic (total cost), environmental (Green House Gasses or GHG emissions) and social (accident risks).

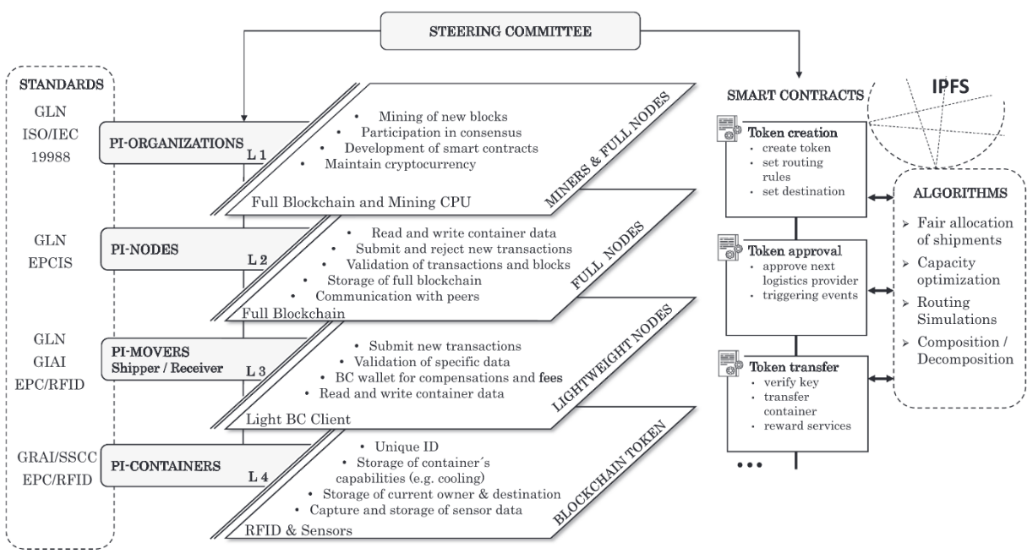


Figure 13 conceptual framework of Blockchain design architecture in PI, source: Treiblmaier (2019)

In Marino et al. (2019), the solutions for tackling the challenges on implementation of Internet of Things (IoT) in PI are discussed. Challenges of efficient implementation of IoT in PI are due to the modularity and dynamicity of PI systems. This paper explores the role of IoT in designing of hyper-connected and interoperable π-containers to achieve the goal of EU H2020 ICONET project, which is to extend the research around the PI concept by designing a new networked architecture for interconnected logistics hubs and by developing a cloud-based PI framework and platform. In Treiblmaier (2019), this research provides a decentralised approach based on Blockchain technology, which offers tackles the barriers concerning the exchange of value and physical assets in logistics networks under the PI paradigm. This paper presents a conceptual framework of Blockchain design architecture, which comprises a four-layered framework as shown in Figure 13 and illustrates its application through an industry case study.

In Venkatadri et al. (2016), a MILP model for one-way optimal dispatch between a pair of nodes is developed and is extended for the two-way point-to-point (P2P) optimal dispatch between a pair of nodes. This model is used to characterise the performance of both the networks on the basis of the following logistics KPIs: total cost, inventory cost, transportation cost, number of truck trips or sector trips, average number of transfers, and average delivery time. This paper also presents the direction of implementing the P2P model to traditional and PI based logistics network.

In Fazili et al. (2017), a Monte-Carlo based comparison is presented within a sequential three-phase optimisation framework to quantify the advantages and disadvantages of PI logistics system over Conventional (CO) logistics network. This paper provides the logistics and routing optimization framework of three systems, PI, CO and intermediate hybrid (HY) and compares them on the basis of a three-phased optimisation framework on following KPIs: Number of container packing and unpacking instances, total hours of container routing, number of trucks in service, average hours worked per truck, percentage drivers back home at the end of the day, and total systems cost including the costs operations, social impact, material handling and fixed installation.

The scope of PI and its application is diverse. Collaboration of PI concept with different sectors such as humanitarian logistics is the future of making supply chains sustainable by interconnecting them globally. In Abdoulkadre et al. (2014), an interconnected humanitarian logistics system based on PI paradigm is proposed. This paper provides literature on the main humanitarian logistics and the issues encountered in current practices with a proposition of repositioning it through a PI conceptual framework. Ülkü et al. (2015) also provides the insights on humanitarian logistics and challenges faced due to inefficiencies in supply chains. Abdoulkadre et al. (2014) states that "the aim is to enable efficient interconnectivity of individuals, donors, contractors, suppliers, NGOs, international institutions, government and beneficiaries."

As observed from the literature, the PI has gathered a lot of research interest; however, there are a number of questions which remain unaddressed. This thesis aims to fill the gap in literature by comparing the logistics performances between peddling in conventional logistics, PI logistics, and a combination of these both systems, which we reefer to as a hybrid model. Peddling generally improves vehicle capacity utilization, but also involves longer travel distance. PI tries to improve vehicle capacity utilization through consolidation and also distance travelled by locating hubs strategically. The thesis analyzes the costs of both configurations in addition to proposing a hybrid model to potentially realize the benefits offered by each. Additionally, we emphasize the potential enabling capacities to PI of those new (technological) paradigms such as IoT, Big Data, Industry 4.0 etc.

CHAPTER 3 PROBLEM FORMULATION

In this chapter, we will provide the mathematical formulation for our freight delivery problem with the view of optimizing the system wide transportation cost for the three supply chain networks PI (Model P), Standard model (Model S) and Hybrid model (Model H). In the following subsection, we have discussed the three settings:

MODEL P – PHYSICAL INTERNET

In this model there are a set of multiple suppliers s, multiple demand points/buyers d and uncapacitated consolidation π-hubs c in a 2-echelon framework. Each Supplier own a homogenous fleet of trucks $t_1$for direct shipment to π-hubs and each π-hub owns a homogenous fleet of trucks t_2 for direct shipment to buyers. There is a set of π-containers i, which are assigned to suppliers for encapsulation of the products manufactured or assembled at the supplier's facility. The π-containers have different sizes q_i, which interconnect and form a composite cluster that is loaded in the truck with capacity constraint. Each buyer has a known demand of π-containers from specific suppliers and supplier fulfils the demand by shipping it through a π-hub. We present a binary linear program adapted from Küçükoğlu & Öztürk (2017) in which they present a two-stage Mixed Integer Linear Programming (MILP) model for the transportation problem of cross-docking network design integrated with truck–door assignments to minimize total transportation costs from suppliers to customers. For our research, we have focused on the first stage of their model, which formulates the transportation problem of the network with two-dimensional truck-loading constraints. Their problem consisted of suppliers, customers (or destinations) and cross-docking centers. The products flow from suppliers to customers through cross-docking centers according to customer demand. Each product from the suppliers is loaded into incoming and outgoing trucks according to the two-dimensional truck-loading constraints. We eliminated the two-dimensional truck-loading constraints, but we introduce the concept of π- containers with size constraint. The objective of this model is to minimize the overall logistics cost. Table 4 below gives the set of parameters and decision variables considered. We used Binary Linear Programming (BLP) to solve this model, as the objective function is linear, and the variables are binary. The linear program implemented in GUSEK for Model P is presented in Appendix I.

Table 4 Parameters and decision variables for Model P

Parameters	
s	Index for supplier $s \in S$, $\lvert S \rvert = n$.
c	Index for consolidation π-hub $c \in C$, $\lvert C \rvert = h$.
d	Index for demand point (buyer/customer) $d \in D$, $\lvert D \rvert = m$.
i	Index for an order consolidated in a π-container $i \in I$, $\lvert I \rvert = o$.
t_1	Index for a truck between suppliers and π-hubs $t_1 \in T_1$, $\lvert T_1 \rvert = \overline{t_1}$.
t_2	Index for a truck between π-hubs and demand points $t_2 \in T_2$, $\lvert T_2 \rvert = \overline{t_2}$.
sl_i	Supplier label of π-container i; $i \in I$.
dl_i	Demand point label of π-container i; $i \in I$.
st_{t_1}	Supplier label of truck t_1 between suppliers and π-hubs, $t_1 \in T_1$.
ct_{t_2}	PI hub label of truck t_2; $t_2 \in T_2$.
T_s	Trucks available at supplier s; s $\in S$.
T_c	Trucks available at π-hubs c; $c \in C$.

I_d	Set of π-containers destined to d, $d \in D$.
q_i	Size of π-container i; $i \in I$.
Q	Maximum capacity of a truck.
td_{sc}	Minimum travel distance from supplier s to π-hub c, s $\in S, c \in C$.
td_{cd}	Minimum travel distance from π-hub c to demand point d; $c \in C, d \in D$.
Surrogate sets	
ε_i	$\{t_1 \in T_1: st_{t_1} = sl_i\}$; If the trucks belong to first leg (i.e. between suppliers and π-hubs), this is the subset of trucks which have same supplier label as of π-containers.
ρ_{t_1}	$\{i \in I: sl_i = st_{t_1}\}$; For all the π-containers, this is the subset of π-containers with same supplier label on the trucks belonging to first leg.
π_i	$\{i \in I: st_{t_1} = sl_i\}$; For all the π-containers, this is the subset of supplier trucks with same supplier label on the π-containers.
Decision variables	
z_{it_1c}	$\begin{Bmatrix} 1, & \text{if π-container } i \text{ is transported to π-hub } c \text{ on a truck } t_1 \\ 0, & \text{otherwise} \end{Bmatrix}$
$z^o{}_{it_2d}$	$\begin{Bmatrix} 1, & \text{if π-container } i \text{ is transported to demand point } d \text{ on a truck } t_2 \\ 0, & \text{otherwise} \end{Bmatrix}$
v_{t_1c}	$\begin{Bmatrix} 1, & \text{if truck } t_1 \text{ is assigned to π-hub } c \\ 0, & \text{otherwise} \end{Bmatrix}$
$v^o{}_{t_2d}$	$\begin{Bmatrix} 1, & \text{if truck } t_2 \text{ is assigned to demand point } d \\ 0, & \text{otherwise} \end{Bmatrix}$

Objective function for Model P:

$$\underset{z_{it_1c}, z^o{}_{it_2d}, v_{t_1c}, v^o{}_{t_2d} \ \forall\, i, t_1, t_2, c, d}{Min\, Z_P} \tag{P.0}$$

$$where\ Z_P = \sum_{s\in S}\sum_{c\in C}\sum_{t_1\in T_s} td_{sc} v_{t_1c} + \sum_{c\in C}\sum_{d\in D}\sum_{t_2\in T_c} td_{cd} v^o{}_{t_2d}$$

Subject to:

$$\sum_{t_1\in \varepsilon_i}\sum_{c\in C} z_{it_1c} = 1 \ \ \forall i \ \in I \tag{P.1}$$

$$\sum_{c\in C} v_{t_1c} \le 1 \ \ \ \forall t_1 \in T_1 \tag{P.2}$$

$$\sum_{i\in \rho_{t_1}} z_{it_1c} \le M.v_{t_1c} \ \ \ \forall t_1 \in T_1, c \in C \tag{P.3}$$

$$\sum_{i\in \pi_i}\sum_{c\in C} z_{it_1c} q_i \le Q \ \ \forall t_1 \in T_1 \tag{P.4}$$

$$\sum_{t_2\in T_2}\sum_{d\in dl_i} z^o{}_{it_2d} = 1 \ \ \forall i \ \in I \tag{P.5}$$

$$\sum_{d\in D} v^o{}_{t_2d} \le 1 \ \ \ \forall t_2 \in T_2 \tag{P.6}$$

$$\sum_{i\in I_d} z^o{}_{it_2d} \le M.v^o{}_{t_2d} \ \ \ \forall t_2 \in T_2, d \in D \tag{P.7}$$

$$\sum_{i\in I}\sum_{d\in dl_i} z^o{}_{it_2d} q_i \le Q \ \forall t_2 \in T_2 \tag{P.8}$$

$$\sum_{t_1\in \varepsilon_i} z_{it_1c} = \sum_{t_2\in T_c}\sum_{d\in dl_i} z^o{}_{it_2d} \ \ \ \forall i \ \in I, c \in C \tag{P.9}$$

$$z_{it_1c}, z^o{}_{it_2d}, v_{t_1c}, v^o{}_{t_2d} \ \in Binary \tag{P.10}$$

The objective function (P.0) minimizes the total transportation cost of the incoming and outgoing trucks from π-hubs in the PI network. Constraints (P.1) ensure that each π-container can be transported to only one π-hub by only one of the supplier trucks. Similarly, constraint (P.5) ensures that each π-container can be delivered to its destination by only one of the vehicles available at π-hubs. Constraints (P.2) and (P.6) show that each of the available trucks at the supplier and π-hub is used at most once and assigned to one location. Constraint (P.3) ensures that a truck at supplier can only be used for transportation if it is loaded with at least one π-container. Similarly, constraint (P.7) ensures that a truck at π-hub can only be used for transportation if it is loaded with at least one π-container. Constraint (P.4) and (P.8) ensures that only those π-containers will be transported in a truck in which the sum of their sizes is less than or equal to the truck capacity. Constraint (P.9) is a flow balance constraint that maintains the product continuity at π-hubs, i.e., if a π-container is dropped at a π-hub, and then it must be delivered from that same hub to its destination. Finally, constraints (P.10) impose the bounds on the decision variables.

MODEL S - PEDDLING

This configuration consists of multiple suppliers s and multiple demand points d. Every demand point owns a homogenous fleet of trucks T_d, performing the freight delivery in peddling fashion. We adapted this model from Sungur et al. (2008). Each of the truck has a maximum capacity of Q, which limits the number of suppliers it can visit before returning to the demand point. Each route must start at a demand point, visit a subset of suppliers and then return to the demand point. All suppliers must be visited exactly once. We represent the problem using a graph $G\ (S^o, \partial)$, in which $\partial \in S \cup T_d$ is a set of nodes associated to suppliers s and the homogenous fleet of trucks t_3 at a demand point. Set ∂ contains the arcs (x, y) for each pair of nodes $x, y \in S^o$. The cost of crossing an arc $(x, y) \in \partial$ is td_{xy}. Each supplier has a requirement to fulfil the demand $d_x > 0$ for each $x \in S$ and $d_r = 0$ from the demand point. For each demand point, the model is implemented separately as it works with a fleet of truck at a single demand point. The objective is to minimize the total logistics cost of the network, which is obtained by addition of all the minimum transportation costs acquired from implementation of Model S for each demand point. We used Mixed Binary Linear Programming (MBLP) to solve this model, due to linear objective function and mixed variables (binary and continuous). The linear programming mathematical model is presented as follows:

Parameters	
s	Index for supplier $s \in S$, $\lvert S \rvert = n$.
T_d	Index for homogenous trucks at demand point $t_3 \in T_d$, $\lvert T_d \rvert = r$.
Q	Maximum capacity of a truck at demand point d.
s^o	Index for supplier and homogenous trucks at demand point $s^o \in S^o$, $\lvert S^o \rvert = n \cup r$.
td_{xy}	Minimum travel distance between two nodes x and y; $x, y \in S^o$.
d_x	Index for size of π-containers required from each supplier s; $d_x > 0, d_r = 0, x \in S$
Decision variables	
z_{xy}	$\begin{cases} 1, & \text{if π-container } i \text{ is transported supplier } x \text{ to supplier } y \\ 0, & \text{otherwise} \end{cases}; x, y \in S^o$
a_x	Cumulated π-containers from supplier s on the route; $x \in S^o, x \geq 0$

Objective function for Model S:

$$\underset{z_{xy},\, a_y\ \forall x, y}{Min\ Z_S} = \sum_{i \in S^o} \sum_{j \in S^o} td_{xy} z_{xy} \tag{S.0}$$

Subject to:

$$\sum_{i \in S} z_{xy} = 1 \ \ \forall\, y \in S^o \tag{S.1}$$

$$\sum_{j \in S} z_{xy} = 1 \ \ \forall\, x \in S^o \tag{S.2}$$

$$a_x \geq 0 \qquad \forall\, x \in S^o \tag{S.3}$$

$$d_x \leq a_x \leq Q \qquad \forall\, x \in S^o \tag{S.4}$$

$$a_y \geq a_x + d_y z_{xy} - Q(1 - z_{xy}) \ \ \forall\, x\,, y \in S^o \tag{S.5}$$

$$z_{xy} \in Binary \tag{S.6}$$

The Objective function (S.0) imposes that the total travel cost of the route in between supplier s and demand point d is minimised. Constraints (S.1) and (S.2) ensure that all suppliers are visited exactly once. Constraints (S.4) and (S.5) ensure together that the vehicle capacity is not exceeded. Constraints (S.5) also avoid subtours in the solution. Constraint (S.3) imposes that the π-containers picked up from a supplier s is a positive. Finally, constraint (S.6) introduces the boundary limitation on the decision variable z_{xy}.

MODEL H - HYBRID

This configuration is an integrated version of Model P and Model S, so it is a hybrid model. As Model P, it is a 2-echelon model with multiple suppliers and multiple demand points. Each demand point has a specific requirement of π-containers i with different sizes from multiple suppliers. Supplier must fulfil the requirement by delivering the freight to demand point as per requirement through a π-hub c. Each π-hub owns a homogenous fleet of trucks t_2 for collecting π-containers from suppliers in peddling fashion and for direct shipment to demand point. There is a set of π-containers i that are assigned to suppliers for encapsulation of the products at the supplier's facility. The π-containers have different sizes that are loaded in the truck with capacity constraint. We implemented Model S in the first leg of the network, which follows the peddling logistics in between suppliers and π-hubs. Each truck owned by π-hubs collects the π-containers from multiple suppliers and return to the same π-hub for consolidation. For the second leg, the consolidated shipment at the π-hub is then shipped directly to the demand point.

The heuristics of the integration process is as follows:

1. The solutions obtained from solving Model P, provides us with the data of π-containers being received at the π-hubs for consolidation and for further direct shipment on the second leg. Utilization of same parameters ensures that no matter what the route is the quantity of π-containers received at the π-hubs remains the same. This obtained data of quantity of π-containers serve as the demand parameter for the first leg of the model.
2. Demand parameters (quantity of π-containers at π-hubs) obtained in the first step is used to perform peddling on the first leg, which lead us to implement the Model S.

3. After implementing the Model S for each π-hub receiving π-containers from suppliers in peddling fashion, we add the minimum transportation costs from all the routes and obtain the minimum total logistics cost for the first leg. As for the second leg, previously implemented Model P gave us the total minimum transportation cost for the direct shipments from π-hubs to demand points.

Total Cost = Transportation cost (First leg) + Transportation cost (Second leg)

Model S Model P

CHAPTER 4 NUMERICAL ANALYSIS

In this chapter, we will discuss the implementation of all the three models (Model P, Model S, and Model H) proposed in chapter 3 on a case study of Mexican automotive industry and the results obtained by running the proposed linear programming mathematical formulation. In addition, we will compare the three configurations based on collected data and selected parameters. GUSEK (GLPK Under Scite Extended Kit, GLPSOL: GLPK LP/MIP Solver, v4.65) was used to implement the mathematical models and solved by GUROBI 8.0.1 platform. The codes for the models including data sets are provided in Appendix 1. All the software was operated in 64-bit personal computer with Intel(R) Core (TM) i7-7500U CPU, 2.7GHz.

DATA COLLECTION

We started with a set of data consisting of coordinate locations of 25 Original Equipment Manufacturers (OEM) and 149 tier 1 suppliers all over Mexico. For our study, we chose five OEMs and 30 suppliers as depicted in the Figure 14.

The first step was to utilize these coordinates (Table. 5 and 6) and figure out the routing distances between the nodes. To accomplish this task, we used Geopy 1.20.0 library of python to calculate the geodesic distance between two points using the geodesic distance or the great-circle distance, with a default of the geodesic distance available as the function geopy.distance.distance (Python Software Foundation, 2019).

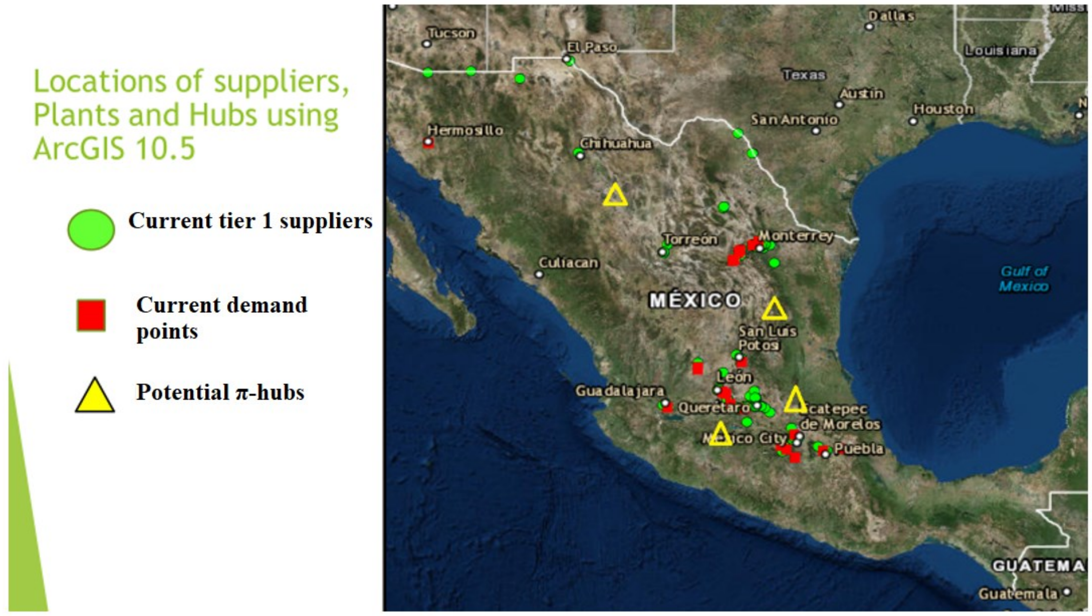


Figure 14 Locations of current tier-1 suppliers, plants & potential π-hubs using ArcGIS

Here's an example application of the geodesic distance:

```
>>> from geopy.distance import geodesic

>>> newport_ri = (41.49008, -71.312796)

>>> cleveland_oh = (41.499498, -81.695391)

>>> print(geodesic(newport_ri, cleveland_oh).miles)

538.390445368
```

Without loss of generality, the geodesic distance is used in our analysis. Actual road distances may also be used. In the case of the Mexican Automotive industry, the geodesic distance is not a bad approximation given the general North West/South East orientation of highways.

Table 5 Coordinates of suppliers.

Suppliers	X	Y
Brose	20.555	-100.26434
Brose	20.628	-100.44201
Brose	19.115	-98.258
Industrias Norm	19.113	-98.25806
Rassini Suspensiones	28.689	-100.52078
Rassini Suspensiones	19.514	-99.086
Rassini Frenos	19.263	-98.41653
Rassini BYPASA	20.368	-99.96755
Unicar Plastics	25.394	-100.93449
Unicar Plastics	19.102	-98.20617
Accuride International	32.586	-115.3815
Accuride de Mexico	25.946	-100.22842
Cemm Mex	25.664	-100.15756
Cifunsa	25.458	-100.99398
Cifunsa	22.106	-100.90932
Cifunsa	20.699	-101.29425
CSA - Castellón México	25.781	-100.13881
DBG	25.744	-100.21524
Denso	25.771	-100.16737
Denso - Air Systems De Mexico	26.932	-101.47303
Denso - Hamaden México	25.915	-100.29368
Denso - Asmo Manufacturing	20.78	-101.31986
Denso	25.645	-100.18306
Denso	21.01	-101.47352
Ficosa	25.856	-100.29158
Ficosa	25.808	-100.35587
Frisa	25.679	-100.43329
Frisa	25.755	-100.5399
Port 1	25.738	-99.98302
Port 2	25.776	-100.14799

Table 6 Coordinates of demand points.

Plants	X	Y
Volkswagen	19.117	-98.25169
Audi	19.206	-97.74914
Navistar International	21.01	-101.4726
Caterpillar	25.733	-100.5222
Daimler (Truck Manufacturing Plant)	25.241	-101.1589

Once we gathered the distances between the nodes, the next step was to locate the potential π-hubs, and for this, we opted the K-means clustering algorithm (Keen, 2017). We used python to solve the clustering algorithm, which consists of three steps:

- Initialization – K initial "means" (centroids) are generated at random
- Assignment – K clusters are created by associating each observation with the nearest centroid
- Update – The centroid of the clusters becomes the new mean

The application of this algorithm on our chosen data set gave us the outcome depicted in Figure 15.

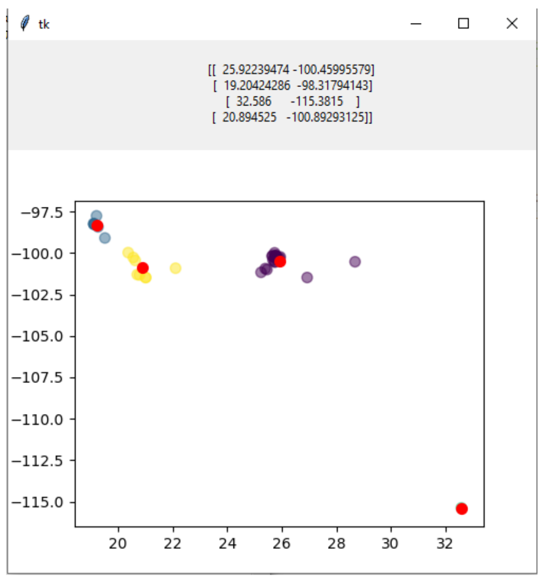


Figure 15 Location of potential π-hubs using K-means clustering

After gathering the potential π-hubs location, we again used the Geopy library to get the routing distances, including the recently added nodes (i.e., π-hubs). These computations provided us with our significant parameters to our transportation problem. But a critical parameter was still missing, the sizes of the π- containers. For this parameter, we settled our search to the random generation of the sizes as a ratio of truck volume.

Finally, after gathering all the required parameters and data sets, the subsequent task was to model this into a PI system.

SELECTION OF PARAMETERS

As stated in the beginning of this chapter, our primary problem of the PI system consists of a data set of 30 suppliers, four PI hubs, and five destinations/OEMs. One hundred products were selected for our network optimization, which was randomly divided among the suppliers. Demands at the destinations were also generated randomly. Considering the number of products, we selected 45 trucks for the first leg and 35 trucks for the second leg. Due to a lack of standardization in dimensions of PI containers at the current stage of research, the products were assumed to be a PI container with a volume ratio of the capacity of trucks with a maximum capacity of 50% volume of a truck's capacity. Depending on the size ratios of the PI containers at the supplier's end, a minimum of one vehicle to a maximum of three trucks was assigned to each supplier. Similarly, a minimum of eight trucks was attached to each hub. We utilized distances obtained using Geopy 1.20.0 library of python as a metric for our cost parameter, which was used to calculate labor cost, truck cost, and fuel cost.

The distance being the base metric for our calculations, all the costs (fuel, labour, truck) depend on it. As per the Mexican statistics, we assumed fuel cost to be 3.3 km/litre, labor cost to be 4.6 $/hr. The cost of a new truck of $175,000 was taken with an average of 140,000 km/yr., which runs at 83.04 km/hr. Using this data collected, we converted all the costs to a dollar per kilometer standards. This resulted in fuel cost to be 0.303 $/KM, labour cost to be 0.06 $/km, and truck cost to be 0.1643 $/km.

Table 7 below provides the base parameter utilized for all the three models (P, S and H).

Table 7 Base parameters

Model P					
$\|S\|$	$\|C\|$	$\|D\|$	$\|I\|$	$\|T_1\|$	$\|T_2\|$
30	4	5	100	45	35

td_{sc}

	C1	C2	C3	C4
S1	592.58	194.74	1525.50	92.29
S2	583.20	213.60	1507.77	72.10
S3	793.31	77.36	1781.60	354.01
S4	793.52	77.41	1781.77	354.13
S5	314.96	1056.23	956.21	871.52
S6	726.75	27.15	1692.55	257.37
S7	772.50	58.14	1758.32	331.04
S8	616.56	158.46	1560.93	129.01
S9	55.11	707.50	1094.10	503.50
S10	796.42	82.99	1786.17	359.34
S11	1601.30	2202.88	530.36	1923.25
S12	54.13	750.63	1116.43	571.38
S13	64.50	718.52	1139.72	541.65
S14	50.84	716.06	1085.03	510.47
S15	418.20	371.93	1349.47	138.87
S16	576.95	288.70	1448.75	28.66
S17	63.06	731.01	1134.01	554.79
S18	56.35	728.29	1129.94	549.42
S19	60.42	730.40	1132.25	553.19
S20	138.21	886.76	953.18	675.43
S21	47.18	748.42	1112.86	566.99
S22	568.24	295.83	1439.86	26.19
S23	62.91	716.89	1138.80	539.12
S24	544.66	323.49	1409.77	43.21
S25	47.08	741.94	1116.66	560.53
S26	41.13	737.94	1114.29	554.33
S27	38.85	725.49	1116.01	539.09
S28	25.35	736.07	1102.42	546.26
S29	79.24	723.83	1149.65	553.10
S30	62.24	730.62	1133.55	554.08

td_{cd}

	D1	D2	D3	D4	D5
C1	793.35	802.35	544.63	28.11	79.92
C2	77.95	128.48	323.43	733.3	698.38
C3	1781.88	1808.19	1409.81	1105.26	1086.83
C4	354.46	394.53	43.13	544.03	486.35

Model S		
Demand Point 1		
$\lvert S \rvert$	$\lvert T_d \rvert$	$\lvert S^o \rvert$
16	6	22

td_{xy}

	S2	S7	S8	S9	S10	S11	S12	S13	S14	S15	S19	S20	S22	S26	S28	S30
S2	10000.00	260.49	57.25	532.35	288.89	1989.34	591.74	560.73	540.03	171.32	572.56	708.77	92.86	576.06	570.18	573.22
S7	260.49	10000.00	203.52	729.21	28.44	2246.51	766.00	733.87	738.01	408.85	745.63	908.13	347.06	754.49	754.06	745.70
S8	57.25	203.52	10000.00	567.57	231.95	2044.75	620.82	589.21	575.65	216.51	601.13	745.79	148.05	606.20	601.86	601.63
S9	532.35	729.21	567.57	10000.00	753.80	1614.48	93.67	83.54	9.29	365.62	87.62	179.26	514.56	74.07	56.37	89.59
S10	288.89	28.44	231.95	753.80	10000.00	2274.81	788.81	756.70	762.66	436.70	768.42	932.50	375.14	777.65	777.63	768.44
S11	1989.34	2246.51	2044.75	1614.48	2274.81	10000.00	1642.55	1664.64	1605.60	1840.81	1657.69	1480.79	1913.38	1639.37	1626.63	1659.07
S12	591.74	766.00	620.82	93.67	788.81	1642.55	10000.00	32.15	93.96	432.55	20.40	165.46	585.13	19.95	37.72	20.54
S13	560.73	733.87	589.21	83.54	756.70	1664.64	32.15	10000.00	86.97	402.94	11.94	192.55	555.90	25.51	39.62	12.49
S14	540.03	738.01	575.65	9.29	762.66	1605.60	93.96	86.97	10000.00	372.83	89.89	170.73	521.24	74.88	56.25	91.90
S15	171.32	408.85	216.51	365.62	436.70	1840.81	432.55	402.94	372.83	10000.00	414.44	539.65	153.44	415.47	407.48	415.35
S19	572.56	745.63	601.13	87.62	768.42	1657.69	20.40	11.94	89.89	414.44	10000.00	183.28	567.31	19.32	37.35	2.02
S20	708.77	908.13	745.79	179.26	932.50	1480.79	165.46	192.55	170.73	539.65	183.28	10000.00	684.25	167.35	160.54	184.26
S22	92.86	347.06	148.05	514.56	375.14	1913.38	585.13	555.90	521.24	153.44	567.31	684.25	10000.00	567.68	558.90	568.27
S26	576.06	754.49	606.20	74.07	777.65	1639.37	19.95	25.51	74.88	415.47	19.32	167.35	567.68	10000.00	19.35	21.11
S28	570.18	754.06	601.86	56.37	777.63	1626.63	37.72	39.62	56.25	407.48	37.35	160.54	558.90	19.35	10000.00	39.32
S30	573.22	745.70	601.63	89.59	768.44	1659.07	20.54	12.49	91.90	415.35	2.02	184.26	568.27	21.11	39.32	10000.00

Demand Point 2		
$\lvert S \rvert$	$\lvert T_d \rvert$	$\lvert S^o \rvert$
13	6	19

td_{xy}

	S3	S6	S7	S10	S11	S16	S18	S19	S22	S23	S24	S25	S29
S3	10000.00	97.56	23.41	5.63	2269.92	363.02	764.03	765.64	369.71	752.56	396.46	778.09	757.45
S6	97.56	10000.00	75.56	103.07	2177.06	265.57	702.36	704.53	272.38	690.97	299.49	715.95	698.17
S7	23.41	75.56	10000.00	28.44	2246.51	340.48	743.93	745.63	347.06	732.46	373.60	757.93	737.73
S10	5.63	103.07	28.44	10000.00	2274.81	368.47	766.84	768.42	375.14	755.37	401.83	780.93	760.12
S11	2269.92	2177.06	2246.51	2274.81	10000.00	1921.73	1655.11	1657.69	1913.38	1663.54	1883.88	1642.17	1675.44
S16	363.02	265.57	340.48	368.47	1921.73	10000.00	571.70	575.60	9.39	561.57	39.28	582.50	576.10
S18	764.03	702.36	743.93	766.84	1655.11	571.70	10000.00	5.66	563.38	11.47	541.82	14.61	23.27
S19	765.64	704.53	745.63	768.42	1657.69	575.60	5.66	10000.00	567.31	14.10	545.91	15.62	18.82
S22	369.71	272.38	347.06	375.14	1913.38	9.39	563.38	567.31	10000.00	553.29	30.15	574.10	567.95
S23	752.56	690.97	732.46	755.37	1663.54	561.57	11.47	14.10	553.29	10000.00	531.95	25.86	22.55
S24	396.46	299.49	373.60	401.83	1883.88	39.28	541.82	545.91	30.15	531.95	10000.00	552.17	547.28
S25	778.09	715.95	757.93	780.93	1642.17	582.50	14.61	15.62	574.10	25.86	552.17	10000.00	33.56
S29	757.45	698.17	737.73	760.12	1675.44	576.10	23.27	18.82	567.95	22.55	547.28	33.56	10000.00

Demand Point 3

$\|S\|$	$\|T_d\|$	$\|S^o\|$
14	6	20

td_{xy}

	S1	S4	S6	S7	S9	S12	S13	S14	S17	S20	S21	S23	S25	S26
S1	10000.00	264.09	168.97	240.75	542.43	599.46	568.20	550.28	581.25	719.67	596.01	566.04	589.45	584.18
S4	264.09	10000.00	97.66	23.56	750.69	786.24	754.12	759.53	766.19	929.46	784.67	752.77	778.30	774.98
S6	168.97	97.66	10000.00	75.56	680.83	724.73	692.63	689.36	705.17	860.08	722.44	690.97	715.95	711.87
S7	240.75	23.56	75.56	10000.00	729.21	766.00	733.87	738.01	746.01	908.13	764.32	732.46	757.93	754.49
S9	542.43	750.69	680.83	729.21	10000.00	93.67	83.54	9.29	90.66	179.26	86.50	80.40	82.42	74.07
S12	599.46	786.24	724.73	766.00	93.67	10000.00	32.15	93.96	20.42	165.46	7.38	33.78	11.83	19.95
S13	568.20	754.12	692.63	733.87	83.54	32.15	10000.00	86.97	13.14	192.55	31.06	3.32	25.22	25.51
S14	550.28	759.53	689.36	738.01	9.29	93.96	86.97	10000.00	92.96	170.73	86.64	83.97	83.16	74.88
S17	581.25	766.19	705.17	746.01	90.66	20.42	13.14	92.96	10000.00	184.53	21.50	15.76	17.42	21.94
S20	719.67	929.46	860.08	908.13	179.26	165.46	192.55	170.73	184.53	10000.00	163.03	192.40	167.82	167.35
S21	596.01	784.67	722.44	764.32	86.50	7.38	31.06	86.64	21.50	163.03	10000.00	32.00	6.56	13.43
S23	566.04	752.77	690.97	732.46	80.40	33.78	3.32	83.97	15.76	192.40	32.00	10000.00	25.86	25.06
S25	589.45	778.30	715.95	757.93	82.42	11.83	25.22	83.16	17.42	167.82	6.56	25.86	10000.00	8.36
S26	584.18	774.98	711.87	754.49	74.07	19.95	25.51	74.88	21.94	167.35	13.43	25.06	8.36	10000.00

Demand Point 4

$\|S\|$	$\|T_d\|$	$\|S^o\|$
17	7	23

td_{xy}

	S2	S3	S4	S9	S10	S11	S15	S16	S17	S18	S20	S21	S23	S27	S28	S29	S30
S2	10000.00	283.66	283.79	532.35	288.89	1989.34	171.32	89.02	573.82	569.35	708.77	588.08	558.49	561.65	570.18	570.14	573.22
S3	283.66	10000.00	0.22	750.49	5.63	2269.92	432.12	363.02	765.97	764.03	929.26	784.46	752.56	763.32	774.63	757.45	765.67
S4	283.79	0.22	10000.00	750.69	5.59	2270.08	432.29	363.12	766.19	764.24	929.46	784.67	752.77	763.53	774.84	757.67	765.89
S9	532.35	750.49	750.69	10000.00	753.80	1614.48	365.62	523.36	90.66	81.97	179.26	86.50	80.40	59.44	56.37	102.82	89.59
S10	288.89	5.63	5.59	753.80	10000.00	2274.81	436.70	368.47	768.73	766.84	932.50	787.28	755.37	766.28	777.63	760.12	768.44
S11	1989.34	2269.92	2270.08	1614.48	2274.81	10000.00	1840.81	1921.73	1659.58	1655.11	1480.79	1638.66	1663.54	1640.15	1626.63	1675.44	1659.07
S15	171.32	432.12	432.29	365.62	436.70	1840.81	10000.00	161.45	416.07	410.63	539.65	428.13	400.38	400.24	407.48	414.68	415.35
S16	89.02	363.02	363.12	523.36	368.47	1921.73	161.45	10000.00	577.28	571.70	693.32	588.92	561.57	560.69	567.46	576.10	576.55
S17	573.82	765.97	766.19	90.66	768.73	1659.58	416.07	577.28	10000.00	8.69	184.53	21.50	15.76	31.60	40.27	16.32	1.07
S18	569.35	764.03	764.24	81.97	766.84	1655.11	410.63	571.70	8.69	10000.00	182.10	20.57	11.47	23.01	32.54	23.27	7.62
S20	708.77	929.26	929.46	179.26	932.50	1480.79	539.65	693.32	184.53	182.10	10000.00	163.03	192.40	173.65	160.54	199.18	184.26
S21	588.08	784.46	784.67	86.50	787.28	1638.66	428.13	588.92	21.50	20.57	163.03	10000.00	32.00	29.73	30.39	36.80	21.25
S23	558.49	752.56	752.77	80.40	755.37	1663.54	400.38	561.57	15.76	11.47	192.40	32.00	10000.00	25.36	37.79	22.55	14.98
S27	561.65	763.32	763.53	59.44	766.28	1640.15	400.24	560.69	31.60	23.01	173.65	29.73	25.36	10000.00	13.62	45.59	30.55
S28	570.18	774.63	774.84	56.37	777.63	1626.63	407.48	567.46	40.27	32.54	160.54	30.39	37.79	13.62	10000.00	55.81	39.32
S29	570.14	757.45	757.67	102.82	760.12	1675.44	414.68	576.10	16.32	23.27	199.18	36.80	22.55	45.59	55.81	10000.00	17.05

Demand Point 5

$\|S\|$	$\|T_d\|$	$\|S^o\|$
18	6	24

td_{xy}

	S1	S2	S5	S6	S8	S9	S14	S15	S16	S19	S22	S24	S25	S26	S27	S28	S29	S30
S1	10000.00	20.20	904.83	168.97	37.26	542.43	550.28	184.95	108.37	580.08	112.63	135.51	589.45	584.18	570.03	578.90	577.04	580.67
S2	20.20	10000.00	896.38	188.15	57.25	532.35	540.03	171.32	89.02	572.56	92.86	115.32	581.53	576.06	561.65	570.18	570.14	573.22
S5	904.83	896.38	10000.00	1030.52	926.94	368.67	362.31	733.04	891.87	326.34	883.13	859.25	315.83	320.77	334.81	326.25	332.42	326.00
S6	168.97	188.15	1030.52	10000.00	132.32	680.83	689.36	344.93	265.57	704.53	272.38	299.49	715.95	711.87	699.31	709.81	698.17	704.77
S8	37.26	57.25	926.94	132.32	10000.00	567.57	575.65	216.51	142.97	601.13	148.05	172.15	611.14	606.20	592.48	601.86	597.12	601.63
S9	542.43	532.35	368.67	680.83	567.57	10000.00	9.29	365.62	523.36	87.62	514.56	490.58	82.42	74.07	59.44	56.37	102.82	89.59
S14	550.28	540.03	362.31	689.36	575.65	9.29	10000.00	372.83	530.07	89.89	521.24	497.01	83.16	74.88	61.37	56.25	106.05	91.90
S15	184.95	171.32	733.04	344.93	216.51	365.62	372.83	10000.00	161.45	414.44	153.44	135.12	421.68	415.47	400.24	407.48	414.68	415.35
S16	108.37	89.02	891.87	265.57	142.97	523.36	530.07	161.45	10000.00	575.60	9.39	39.28	582.50	576.12	560.69	567.46	576.10	576.55
S19	580.08	572.56	326.34	704.53	601.13	87.62	89.89	414.44	575.60	10000.00	567.31	545.91	15.62	19.32	28.54	37.35	18.82	2.02
S22	112.63	92.86	883.13	272.38	148.05	514.56	521.24	153.44	9.39	567.31	10000.00	30.15	574.10	567.68	552.22	558.90	567.95	568.27
S24	135.51	115.32	859.25	299.49	172.15	490.58	497.01	135.12	39.28	545.91	30.15	10000.00	552.17	545.56	529.91	536.15	547.28	546.93
S25	589.45	581.53	315.83	715.95	611.14	82.42	83.16	421.68	582.50	15.62	574.10	552.17	10000.00	8.36	24.26	27.28	33.56	16.90
S26	584.18	576.06	320.77	711.87	606.20	74.07	74.88	415.47	576.12	19.32	567.68	545.56	8.36	10000.00	16.31	19.35	38.14	21.11
S27	570.03	561.65	334.81	699.31	592.48	59.44	61.37	400.24	560.69	28.54	552.22	529.91	24.26	16.31	10000.00	13.62	45.59	30.55
S28	578.90	570.18	326.25	709.81	601.86	56.37	56.25	407.48	567.46	37.35	558.90	536.15	27.28	19.35	13.62	10000.00	55.81	39.32
S29	577.04	570.14	332.42	698.17	597.12	102.82	106.05	414.68	576.10	18.82	567.95	547.28	33.56	38.14	45.59	55.81	10000.00	17.05
S30	580.67	573.22	326.00	704.77	601.63	89.59	91.90	415.35	576.55	2.02	568.27	546.93	16.90	21.11	30.55	39.32	17.05	10000.00

Model H.1 (implementation of Model S on first leg)

Π-hub 1

$\|S\|$	$\|T_c\|$	$\|S^o\|$
15	9	26

td_{xy}

	S5	S9	S13	S14	S17	S18	S19	S20	S21	S23	S25	S27	S28	S29	S30
S5	10000.00	368.67	1089.06	1089.28	325.55	328.86	326.34	216.65	309.27	340.12	315.83	334.81	326.25	332.42	326.00
S9	368.67	10000.00	750.49	750.69	90.66	81.97	87.62	179.26	86.50	80.40	82.42	59.44	56.37	102.82	89.59
S13	1089.06	750.49	10000.00	0.22	765.97	764.03	765.64	929.26	784.46	752.56	778.09	763.32	774.63	757.45	765.67
S14	1089.28	750.69	0.22	10000.00	766.19	764.24	765.86	929.46	784.67	752.77	778.30	763.53	774.84	757.67	765.89
S17	325.55	90.66	765.97	766.19	10000.00	8.69	3.07	184.53	21.50	15.76	17.42	31.60	40.27	16.32	1.07
S18	328.86	81.97	764.03	764.24	8.69	10000.00	5.66	182.10	20.57	11.47	14.61	23.01	32.54	23.27	7.62
S19	326.34	87.62	765.64	765.86	3.07	5.66	10000.00	183.28	20.40	14.10	15.62	28.54	37.35	18.82	2.02
S20	216.65	179.26	929.26	929.46	184.53	182.10	183.28	10000.00	163.03	192.40	167.82	173.65	160.54	199.18	184.26
S21	309.27	86.50	784.46	784.67	21.50	20.57	20.40	163.03	10000.00	32.00	6.56	29.73	30.39	36.80	21.25
S23	340.12	80.40	752.56	752.77	15.76	11.47	14.10	192.40	32.00	10000.00	25.86	25.36	37.79	22.55	14.98
S25	315.83	82.42	778.09	778.30	17.42	14.61	15.62	167.82	6.56	25.86	10000.00	24.26	27.28	33.56	16.90
S27	334.81	59.44	763.32	763.53	31.60	23.01	28.54	173.65	29.73	25.36	24.26	10000.00	13.62	45.59	30.55
S28	326.25	56.37	774.63	774.84	40.27	32.54	37.35	160.54	30.39	37.79	27.28	13.62	10000.00	55.81	39.32
S29	332.42	102.82	757.45	757.67	16.32	23.27	18.82	199.18	36.80	22.55	33.56	45.59	55.81	10000.00	17.05
S30	326.00	89.59	765.67	765.89	1.07	7.62	2.02	184.26	21.25	14.98	16.90	30.55	39.32	17.05	10000.00

Π-hub 2

$\|S\|$	$\|T_c\|$	$\|S^o\|$
8	7	15

td_{xy}

	S3	S4	S6	S7	S10	S11	S14	S30
S3	10000.00	0.22	97.56	23.41	5.63	2269.92	759.33	765.67
S4	0.22	10000.00	97.66	23.56	5.59	2270.08	759.53	765.89
S6	97.56	97.66	10000.00	75.56	103.07	2177.06	689.36	704.77
S7	23.41	23.56	75.56	10000.00	28.44	2246.51	738.01	745.70
S10	5.63	5.59	103.07	28.44	10000.00	2274.81	762.66	768.44
S11	2269.92	2270.08	2177.06	2246.51	2274.81	10000.00	1605.60	1659.07
S14	759.33	759.53	689.36	738.01	762.66	1605.60	10000.00	91.90
S30	765.67	765.89	704.77	745.70	768.44	1659.07	91.90	10000.00

Π-hub 3		
$\lvert S \rvert$	$\lvert T_c \rvert$	$\lvert S^o \rvert$
10	8	18

td_{xy}

	S1	S2	S8	S9	S12	S15	S16	S22	S24	S26
S1	10000.00	20.20	37.26	542.43	599.46	184.95	108.37	112.63	135.51	584.18
S2	20.20	10000.00	57.25	532.35	591.74	171.32	89.02	92.86	115.32	576.06
S8	37.26	57.25	10000.00	567.57	620.82	216.51	142.97	148.05	172.15	606.20
S9	542.43	532.35	567.57	10000.00	93.67	365.62	523.36	514.56	490.58	74.07
S12	599.46	591.74	620.82	93.67	10000.00	432.55	593.49	585.13	563.34	19.95
S15	184.95	171.32	216.51	365.62	432.55	10000.00	161.45	153.44	135.12	415.47
S16	108.37	89.02	142.97	523.36	593.49	161.45	10000.00	9.39	39.28	576.12
S22	112.63	92.86	148.05	514.56	585.13	153.44	9.39	10000.00	30.15	567.68
S24	135.51	115.32	172.15	490.58	563.34	135.12	39.28	30.15	10000.00	545.56
S26	584.18	576.06	606.20	74.07	19.95	415.47	576.12	567.68	545.56	10000.00

As observed in the solutions obtained from implementation of Model P, in Model H.1 the first leg of our hybrid configuration has only three π-hub as compared to Model P, which has four. This is due to the fact that post optimization of Model P, the results show that only three out of four π-hubs are consumed in the network. This limits our implementation of Model S on the first leg of Model H (i.e. H.1) to only three π-hubs.

STATIC OPTIMAL RESULTS

This section focuses on the mathematical results obtained from implementation of the models on the Mexican automotive case study using GUSEK solver and using the results to compare the performance of the three different configurations. As the distance being the base metric for our calculations, all the costs including fuel, labour, truck relies on it. Using the collected data, we converted all the costs to a dollar per kilometer standards shown in Table 8.

Table 8 Cost parameters

Fuel cost	0.303 $/km
Labour cost	0.06 $/km
Truck cost	0.1643 $/km

Findings are as follows:

MODEL P

The results obtained from implementing the Model P in GUROBI are shown in the Figure 16. The optimal solution obtained is 16173.7 in 22.3 minutes. This is a distance metric and does not include the backhaul of trucks. For the total transportation cost of the network, we must double the distance and then multiply the cost parameters as shown below.

Model P - PI	Distance	Fuel cost	Labour cost	Truck cost	Total cost
Network objective	16173.87	$1,788,927.73	$327,022.19	$ 970,187.98	$3,086,137.90
Total Costs (2XNetwork objective)	32347.73	$3,577,855.46	$654,044.39	$1,940,375.95	
				Total	**$6,172,275.80**

After performing these calculations, the total fuel cost is $3,577,855.46, labour cost is $654,044.39, and truck cost is $1,940,375.95. The system wide transportation cost is the sum of total fuel, labour and truck cost, which is $6,172,275.80.

```
 190809  6776     cutoff   72       16684.7147 16584.3779  0.60%   195 1300s
 192653  6139 16592.0620   84    93 16684.7147 16592.0620  0.56%   193 1305s
 194367  5674     cutoff   76       16173.7147 16597.7721  0.52%   192 1310s
 196079  5003 infeasible   83       16173.7147 16605.0963  0.48%   191 1315s
 197788  4331 16640.9703   88   158 16173.7147 16613.5007  0.43%   190 1320s
 199530  3509     cutoff   78       16173.7147 16623.5680  0.37%   189 1325s
 201230  2816     cutoff   84       16173.7147 16628.9632  0.33%   188 1330s
 203601  1622 16648.2494   90    43 16173.7147 16648.2494  0.22%   186 1335s
 205931   154 infeasible   94       16173.7147 16677.5076  0.04%   184 1340s

Cutting planes:
  Gomory: 136
  Cover: 1744
  Implied bound: 21
  Clique: 74
  MIR: 296
  StrongCG: 112
  Flow cover: 493
  GUB cover: 3
  Inf proof: 19
  Zero half: 94

Explored 206201 nodes (37994211 simplex iterations) in 1340.51 seconds
Thread count was 6 (of 6 available processors)

Solution count 10: 16173.7 16173.7 16173.7 ... 16173.7

Optimal solution found (tolerance 1.00e-04)
Best objective 1.61738671604099e+04, best bound 1.6172548764e+04, gap 0.0050%
```

Figure 16 GUROBI solution - Model P

MODEL S

The mathematical formulation is implemented on each demand point separately and the results obtained are discussed as follows:

Demand Point 1

As shown in the Figure 17, the optimal solution obtained is 10395.59 in 91.41 minutes or 1.51 hours. After performing the calculations, the fuel cost is $1,149,815.51, labour cost is $210,190.26, and truck cost is $623,578.68. The total transportation cost for Demand point 1 is $1,983,584.45.

```
 15693750 155500     cutoff   62      10395.5884 10279.5083  1.12%  29.1 5445s
 15712862 141848     cutoff   84      10395.5884 10286.3364  1.05%  29.1 5450s
 15731375 128517 infeasible   74      10395.5884 10293.4411  0.98%  29.1 5455s
 15751228 113979     cutoff   68      10395.5884 10301.4986  0.91%  29.0 5460s
 15772675 97840     cutoff   80      10395.5884 10311.0643  0.81%  29.0 5465s
 15795200 80432     cutoff   68      10395.5884 10322.4052  0.70%  29.0 5470s
 15818568 61723 infeasible   65      10395.5884 10335.8665  0.57%  29.0 5475s
 15842119 41648     cutoff   76      10395.5884 10352.2401  0.42%  29.0 5480s
 15870926 14824     cutoff   86      10395.5884 10378.2536  0.17%  28.9 5485s

Cutting planes:
  Gomory: 7
  Cover: 1
  Implied bound: 43
  Clique: 1
  MIR: 214
  StrongCG: 9
  Flow cover: 332
  GUB cover: 7
  Inf proof: 51
  Zero half: 26

Explored 15885211 nodes (459010664 simplex iterations) in 5487.98 seconds
Thread count was 6 (of 6 available processors)

Solution count 10: 10395.6 10395.6 10395.6 ... 10395.6

Optimal solution found (tolerance 1.00e-04)
Best objective 1.039559231066e+04, best bound 1.039456507456e+04, gap 0.0099%
```

Figure 17 GUROBI solution - Demand point 1

```
 58186 12132 5475.10759   39   25 6914.14660 5069.07863  26.7%  27.9   20s
 84941 17361     cutoff   42      6914.14660 5296.66949  23.4%  28.2   25s
 114755 20626 6511.80868   42   26 6914.14660 5529.94444  20.0%  28.4   30s
 147808 21451     cutoff   63      6914.14660 5767.71589  16.6%  28.1   35s
*175778 20001             67    6910.9794404 5962.92166  13.7%  27.9   39s
 180239 19436 infeasible   41      6910.97944 5999.23942  13.2%  27.9   40s
H193421 17471                   6910.9793670 6100.60945  11.7%  27.8   42s
H195064 17193                   6910.9791739 6118.01200  11.5%  27.8   42s
 208322 14236 6440.35880   49   33 6910.97917 6237.86686  9.74%  27.6   45s

Cutting planes:
  Learned: 2
  Gomory: 17
  Implied bound: 33
  Clique: 1
  MIR: 74
  StrongCG: 3
  Flow cover: 157
  GUB cover: 1
  Inf proof: 28
  Zero half: 21

Explored 238068 nodes (6454136 simplex iterations) in 49.94 seconds
Thread count was 6 (of 6 available processors)

Solution count 10: 6910.98 6910.98 6910.98 ... 6914.15

Optimal solution found (tolerance 1.00e-04)
Best objective 6.910979440388e+03, best bound 6.910979173889e+03, gap 0.0000%
```

Figure 18 GUROBI solution - Demand point 2

Demand Point 2

Figure 18 displays the optimal solution as 6910.97 in 45 seconds. After performing the calculations, the fuel cost is $764,396.21, labour cost is $139,734.28, and truck cost is $414,554.48. The total transportation cost for Demand point 2 is $1,318,684.97.

Demand Point 3

Displayed in Figure 19, the optimal solution obtained is 5529.55 in 5.67 minutes. After performing the calculations, the fuel cost is $611,602.84, labour cost is $111,803.12, and truck cost is $331,690.16. The total transportation cost for Demand point 3 is $1,055,096.11.

Demand Point 4

As shown in the Figure 20, the optimal solution is found to be 7360.98 in one second. After performing the calculations, the fuel cost is $814,169.53, labour cost is $148,833.01, and truck cost is $441,548.02. The total transportation cost for Demand point 4 is $1,404,550.56.

Demand Point 5

Figure 21 displays the optimal solution that is 5633.87, in a runtime of 91.4 minutes or 1.51 hours. After performing the calculations, the fuel cost is $623,140.20, labour cost is $113,912.19, and truck cost is $337,947.21. The total transportation cost for Demand point 4 is $1,074,999.60.

```
 1228387 87781 5390.33105   52   24 5529.55722 5258.09210  4.91%  33.5  290s
 1253060 85141      cutoff   64      5529.55722 5300.49987  4.14%  33.4  295s
 1278692 82812 5428.02535   80   30 5529.55722 5329.73559  3.61%  33.2  300s
 1299073 80329 5493.66152   55   35 5529.55722 5347.61610  3.29%  33.1  305s
 1321353 76561 5480.35354   58   30 5529.55722 5365.14697  2.97%  32.9  310s
 1345892 71333      cutoff   67      5529.55722 5381.40499  2.68%  32.8  315s
 1371091 64268      cutoff   66      5529.55722 5397.23189  2.39%  32.6  320s
 1395223 55970 5435.47847   64   39 5529.55722 5411.88945  2.13%  32.4  325s
 1421951 44680 5511.93741   82   26 5529.55722 5428.89353  1.82%  32.2  330s
 1447101 32317 5460.31672   70   40 5529.55722 5446.46905  1.50%  32.0  335s
 1476159 15477      cutoff   78      5529.55722 5474.38626  1.00%  31.7  340s

Cutting planes:
  Gomory: 3
  Implied bound: 28
  MIR: 164
  StrongCG: 10
  Flow cover: 268
  GUB cover: 1
  Inf proof: 14
  Zero half: 14

Explored 1496137 nodes (47103709 simplex iterations) in 342.86 seconds
Thread count was 6 (of 6 available processors)

Solution count 10: 5529.56 5529.56 5529.56 ... 5529.56

Optimal solution found (tolerance 1.00e-04)
Best objective 5.529559892744e+03, best bound 5.529557218879e+03, gap 0.0000%
```

Figure 19 GUROBI solution – Demand point 3

```
     0     0 5772.60277    0   63 7400.42392 5772.60277  22.0%     -    0s
     0     0 5774.06625    0   63 7400.42392 5774.06625  22.0%     -    0s
     0     0 5774.06625    0   63 7400.42392 5774.06625  22.0%     -    0s
     0     0 5775.69325    0   57 7400.42392 5775.69325  22.0%     -    0s
     0     0 5776.22450    0   59 7400.42392 5776.22450  21.9%     -    0s
     0     0 5776.23065    0   60 7400.42392 5776.23065  21.9%     -    0s
     0     0 5776.44372    0   61 7400.42392 5776.44372  21.9%     -    0s
     0     0 5776.44372    0   55 7400.42392 5776.44372  21.9%     -    0s
     0     2 5776.44372    0   52 7400.42392 5776.44372  21.9%     -    0s
H  894   502                    7400.4239051 6488.16133  12.3%  17.0    0s
H  907   479                    7370.8493383 6488.16133  12.0%  17.1    0s
H 2084   616                    7370.8489432 6853.37519  7.02%  23.2    0s
H 2090   619                    7370.8489423 6853.37519  7.02%  23.2    0s
* 3046   635              40    7370.6876101 7204.99358  2.25%  23.9    0s
H 3311   678                    7370.6876092 7215.41673  2.11%  23.3    0s
H 3335   690                    7370.6876060 7219.07320  2.06%  23.2    0s
H 4106   967                    7360.9847962 7260.85217  1.36%  22.0    0s
H 6451  1400                    7360.9847944 7280.17613  1.10%  22.3    1s

Cutting planes:
  Learned: 1

Explored 30553 nodes (506457 simplex iterations) in 4.89 seconds
Thread count was 6 (of 6 available processors)

Solution count 10: 7360.98 7360.98 7370.69 ... 7400.42

Optimal solution found (tolerance 1.00e-04)
Best objective 7.360984794353e+03, best bound 7.360984794353e+03, gap 0.0000%
```

Figure 20 GUROBI solution - Demand point 4

```
 3702032 1206420     cutoff   62          5633.86884 5402.19054  1.12%  29.1 5445s
 3712517 1208117     cutoff   84          5633.86884 5402.39017  1.05%  29.1 5450s
 3724875 1210277 infeasible   59          5633.86884 5402.64216  0.98%  29.1 5455s
 3736165 1212194     cutoff   70       34 5633.86884 5402.86840  0.91%  29.0 5460s
 3746301 1213996     cutoff   73          5633.86884 5403.07228  0.81%  29.0 5465s
 3757961 1215916     cutoff   65          5633.86884 5403.31103  0.70%  29.0 5470s
 3769395 1217754     cutoff   55       17 5633.86884 5403.55205  0.57%  29.0 5475s
 3780386 1219715 infeasible   60       42 5633.86884 5403.79023  0.42%  29.0 5480s
 3791812 1221603     cutoff   58       36 5633.86884 5404.03760  0.17%  28.9 5485s
 3803205 1223503     cutoff   77       37 5633.86884 5404.26947

Cutting planes:
  Gomory: 7
  Cover: 1
  Implied bound: 43
  Clique: 1
  MIR: 214
  StrongCG: 9
  Flow cover: 332
  GUB cover: 7
  Inf proof: 51
  Zero half: 26

Explored 15885211 nodes (459010664 simplex iterations) in 5487.98 seconds
Thread count was 6 (of 6 available processors)

Solution count 10: 5633.8  5633.8  5633.8  ... 5633.8

Optimal solution found (tolerance 1.00e-04)
Best objective 5.63387654126e+03, best bound 5.6326253621e+03, gap 0.0030%
```

Figure 21 GUROBI solution - Demand point 5

For the system wide transportation cost of Model S, we sum all the results obtained from individual Demand point model implementation.

Total transportation cost for Model S =	Transportation cost of Demand point 1 + Transportation cost of Demand point 2 + Transportation cost of Demand point 3 + Transportation cost of Demand point 4 + Transportation cost of Demand point 5

The system wide transportation cost achieved for Model S is $6,836,915.70.

MODEL H

As guided by the heuristics for the integration process of Model S on the first leg and Model P on the second of the model, the second step is to implement Model S on each of the π-hubs (Model H.1). The results obtained from the implementation of Model H.1 were achieved in less than one second and are discussed as follows:

Π – Hub 1

As shown in the Figure 22, the optimal solution is 3027.98. After performing the calculations, the fuel cost is $334,912.86, labour cost is $61,223.23, and truck cost is $181,633.06. The total transportation cost for π-hub 1 is $1,404,550.56.

```
     0     0 2854.07500    0   26          - 2854.07500      -     -    0s
     0     0 2854.07500    0   26          - 2854.07500      -     -    0s
     0     0 2854.07500    0   24          - 2854.07500      -     -    0s
H    0     0                    4731.6200000 2854.07500  39.7%     -    0s
     0     0 2854.07500    0   18 4731.62000 2854.07500  39.7%     -    0s
H    0     0                    4669.6300000 2854.07500  38.9%     -    0s
     0     2 2854.07500    0   18 4669.63000 2854.07500  38.9%     -    0s
H   39    35                    3071.6500000 2865.60293  6.71%  28.8    0s
H   71    45                    3038.3200000 2875.16483  5.37%  22.5    0s
H  127    73                    3038.3100000 2875.16483  5.37%  18.8    0s
H  147    82                    3028.0000000 2875.16483  5.05%  18.2    0s
H  193    89                    3027.9900000 2875.16483  5.05%  17.5    0s

Cutting planes:
  Learned: 1
  Cover: 6
  Implied bound: 21
  Clique: 1
  MIR: 27
  StrongCG: 6
  GUB cover: 1

Explored 1105 nodes (15223 simplex iterations) in 0.24 seconds
Thread count was 6 (of 6 available processors)

Solution count 7: 3027.99 3028 3038.31 ... 4731.62

Optimal solution found (tolerance 1.00e-04)
Best objective 3.027990000000e+03, best bound 3.027990000000e+03, gap 0.0000%
```

Figure 22 GUROBI solution – π-hub 1

Π – Hub 2

Figure 23 displays the optimal solution, 8252.52. After performing the calculations, the fuel cost is $912,778.99, labour cost is $166,859.17, and truck cost is $495,026.82. The total transportation cost for π-hub 2 is $1,574,664.98.

.

```
    Nodes    |    Current Node    |     Objective Bounds      |     Work
 Expl Unexpl |  Obj  Depth IntInf | Incumbent    BestBd   Gap | It/Node Time

     0     0 6554.14960    0   11 11148.0600 6554.14960  41.2%     -    0s
H    0     0                    11031.650000 6554.14960  40.6%     -    0s
H    0     0                    9611.8700000 6554.14960  31.8%     -    0s
H    0     0                    8252.5000000 6554.14960  20.6%     -    0s
     0     0 6830.91074    0   25 8252.50000 6830.91074  17.2%     -    0s
     0     0 7050.39300    0   24 8252.50000 7050.39300  14.6%     -    0s
     0     0 7050.39300    0   24 8252.50000 7050.39300  14.6%     -    0s
     0     0 8216.22190    0   11 8252.50000 8216.22190  0.44%     -    0s
     0     0 8216.22190    0   11 8252.50000 8216.22190  0.44%     -    0s
     0     0 8216.22190    0   16 8252.50000 8216.22190  0.44%     -    0s
     0     0 8220.68122    0    9 8252.50000 8220.68122  0.39%     -    0s
     0     0     cutoff    0      8252.50000 8252.50000  0.00%     -    0s

Cutting planes:
  Learned: 1
  Gomory: 1
  Implied bound: 4

Explored 1 nodes (316 simplex iterations) in 0.04 seconds
Thread count was 6 (of 6 available processors)

Solution count 5: 8252.5 8252.5 9611.87 ... 11148.1

Optimal solution found (tolerance 1.00e-04)
Best objective 8.252500000000e+03, best bound 8.252500000000e+03, gap 0.0000%
```

Figure 23 GUROBI solution – π-hub 2

```
    Nodes    |    Current Node    |     Objective Bounds      |     Work
 Expl Unexpl |  Obj  Depth IntInf | Incumbent    BestBd   Gap | It/Node Time

     0     0 4676.60470    0   16 7017.14000 4676.60470  33.4%     -    0s
H    0     0                    5947.2600000 4676.60470  21.4%     -    0s
     0     0 4842.17868    0   17 5947.26000 4842.17868  18.6%     -    0s
     0     0 4876.26005    0   20 5947.26000 4876.26005  18.0%     -    0s
     0     0 4876.26005    0   21 5947.26000 4876.26005  18.0%     -    0s
     0     0 4893.83369    0   16 5947.26000 4893.83369  17.7%     -    0s
     0     0 5134.69000    0   12 5947.26000 5134.69000  13.7%     -    0s
     0     0 5941.24929    0   11 5947.26000 5941.24929  0.10%     -    0s
     0     0 5941.24929    0    8 5947.26000 5941.24929  0.10%     -    0s
     0     0 5941.24929    0    9 5947.26000 5941.24929  0.10%     -    0s
     0     0     cutoff    0      5947.26000 5947.26000  0.00%     -    0s

Cutting planes:
  Learned: 2
  Gomory: 1
  Implied bound: 1
  MIR: 1
  Zero half: 1

Explored 1 nodes (434 simplex iterations) in 0.05 seconds
Thread count was 6 (of 6 available processors)

Solution count 4: 5947.26 5947.26 5947.26 7017.14

Optimal solution found (tolerance 1.00e-04)
Best objective 5.947260000000e+03, best bound 5.947260000000e+03, gap 0.0000%
```

Figure 24 GUROBI solution – π-hub 3

Π – Hub 3

As shown in the Figure 24, the optimal solution obtained is 5947.28. After performing the calculations, the fuel cost is $657,804.79, labour cost is $120,249.00, and truck cost is $356,746.83. The total transportation cost for π-hub 3 is $1,134,800.62.

A "split delivery" would happen when the size (weight and/or volume) of an order (a load of possibly different products consolidated for a particular customer, i.e. consignee) is bigger than the vehicle's transport capacity. The delivery of such larger freight orders can be handled by utilizing a mix of full truck load (FTL) and less-than-truck load (LTL); for example, see Ülkü (2012). As it can be observed in Table 9, are some additional trucks required under Model H (first leg). These additional trucks are for split deliveries, i.e. π-containers from suppliers to the π-hubs which utilize full trucks loads are dispatched in full. Only those that require split deliveries because of less than truck load utilization is consolidated for stage 1 in Model H. Adding the direct full truck load direct dispatch costs to the π- hubs and accumulating the results obtained from the Model H.1, the system-wide transportation cost of Model H turns out to be $4,391,559.64.

COMPARISON BETWEEN THREE MODELS

In this section, the performances of system wide optimization of all three proposed methods i.e., PI system (Model P), peddling (Model S), and hybrid PI system (Model H), are compared. Before starting the comparison, it is essential to specify that our comparison metric be purely based on the primary objective value, i.e., the total transportation cost, which includes fuel cost, labor cost, and truck cost. Table 9 provides a summary of all the freight delivery networks.

Table 9 Computational analysis

Model P - Physical Internet	Distance	Fuel cost	Labour cost	Truck cost	Total cost
Network objective	16173.87	$ 1,788,927.73	$ 327,022.19	$ 970,187.98	$ 3,086,137.90
Total Costs (2 X Network Objective)	32347.73432	$ 3,577,855.46	$ 654,044.39	$ 1,940,375.95	
				Total Config 1	**$ 6,172,275.80**
Model S - Peddling (Per Plant)	Distance	Fuel cost	Labour cost	Truck cost	Total cost
Demand point 1	10395.59231	$ 1,149,815.51	$ 210,190.26	$ 623,578.68	$ 1,983,584.45
Demand point 2	6910.97944	$ 764,396.21	$ 139,734.28	$ 414,554.48	$ 1,318,684.97
Demand point 3	5529.559893	$ 611,602.84	$ 111,803.12	$ 331,690.16	$ 1,055,096.11
Demand point 4	7360.984794	$ 814,169.53	$ 148,833.01	$ 441,548.02	$ 1,404,550.56
Demand point 5	5633.870333	$ 623,140.20	$ 113,912.19	$ 337,947.21	$ 1,074,999.60
Total Costs	35830.98677	$ 3,963,124.29	$ 724,472.87	$ 2,149,318.54	
				Total Config 2	**$ 6,836,915.70**
Model H - PI & Peddling					
First leg(Peddling)	Distance	Fuel cost	Labour cost	Truck cost	Total cost
PI - Hub 1	3027.98	$ 334,912.86	$ 61,223.23	$ 181,633.06	$ 577,769.15
PI - Hub 2	8252.52	$ 912,778.99	$ 166,859.17	$ 495,026.82	$ 1,574,664.98
PI - Hub 3	5947.28	$ 657,804.79	$ 120,249.00	$ 356,746.83	$ 1,134,800.62
Additional trucks (Hub1)	103.90	$ 11,492.32	$ 2,100.84	$ 6,232.62	$ 19,825.78
Additional trucks (Hub2)	4571.81	$ 505,670.05	$ 92,438.24	$ 274,239.70	$ 872,347.98
Additional trucks (Hub3)	1111.84	$ 122,976.70	$ 22,480.57	$ 66,693.87	$ 212,151.13
Total Costs	23015.34	$ 2,545,635.70	$ 465,351.04	$ 1,380,572.90	$ 4,391,559.64
Second leg(PI)	Distance	Fuel cost	Labour cost	Truck cost	Total cost
PI - Hub 1	2970.89	$ 328,598.59	$ 60,068.96	$ 178,208.65	$ 566,876.21
PI - Hub 2	2794.16	$ 309,051.44	$ 56,495.68	$ 167,607.66	$ 533,154.78
PI - Hub 3	3171.980087	$ 350,840.22	$ 64,134.81	$ 190,270.94	$ 605,245.97
Total Costs	8937.04	$ 988,490.26	$ 180,699.45	$ 536,087.26	$ 1,705,276.96
				Total Config 3	**$ 6,096,836.60**

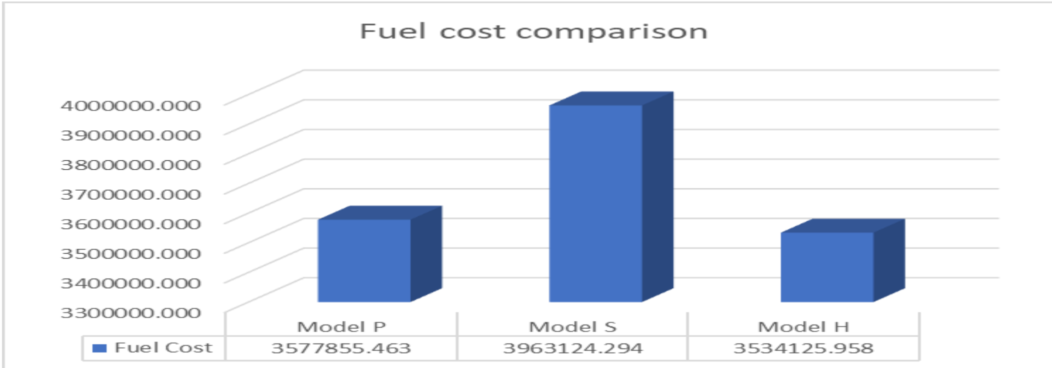


Figure 25 Fuel cost analysis

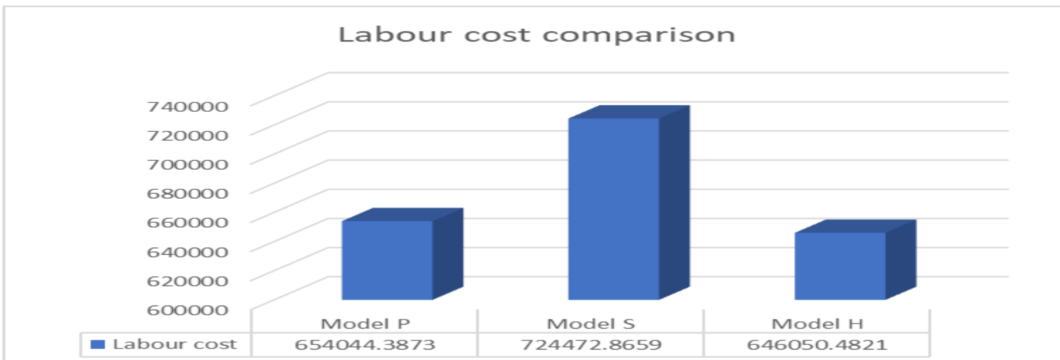


Figure 26 Labour cost analysis

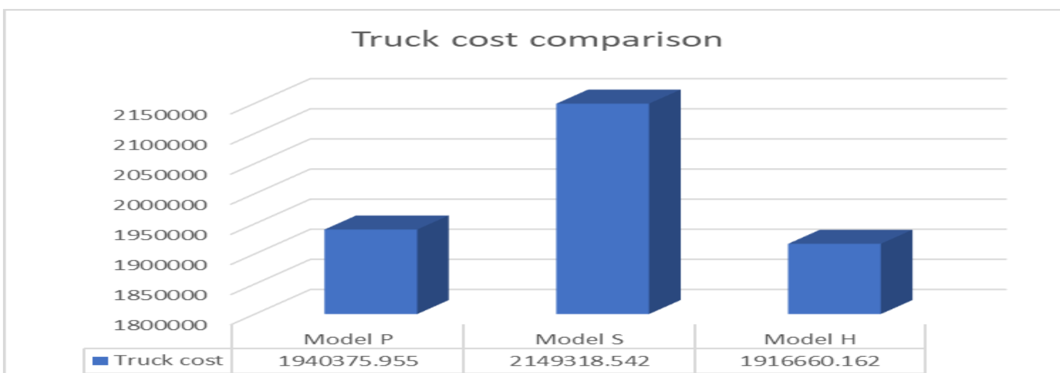


Figure 27 Truck cost analysis

Figure 25, 26 and 27 depicts the comparison between the three models on the performance metric of fuel cost, labour cost and truck cost. In Figure 28, system-wide transportation cost analysis is depicted, which shows that Model H and Model P show an improvement of 10.82% and 9.72% respectively in contrast to Model S. Higher degree of improvement in Model H is due to integration of peddling (Model S) on the first leg which saves the empty backhauls of the trucks. The results also depict that in Model P, there is a possibility of freight delivery of less than truckloads, which is eliminated by applying the Hybrid approach.

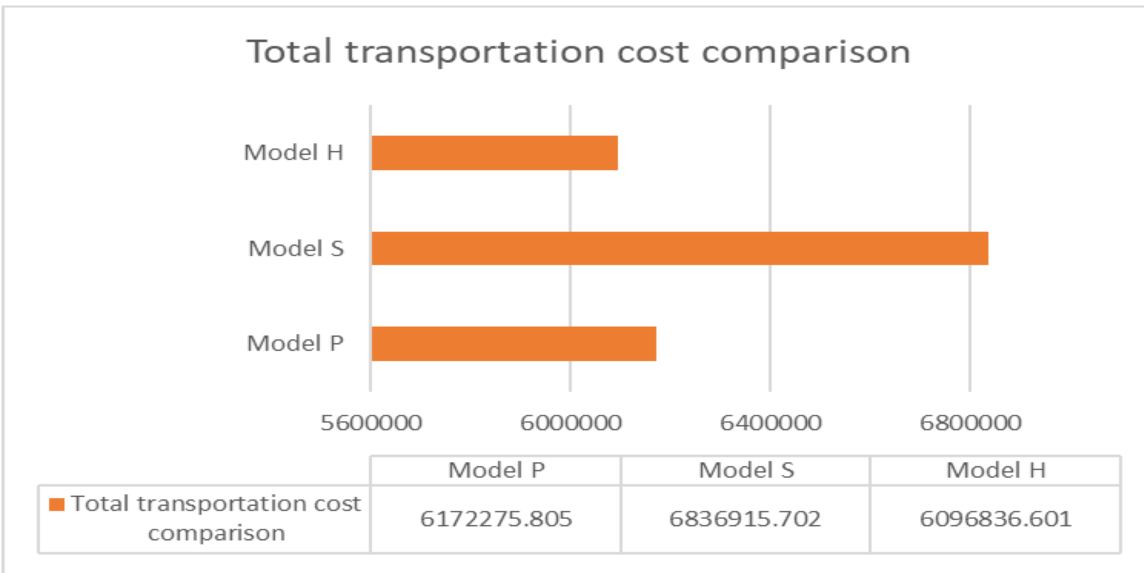


Figure 28 System-wide transportation cost analysis

Figure 29 depicts the comparison analysis of the three models on the basis of average vehicle capacity utilization or average fill rate of a vehicle ("vehicle utilization," hereafter). It shows that Model S overall utilizes 85.7% of vehicles capacity. Model P vehicle utilization is 63.2% on the first leg and 88.9% on the second leg. Model H utilization is 88.9% for the whole network. Model H shows a better systemwide vehicle utilization rate as compared to Model P and Model S. Integration of both the models in hybrid configuration offers the benefits of higher vehicle utilization on the first leg due to implementation of peddling and on the second leg due to consolidation at π-hubs.

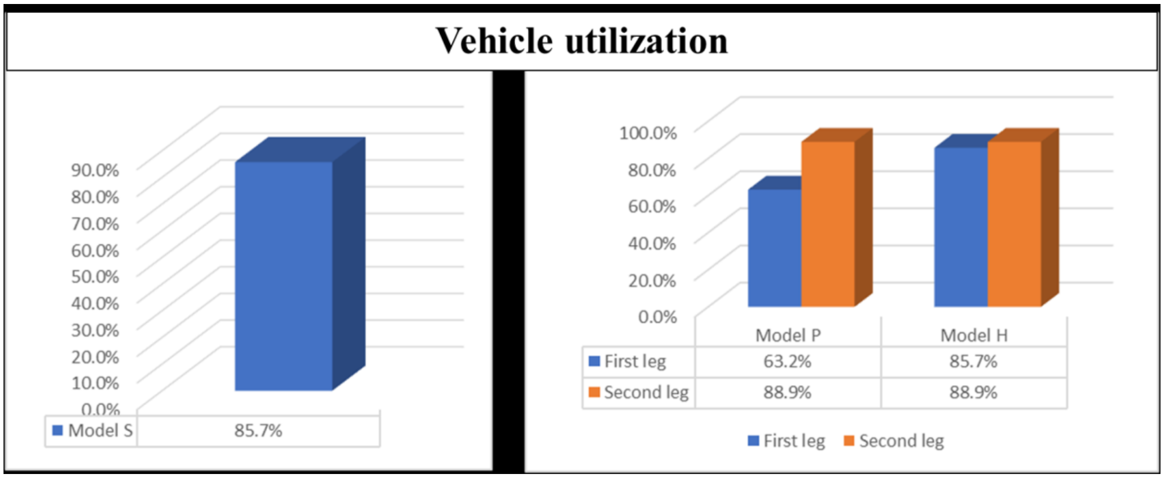


Figure 29 Vehicle utilization analysis (P, S, H)

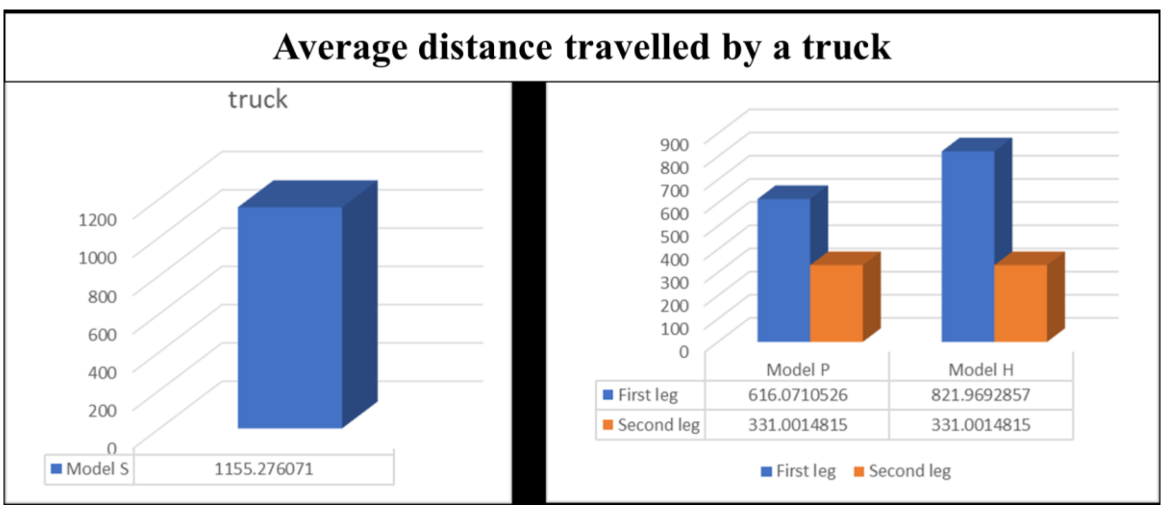


Figure 30 Average distance travelled by a vehicle

In contrast to vehicle utilization, average distance travelled by a truck in Model S is highest as compared to Model P and H (Figure 30), due to long hauls between suppliers and demand points without transit points. However, Model P shows reduction in average distance travelled for the whole network as compared to Model S, due to consolidation of π-containers at π-hubs. Model H shows an increase in average distance travelled on the first leg due to peddling as compared to Model P, but similar results on second leg after consolidation at π-hubs. Even though an increase of average distance travelled is observed on the first leg of Model H, its higher vehicle utilization has more impact on the results making it the best out of the three.

CHAPTER 5 CONCLUDING REMARKS

This study investigates numerous research papers regarding PI, which enlightened us with the core concept of PI. Tremblay et al. (2015) stated on PI that, "It is a hyper-connected global logistics system enabling seamless open asset sharing and flow consolidation." The reason being its intensive connectivity among digital, physical, operational, business, legal, and interpersonal layers. Imitating the digital internet, being its principal concept, has inspired the researchers not only to reduce empty mileage but also making sure each vehicle is loaded to its full potential. One substantial segment of PI is the PI container (or π containers), which are like the data packets of the digital Internet. These are world-standard, smart, green modular containers for transport, handling, and packaging purposes, which assist in seamless open asset sharing and consolidation across interconnected networks and modes. Another vital part of PI is the open π-hubs, which would replace the standalone warehouses, leading to less use of energy and resources. A study estimated that if only a fourth of the current distribution infrastructure in the US was rebuilt according to the principles of PI, an annual savings of $100 billion could be achieved, and carbon dioxide output reduced by one-third (University of Arkansas, 2012).

We adapted our Model P from one of the recent researches conducted in cross-docking and consolidated shipment (Küçükoğlu & Öztürk, 2017), with some rendering to elevate it to become a part of the PI infrastructure. A test case with a gathered data set was conducted. The results gave us a brief insight into the full-scale system. The research findings show that on the basis of systemwide transportation cost Model P (PI system) shows an improvement of 9.7213%, and Model H (Hybrid PI system) shows an improvement of 10.8248% in comparison to Model S, that is our standard model based on the concept of peddling. It is important to recognize that these results are based on the case study data. For further generalization, either more case studies or sensitivity analysis for varied data parameters is required. An interesting result is the fact that Model H performed better than Model P, which suggests that the PI configuration can potentially be improved by peddling, especially when there are suppliers in close proximity with partial truck loads.

For the distance parameters, we have considered geodesic distances, which gives a close approximation to the actual network distances. The reason being the network span from the North West to the South East of Mexico. The use of actual network distances will affect the values of the results obtained but the comparison analysis method will remain the same.

Run time of solving the models varies from couple of second to a few hours, due to the network selection which consists of 30 suppliers, five demand points, four π-hubs in a two-echelon framework operating on a set of 100 π-containers. If we wish to increase the number of nodes, π-containers or multiple series of π-hubs, the runtime will go up substantially, since these formulations are NP-hard.

Results obtained from implementation of the models and their comparison show that benefits of PI in terms of system wide cost reduction is higher than standard/conventional model (peddling), due to higher vehicle utilization and reduced distance travelled because of consolidation at π-hubs. The hybrid model shows even better results a compared to PI and standard model, due to much higher vehicle utilization because of integration of peddling on the first leg and it still enables the network to have reduction in distance travelled by trucks because of consolidation at π-hubs. This reduction in travel distance reduces the GHG emissions from the trucks, enabling the positive impact on environmental sustainability. The consolidation at π-hubs enables drivers to get back to their homes early, which provides them more family time and time to rest. This enables drivers to work more efficiently and reduces the possibility of getting distracted en route because of restlessness, adding the positive impact on social sustainability.

This thesis did not include the cost of material handling at the π-hubs. At the same time, the consolidation costs in peddling was not included either. Adding both can improve the comparative analysis of the configurations.

For future extensions, the stochastic version of the problem can be developed to add uncertainties in the model such as delay in lead time at supplier or π-hubs end, varying demand orders with multi period simulation. Trade-offs between conventional (CO), PI, and hybrid systems with a complete perspective of PI infrastructure, including all the fixed and variable costs involved at π-hubs and π-movers. Development of metaheuristics solutions using big data, to assess the real-time scenarios within time constraints to achieve an optimal solution with inclusion of inter hub consolidation with bin packing and sorting inside the PI hubs is another promising research avenue.

Introduction of innovative technologies such as Big Data, Internet of Things (IOT), and Industry 4.0, to the infrastructure for more accurate implementation of the PI system. Researchers from different fields with different backgrounds can engage in cooperation to pursue interdisciplinary research applying the PI vision to, for example, the study of humanitarian logistics. These studies will provoke the firms to collaborate and lead together towards the development of PI infrastructure as it introduces dimensions of socio-environmental sustainability in addition to traditional economic considerations.

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APPENDIX I

i. MODEL P

```
#Sets
#Module1
set S; #Set of suppliers
set C; #Set of PI hubs
set PR; #Set of products
set T; #Set of trucks, TR in paper
set dem{i in PR}; #Supplier of product i
set TL{k1 in T}; #Supplier of truck k1
set SL{s in S}; #Trucks at supplier s, redundant but needed because GUSEK does not
accept cst[TL[k],c]
#Module2
set D; #Set of destinations
set TP; #Set of trucks, TR' in paper
set demP{i in PR}; #Destination of product i
set TLP{k2 in TP};#Pi Hub of truck k2
set SLP{c in C}; #Trucks at PI hub c, redundant but needed because GUSEK does not
accept cst'[TL'[k],c]
set prD{d in D}; #Products going to a destination
#Parameters
#Module1
param q{i in PR}; #Size of PI container carrying product i
param cst{s in S, c in C}; #Cost of shipping one full container from s to c
#Module2
param cstP{c in C,d in D}; #Cost of shipping one full container from c to d
#Variables
#Module1
var z{i in PR, k1 in T, c in C}, binary;
```

```
var v{k1 in T, c in C}, binary;

#Module2

var zP{i in PR, k2 in TP, d in D}, binary;

var vP{k2 in TP, d in D}, binary;

#Objective function

minimize cost: sum{s in S, c in C, k1 in SL[s]} cst[s,c] * v[k1,c] +

        sum{c in C,d in D, k2 in SLP[c]} cstP[c,d] * vP[k2,d]; #C1

#Constraints

#Module1

s.t. C2{i in PR}      : sum{k1 in T, c in C: TL[k1] within dem[i]} z[i,k1,c] = 1;

s.t. C3{k1 in T}      : sum{c in C} v[k1,c] <= 1;

s.t. C4{k1 in T,c in C}: sum{i in PR: dem[i] within TL[k1]}z[i,k1,c] <= 1000*v[k1,c];

s.t. D1{k1 in T}      : sum{i in PR, c in C: TL[k1] within dem[i]} z[i,k1,c]* q[i] <= 1;

#Module2

#s.t. C5{i in PR}      : sum{k2 in TP, d in demP[i]} zP[i,k2,d] = 1;

s.t. C5{i in PR}      : sum{k2 in TP, d in demP[i]} zP[i,k2,d] = 1;

s.t. C6{k2 in TP}     : sum{d in D} vP[k2,d] <= 1;

#s.t. C7{k2 in TP,d in D}: sum{i in PR:demP[i] == d} zP[i,k2,d] <= 1000*vP[k2,d];

s.t. C7{k2 in TP,d in D}: sum{i in prD[d]} zP[i,k2,d] <= 1000*vP[k2,d];

s.t. D2{k2 in TP}     : sum{i in PR, d in demP[i]} zP[i,k2,d]* q[i] <= 1;

#Flow Balance

s.t. C8{i in PR,c in C} : sum{k1 in T:TL[k1] within dem[i]}z[i,k1,c] = sum{k2 in
SLP[c]} sum{d in demP[i]}zP[i,k2,d];

solve;

display z, v, zP, vP;

data;

#Sets

#Module1

set S:= S1   S2   S3   S4   S5   S6   S7   S8   S9   S10  S11
        S12  S13  S14  S15  S16  S17  S18  S19  S20  S21  S22
        S23  S24  S25  S26  S27  S28  S29  S30;
```

```
set C:= C1	C2	C3	C4;

set PR:= PR1	PR2	PR3	PR4	PR5	PR6	PR7	PR8	PR9	PR10	PR11
	PR12	PR13	PR14	PR15	PR16	PR17	PR18	PR19	PR20	PR21	PR22
	PR23	PR24	PR25	PR26	PR27	PR28	PR29	PR30	PR31	PR32	PR33
	PR34	PR35	PR36	PR37	PR38	PR39	PR40	PR41	PR42	PR43	PR44
	PR45	PR46	PR47	PR48	PR49	PR50	PR51	PR52	PR53	PR54	PR55
	PR56	PR57	PR58	PR59	PR60	PR61	PR62	PR63	PR64	PR65	PR66
	PR67	PR68	PR69	PR70	PR71	PR72	PR73	PR74	PR75	PR76	PR77
	PR78	PR79	PR80	PR81	PR82	PR83	PR84	PR85	PR86	PR87	PR88
	PR89	PR90	PR91	PR92	PR93	PR94	PR95	PR96	PR97	PR98	PR99
	PR100;

set T:= TR1	TR2	TR3	TR4	TR5	TR6	TR7	TR8	TR9	TR10	TR11
	TR12	TR13	TR14	TR15	TR16	TR17	TR18	TR19	TR20	TR21	TR22
	TR23	TR24	TR25	TR26	TR27	TR28	TR29	TR30	TR31	TR32	TR33
	TR34	TR35	TR36	TR37	TR38	TR39	TR40	TR41	TR42	TR43	TR44
	TR45;

#Module2

set D := D1	D2	D3	D4	D5;

set TP:= TRP1 TRP2 TRP3 TRP4 TRP5 TRP6 TRP7 TRP8 TRP9 TRP10 TRP11
	TRP12 TRP13 TRP14 TRP15 TRP16 TRP17 TRP18 TRP19 TRP20 TRP21 TRP22
	TRP23 TRP24 TRP25 TRP26 TRP27 TRP28 TRP29 TRP30 TRP31 TRP32 TRP33
	TRP34 TRP35;

#Parameters

#Module1

set	dem["PR1"] :=	S6	;
set	dem["PR2"] :=	S9	;
set	dem["PR3"] :=	S13	;
set	dem["PR4"] :=	S14	;
set	dem["PR5"] :=	S14	;
set	dem["PR6"] :=	S26	;
set	dem["PR7"] :=	S14	;
set	dem["PR8"] :=	S22	;
set	dem["PR9"] :=	S22	;
set	dem["PR10"] :=	S10	;
set	dem["PR11"] :=	S4	;
set	dem["PR12"] :=	S6	;
set	dem["PR13"] :=	S20	;
set	dem["PR14"] :=	S26	;
set	dem["PR15"] :=	S15	;
set	dem["PR16"] :=	S12	;
set	dem["PR17"] :=	S24	;
set	dem["PR18"] :=	S15	;
set	dem["PR19"] :=	S7	;
set	dem["PR20"] :=	S10	;
set	dem["PR21"] :=	S16	;
set	dem["PR22"] :=	S2	;
set	dem["PR23"] :=	S24	;
set	dem["PR24"] :=	S6	;
```

```
set dem["PR25"] := S11 ;
set dem["PR26"] := S7 ;
set dem["PR27"] := S20 ;
set dem["PR28"] := S3 ;
set dem["PR29"] := S30 ;
set dem["PR30"] := S1 ;
set dem["PR31"] := S11 ;
set dem["PR32"] := S3 ;
set dem["PR33"] := S9 ;
set dem["PR34"] := S23 ;
set dem["PR35"] := S14 ;
set dem["PR36"] := S8 ;
set dem["PR37"] := S23 ;
set dem["PR38"] := S23 ;
set dem["PR39"] := S28 ;
set dem["PR40"] := S1 ;
set dem["PR41"] := S25 ;
set dem["PR42"] := S1 ;
set dem["PR43"] := S6 ;
set dem["PR44"] := S30 ;
set dem["PR45"] := S9 ;
set dem["PR46"] := S27 ;
set dem["PR47"] := S26 ;
set dem["PR48"] := S8 ;
set dem["PR49"] := S20 ;
set dem["PR50"] := S4 ;
set dem["PR51"] := S15 ;
set dem["PR52"] := S28 ;
set dem["PR53"] := S17 ;
set dem["PR54"] := S7 ;
set dem["PR55"] := S21 ;
set dem["PR56"] := S11 ;
set dem["PR57"] := S16 ;
set dem["PR58"] := S30 ;
set dem["PR59"] := S3 ;
set dem["PR60"] := S20 ;
set dem["PR61"] := S16 ;
set dem["PR62"] := S9 ;
set dem["PR63"] := S21 ;
set dem["PR64"] := S28 ;
set dem["PR65"] := S10 ;
set dem["PR66"] := S9 ;
set dem["PR67"] := S25 ;
set dem["PR68"] := S19 ;
set dem["PR69"] := S14 ;
set dem["PR70"] := S29 ;
set dem["PR71"] := S19 ;
set dem["PR72"] := S17 ;
set dem["PR73"] := S3 ;
set dem["PR74"] := S22 ;
set dem["PR75"] := S9 ;
set dem["PR76"] := S28 ;
set dem["PR77"] := S7 ;
set dem["PR78"] := S3 ;
set dem["PR79"] := S25 ;
set dem["PR80"] := S11 ;
set dem["PR81"] := S5 ;
set dem["PR82"] := S22 ;
set dem["PR83"] := S11 ;
set dem["PR84"] := S24 ;
```

```
set dem["PR85"] :=   S3  ;
set dem["PR86"] :=   S29 ;
set dem["PR87"] :=   S18 ;
set dem["PR88"] :=   S25 ;
set dem["PR89"] :=   S4  ;
set dem["PR90"] :=   S16 ;
set dem["PR91"] :=   S24 ;
set dem["PR92"] :=   S18 ;
set dem["PR93"] :=   S20 ;
set dem["PR94"] :=   S13 ;
set dem["PR95"] :=   S21 ;
set dem["PR96"] :=   S29 ;
set dem["PR97"] :=   S7  ;
set dem["PR98"] :=   S11 ;
set dem["PR99"] :=   S30 ;
set dem["PR100"] :=  S27 ;
set TL["TR1"] := S1  ;
set TL["TR2"] := S1  ;
set TL["TR3"] := S2  ;
set TL["TR4"] := S2  ;
set TL["TR5"] := S3  ;
set TL["TR6"] := S3  ;
set TL["TR7"] := S4  ;
set TL["TR8"] := S4  ;
set TL["TR9"] := S5  ;
set TL["TR10"] :=S5  ;
set TL["TR11"] :=S6  ;
set TL["TR12"] :=S6  ;
set TL["TR13"] :=S7  ;
set TL["TR14"] :=S7  ;
set TL["TR15"] :=S8  ;
set TL["TR16"] :=S9  ;
set TL["TR17"] :=S9  ;
set TL["TR18"] :=S10 ;
set TL["TR19"] :=    S11 ;
set TL["TR20"] :=    S11 ;
set TL["TR21"] :=    S12 ;
set TL["TR22"] :=    S13 ;
set TL["TR23"] :=    S14 ;
set TL["TR24"] :=    S14 ;
set TL["TR25"] :=    S15 ;
set TL["TR26"] :=    S15 ;
set TL["TR27"] :=    S16 ;
set TL["TR28"] :=    S17 ;
set TL["TR29"] :=    S18 ;
set TL["TR30"] :=    S19 ;
set TL["TR31"] :=    S20 ;
set TL["TR32"] :=    S21 ;
set TL["TR33"] :=    S22 ;
set TL["TR34"] :=    S23 ;
set TL["TR35"] :=    S24 ;
set TL["TR36"] :=    S24 ;
set TL["TR37"] :=    S25 ;
set TL["TR38"] :=    S26 ;
set TL["TR39"] :=    S27 ;
set TL["TR40"] :=    S28 ;
set TL["TR41"] :=    S29 ;
set TL["TR42"] :=    S29 ;
set TL["TR43"] :=    S29 ;
set TL["TR44"] :=    S30 ;
```

```
set	TL["TR45"] :=S30	;

set	SL["S1"] :=	TR1	TR2	;
set	SL["S2"] :=	TR3	TR4	;
set	SL["S3"] :=	TR5	TR6	;
set	SL["S4"] :=	TR7	TR8	;
set	SL["S5"] :=	TR9	TR10	;
set	SL["S6"] :=	TR11	TR12	;
set	SL["S7"] :=	TR13	TR14	;
set	SL["S8"] :=	TR15		;
set	SL["S9"] :=	TR16	TR17	;
set	SL["S10"] :=	TR18		;
set	SL["S11"] :=	TR19	TR20	;
set	SL["S12"] :=	TR21		;
set	SL["S13"] :=	TR22		;
set	SL["S14"] :=	TR23	TR24	;
set	SL["S15"] :=	TR25	TR26	;
set	SL["S16"] :=	TR27		;
set	SL["S17"] :=	TR28		;
set	SL["S18"] :=	TR29		;
set	SL["S19"] :=	TR30		;
set	SL["S20"] :=	TR31		;
set	SL["S21"] :=	TR32		;
set	SL["S22"] :=	TR33		;
set	SL["S23"] :=	TR34		;
set	SL["S24"] :=	TR35	TR36	;
set	SL["S25"] :=	TR37		;
set	SL["S26"] :=	TR38		;
set	SL["S27"] :=	TR39		;
set	SL["S28"] :=	TR40		;
set	SL["S29"] :=TR41 TR42 TR43;
set	SL["S30"] :=	TR44	TR45	;

param q:=
PR1	0.40
PR2	0.09
PR3	0.07
PR4	0.01
PR5	0.05
PR6	0.25
PR7	0.36
PR8	0.17
PR9	0.06
PR10	0.17
PR11	0.23
PR12	0.41
PR13	0.28
PR14	0.10
PR15	0.15
PR16	0.42
PR17	0.36
PR18	0.48
PR19	0.49
PR20	0.13
PR21	0.15
PR22	0.48
PR23	0.21
PR24	0.35
PR25	0.11
PR26	0.39
```

PR27 0.00

PR28 0.13

PR29 0.10

PR30 0.28

PR31 0.06

PR32 0.31

PR33 0.37

PR34 0.12

PR35 0.46

PR36 0.32

PR37 0.22

PR38 0.49

PR39 0.00

PR40 0.40

PR41 0.18

PR42 0.17

PR43 0.07

PR44 0.35

PR45 0.31

PR46 0.10

PR47 0.49

PR48 0.34

PR49 0.01

PR50 0.00

PR51 0.31

PR52 0.50

PR53 0.40

PR54 0.14

PR55 0.11

PR56 0.24

PR57 0.20

PR58 0.45

PR59 0.47

PR60 0.40

PR61 0.01

PR62 0.12

PR63 0.28

PR64 0.03

PR65 0.45

PR66 0.06

PR67 0.06

PR68 0.16

PR69 0.39

PR70 0.36

PR71 0.40

PR72 0.35

PR73 0.34

PR74 0.07

PR75 0.13

PR76 0.29

PR77 0.23

PR78 0.21

PR79 0.24

PR80 0.09

PR81 0.32

PR82 0.46

PR83 0.04

PR84 0.35

PR85 0.39

PR86 0.46

PR87 0.05

PR88 0.26

PR89 0.18

PR90 0.01

PR91 0.31

PR92 0.25

PR93 0.01

PR94 0.08

PR95 0.38

PR96 0.30

PR97 0.16

PR98 0.09

PR99 0.41

PR100 0.24;

param cst: C1 C2 C3 C4:=

S1	597.1620962	252.9461093	2008.164414	75.49158562
S2	588.7135171	272.7088828	1989.338723	55.4657387

S3	789.9594495	11.75213764	2269.923157	339.0306011
S4	790.1712238	11.93721398	2270.075006	339.1567507
S5	307.6915785	1078.06985	1484.807443	867.5190457
S6	726.3614207	87.62839466	2177.056064	243.138152
S7	769.5848169	12.24022177	2246.513847	315.9002088
S8	619.6675189	215.7180162	2044.753688	112.6990671
S9	75.59317425	738.9662935	1614.482094	500.3375289
S10	792.8828874	16.34289727	2274.81377	344.2863317
S11	1623.914368	2258.471538	0	1935.250612
S12	23.30128017	774.8455439	1642.546348	565.7725154
S13	41.73855026	742.7226944	1664.639662	535.6301569
S14	74.36354741	747.8023006	1605.597606	507.5410197
S15	426.810337	420.4580457	1840.807071	134.7207336
S16	587.0244201	352.6909771	1921.726141	47.04263447
S17	35.77607549	754.8115447	1659.576183	548.7748736
S18	31.51733934	752.8248008	1655.105963	543.6557821
S19	33.77401336	754.4684722	1657.685186	547.2723974
S20	150.9261333	917.7768303	1480.787347	673.9184573
S21	16.64964803	773.2452117	1638.65565	561.5880907
S22	578.5012773	359.2868077	1913.376285	46.15882131
S23	41.47329808	741.3555829	1663.543421	533.179004
S24	555.9220566	385.8378578	1883.880683	61.64203185
S25	18.39051116	766.8714387	1642.169393	555.0922292
S26	16.43962751	763.5162414	1639.368131	549.0957306
S27	27.19563553	752.0181899	1640.145781	534.0755631
S28	20.26011281	763.2933618	1626.62842	541.6605925
S29	51.9515964	746.3627944	1675.436332	546.5193865
S30	35.20742193	754.5078683	1659.069432	548.0938858

;

#Module2

```
set   demP[ "PR1"  ] :=   D2   ;      set   demP[ "PR30"] :=   D5   ;
set   demP[ "PR2"  ] :=   D1   ;      set   demP[ "PR31"] :=   D1   ;
set   demP[ "PR3"  ] :=   D1   ;      set   demP[ "PR32"] :=   D1   ;
set   demP[ "PR4"  ] :=   D1   ;      set   demP[ "PR33"] :=   D3   ;
set   demP[ "PR5"  ] :=   D5   ;      set   demP[ "PR34"] :=   D4   ;
set   demP[ "PR6"  ] :=   D5   ;      set   demP[ "PR35"] :=   D3   ;
set   demP[ "PR7"  ] :=   D1   ;      set   demP[ "PR36"] :=   D1   ;
set   demP[ "PR8"  ] :=   D2   ;      set   demP[ "PR37"] :=   D2   ;
set   demP[ "PR9"  ] :=   D2   ;      set   demP[ "PR38"] :=   D3   ;
set   demP[ "PR10"] :=   D4   ;      set   demP[ "PR39"] :=   D5   ;
set   demP[ "PR11"] :=   D4   ;      set   demP[ "PR40"] :=   D3   ;
set   demP[ "PR12"] :=   D5   ;      set   demP[ "PR41"] :=   D3   ;
set   demP[ "PR13"] :=   D5   ;      set   demP[ "PR42"] :=   D4   ;
set   demP[ "PR14"] :=   D1   ;      set   demP[ "PR43"] :=   D3   ;
set   demP[ "PR15"] :=   D4   ;      set   demP[ "PR44"] :=   D1   ;
set   demP[ "PR16"] :=   D1   ;      set   demP[ "PR45"] :=   D1   ;
set   demP[ "PR17"] :=   D5   ;      set   demP[ "PR46"] :=   D5   ;
set   demP[ "PR18"] :=   D1   ;      set   demP[ "PR47"] :=   D3   ;
set   demP[ "PR19"] :=   D1   ;      set   demP[ "PR48"] :=   D5   ;
set   demP[ "PR20"] :=   D2   ;      set   demP[ "PR49"] :=   D1   ;
set   demP[ "PR21"] :=   D4   ;      set   demP[ "PR50"] :=   D3   ;
set   demP[ "PR22"] :=   D4   ;      set   demP[ "PR51"] :=   D5   ;
set   demP[ "PR23"] :=   D5   ;      set   demP[ "PR52"] :=   D1   ;
set   demP[ "PR24"] :=   D5   ;      set   demP[ "PR53"] :=   D4   ;
set   demP[ "PR25"] :=   D2   ;      set   demP[ "PR54"] :=   D1   ;
set   demP[ "PR26"] :=   D3   ;      set   demP[ "PR55"] :=   D4   ;
set   demP[ "PR27"] :=   D3   ;      set   demP[ "PR56"] :=   D4   ;
set   demP[ "PR28"] :=   D5   ;      set   demP[ "PR57"] :=   D5   ;
set   demP[ "PR29"] :=   D5   ;      set   demP[ "PR58"] :=   D4   ;
```

```
set    demP[ "PR59"] :=   D2   ;        set    demP[ "PR80"] :=   D2   ;
set    demP[ "PR60"] :=   D4   ;        set    demP[ "PR81"] :=   D5   ;
set    demP[ "PR61"] :=   D2   ;        set    demP[ "PR82"] :=   D5   ;
set    demP[ "PR62"] :=   D4   ;        set    demP[ "PR83"] :=   D3   ;
set    demP[ "PR63"] :=   D4   ;        set    demP[ "PR84"] :=   D2   ;
set    demP[ "PR64"] :=   D5   ;        set    demP[ "PR85"] :=   D4   ;
set    demP[ "PR65"] :=   D1   ;        set    demP[ "PR86"] :=   D5   ;
set    demP[ "PR66"] :=   D5   ;        set    demP[ "PR87"] :=   D2   ;
set    demP[ "PR67"] :=   D2   ;        set    demP[ "PR88"] :=   D5   ;
set    demP[ "PR68"] :=   D2   ;        set    demP[ "PR89"] :=   D3   ;
set    demP[ "PR69"] :=   D1   ;        set    demP[ "PR90"] :=   D2   ;
set    demP[ "PR70"] :=   D2   ;        set    demP[ "PR91"] :=   D2   ;
set    demP[ "PR71"] :=   D1   ;        set    demP[ "PR92"] :=   D4   ;
set    demP[ "PR72"] :=   D3   ;        set    demP[ "PR93"] :=   D4   ;
set    demP[ "PR73"] :=   D4   ;        set    demP[ "PR94"] :=   D3   ;
set    demP[ "PR74"] :=   D1   ;        set    demP[ "PR95"] :=   D3   ;
set    demP[ "PR75"] :=   D2   ;        set    demP[ "PR96"] :=   D4   ;
set    demP[ "PR76"] :=   D4   ;        set    demP[ "PR97"] :=   D3   ;
set    demP[ "PR77"] :=   D2   ;        set    demP[ "PR98"] :=   D3   ;
set    demP[ "PR78"] :=   D4   ;        set    demP[ "PR99"] :=   D4   ;
set    demP[ "PR79"] :=   D5   ;        set    demP[ "PR100] :=   D4   ;


set    prD["D1"] :=  PR2   PR3   PR4   PR7   PR14  PR16  PR18  PR19  PR31
       PR32  PR36  PR44  PR45  PR49  PR52  PR54  PR65  PR69  PR71  PR74;

set    prD["D2"] :=  PR1   PR8   PR9   PR20  PR25  PR37  PR59  PR61  PR67
       PR68  PR70  PR75  PR77  PR80  PR84  PR87  PR90  PR91;

set    prD["D3"] :=  PR26  PR27  PR33  PR35  PR38  PR40  PR41  PR43  PR47
       PR50  PR72  PR83  PR89  PR94  PR95  PR97  PR98;
```

```
set  prD["D4"] :=  PR10  PR11  PR15  PR21  PR22  PR34  PR42  PR53  PR55
     PR56  PR58  PR60  PR62  PR63  PR73  PR76  PR78  PR85  PR92  PR93
     PR96  PR99  PR100;

set  prD["D5"] :=  PR5  PR6  PR12  PR13  PR17  PR23  PR24  PR28  PR29
     PR30  PR39  PR46  PR48  PR51  PR57  PR64  PR66  PR79  PR81  PR82
     PR86  PR88  ;

set  TLP["  TRP1  "] :=  C1  ;
set  TLP["  TRP2  "] :=  C1  ;
set  TLP["  TRP3  "] :=  C1  ;
set  TLP["  TRP4  "] :=  C1  ;
set  TLP["  TRP5  "] :=  C1  ;
set  TLP["  TRP6  "] :=  C1  ;
set  TLP["  TRP7  "] :=  C1  ;
set  TLP["  TRP8  "] :=  C1  ;
set  TLP["  TRP9  "] :=  C1  ;
set  TLP["  TRP10 "] :=  C2  ;
set  TLP["  TRP11 "] :=  C2  ;
set  TLP["  TRP12 "] :=  C2  ;
set  TLP["  TRP13 "] :=  C2  ;
set  TLP["  TRP14 "] :=  C2  ;
set  TLP["  TRP15 "] :=  C2  ;
set  TLP["  TRP16 "] :=  C2  ;
set  TLP["  TRP17 "] :=  C2  ;
set  TLP["  TRP18 "] :=  C2  ;
set  TLP["  TRP19 "] :=  C3  ;
set  TLP["  TRP20 "] :=  C3  ;
set  TLP["  TRP21 "] :=  C3  ;
set  TLP["  TRP22 "] :=  C3  ;
set  TLP["  TRP23 "] :=  C3  ;
set  TLP["  TRP24 "] :=  C3  ;
set  TLP["  TRP25 "] :=  C3  ;
set  TLP["  TRP26 "] :=  C3  ;
set  TLP["  TRP27 "] :=  C4  ;
set  TLP["  TRP28 "] :=  C4  ;
set  TLP["  TRP29 "] :=  C4  ;
set  TLP["  TRP30 "] :=  C4  ;
set  TLP["  TRP31 "] :=  C4  ;
set  TLP["  TRP32 "] :=  C4  ;
set  TLP["  TRP33 "] :=  C4  ;
set  TLP["  TRP34 "] :=  C4  ;
set  TLP["  TRP35 "] :=  C4  ;
```

```
set     SLP["C1"] :=  TRP1   TRP2   TRP3   TRP4   TRP5   TRP6   TRP7   TRP8   TRP9
        ;
set     SLP["C2"] :=  TRP10 TRP11 TRP12 TRP13 TRP14 TRP15 TRP16 TRP17 TRP18
        ;
set     SLP["C3"] :=  TRP19 TRP20 TRP21 TRP22 TRP23 TRP24 TRP25 TRP26
        ;
set     SLP["C4"] :=  TRP27 TRP28 TRP29 TRP30 TRP31 TRP32 TRP33 TRP34 TRP35
        ;


param cstP:D1 D2 D3 D4 D5:=
C1      789.974143    796.9210297   555.8827644   21.95095002   103.1889164
C2      11.97488531   59.72829641   385.7672308   760.4325319   732.1501676
C3      2270.269685   2301.170251   1883.931066   1629.409394   1605.007803
C4      339.4613726   378.2486128   61.55319953   539.3548557   484.1158248
;

end;
```

ii. MODEL S

Model S requires implementation on all the demand points. Here, we present the basic GUSEK model used for all the cases, with the example of demand point 1 and provide the data sets for rest of the demand points in subsections.

Basic GUSEK code (Demand point 1):

```
set S;
```

```
set Sprime;
param cst{i in S, j in S};
param demand{i in Sprime};
var x{i in S, j in S}, binary;
var a{i in Sprime},>=0;
minimize cost: sum{i in S, j in S} cst[i,j]*x[i,j];
s.t. C1{j in S}: sum{i in S} x[i,j] = 1;
s.t. C2{i in S}: sum{j in S} x[i,j] = 1;
s.t. C3{i in Sprime}: a[i] >=0;
s.t. C4{i in Sprime}: a[i] <=1-demand[i];
s.t. C5{i in Sprime,j in Sprime}: a[i] + demand[i] - a[j] - 1 + x[i,j] <=0;
solve;
display x,a;
data;
set S:= S2	S7	S8	S9	S10	S11	S12	S13	S14	S15	S19
	S20	S22	S26	S28	S30	T31	T32	T33	T34	T35	T36;
set Sprime:=S2		S7	S8	S9	S10	S11	S12	S13	S14	S15
	S19	S20	S22	S26	S28	S30	;
param cst:S2	S7	S8	S9	S10	S11	S12	S13	S14	S15	S19
	S20	S22	S26	S28	S30	T31	T32	T33	T34	T35	T36:=
S2	10000	260.493493	57.25282319	532.3452058	288.893476	1989.338723
	591.7372724	560.7324314	540.0311001	171.3219546	572.5640408
	708.7686443	92.85968259	576.0577218	570.1848943	573.2196348
	284.0829431	284.0829431	284.0829431	284.0829431	284.0829431
	284.0829431
S7	260.493493	10000	203.5244452	729.2078897	28.43524969	2246.513847
	766.0006292	733.8651428	738.0147071	408.854159	745.634496
	908.1274319	347.0594633	754.4919127	754.0607017	745.696772
	23.7628355	23.7628355	23.7628355	23.7628355	23.7628355
	23.7628355
S8	57.25282319	203.5244452	10000	567.5691179	231.9501071	2044.753688
	620.8186185	589.209801	575.6539856	216.5055406	601.1343173
	745.7912304	148.0452608	606.2024708	601.8599863	601.6259382
	227.1776921	227.1776921	227.1776921	227.1776921	227.1776921
	227.1776921
```

S9 532.3452058 729.2078897 567.5691179 10000 753.802043 1614.482094
93.67365386 83.53740445 9.291731156 365.6184061 87.61658119
179.2642444 514.5649714 74.06655944 56.37122736 89.5889954
750.5572656 750.5572656 750.5572656 750.5572656 750.5572656
750.5572656

S10 288.893476 28.43524969 231.9501071 753.802043 10000 2274.81377
788.8065136 756.7001407 762.6638798 436.699626 768.4211185
932.4989387 375.1405069 777.6549144 777.6338479 768.4378534
5.050708557 5.050708557 5.050708557 5.050708557 5.050708557
5.050708557

S11 1989.338723 2246.513847 2044.753688 1614.482094 2274.81377 10000
1642.546348 1664.639662 1605.597606 1840.807071 1657.685186
1480.787347 1913.376285 1639.368131 1626.62842 1659.069432
2270.269685 2270.269685 2270.269685 2270.269685 2270.269685
2270.269685

S12 591.7372724 766.0006292 620.8186185 93.67365386 788.8065136
1642.546348 10000 32.14935195 93.95722683 432.549403 20.39546494
165.4565662 585.1270996 19.95120594 37.71718322 20.5449826
786.0193532 786.0193532 786.0193532 786.0193532 786.0193532
786.0193532

S13 560.7324314 733.8651428 589.209801 83.53740445 756.7001407
1664.639662 32.14935195 10000 86.97337465 402.9439193 11.93839371
192.5477808 555.9008 25.51380445 39.61954892 12.49069595
753.9043685 753.9043685 753.9043685 753.9043685 753.9043685
753.9043685

S14 540.0311001 738.0147071 575.6539856 9.291731156 762.6638798
1605.597606 93.95722683 86.97337465 10000 372.8254104 89.89256557
170.7280672 521.2361589 74.87967999 56.24796353 91.89810458
759.4046838 759.4046838 759.4046838 759.4046838 759.4046838
759.4046838

S15 171.3219546 408.854159 216.5055406 365.6184061 436.699626
1840.807071 432.549403 402.9439193 372.8254104 10000 414.4435255
539.6464273 153.4445608 415.4660494 407.4834317 415.3521454
432.406046 432.406046 432.406046 432.406046 432.406046
432.406046

S19 572.5640408 745.634496 601.1343173 87.61658119 768.4211185
1657.685186 20.39546494 11.93839371 89.89256557 414.4435255 10000
183.2761914 567.3108212 19.31584066 37.34837984 2.018657841
765.637742 765.637742 765.637742 765.637742 765.637742
765.637742

S20 708.7686443 908.1274319 745.7912304 179.2642444 932.4989387
1480.787347 165.4565662 192.5477808 170.7280672 539.6464273

183.2761914 10000 684.2492053 167.3528992 160.5433013 184.2615234
929.3187763 929.3187763 929.3187763 929.3187763 929.3187763
929.3187763

S22 92.85968259 347.0594633 148.0452608 514.5649714 375.1405069
1913.376285 585.1270996 555.9008 521.2361589 153.4445608
567.3108212 684.2492053 10000 567.6828034 558.8980838 568.2674943
370.1942087 370.1942087 370.1942087 370.1942087 370.1942087
370.1942087

S26 576.0577218 754.4919127 606.2024708 74.06655944 777.6549144
1639.368131 19.95120594 25.51380445 74.87967999 415.4660494
19.31584066 167.3528992 567.6828034 10000 19.34580329 21.1144608
774.7791898 774.7791898 774.7791898 774.7791898 774.7791898
774.7791898

S28 570.1848943 754.0607017 601.8599863 56.37122736 777.6338479
1626.62842 37.71718322 39.61954892 56.24796353 407.4834317
37.34837984 160.5433013 558.8980838 19.34580329 10000 39.31531566
774.655285 774.655285 774.655285 774.655285 774.655285
774.655285

S30 573.2196348 745.696772 601.6259382 89.5889954 768.4378534
1659.069432 20.5449826 12.49069595 91.89810458 415.3521454
2.018657841 184.2615234 568.2674943 21.1144608 39.31531566 10000
765.6656044 765.6656044 765.6656044 765.6656044 765.6656044
765.6656044

T31 284.0829431 23.7628355 227.1776921 750.5572656 5.050708557
2270.269685 786.0193532 753.9043685 759.4046838 432.406046
765.637742 929.3187763 370.1942087 774.7791898 774.655285
765.6656044 0 0 0 0 0 0

T32 284.0829431 23.7628355 227.1776921 750.5572656 5.050708557
2270.269685 786.0193532 753.9043685 759.4046838 432.406046
765.637742 929.3187763 370.1942087 774.7791898 774.655285
765.6656044 0 0 0 0 0 0

T33 284.0829431 23.7628355 227.1776921 750.5572656 5.050708557
2270.269685 786.0193532 753.9043685 759.4046838 432.406046
765.637742 929.3187763 370.1942087 774.7791898 774.655285
765.6656044 0 0 0 0 0 0

T34 284.0829431 23.7628355 227.1776921 750.5572656 5.050708557
2270.269685 786.0193532 753.9043685 759.4046838 432.406046
765.637742 929.3187763 370.1942087 774.7791898 774.655285
765.6656044 0 0 0 0 0 0

T35 284.0829431 23.7628355 227.1776921 750.5572656 5.050708557
2270.269685 786.0193532 753.9043685 759.4046838 432.406046

```
        765.637742    929.3187763   370.1942087   774.7791898   774.655285
        765.6656044   0      0      0      0      0      0

T36     284.0829431   23.7628355    227.1776921   750.5572656   5.050708557
        2270.269685   786.0193532   753.9043685   759.4046838   432.406046
        765.637742    929.3187763   370.1942087   774.7791898   774.655285
        765.6656044   0      0      0      0      0      0;

param demand:=

S2      0.31

S7      0.63

S8      0.32

S9      0.4

S10     0.45

S11     0.06

S12     0.42

S13     0.08

S14     0.75

S15     0.48

S19     0.4

S20     0.01

S22     0.07

S26     0.1

S28     0.5

S30     0.35

;


end ;
```

Data for rest of the demand points are as follows:

Demand point 2

set S:= S3 S6 S7 S10 S11 S16 S18 S19 S22 S23 S24
S25 S29 T31 T32 T33 T34 T35 T36;

set Sprime:=S3 S6 S7 S10 S11 S16 S18 S19 S22 S23
S24 S25 S29;

param cst:S3 S6 S7 S10 S11 S16 S18 S19 S22 S23 S24
S25 S29 T31 T32 T33 T34 T35 T36:=

S3 10000 97.55929591 23.40931354 5.634278943 2269.923157 363.0162536
764.0258267 765.6437782 369.7135261 752.5558264 396.4598063
778.090907 757.4534532 54.39963984 54.39963984 54.39963984
54.39963984 54.39963984 54.39963984

S6 97.55929591 10000 75.5633219 103.0706601 2177.056064 265.5689056
702.3593053 704.5293461 272.3843852 690.966039 299.4872006
715.9467632 698.1661301 144.3644981 144.3644981 144.3644981
144.3644981 144.3644981 144.3644981

S7 23.40931354 75.5633219 10000 28.43524969 2246.513847 340.4766177
743.9298125 745.634496 347.0594633 732.463516 373.5979205
757.9308039 737.7250324 70.35293231 70.35293231 70.35293231
70.35293231 70.35293231 70.35293231

S10 5.634278943 103.0706601 28.43524969 10000 2274.81377 368.4694529
766.8378909 768.4211185 375.1405069 755.3672399 401.8283414
780.9277424 760.1211182 49.38192727 49.38192727 49.38192727
49.38192727 49.38192727 49.38192727

S11 2269.923157 2177.056064 2246.513847 2274.81377 10000 1921.726141
1655.105963 1657.685186 1913.376285 1663.543421 1883.880683
1642.169393 1675.436332 2301.170251 2301.170251 2301.170251
2301.170251 2301.170251 2301.170251

S16 363.0162536 265.5689056 340.4766177 368.4694529 1921.726141 10000
571.7016909 575.6031281 9.392282905 561.5678294 39.27968727
582.497711 576.0952543 406.0036241 406.0036241 406.0036241
406.0036241 406.0036241 406.0036241

S18 764.0258267 702.3593053 743.9298125 766.8378909 1655.105963
571.7016909 10000 5.656531424 563.3779514 11.47082983 541.8244603

14.61183632 23.26890527 769.8071147 769.8071147 769.8071147
769.8071147 769.8071147 769.8071147

S19 765.6437782 704.5293461 745.634496 768.4211185 1657.685186
575.6031281 5.656531424 10000 567.3108212 14.09849003 545.909747
15.61797409 18.82366337 771.0382561 771.0382561 771.0382561
771.0382561 771.0382561 771.0382561

S22 369.7135261 272.3843852 347.0594633 375.1405069 1913.376285
9.392282905 563.3779514 567.3108212 10000 553.2864116 30.14758835
574.1000284 567.9527721 412.102085 412.102085 412.102085
412.102085 412.102085 412.102085

S23 752.5558264 690.966039 732.463516 755.3672399 1663.543421
561.5678294 11.47082983 14.09849003 553.2864116 10000 531.9517934
25.85727948 22.55484897 758.356394 758.356394 758.356394
758.356394 758.356394 758.356394

S24 396.4598063 299.4872006 373.5979205 401.8283414 1883.880683
39.27968727 541.8244603 545.909747 30.14758835 531.9517934 10000
552.1669211 547.2812674 437.5450111 437.5450111 437.5450111
437.5450111 437.5450111 437.5450111

S25 778.090907 715.9467632 757.9308039 780.9277424 1642.169393
582.497711 14.61183632 15.61797409 574.1000284 25.85727948
552.1669211 10000 33.56212767 784.1148737 784.1148737 784.1148737
784.1148737 784.1148737 784.1148737

S29 757.4534532 698.1661301 737.7250324 760.1211182 1675.436332
576.0952543 23.26890527 18.82366337 567.9527721 22.55484897
547.2812674 33.56212767 10000 761.6643319 761.6643319 761.6643319
761.6643319 761.6643319 761.6643319

T31 54.39963984 144.3644981 70.35293231 49.38192727 2301.170251
406.0036241 769.8071147 771.0382561 412.102085 758.356394
437.5450111 784.1148737 761.6643319 0 0 0 0 0
0

T32 54.39963984 144.3644981 70.35293231 49.38192727 2301.170251
406.0036241 769.8071147 771.0382561 412.102085 758.356394
437.5450111 784.1148737 761.6643319 0 0 0 0 0
0

T33 54.39963984 144.3644981 70.35293231 49.38192727 2301.170251
406.0036241 769.8071147 771.0382561 412.102085 758.356394
437.5450111 784.1148737 761.6643319 0 0 0 0 0
0

T34 54.39963984 144.3644981 70.35293231 49.38192727 2301.170251
406.0036241 769.8071147 771.0382561 412.102085 758.356394

437.5450111 784.1148737 761.6643319 0 0 0 0 0
0

T35 54.39963984 144.3644981 70.35293231 49.38192727 2301.170251
406.0036241 769.8071147 771.0382561 412.102085 758.356394
437.5450111 784.1148737 761.6643319 0 0 0 0 0
0

T36 54.39963984 144.3644981 70.35293231 49.38192727 2301.170251
406.0036241 769.8071147 771.0382561 412.102085 758.356394
437.5450111 784.1148737 761.6643319 0 0 0 0 0
0

;

param demand:=

S3 0.47

S6 0.4

S7 0.23

S10 0.26

S11 0.2

S16 0.02

S18 0.05

S19 0.16

S22 0.23

S23 0.22

S24 0.66

S25 0.06

S29 0.36

;

Demand point 3

set S:= S1 S4 S6 S7 S9 S12 S13 S14 S17 S20 S21
S23 S25 S26 T31 T32 T33 T34 T35 T36;

set Sprime:=S1 S4 S6 S7 S9 S12 S13 S14 S17 S20
S21 S23 S25 S26;

param cst:S1 S4 S6 S7 S9 S12 S13 S14 S17 S20 S21
S23 S25 S26 T31 T32 T33 T34 T35 T36:=

S1 10000 264.093266 168.9709538 240.7451182 542.4252109 599.4639162
568.2005307 550.2756626 581.2470309 719.6668055 596.0131797
566.0439645 589.4517056 584.1826184 135.4246631 135.4246631
135.4246631 135.4246631 135.4246631 135.4246631

S4 264.093266 10000 97.65550177 23.56180609 750.6903744 786.2383906
754.1219724 759.5348911 766.1861178 929.4641695 784.6705972
752.7691313 778.3038718 774.9823376 396.5048053 396.5048053
396.5048053 396.5048053 396.5048053 396.5048053

S6 168.9709538 97.65550177 10000 75.5633219 680.8276698 724.7250869
692.6292501 689.3625829 705.1724902 860.0791955 722.441642
690.966039 715.9467632 711.8702395 299.4196278 299.4196278
299.4196278 299.4196278 299.4196278 299.4196278

S7 240.7451182 23.56180609 75.5633219 10000 729.2078897 766.0006292
733.8651428 738.0147071 746.0121333 908.1274319 764.3213788
732.463516 757.9308039 754.4919127 373.5272788 373.5272788
373.5272788 373.5272788 373.5272788 373.5272788

S9 542.4252109 750.6903744 680.8276698 729.2078897 10000 93.67365386
83.53740445 9.291731156 90.66175291 179.2642444 86.49691394
80.40293634 82.42431827 74.06655944 490.5472217 490.5472217
490.5472217 490.5472217 490.5472217 490.5472217

S12 599.4639162 786.2383906 724.7250869 766.0006292 93.67365386 10000
32.14935195 93.95722683 20.42084347 165.4565662 7.38046507
33.77639209 11.8348401 19.95120594 563.3009231 563.3009231
563.3009231 563.3009231 563.3009231 563.3009231

S13 568.2005307 754.1219724 692.6292501 733.8651428 83.53740445
32.14935195 10000 86.97337465 13.14471672 192.5477808 31.05956803
3.316088619 25.2177131 25.51380445 534.5991633 534.5991633
534.5991633 534.5991633 534.5991633 534.5991633

S14 550.2756626 759.5348911 689.3625829 738.0147071 9.291731156
93.95722683 86.97337465 10000 92.96006923 170.7280672 86.64133481

83.96666624 83.15673797 74.87967999 496.9835821 496.9835821
496.9835821 496.9835821 496.9835821 496.9835821

S17 581.2470309 766.1861178 705.1724902 746.0121333 90.66175291
20.42084347 13.14471672 92.96006923 10000 184.5298631 21.49881833
15.75892894 17.41785182 21.93751304 547.6588755 547.6588755
547.6588755 547.6588755 547.6588755 547.6588755

S20 719.6668055 929.4641695 860.0791955 908.1274319 179.2642444
165.4565662 192.5477808 170.7280672 184.5298631 10000 163.0313786
192.3990076 167.8160535 167.3528992 658.4750482 658.4750482
658.4750482 658.4750482 658.4750482 658.4750482

S21 596.0131797 784.6705972 722.441642 764.3213788 86.49691394
7.38046507 31.05956803 86.64133481 21.49881833 163.0313786 10000
32.00064935 6.563872698 13.4268764 558.4768636 558.4768636
558.4768636 558.4768636 558.4768636 558.4768636

S23 566.0439645 752.7691313 690.966039 732.463516 80.40293634
33.77639209 3.316088619 83.96666624 15.75892894 192.3990076
32.00064935 10000 25.85727948 25.06342342 531.9069824 531.9069824
531.9069824 531.9069824 531.9069824 531.9069824

S25 589.4517056 778.3038718 715.9467632 757.9308039 82.42431827
11.8348401 25.2177131 83.15673797 17.41785182 167.8160535
6.563872698 25.85727948 10000 8.359960417 552.1247272 552.1247272
552.1247272 552.1247272 552.1247272 552.1247272

S26 584.1826184 774.9823376 711.8702395 754.4919127 74.06655944
19.95120594 25.51380445 74.87967999 21.93751304 167.3528992
13.4268764 25.06342342 8.359960417 10000 545.5154609 545.5154609
545.5154609 545.5154609 545.5154609 545.5154609

T31 135.4246631 396.5048053 299.4196278 373.5272788 490.5472217
563.3009231 534.5991633 496.9835821 547.6588755 658.4750482
558.4768636 531.9069824 552.1247272 545.5154609 0 0 0
0 0 0

T32 135.4246631 396.5048053 299.4196278 373.5272788 490.5472217
563.3009231 534.5991633 496.9835821 547.6588755 658.4750482
558.4768636 531.9069824 552.1247272 545.5154609 0 0 0
0 0 0

T33 135.4246631 396.5048053 299.4196278 373.5272788 490.5472217
563.3009231 534.5991633 496.9835821 547.6588755 658.4750482
558.4768636 531.9069824 552.1247272 545.5154609 0 0 0
0 0 0

T34 135.4246631 396.5048053 299.4196278 373.5272788 490.5472217
563.3009231 534.5991633 496.9835821 547.6588755 658.4750482

558.4768636 531.9069824 552.1247272 545.5154609 0 0 0
0 0 0

T35 135.4246631 396.5048053 299.4196278 373.5272788 490.5472217
563.3009231 534.5991633 496.9835821 547.6588755 658.4750482
558.4768636 531.9069824 552.1247272 545.5154609 0 0 0
0 0 0

T36 135.4246631 396.5048053 299.4196278 373.5272788 490.5472217
563.3009231 534.5991633 496.9835821 547.6588755 658.4750482
558.4768636 531.9069824 552.1247272 545.5154609 0 0 0
0 0 0

;

param demand:=

S1 0.4

S4 0.33

S6 0.07

S7 0.55

S9 0.37

S12 0.13

S13 0.08

S14 0.46

S17 0.35

S20 0.15

S21 0.38

S23 0.49

S25 0.18

S26 0.49

;

Demand point 4

set S:= S1 S2 S3 S4 S9 S10 S11 S15 S16 S17 S18
S20 S21 S23 S27 S28 S29 S30 T31 T32 T33 T34
T35 T36;

set Sprime:=S1 S2 S3 S4 S9 S10 S11 S15 S16 S17
S18 S20 S21 S23 S27 S28 S29 S30;

param cst:S1 S2 S3 S4 S9 S10 S11 S15 S16 S17 S18
S20 S21 S23 S27 S28 S29 S30 T31 T32 T33 T34
T35 T36:=

S1 10000 20.19683283 263.9622572 264.093266 542.4252109 269.1642984
2008.164414 184.9494123 108.3686556 581.2470309 577.0131043
719.6668055 596.0131797 566.0439645 570.0252538 578.8996335
577.0406792 580.6712365 576.3819004 576.3819004 576.3819004
576.3819004 576.3819004 576.3819004

S2 20.19683283 10000 283.6576358 283.7856835 532.3452058 288.893476
1989.338723 171.3219546 89.01924603 573.8246625 569.3455881
708.7686443 588.0834128 558.4931287 561.6470748 570.1848943
570.1385166 573.2196348 567.7211237 567.7211237 567.7211237
567.7211237 567.7211237 567.7211237

S3 263.9622572 283.6576358 10000 0.222479495 750.4850624 5.634278943
2269.923157 432.1242127 363.0162536 765.9721356 764.0258267
929.2575191 784.457501 752.5558264 763.3221838 774.628939
757.4534532 765.6734545 771.7642986 771.7642986 771.7642986
771.7642986 771.7642986 771.7642986

S4 264.093266 283.7856835 0.222479495 10000 750.6903744 5.587545983
2270.075006 432.2925327 363.1204481 766.1861178 764.2391201
929.4641695 784.6705972 752.7691313 763.5334704 774.8395257
757.6685147 765.8873542 771.9749719 771.9749719 771.9749719
771.9749719 771.9749719 771.9749719

S9 542.4252109 532.3452058 750.4850624 750.6903744 10000 753.802043
1614.482094 365.6184061 523.3559622 90.66175291 81.97216812
179.2642444 86.49691394 80.40293634 59.439304 56.37122736
102.8194348 89.5889954 55.96620948 55.96620948 55.96620948
55.96620948 55.96620948 55.96620948

S10 269.1642984 288.893476 5.634278943 5.587545983 753.802043 10000
2274.81377 436.699626 368.4694529 768.7299066 766.8378909
932.4989387 787.2842477 755.3672399 766.2800846 777.6338479
760.1211182 768.4378534 774.7635064 774.7635064 774.7635064
774.7635064 774.7635064 774.7635064

S11 2008.164414 1989.338723 2269.923157 2270.075006 1614.482094
2274.81377 10000 1840.807071 1921.726141 1659.576183 1655.105963
1480.787347 1638.65565 1663.543421 1640.145781 1626.62842
1675.436332 1659.069432 1629.409394 1629.409394 1629.409394
1629.409394 1629.409394 1629.409394

S15 184.9494123 171.3219546 432.1242127 432.2925327 365.6184061
436.699626 1840.807071 10000 161.4466632 416.0725878 410.6298421
539.6464273 428.13073 400.3847917 400.2353163 407.4834317
414.6844702 415.3521454 405.2297312 405.2297312 405.2297312
405.2297312 405.2297312 405.2297312

S16 108.3686556 89.01924603 363.0162536 363.1204481 523.3559622
368.4694529 1921.726141 161.4466632 10000 577.280826 571.7016909
693.3171572 588.9158826 561.5678294 560.6934964 567.4566342
576.0952543 576.5460057 565.2945161 565.2945161 565.2945161
565.2945161 565.2945161 565.2945161

S17 581.2470309 573.8246625 765.9721356 766.1861178 90.66175291
768.7299066 1659.576183 416.0725878 577.280826 10000 8.689593852
184.5298631 21.49881833 15.75892894 31.60339877 40.26826505
16.3178498 1.074249151 38.76212482 38.76212482 38.76212482
38.76212482 38.76212482 38.76212482

S18 577.0131043 569.3455881 764.0258267 764.2391201 81.97216812
766.8378909 1655.105963 410.6298421 571.7016909 8.689593852 10000
182.0981688 20.57134177 11.47082983 23.01009017 32.53886906
23.26890527 7.616939414 30.76886627 30.76886627 30.76886627
30.76886627 30.76886627 30.76886627

S20 719.6668055 708.7686443 929.2575191 929.4641695 179.2642444
932.4989387 1480.787347 539.6464273 693.3171572 184.5298631
182.0981688 10000 163.0313786 192.3990076 173.6458591 160.5433013
199.1825794 184.2615234 163.5556597 163.5556597 163.5556597
163.5556597 163.5556597 163.5556597

S21 596.0131797 588.0834128 784.457501 784.6705972 86.49691394
787.2842477 1638.65565 428.13073 588.9158826 21.49881833
20.57134177 163.0313786 10000 32.00064935 29.73208022 30.39337347
36.79903044 21.24747584 30.53230462 30.53230462 30.53230462
30.53230462 30.53230462 30.53230462

S23 566.0439645 558.4931287 752.5558264 752.7691313 80.40293634
755.3672399 1663.543421 400.3847917 561.5678294 15.75892894
11.47082983 192.3990076 32.00064935 10000 25.36322407 37.78801993
22.55484897 14.98430879 35.36619278 35.36619278 35.36619278
35.36619278 35.36619278 35.36619278

S27 570.0252538 561.6470748 763.3221838 763.5334704 59.439304
766.2800846 1640.145781 400.2353163 560.6934964 31.60339877

23.01009017 173.6458591 29.73208022 25.36322407 10000 13.61929571
45.58625191 30.54671408 10.74807758 10.74807758 10.74807758
10.74807758 10.74807758 10.74807758

S28 578.8996335 570.1848943 774.628939 774.8395257 56.37122736
777.6338479 1626.62842 407.4834317 567.4566342 40.26826505
32.53886906 160.5433013 30.39337347 37.78801993 13.61929571 10000
55.80694845 39.31531566 3.012712864 3.012712864 3.012712864
3.012712864 3.012712864 3.012712864

S29 577.0406792 570.1385166 757.4534532 757.6685147 102.8194348
760.1211182 1675.436332 414.6844702 576.0952543 16.3178498
23.26890527 199.1825794 36.79903044 22.55484897 45.58625191
55.80694845 10000 17.05307871 54.0088875 54.0088875 54.0088875
54.0088875 54.0088875 54.0088875

S30 580.6712365 573.2196348 765.6734545 765.8873542 89.5889954
768.4378534 1659.069432 415.3521454 576.5460057 1.074249151
7.616939414 184.2615234 21.24747584 14.98430879 30.54671408
39.31531566 17.05307871 10000 37.77826533 37.77826533 37.77826533
37.77826533 37.77826533 37.77826533

T31 576.3819004 567.7211237 771.7642986 771.9749719 55.96620948
774.7635064 1629.409394 405.2297312 565.2945161 38.76212482
30.76886627 163.5556597 30.53230462 35.36619278 10.74807758
3.012712864 54.0088875 37.77826533 0 0 0 0 0
0

T32 576.3819004 567.7211237 771.7642986 771.9749719 55.96620948
774.7635064 1629.409394 405.2297312 565.2945161 38.76212482
30.76886627 163.5556597 30.53230462 35.36619278 10.74807758
3.012712864 54.0088875 37.77826533 0 0 0 0 0
0

T33 576.3819004 567.7211237 771.7642986 771.9749719 55.96620948
774.7635064 1629.409394 405.2297312 565.2945161 38.76212482
30.76886627 163.5556597 30.53230462 35.36619278 10.74807758
3.012712864 54.0088875 37.77826533 0 0 0 0 0
0

T34 576.3819004 567.7211237 771.7642986 771.9749719 55.96620948
774.7635064 1629.409394 405.2297312 565.2945161 38.76212482
30.76886627 163.5556597 30.53230462 35.36619278 10.74807758
3.012712864 54.0088875 37.77826533 0 0 0 0 0
0

T35 576.3819004 567.7211237 771.7642986 771.9749719 55.96620948
774.7635064 1629.409394 405.2297312 565.2945161 38.76212482
30.76886627 163.5556597 30.53230462 35.36619278 10.74807758

3.012712864 54.0088875 37.77826533 0 0 0 0 0
0

T36 576.3819004 567.7211237 771.7642986 771.9749719 55.96620948
774.7635064 1629.409394 405.2297312 565.2945161 38.76212482
30.76886627 163.5556597 30.53230462 35.36619278 10.74807758
3.012712864 54.0088875 37.77826533 0 0 0 0 0
0

;

param demand:=

S1 0.17

S2 0.48

S3 0.94

S4 0.23

S9 0.12

S10 0.17

S11 0.24

S15 0.15

S16 0.15

S17 0.4

S18 0.25

S20 0.41

S21 0.39

S23 0.12

S27 0.24

S28 0.29

S29 0.3

S30 0.86

;

Demand point 5

set S:= S1 S2 S5 S6 S8 S9 S14 S15 S16 S19 S22
S24 S25 S26 S27 S28 S29 S30 T31 T32 T33 T34
T35 T36;

set Sprime:=S1 S2 S5 S6 S8 S9 S14 S15 S16 S19
S22 S24 S25 S26 S27 S28 S29 S30;

param cst:S1 S2 S5 S6 S8 S9 S14 S15 S16 S19 S22
S24 S25 S26 S27 S28 S29 S30 T31 T32 T33 T34
T35 T36:=

S1 10000 20.19683283 904.831187 168.9709538 37.26095138 542.4252109
550.2756626 184.9494123 108.3686556 580.078181 112.6289545
135.5051511 589.4517056 584.1826184 570.0252538 578.8996335
577.0406792 580.6712365 529.0928867 529.0928867 529.0928867
529.0928867 529.0928867 529.0928867

S2 20.19683283 10000 896.3788195 188.1504083 57.25282319 532.3452058
540.0311001 171.3219546 89.01924603 572.5640408 92.85968259
115.3174714 581.5308203 576.0577218 561.6470748 570.1848943
570.1385166 573.2196348 518.2094916 518.2094916 518.2094916
518.2094916 518.2094916 518.2094916

S5 904.831187 896.3788195 10000 1030.521422 926.9404607 368.6706045
362.3119306 733.0350251 891.8693494 326.3426041 883.1273639
859.2481694 315.8288086 320.7674108 334.8090142 326.2518513
332.4159931 326.0007372 388.5348196 388.5348196 388.5348196
388.5348196 388.5348196 388.5348196

S6 168.9709538 188.1504083 1030.521422 10000 132.3190595 680.8276698
689.3625829 344.9308651 265.5689056 704.5293461 272.3843852
299.4872006 715.9467632 711.8702395 699.3113664 709.8053659
698.1661301 704.7682421 671.535024 671.535024 671.535024
671.535024 671.535024 671.535024

S8 37.26095138 57.25282319 926.9404607 132.3190595 10000 567.5691179
575.6539856 216.5055406 142.9681602 601.1343173 148.0452608
172.154495 611.1366846 606.2024708 592.4752383 601.8599863
597.1196951 601.6259382 555.4748533 555.4748533 555.4748533
555.4748533 555.4748533 555.4748533

S9 542.4252109 532.3452058 368.6706045 680.8276698 567.5691179 10000
9.291731156 365.6184061 523.3559622 87.61658119 514.5649714
490.5798667 82.42431827 74.06655944 59.439304 56.37122736
102.8194348 89.5889954 28.22627028 28.22627028 28.22627028
28.22627028 28.22627028 28.22627028

S14 550.2756626 540.0311001 362.3119306 689.3625829 575.6539856
9.291731156 10000 372.8254104 530.0673393 89.89256557 521.2361589
497.014968 83.15673797 74.87967999 61.37476153 56.24796353
106.0528415 91.89810458 29.23573673 29.23573673 29.23573673
29.23573673 29.23573673 29.23573673

S15 184.9494123 171.3219546 733.0350251 344.9308651 216.5055406
365.6184061 372.8254104 10000 161.4466632 414.4435255 153.4445608
135.1167625 421.6755181 415.4660494 400.2353163 407.4834317
414.6844702 415.3521454 349.5659369 349.5659369 349.5659369
349.5659369 349.5659369 349.5659369

S16 108.3686556 89.01924603 891.8693494 265.5689056 142.9681602
523.3559622 530.0673393 161.4466632 10000 575.6031281 9.392282905
39.27968727 582.497711 576.1195318 560.6934964 567.4566342
576.0952543 576.5460057 505.2824368 505.2824368 505.2824368
505.2824368 505.2824368 505.2824368

S19 580.078181 572.5640408 326.3426041 704.5293461 601.1343173
87.61658119 89.89256557 414.4435255 575.6031281 10000 567.3108212
545.909747 15.61797409 19.31584066 28.53511525 37.34837984
18.82366337 2.018657841 115.6267664 115.6267664 115.6267664
115.6267664 115.6267664 115.6267664

S22 112.6289545 92.85968259 883.1273639 272.3843852 148.0452608
514.5649714 521.2361589 153.4445608 9.392282905 567.3108212 10000
30.14758835 574.1000284 567.6828034 552.2188284 558.8980838
567.9527721 568.2674943 496.3589874 496.3589874 496.3589874
496.3589874 496.3589874 496.3589874

S24 135.5051511 115.3174714 859.2481694 299.4872006 172.154495
490.5798667 497.014968 135.1167625 39.27968727 545.909747
30.14758835 10000 552.1669211 545.5568264 529.9112454 536.1485846
547.2812674 546.9336664 471.6088027 471.6088027 471.6088027
471.6088027 471.6088027 471.6088027

S25 589.4517056 581.5308203 315.8288086 715.9467632 611.1366846
82.42431827 83.15673797 421.6755181 582.497711 15.61797409
574.1000284 552.1669211 10000 8.359960417 24.26388344 27.277629
33.56212767 16.90310272 110.640342 110.640342 110.640342
110.640342 110.640342 110.640342

S26 584.1826184 576.0577218 320.7674108 711.8702395 606.2024708
74.06655944 74.87967999 415.4660494 576.1195318 19.31584066
567.6828034 545.5568264 8.359960417 10000 16.30594992 19.34580329
38.13762354 21.1144608 102.2843749 102.2843749 102.2843749
102.2843749 102.2843749 102.2843749

S27 570.0252538 561.6470748 334.8090142 699.3113664 592.4752383
59.439304 61.37476153 400.2353163 560.6934964 28.53511525

552.2188284 529.9112454 24.26388344 16.30594992 10000 13.61929571
45.58625191 30.54671408 87.60450172 87.60450172 87.60450172
87.60450172 87.60450172 87.60450172

S28 578.8996335 570.1848943 326.2518513 709.8053659 601.8599863
56.37122736 56.24796353 407.4834317 567.4566342 37.34837984
558.8980838 536.1485846 27.277629 19.34580329 13.61929571 10000
55.80694845 39.31531566 84.38646482 84.38646482 84.38646482
84.38646482 84.38646482 84.38646482

S29 577.0406792 570.1385166 332.4159931 698.1661301 597.1196951
102.8194348 106.0528415 414.6844702 576.0952543 18.82366337
567.9527721 547.2812674 33.56212767 38.13762354 45.58625191
55.80694845 10000 17.05307871 130.3029471 130.3029471 130.3029471
130.3029471 130.3029471 130.3029471

S30 580.6712365 573.2196348 326.0007372 704.7682421 601.6259382
89.5889954 91.89810458 415.3521454 576.5460057 2.018657841
568.2674943 546.9336664 16.90310272 21.1144608 30.54671408
39.31531566 17.05307871 10000 117.5829746 117.5829746 117.5829746
117.5829746 117.5829746 117.5829746

T31 529.0928867 518.2094916 388.5348196 671.535024 555.4748533
28.22627028 29.23573673 349.5659369 505.2824368 115.6267664
496.3589874 471.6088027 110.640342 102.2843749 87.60450172
84.38646482 130.3029471 117.5829746 0 0 0 0 0
0

T32 529.0928867 518.2094916 388.5348196 671.535024 555.4748533
28.22627028 29.23573673 349.5659369 505.2824368 115.6267664
496.3589874 471.6088027 110.640342 102.2843749 87.60450172
84.38646482 130.3029471 117.5829746 0 0 0 0 0
0

T33 529.0928867 518.2094916 388.5348196 671.535024 555.4748533
28.22627028 29.23573673 349.5659369 505.2824368 115.6267664
496.3589874 471.6088027 110.640342 102.2843749 87.60450172
84.38646482 130.3029471 117.5829746 0 0 0 0 0
0

T34 529.0928867 518.2094916 388.5348196 671.535024 555.4748533
28.22627028 29.23573673 349.5659369 505.2824368 115.6267664
496.3589874 471.6088027 110.640342 102.2843749 87.60450172
84.38646482 130.3029471 117.5829746 0 0 0 0 0
0

T35 529.0928867 518.2094916 388.5348196 671.535024 555.4748533
28.22627028 29.23573673 349.5659369 505.2824368 115.6267664
496.3589874 471.6088027 110.640342 102.2843749 87.60450172

84.38646482 130.3029471 117.5829746 0 0 0 0 0
0

T36 529.0928867 518.2094916 388.5348196 671.535024 555.4748533
28.22627028 29.23573673 349.5659369 505.2824368 115.6267664
496.3589874 471.6088027 110.640342 102.2843749 87.60450172
84.38646482 130.3029471 117.5829746 0 0 0 0 0
0

;

param demand:=

S1 0.28

S2 0.13

S5 0.32

S6 0.76

S8 0.34

S9 0.06

S14 0.05

S15 0.31

S16 0.2

S19 0.28

S22 0.46

S24 0.57

S25 0.5

S26 0.25

S27 0.1

S28 0.18

S29 0.46

S30 0.1

;

i. MODEL H

Model H requires implementation on all the π-hubs. Here, we present the basic GUSEK model used for all the cases, with the example of π-hub 1 and provide the data sets for rest of the demand points in subsections.

Basic GUSEK code (Π-hub 1):

```
set S;
set Sprime;

param cst{i in S, j in S};
param demand{i in Sprime};

var x{i in S, j in S}, binary;
var a{i in Sprime},>=0;

minimize cost: sum{i in S, j in S} cst[i,j]*x[i,j];

s.t. C1{j in S}: sum{i in S} x[i,j] = 1;
s.t. C2{i in S}: sum{j in S} x[i,j] = 1;
s.t. C3{i in Sprime}: a[i] >=0;
s.t. C4{i in Sprime}: a[i] <=1-demand[i];
s.t. C5{i in Sprime,j in Sprime}: a[i] + demand[i] - a[j] - 1 + x[i,j] <=0;

solve;

display x,a;

data;
```

```
set S:= S5  S9   S13  S14  S17  S18  S19  S20  S21  S23  S25
    S27  S28  S29  S30  T31  T32  T33  T34  T35  T36  T37
    T38  T39  T40  T41;

set Sprime:=S5  S9   S13  S14  S17  S18  S19  S20  S21  S23
    S25  S27  S28  S29  S30;


param cst:S5    S9   S13  S14  S17  S18  S19  S20  S21  S23
    S25  S27  S28  S29  S30  T31  T32  T33  T34  T35  T36
    T37  T38  T39  T40  T41:=

S5  10000  368.6706045  1089.0601  1089.27655  325.5522349  328.8597796
    326.3426041  216.6549036  309.27 340.122036  315.8288086  334.8090142
    326.2518513  332.4159931  326.0007372  307.6915785  307.6915785
    307.6915785  307.6915785  307.6915785  307.6915785  307.6915785
    307.6915785  307.6915785  307.6915785  307.6915785

S9  368.6706045  10000  750.4850624  750.6903744  90.66175291  81.97216812
    87.61658119  179.2642444  86.49691394  80.40293634  82.42431827
    59.439304  56.37122736  102.8194348  89.5889954  75.59317425
    75.59317425  75.59317425  75.59317425  75.59317425  75.59317425
    75.59317425  75.59317425  75.59317425  75.59317425  75.59317425

S13  1089.0601  750.4850624  10000  0.222479495  765.9721356
    764.0258267  765.6437782  929.2575191  784.457501  752.5558264
    778.090907  763.3221838  774.628939  757.4534532  765.6734545
    789.9594495  789.9594495  789.9594495  789.9594495  789.9594495
    789.9594495  789.9594495  789.9594495  789.9594495  789.9594495
    789.9594495

S14  1089.27655  750.6903744  0.222479495  10000  766.1861178
    764.2391201  765.8575156  929.4641695  784.6705972  752.7691313
    778.3038718  763.5334704  774.8395257  757.6685147  765.8873542
    790.1712238  790.1712238  790.1712238  790.1712238  790.1712238
    790.1712238  790.1712238  790.1712238  790.1712238  790.1712238
    790.1712238

S17  325.5522349  90.66175291  765.9721356  766.1861178  10000
    8.689593852  3.06832229  184.5298631  21.49881833  15.75892894
    17.41785182  31.60339877  40.26826505  16.3178498  1.074249151
    35.77607549  35.77607549  35.77607549  35.77607549  35.77607549
    35.77607549  35.77607549  35.77607549  35.77607549  35.77607549
    35.77607549

S18  328.8597796  81.97216812  764.0258267  764.2391201  8.689593852
    10000  5.656531424  182.0981688  20.57134177  11.47082983  14.61183632
    23.01009017  32.53886906  23.26890527  7.616939414  31.51733934
```

31.51733934 31.51733934 31.51733934 31.51733934 31.51733934
31.51733934 31.51733934 31.51733934 31.51733934 31.51733934

S19 326.3426041 87.61658119 765.6437782 765.8575156 3.06832229
5.656531424 10000 183.2761914 20.40018271 14.09849003 15.61797409
28.53511525 37.34837984 18.82366337 2.018657841 33.77401336
33.77401336 33.77401336 33.77401336 33.77401336 33.77401336
33.77401336 33.77401336 33.77401336 33.77401336 33.77401336

S20 216.6549036 179.2642444 929.2575191 929.4641695 184.5298631
182.0981688 183.2761914 10000 163.0313786 192.3990076 167.8160535
173.6458591 160.5433013 199.1825794 184.2615234 150.9261333
150.9261333 150.9261333 150.9261333 150.9261333 150.9261333
150.9261333 150.9261333 150.9261333 150.9261333 150.9261333

S21 309.27 86.49691394 784.457501 784.6705972 21.49881833
20.57134177 20.40018271 163.0313786 10000 32.00064935 6.563872698
29.73208022 30.39337347 36.79903044 21.24747584 16.64964803
16.64964803 16.64964803 16.64964803 16.64964803 16.64964803
16.64964803 16.64964803 16.64964803 16.64964803 16.64964803

S23 340.122036 80.40293634 752.5558264 752.7691313 15.75892894
11.47082983 14.09849003 192.3990076 32.00064935 10000 25.85727948
25.36322407 37.78801993 22.55484897 14.98430879 41.47329808
41.47329808 41.47329808 41.47329808 41.47329808 41.47329808
41.47329808 41.47329808 41.47329808 41.47329808 41.47329808

S25 315.8288086 82.42431827 778.090907 778.3038718 17.41785182
14.61183632 15.61797409 167.8160535 6.563872698 25.85727948 10000
24.26388344 27.277629 33.56212767 16.90310272 18.39051116
18.39051116 18.39051116 18.39051116 18.39051116 18.39051116
18.39051116 18.39051116 18.39051116 18.39051116 18.39051116

S27 334.8090142 59.439304 763.3221838 763.5334704 31.60339877
23.01009017 28.53511525 173.6458591 29.73208022 25.36322407
24.26388344 10000 13.61929571 45.58625191 30.54671408 27.19563553
27.19563553 27.19563553 27.19563553 27.19563553 27.19563553
27.19563553 27.19563553 27.19563553 27.19563553 27.19563553

S28 326.2518513 56.37122736 774.628939 774.8395257 40.26826505
32.53886906 37.34837984 160.5433013 30.39337347 37.78801993
27.277629 13.61929571 10000 55.80694845 39.31531566 20.26011281
20.26011281 20.26011281 20.26011281 20.26011281 20.26011281
20.26011281 20.26011281 20.26011281 20.26011281 20.26011281

S29 332.4159931 102.8194348 757.4534532 757.6685147 16.3178498
23.26890527 18.82366337 199.1825794 36.79903044 22.55484897
33.56212767 45.58625191 55.80694845 10000 17.05307871 51.9515964
51.9515964 51.9515964 51.9515964 51.9515964 51.9515964
51.9515964 51.9515964 51.9515964 51.9515964 51.9515964

S30 326.0007372 89.5889954 765.6734545 765.8873542 1.074249151
7.616939414 2.018657841 184.2615234 21.24747584 14.98430879
16.90310272 30.54671408 39.31531566 17.05307871 10000 35.20742193
35.20742193 35.20742193 35.20742193 35.20742193 35.20742193
35.20742193 35.20742193 35.20742193 35.20742193 35.20742193

T31 307.6915785 75.59317425 789.9594495 790.1712238 35.77607549
31.51733934 33.77401336 150.9261333 16.64964803 41.47329808
18.39051116 27.19563553 20.26011281 51.9515964 35.20742193 0
0 0 0 0 0 0 0 0 0 0

T32 307.6915785 75.59317425 789.9594495 790.1712238 35.77607549
31.51733934 33.77401336 150.9261333 16.64964803 41.47329808
18.39051116 27.19563553 20.26011281 51.9515964 35.20742193 0
0 0 0 0 0 0 0 0 0 0

T33 307.6915785 75.59317425 789.9594495 790.1712238 35.77607549
31.51733934 33.77401336 150.9261333 16.64964803 41.47329808
18.39051116 27.19563553 20.26011281 51.9515964 35.20742193 0
0 0 0 0 0 0 0 0 0 0

T34 307.6915785 75.59317425 789.9594495 790.1712238 35.77607549
31.51733934 33.77401336 150.9261333 16.64964803 41.47329808
18.39051116 27.19563553 20.26011281 51.9515964 35.20742193 0
0 0 0 0 0 0 0 0 0 0

T35 307.6915785 75.59317425 789.9594495 790.1712238 35.77607549
31.51733934 33.77401336 150.9261333 16.64964803 41.47329808
18.39051116 27.19563553 20.26011281 51.9515964 35.20742193 0
0 0 0 0 0 0 0 0 0 0

T36 307.6915785 75.59317425 789.9594495 790.1712238 35.77607549
31.51733934 33.77401336 150.9261333 16.64964803 41.47329808
18.39051116 27.19563553 20.26011281 51.9515964 35.20742193 0
0 0 0 0 0 0 0 0 0 0

T37 307.6915785 75.59317425 789.9594495 790.1712238 35.77607549
31.51733934 33.77401336 150.9261333 16.64964803 41.47329808
18.39051116 27.19563553 20.26011281 51.9515964 35.20742193 0
0 0 0 0 0 0 0 0 0 0

T38 307.6915785 75.59317425 789.9594495 790.1712238 35.77607549
31.51733934 33.77401336 150.9261333 16.64964803 41.47329808
18.39051116 27.19563553 20.26011281 51.9515964 35.20742193 0
0 0 0 0 0 0 0 0 0 0

T39 307.6915785 75.59317425 789.9594495 790.1712238 35.77607549
31.51733934 33.77401336 150.9261333 16.64964803 41.47329808
18.39051116 27.19563553 20.26011281 51.9515964 35.20742193 0
0 0 0 0 0 0 0 0 0 0

```
T40         307.6915785   75.59317425   789.9594495   790.1712238   35.77607549
    31.51733934   33.77401336   150.9261333   16.64964803   41.47329808
    18.39051116   27.19563553   20.26011281   51.9515964    35.20742193   0
    0         0         0         0         0         0         0         0         0         0

T41         307.6915785   75.59317425   789.9594495   790.1712238   35.77607549
    31.51733934   33.77401336   150.9261333   16.64964803   41.47329808
    18.39051116   27.19563553   20.26011281   51.9515964    35.20742193   0
    0         0         0         0         0         0         0         0         0         0;


param demand:=

S5  0.32

S9  0.31

S13         0.15

S14         0.46

S17         0.75

S18         0.3

S19         0.56

S20         0.7

S21         0.77

S23         0.83

S25         0.74

S27         0.34

S28         0.82

S29         0.12

S30         0.55;


end ;
```

Π-hub 2

```
set S:= S3 S4 S6 S7 S10 S11 S14 S30 T31 T32 T33
 T34 T35 T36 T37

;

set Sprime:=S3 S4 S6 S7 S10 S11;


param cst:S3 S4 S6 S7 S10 S11 S14 S30 T31 T32
 T33 T34 T35 T36 T37:=

S3 10000.00 0.22 97.56 23.41 5.63 2269.92 759.33 765.67 789.96
 789.96 789.96 789.96 789.96 789.96 789.96

S4 0.22 10000.00 97.66 23.56 5.59 2270.08 759.53 765.89 790.17
 790.17 790.17 790.17 790.17 790.17 790.17

S6 97.56 97.66 10000.00 75.56 103.07 2177.06 689.36 704.77 726.36
 726.36 726.36 726.36 726.36 726.36 726.36

S7 23.41 23.56 75.56 10000.00 28.44 2246.51 738.01 745.70 769.58
 769.58 769.58 769.58 769.58 769.58 769.58

S10 5.63 5.59 103.07 28.44 10000.00 2274.81 762.66 768.44
 792.88 792.88 792.88 792.88 792.88 792.88 792.88

S11 2269.92 2270.08 2177.06 2246.51 2274.81
 10000.00 1605.60 1659.07 1623.91 1623.91
 1623.91 1623.91 1623.91 1623.91 1623.91

S14 759.33 759.53 689.36 738.01 762.66 1605.60 10000.00 91.90
 74.36 74.36 74.36 74.36 74.36 74.36 74.36

S30 765.67 765.89 704.77 745.70 768.44 1659.07 91.90 10000.00
 35.21 35.21 35.21 35.21 35.21 35.21 35.21

T31 789.96 790.17 726.36 769.58 792.88 1623.91 74.36 35.21 0.00
 0.00 0.00 0.00 0.00 0.00 0.00

T32 789.96 790.17 726.36 769.58 792.88 1623.91 74.36 35.21 0.00
 0.00 0.00 0.00 0.00 0.00 0.00

T33 789.96 790.17 726.36 769.58 792.88 1623.91 74.36 35.21 0.00
 0.00 0.00 0.00 0.00 0.00 0.00

T34 789.96 790.17 726.36 769.58 792.88 1623.91 74.36 35.21 0.00
 0.00 0.00 0.00 0.00 0.00 0.00

T35 789.96 790.17 726.36 769.58 792.88 1623.91 74.36 35.21 0.00
 0.00 0.00 0.00 0.00 0.00 0.00
```

```
T36      789.96 790.17 726.36 769.58 792.88 1623.91      74.36   35.21   0.00
    0.00   0.00   0.00   0.00   0.00   0.00

T37      789.96 790.17 726.36 769.58 792.88 1623.91      74.36   35.21   0.00
    0.00   0.00   0.00   0.00   0.00   0.00

;


param demand:=

S5  0.32

S9  0.31

S13      0.15

S14      0.46

S17      0.75

S18      0.3

S19      0.56

S20      0.7

S21      0.77

S23      0.83

S25      0.74

S27      0.34

S28      0.82

S29      0.12

S30      0.55;
```

Π-hub 3

```
set S:= S1  S2  S8  S9  S12  S15  S16  S22  S24  S26  T31
    T32  T33  T34  T35  T36  T37  T38

;

set Sprime:=S1  S2  S8  S9  S12  S15  S16  S22  S24  S26;

param cst:S1  S2  S8  S9  S12  S15  S16  S22  S24  S26
    T31  T32  T33  T34  T35  T36  T37  T38

:=

S1  10000.00  20.20  37.26  542.43  599.46  184.95  108.37  112.63  135.51  584.18
    597.16  597.16  597.16  597.16  597.16  597.16  597.16  597.16

S2  20.20  10000.00  57.25  532.35  591.74  171.32  89.02  92.86  115.32  576.06
    588.71  588.71  588.71  588.71  588.71  588.71  588.71  588.71

S8  37.26  57.25  10000.00  567.57  620.82  216.51  142.97  148.05  172.15  606.20
    619.67  619.67  619.67  619.67  619.67  619.67  619.67  619.67

S9  542.43  532.35  567.57  10000.00  93.67  365.62  523.36  514.56  490.58  74.07
    75.59  75.59  75.59  75.59  75.59  75.59  75.59  75.59

S12  599.46  591.74  620.82  93.67  10000.00  432.55  593.49  585.13  563.34
    19.95  23.30  23.30  23.30  23.30  23.30  23.30  23.30  23.30

S15  184.95  171.32  216.51  365.62  432.55  10000.00  161.45  153.44  135.12
    415.47  426.81  426.81  426.81  426.81  426.81  426.81  426.81  426.81

S16  108.37  89.02  142.97  523.36  593.49  161.45  10000.00  9.39  39.28
    576.12  587.02  587.02  587.02  587.02  587.02  587.02  587.02  587.02

S22  112.63  92.86  148.05  514.56  585.13  153.44  9.39  10000.00  30.15
    567.68  578.50  578.50  578.50  578.50  578.50  578.50  578.50  578.50

S24  135.51  115.32  172.15  490.58  563.34  135.12  39.28  30.15  10000.00
    545.56  555.92  555.92  555.92  555.92  555.92  555.92  555.92  555.92

S26  584.18  576.06  606.20  74.07  19.95  415.47  576.12  567.68  545.56
    10000.00  16.44  16.44  16.44  16.44  16.44  16.44  16.44  16.44

T31  597.16  588.71  619.67  75.59  23.30  426.81  587.02  578.50  555.92  16.44
    0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00

T32  597.16  588.71  619.67  75.59  23.30  426.81  587.02  578.50  555.92  16.44
    0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
```

```
T33     597.16 588.71 619.67 75.59  23.30  426.81 587.02 578.50 555.92 16.44
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
T34     597.16 588.71 619.67 75.59  23.30  426.81 587.02 578.50 555.92 16.44
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
T35     597.16 588.71 619.67 75.59  23.30  426.81 587.02 578.50 555.92 16.44
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
T36     597.16 588.71 619.67 75.59  23.30  426.81 587.02 578.50 555.92 16.44
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
T37     597.16 588.71 619.67 75.59  23.30  426.81 587.02 578.50 555.92 16.44
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
T38     597.16 588.71 619.67 75.59  23.30  426.81 587.02 578.50 555.92 16.44
    0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00

;

param demand:=
S1  0.85
S2  0.48
S8  0.66
S9  0.77
S12     0.42
S15     0.94
S16     0.37
S22     0.76
S24     0.23
S26     0.84
;
```