YAŞAR UNIVERSITY

GRADUATE SCHOOL

MASTER THESIS

A SUSTAINABILITY COMPARISON OF TRADITIONAL SUPPLY CHAINS AND PHYSICAL INTERNET USING SIMULATION

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PRESENTATION DATE: 24.11.2020

BORNOVA / İZMİR
NOVEMBER 2020

ABSTRACT

A SUSTAINABILITY COMPARISON OF TRADITIONAL SUPPLY CHAINS AND PHYSICAL INTERNET USING SIMULATION

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November 2020

Sustainability has achieved notable attention due to rising global warming. The supply chain was also affected by this, and sustainability in the supply chain processes gained the same importance. In this study, the concept of Physical Internet, which provides full integration in the supply chain with its completely technological structure, is analyzed in the context of the three pillars of sustainability which are environmental, economic, and social. The analysis is conducted by comparing the classic supply chain and Physical Internet in the context of sustainability. Two simulation models that consist of four-echelons are created for comparison by utilizing ARENA Simulation Software. The first simulation model is the classic supply chain and the other simulation model is the Physical Internet model. Performance metrics are carbon dioxide (CO_2) emissions that are produced along with transportation processes, total cost that consists of backorder cost, holding cost and transportation cost, lead time, and average inventory levels are considered as performance metrics and calculated to compare two models in the context of sustainability utilizing Minitab Software.

Key Words: Sustainability, Classic Supply Chain, Physical Internet, Arena Simulation, GHG Emissions, CO_2 Emissions, Lead Time, Logistics, Supply Chain Management, Transportation Cost, Holding Cost, FMCG, Fast Moving Consumer Goods

ÖZ

GELENEKSEL TEDARİK ZİNCİRİ VE FİZİKSEL İNTERNET'İN SİMÜLASYON KULLANILARAK SÜRDÜRÜLEBİLİRLİK KARŞILAŞTIRMASI

Gözaçan, Nazlıcan
Yüksek Lisans Tezi, Uluslararası Lojistik Yönetimi
Danışman: Dr. Öğretim Üyesi Özgür Kabadurmuş
Kasım 2020

Artan küresel ısınma sebebiyle sürdürülebilirlik kavramı daha da önem kazanmıştır. Tedarik zinciri sürdürülebilirliği de bu durumdan etkilenmiştir. Bu çalışmada, tamamen teknolojik yapısı ile tedarik zincirinde tam entegrasyon sağlayan Fiziksel İnternet kavramı, çevresel, ekonomik, ve sosyal olmak üzere üç sürdürülebilirlik bağlamında analiz edilmiştir. Analizde klasik tedarik zinciri ile Fiziksel İnternet'in sürdürülebilirlik bağlamında karşılaştırılmıştır. ARENA Simülasyon Yazılımı kullanılarak 4-kademeli iki simülasyon modeli oluşturulmuştur. İlk simülasyon modeli klasik tedarik zinciridir ve diğer simülasyon modeli Fiziksel İnternet modelidir. Performans metrikleri, bekleyen sipariş maliyeti, elde tutma maliyeti ve nakliye maliyeti, toplam maliyet, teslim süresi ve ortalama stok seviyeleri ile birlikte üretilen karbondioksit (CO_2) emisyonları performans metrikleri olarak kabul edilmiş ve Minitab yazılımı kullanılarak analiz edilmiştir.

AnahtarKelimeler: Sürdürülebilirlik, Klasik Tedarik Zinciri, Fiziksel İnternet, Arena Simülasyonu, Sera Gazı Emisyonları, CO_2 Emisyonları, Teslim Süresi, Lojistik, Tedarik Zinciri Yönetimi, Taşıma Maliyeti, Envanter Maliyeti.

ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisor Assist. Prof. Dr. Özgür Kabadurmuş for his guidance and patience during this study.

I would like to express my enduring love to my parents and my brother, who are always supportive, loving and caring to me in every possible way in my life.

Nazlıcan Gözaçan

İzmir, 2020

TEXT OF OATH

I declare and honestly confirm that my study, titled “A SUSTAINABILITY COMPARISON OF TRADITIONAL SUPPLY CHAINS AND PHYSICAL INTERNET USING SIMULATION” and presented as a Master’s Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Nazlıcan Gözaçan

Signature

………………………………

November 10, 2020

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ABBREVIATIONS

$ARS_{h_s p_k}$	Available amount to meet required space for k type of product of $PI - hub_s$
$ARS_{h_s p_z}$	Available amount to meet required space for z type of product of $PI - hub_s$
AS_{h_s}	Available space in the vehicle for loading at $PI - hub_s$
$B_{p_t r_i}$	Total backorder amount for t type of product at $retailer_i$
$B^A_{h_s p_k}$	Total backorder amount that will be supplied after $OA_{p_t r_i}$ for k type of product at $PI - hub_s$
$B_{h_s p_t}$	Total backorder amount for t type of product at $PI - hub_s$
$B^A_{h_s p_z}$	Total backorder amount that will be supplied after $OA_{p_t r_i}$ for z type of product at $PI - hub_s$
$B^B_{h_s}$	Total backorder amount that will be supplied before $OA_{p_t r_i}$ at $PI - hub_s$
$Distance_{h_j h_s}$	Distance between $PI - hub_j$ and $PI - hub_s$
$Distance_{h_j p_t}$	Distance between $PI - hub_j$ and the producer of t type of product
$Distance_{h_s r_i}$	Distance between $PI - hub_s$ and $retailer_i$
$EOA_{p_t r_i}$	Expected order amount from the producer of t type of product to $retailer_i$
$EOA_{h_j h_s p_t}$	Expected order amount from $PI - hub_s$ to $PI - hub_j$ for the t type of product
$EOA_{h_s p_t r_i}$	Expected order amount from $PI - hub_s$ to $retailer_i$ for the t type of product
EOQ^h	Economic order quantity of PI-hubs
EOQ^r	Economic order quantity of retailers
$EOT_{p_t r_i}$	Estimated ordering time of $retailer_i$ for the t type of product
EOT_{p_t}	Estimated ordering time of all retailers for the t type of product
$EOT^n_{p_z r_l}$	n^{th} earlier estimated ordering time of $retailer_l$ for the z type of product
$EST_{h_s p_k}$	Estimated supply time of the k type of product at $PI - hub_s$
$EST_{h_s p_t r_i}$	Estimated supply time of the order of $retailer_i$ for the k type of product from $PI - hub_s$
$EST^B_{h_s p_t r_i}$	Estimated supply time of the backorder of $retailer_i$ for the k type of product from $PI - hub_s$
$EST_{h_s p_z}$	Estimated supply time of the z type of product at $PI - hub_s$
$EST_{d h_s p_t}$	Estimated supply time of the order of destination_d for the t type of product at $PI - hub_s$
$ETA_{h_j h_s p_t}$	Estimated time of arrival of the order of $PI - hub_j$ for the t type of product from $PI - hub_s$

$ETA_{h_j p_t}$	Estimated time of arrival of the order of $PI - hub_s$ from for the producer of t type of product
$ETA_{h_s p_k}^n$	The order being prepared for k type of product of $PI - hub_s$ with the n^{th} early estimated time of arrival
$ETA_{h_s p_t r_i}$	Estimated time of arrival of the order of $retailer_i$ for the t type of product from $PI - hub_s$
$ETA_{h_s p_t}^n$	The order being prepared for t type of product of $PI - hub_s$ with the n^{th} early estimated time of arrival
$ETA_{c_a h_s p_k}$	Estimated time of arrival of $container_a$ for the k type of product arriving to $PI - hub_s$
$ETA_{c_a h_s p_t}$	Estimated time of arrival of $container_a$ for the t type of product arriving to $PI - hub_s$
$ETA_{p_t r_i}^n$	The order for t type of product of $retailer_i$ with the n^{th} early estimated time of arrival
$INV_{p_t r_i}$	Inventory of $retailer_i$ for t type of product
$INV_{h_j p_t}$	Inventory of $PI - hub_j$ for t type of product
$INV_{h_s p_k}$	Inventory of $PI - hub_s$ for k type of product
$INV_{h_s p_t}$	Inventory of $PI - hub_s$ for t type of product
$OA_{h_j p_t}$	Order amount of $PI - hub_j$ for t type of product
$OA_{p_t r_i}$	Order amount of $retailer_i$ for t type of product
$OA_{d p_t}$	Order amount of destination_d for t type of product
$P_{h_s p_k}^n$	Order amount of k type of product of $PI - hub_s$ being prepared with the n^{th} early estimated time of arrival
$P_{h_s p_t}^n$	Order amount of t type of product of $PI - hub_s$ being prepared with the n^{th} early estimated time of arrival
RL_{h_s}	Remaining load after orders are loaded on the vehicle at $PI - hub_s$
ROP^h	Reorder point of PI-hubs
ROP^r	Reorder point of retailers
RS_{h_s}	Required space for vehicle to departure from $PI - hub_s$
TL_{h_s}	Truckload departured from $PI - hub_s$
$TL_{c_a h_j p_t}$	Truckload that $container_a$ carries for the order of $PI - hub_j$ for t type of product
$TL_{c_a h_s p_k}$	Truckload that $container_a$ carries for the order of $PI - hub_s$ for k type of product
$TL_{c_a h_s p_t}$	Truckload that $container_a$ carries for the order of $PI - hub_s$ for t type of product
$TL_{c_a p_t r_i}$	Truckload that $container_a$ carries for the order of $retailer_i$ for t type of product
$TL_{c_a d p_t}$	Truckload that $container_a$ carries for the order of destination_d for t type of product
WTL_{h_s}	The current waiting truckload in the vehicle at $PI - hub_s$

$d_{p_t r_i}$	Hourly average demand of the customer arriving at $retailer_i$ for t type of product
$demand_{p_t r_i}$	Demand arriving to $retailer_i$ for t type of product
$numEOT_{p_t}$	Number of estimated ordering times found for t type of product
DC	Distribution Center
EOQ	Economic Order Quantity
EST	Estimated Supply Time
ETA	Estimated Time of Arrival
FIFO	First In First Out
KM	Kilometers
PI	Physical Internet
ROP	Reorder Point
TFIN	Time Final
TNOW	Time Now
C	Container set
D	Destination set
H	Set of PI-hubs in the simulation model
$MinTL$	Minimum truckload
R	Set of retailers in the simulation model
S	Orders being prepared set
$TFIN$	Final termination time of simulation
$TNOW$	Current time in simulation
VC	Vehicle capacity
$numLS$	Number of lateral shipments required

CHAPTER 1
INTRODUCTION

Sustainable Supply Chain Management (SSCM) has earned significant recognition over the last decade (Azadi et al., 2015) due to the importance given to sustainability as a response to the growing global warming. This recognition of SSCM evolves to necessity with global impact on the ecosystem (Montreuil, 2012). Currently, logistics and transportation are the main significant causes of greenhouse gasses in developed nations (Ballot et al., 2011). As seen in Figure 1.1., in the European Union (EU) Climate Action Progress Report that is published by European Commission (2019), the transportation sector appears as the second major contributor to greenhouse gas (GHG) emissions after the energy supply sector from 1994 to 2019. According to the same report, it can also be learned that the transportation sector was the fourth sector that produced GHG emissions before 1994. The growing effect of the transportation sector on GHG emissions remains as can be demonstrated by this particular report. Moreover, Montreuil (2012) released thirteen symptoms for unsustainability such as unused goods, underutilized production, never utilized items, unneeded stocks, unsafe logistics, and supply chain networks, undelivered stocks, hard to prove smart technology and infrastructure and lastly decapitated innovation. All of these symptoms address the three pillars of sustainability in the context of supply chain and logistics. Adequate awareness and operations are required in supply chains because of this sustainability problem (Ali et al., 2020). SSCM is defined as "The strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual company and its supply chains." (Carter and Rogers, 2008). Thus, sustainability cannot be achieved in a setting where one of the three pillars of sustainability listed in the SSCM concept is absent in a supply chain (Fekpe and Delaporte, 2018). Global energy consumption, direct and indirect pollution and GHG emissions must be minimized to provide a network of environmentally sustainable logistics and supply chain. Also, additional gains in logistics and supply chain processes can be obtained by efficient communication flow and accessible and accurate data sharing (Montreuil, 2011).

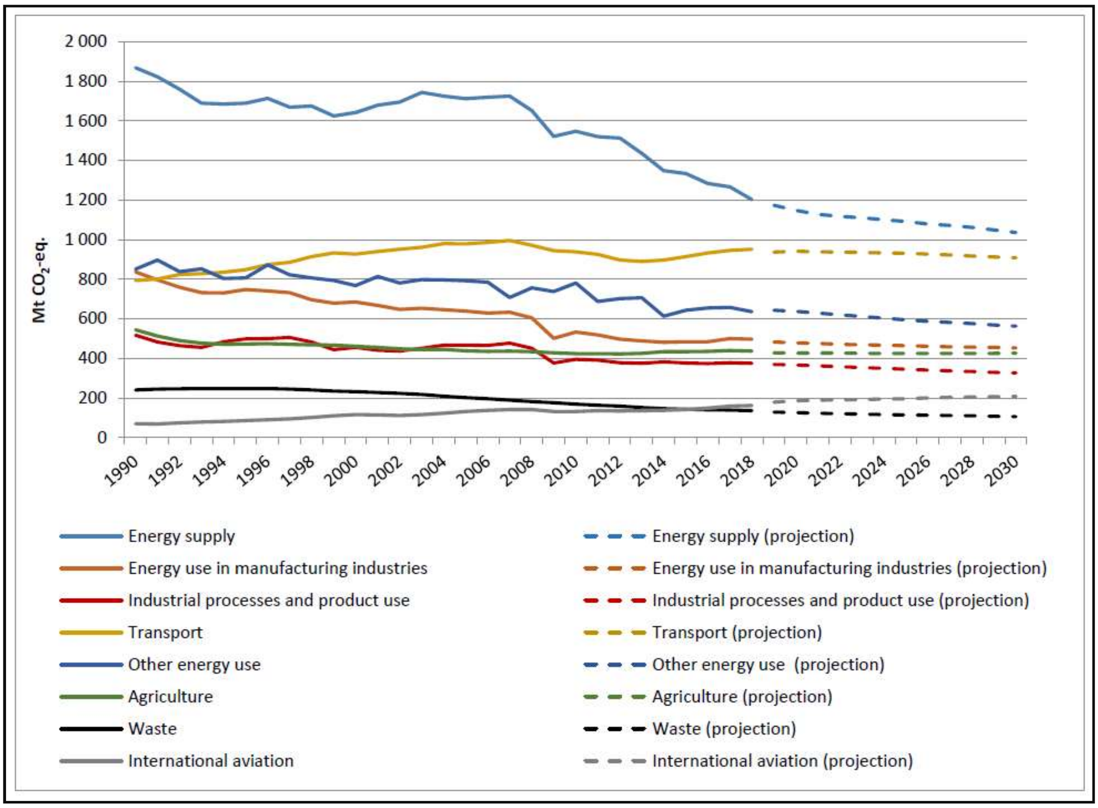

Figure 1.1. EU GHG emissions by sector, historical data (1990-2018) and projections (2019-2030) (European Commission, 2019)

Physical Internet is a new concept that enables increased and efficient communication in supply chains and logistics operations. Physical Internet is defined as “An open global logistics system founded on physical, digital, and operational interconnectivity through encapsulation, interfaces, and protocols (Meller et al., 2012). Ballot et al., (2011) defined Physical Internet as “the natural evolution and integration of container standardization and intelligence, broadband communication, cloud computing, and deregulation in transportation, catalyzed by new logistics business models.” Physical Internet consists of a combination of digital transportation infrastructure that is expanding to substitute analog road networks. The Internet has settled into specialty applications for high-speed (fiber optics), local area networks (Wi-Fi), and local devices (Bluetooth) (Montreuil, 2011).

Physical Internet aims an improvement in the environmental, economic, and social sustainability of logistics services such as transportation, storing, material handling, supply (Montreuil et al., 2010). Also, it inspires the creation of a systematic, comprehensive vision that can provide truly sustainable solutions to the past and present methods and to the symptomatic problems created by current paradigmatic beliefs that support future initiatives (Montreuil, 2011).

As mentioned in the previous paragraphs, Montreuil (2012) released thirteen symptoms for unsustainability. These symptoms include all three pillars of sustainability. Based on these symptoms, Montreuil (2012) explained the objective of Physical Internet in the context of the three pillars of sustainability as follows. Firstly, the environmental aim of Physical Internet is to sustainably minimize worldwide GHG emissions, energy consumption, pollution, and material waste. Thus, the Physical Internet may lead to the achievement of efficiency objectives, with an emphasis on declining CO_2 emissions (Sarraj et al., 2014) and increasing logistics performance (Mangina et al., 2020). Secondly, the economic aim of Physical Internet is to sustainably decrease the global economic cost of logistics, also achieve significant efficiency profits for companies. In the context of social sustainability, more reliable supply, and less lead time improve the performance of suppliers in a supply chain (Mani et al., 2018). Accordingly, the digital structure of the Physical Internet also contributes to this situation since the digitization of logistics processes optimizes workflows and reduces lead times (Kayıkçı, 2018). Thus, the social aim of Physical Internet is to increase the living standards of the logistics workforce and the global population substantially and sustainably by enhancing the quick and efficient accessibility and mobility of physical items (Montreuil, 2012).

In this study, the Physical Internet concept has been compared with the classic supply chain in terms of sustainability. While the classic supply chain is insufficient in the context of environmental, economic, and social pillars of sustainability, Physical Internet is equipped to improve the classic supply chain in terms of three pillars of sustainability as mentioned in the previous paragraphs. The urgency of the solution to this sustainability problem grows with the rising emphasis on sustainability due to the growing global warming. Moreover, sustainability cannot be obtained if there is a lack of one of the three pillars of sustainability. For this reason, all three pillars of sustainability must be taken into consideration at the same time.

However, the Physical Internet studies in the literature are based on only the environmental and economical parts, although there are studies on lead time, these studies are not linked to the concept of social sustainability. Unlike the studies in the literature, this study addresses the social pillar of sustainability as well as economic and environmental pillars by providing an advanced and detailed algorithm flowchart. Supply chain network models of classic supply chain and Physical Internet concepts were created and compared with a hypothetical but realistic supply chain case study by using Arena Simulation. The open global and transparent network offered by the Physical Internet and PI-system's functionality often provides a solution to sustainability concerns of the supply chain. Thus, the 1st hypothesis indicates that the environmental impact of the Physical Internet will be better than the classic model. This hypothesis is analyzed via calculating GHG emissions. The cost factor corresponding to the economic pillar of sustainability is highlighted in different categories in the 2nd, 3rd and 4th hypotheses. By offering alternative options in the supplier selection process, Physical Internet decreases the total distance travelled while reducing the cost of transportation and while providing inventory to be used more efficiently, firstly the average inventory level, then the holding cost and lastly the backorders cost decline accordingly. These correspond to the economic pillar. Moreover, this feature may contribute to the social pillar as well as the economic pillar by lessening lead time and generating fewer backorders. The last two hypotheses that are 5th and 6th correspond to these points. The hypotheses of this research for each performance metric are written below.

H1: Physical Internet generates less GHG Emissions than the classic model.

H2: Physical Internet produces lower transportation costs than the classic model.

H3: Physical Internet causes less holding costs than the classic model.

H4: Physical Internet obtains less backorders cost than the classic model.

H5: Physical Internet creates less average inventory levels than the classic model.

H6: Physical Internet provides shorter lead times than the classic model.

Performance metrics are created to analyze the sustainability of the simulation models based on these described hypotheses. These defined performance metrics consist of GHG emissions released during delivery to measure the environmental pillar; holding, transportation, and backorder costs for the economic pillar; and lead time for the social pillar.

This study has many contributions. Firstly, this study shows that if the Physical Internet structure is applied to the supply chain, the delivery time can be shortened and the social pillar of sustainability may improve. Moreover, the environmental aspect of this study is that the harm to nature from transportation (seen in Figure 1.1.) can be reduced without changing vehicle numbers as well as the cost for economic pillar.

CHAPTER 2
LITERATURE REVIEW

The related topics in this paper are included in the literature review. Physical Internet is the focus of this study with its unique information sharing and lateral shipment provided by the PI-hub and PI-container, which are the Physical Internet features included in the case study. As the result of these features, the Physical Internet can contribute sustainability. Thus, the focus categories are set as Physical Internet, information sharing, lateral shipment and sustainability. Simulation method was preferred in Physical Internet. Besides, it is predominant in conceptual studies since it is a newly developing concept which is summarized in Table 2.1. in terms of focus, methods, performance metrics and facilities the studies examined. Table 2.1. is explained in Chapter 2.1. Also, Table 2.2. summarizes supply chain studies focusing on information sharing, lateral shipment and sustainability. In the publications that focus on information sharing, the first weighted method is simulation, while the second most used method is survey. Furthermore, simulation is also the most commonly used method in the studies that concentrate on sustainability, followed by mixed-integer linear programming (MILP). Simulation and conceptual are the most used methods for all publications, respectively. The number of performance metrics found among all the publications examined is twenty. The top four most studied performance metrics are transportation cost, GHG emissions, inventory cost and inventory level, respectively. Table 2.2. is also explained in Chapter 2.2.

Table 2.1. Summary of Literature Review of Physical Internet

Method

Focus	Author	Conceptual	Data Analysis	Dynamic Pricing	Goal Programming	HFS scheduling	Literature Review	MILP	(MRIO) hybrid	Optimization	Simulation	Survey
Physical Internet	Montreuil et al., (2010)	x										
	Montreuil (2011)	x										
	Lounes & Montreuil (2011)	x										
	Ballot et al., (2011)										x	
	Montreuil (2012)	x										
	Montreuil et al., (2012a)	x										
	Montreuil et al., (2012b)	x										
	Ballot et al., (2012)										x	
	Meller et al., (2012)										x	
	Hakimi et al., (2012)										x	
	Furtado et al., (2013)										x	
	Pan et al., (2013)										x	
	Naccache et al., (2014)										x	
	Sarraj et al., (2014)										x	
	Oktaei et al., (2014)	x										
	Pach et al., (2014)										x	
	Pan & Ballot (2015)										x	
	Pan et al., (2015)										x	
	Yang et al., (2015)										x	
	Crainic & Montreuil (2015)	x										
	Landschützer et al., (2015)	x										
	Montreuil et al (2015)	x										
	Sallez et al., (2015)										x	
	Tretola et al., (2015)	x										
	Ballot & Montreuil (2016)	x										
	Chakroun et al., (2016)	x										
	Kong et al., (2016)					x						
	Qiao et al., (2016)			x								
	Sallez et al., (2016)										x	
	Treiblmaier et al., (2016)						x					
	Venkatadri et al., (2016)										x	
	Wang et al., (2016)	x										
	Zhong et al., (2016)	x										
	Sternbereg & Norman (2017)						x					
	Yang et al., (2017a)									x	x	
	Yang et al., (2017b)									x	x	
	Ji et al., (2019)							x				
	Treiblemainer (2019)	x										
	Matusiewicz (2020)	x										
	Chargui et al. (2020)							x				
	Qiao et al. (2020)			x						x		

Performance Metrics

Author	Backorder	Bullwhip Effect	Inventory Cost	Processing Cost	Transportation Cost	Deterioration Velocities	GHG Emissions	Inventory Level	Inventory Variability	Lost Sales	Service Level	Transportation Capacity	Transshipments Activities	Travelled Distance	Delivery Time	Evacuation Time	Flow Time	On Time Delivery	Lead Time	Utilization
Montreuil et al., (2010)																				
Montreuil (2011)																				
Lounes & Montreuil (2011)																				
Ballot et al., (2011)			x		x		x							x						
Montreuil (2012)																				
Montreuil et al., (2012a)																				
Montreuil et al., (2012b)																				
Ballot et al., (2012)																				x
Meller et al., (2012)																				x
Hakimi et al., (2012)														x						
Furtado et al., (2013)				x	x		x											x		
Pan et al., (2013)			x		x															
Naccache et al., (2014)					x		x										x			
Sarraj et al., (2014)					x		x								x				x	
Oktaei et al., (2014)																				
Pach et al., (2014)																x				
Pan & Ballot (2015)								x						x						
Pan et al., (2015)			x		x															
Yang et al., (2015)			x		x			x		x										
Crainic & Montreuil (2015)							x													
Landschützer et al., (2015)																				
Montreuil et al (2015)																				
Sallez et al., (2015)																x				
Tretola et al., (2015)				x	x												x			
Ballot & Montreuil (2016)																		x		
Chakroun et al., (2016)							x										x			
Kong et al., (2016)						x														
Qiao et al., (2016)					x							x								
Sallez et al., (2016)																x				
Treiblmaier et al., (2016)																				
Venkatadri et al., (2016)			x		x							x			x					
Wang et al., (2016)																				
Zhong et al., (2016)																				
Sternbereg & Norman (2017)																				
Yang et al., (2017a)			x	x								x	x							
Yang et al., (2017b)			x		x	x		x			x									
Ji et al., (2019)	x		x	x	x					x	x									
Treiblemainer (2019)																				
Matusiewicz (2020)																				
Chargui et al. (2020)														x						
Qiao et al. (2020)					x															

Facilities

Author	Distribution center	Logistics	PI-HUB	Producer	Retailer	Transit Centre	Warehouse	Wholesaler
Montreuil et al., (2010)								
Montreuil (2011)								
Lounes & Montreuil (2011)								
Ballot et al., (2011)	x		x	x	x		x	
Montreuil (2012)								
Montreuil et al., (2012a)								
Montreuil et al., (2012b)								
Ballot et al., (2012)	x		x				x	
Meller et al., (2012)						x		
Hakimi et al., (2012)	x		x	x	x		x	
Furtado et al., (2013)			x					
Pan et al., (2013)	x		x		x		x	
Naccache et al., (2014)								
Sarraj et al., (2014)	x		x	x	x		x	
Oktaei et al., (2014)						x		
Pach et al., (2014)			x					
Pan & Ballot (2015)	x			x			x	
Pan et al., (2015)	x		x		x		x	
Yang et al., (2015)	x		x	x	x		x	
Crainic & Montreuil (2015)	x		x	x	x		x	
Landschützer et al., (2015)								
Montreuil et al (2015)								
Sallez et al., (2015)			x					
Tretola et al., (2015)			x	x	x		x	
Ballot & Montreuil (2016)					x			
Chakroun et al., (2016)	x						x	
Kong et al., (2016)		x						
Qiao et al., (2016)			x					
Sallez et al., (2016)			x					
Treiblmaier et al., (2016)								
Venkatadri et al., (2016)			x					
Wang et al., (2016)				x				
Zhong et al., (2016)				x				
Sternbereg & Norman (2017)								
Yang et al., (2017a)	x		x	x	x		x	
Yang et al., (2017b)	x		x	x	x		x	
Ji et al., (2019)	x		x	x	x			
Treiblemainer (2019)								
Matusiewicz (2020)								
Chargui et al. (2020)			x					
Qiao et al. (2020)			x					

Table 2.2. Summary of Literature Review of Supply Chain Studies Focusing on Information Sharing - Lateral Shipment - Sustainability

Focus	Authors	Method											Performance Metrics																				Facilities							
		Conceptual	Data Analysis	Heuristic Solution	Goal Programming	HFS scheduling	Literature Review	MILP	(MRIO) hybrid	Optimization	Simulation	Survey	Backorder	Bullwhip Effect	Inventory Cost	Processing Cost	Transportation Cost	Deterioration Velocities	GHG Emissions	Inventory Level	Inventory Variability	Lost Sales	Service Level	Transportation Capacity	Transshipments Activities	Travelled Distance	Delivery Time	Evacuation Time	Flow Time	On Time Delivery	Lead Time	Utilization	Distribution center	Logistics	PI-HUB	Producer	Retailer	Transit Centre	Warehouse	Wholesaler
Information Sharing	Li et al., (2001)										x				x					x			x							x			x			x	x		x	
	Merkuryev et al., (2002)										x			x									x										x			x	x			x
	Fawcett et al., (2009)											x			x	x	x						x							x				x		x	x			
	Yang et al., (2011)										x				x								x										x			x	x		x	x
	Nativi & Lee (2012)										x		x		x	x																				x	x			
	Lotfi et al., (2013)	x																																						
	Wu et al., (2014)											x																												
	Constantino et al., (2015)										x			x						x													x			x	x			x
	Kim & Chai (2017)											x																												
	Prasoon (2017)										x		x		x																					x	x		x	
	Cannella et al., (2018)										x			x						x	x												x			x	x			x
	Yoon et al., (2020)							x																x												x				
Lateral Shipment	Banerjee et al., (2003)										x		x							x					x						x					x	x			
	Tiacci & Saetta (2011)										x									x					x												x		x	
	Tlili et al., (2012)									x	x				x	x				x		x	x		x												x		x	
	Nasiri et al., (2015)			x																x					x								x				x		x	
	Salehi et al., (2015)							x							x	x	x																x				x		x	
	Firouz et al., (2016)									x	x		x		x	x									x														x	
	Yan & Liu (2017)										x									x	x				x								x			x	x			
	Agarwal (2018)									x	x												x		x											x				
	Zhi & Keskin (2018)			x											x		x																x			x	x			
	Rabbani et al., (2018)			x											x	x	x																x	x		x	x			
	Avci (2019)										x		x		x	x	x								x								x				x			
	Yan et al., (2019)									x					x	x																		x					x	
Sustainability	Woensel et al., (2001)										x								x															x						
	Chaabane et al., (2008)							x								x	x		x															x		x			x	
	Halldórsson et al., (2009)	x																																x						
	Byrne et al., (2010)										x				x		x		x											x		x		x		x				
	Ramudhin et al., (2010)				x												x		x														x	x		x				
	Chaabane et al., (2011)				x												x		x															x		x				
	Dey et al., (2011)						x																																	
	Lee (2011)	x																	x																	x				
	Plambeck (2012)	x																	x															x		x	x			
	Chaabane et al., (2012)							x							x		x		x														x	x		x				
	Pan et al., (2013)										x				x		x																x		x		x		x	
	Lee & Wu (2014)										x						x		x															x		x	x		x	
	Dadhich et al., (2015)								x								x		x															x		x			x	
	Kellner & Igl (2015)										x						x		x															x	x	x				
	Tidy et al., (2016)						x												x																					
	Kaur & Singh (2018)							x							x	x	x		x																	x			x	
	Mangina et al., (2020)		x																x															x						

In the literature search, three different time concepts were found: delivery time, flow time and lead time. The difference between the three concepts can be defined by the descriptions. Firstly, delivery time is the time between the order loading on the vehicle and the delivery of the order. Secondly, the transfer time of all orders from the first destination to the last destination of the vehicle can be defined as flow time. Lastly, lead time is the time between placing the order and receiving it from the supplier from which the order was placed.

The following chapter focuses on the literature review of Physical Internet. The article where the concept of Physical Internet first appeared was published in 2010. For this reason, the literature review of the concept of Physical Internet consists of articles between 2010 and 2020. The summaries of the publications in the Table 2.1. are explained in Chapter 2.1.

2.1. Physical Internet

This chapter interprets Table 2.1. that summarizes the literature review of Physical Internet. Montreuil et al., (2010) presented a primary description of a core component of the physical elements that act as the basis for the Physical Internet network. Sohrabi and Montreuil (2011) exploratory analysis review conducted to assess the possible benefits involved by shifting apart from the existing modes of supply chain architecture. Lounes & Montreuil (2011) discusses Physical Internet as regards facilities, processes, and service construction and operations in the context of the material handling and service logistics culture. Ballot et al., (2011) introduced the idea of Physical Internet as an interconnected logistic network and studied the improving effect of Physical Internet on logistics topology of and its major performance. Montreuil (2012) conducted conceptual research of Physical Internet that explained business models and elements of Physical Internet. Montreuil et al., (2012a) enhanced the study of the previous research and focused on Physical Internet as an “open global logistics system” with its encapsulation, interfaces and protocols. Montreuil et al., (2012b) published a study of the seven-layer Open Logistics Interconnection (OLI) system to support logistics networks to interface inside the Physical Internet. Ballot et al., (2012) researched the Physical Internet, including the road-rail hub, with its framework of accomplishing the targets of the facility, determine tools to evaluate efficiency. Meller et al., (2012) studied Physical Internet's road-based transit center and, as a result, defined business models to include a template. Hakimi et al., (2012) developed the first simulators of Physical Internet -enabled environments and studied the economic, environmental and social impact of a wide-open mobility network across France for the distribution of Fast Moving Consumer Goods (FMCG). They compared the Physical Internet -enabled environments to non- Physical Internet environments. As a result of their simulations with the real data, the overall travelled distance is significantly reduced in the Physical Internet scenario. However, unlike our study, they did not consider sustainability. Similarly, Furtado et al., (2013) focused on Physical Internet and explore a Physical Internet -based transport model, and their simulation proved that the current classic supply chain of their case study is unsustainable, and Physical Internet helps to ensure sustainability by improving efficiency, reducing costs, and also reducing greenhouse gas emissions. Pan et al., (2013b) examined the advantages of introducing Physical Internet -enabled open logistics networks by assessing the effect of PI-hub activities on inventory for FMCG. Naccache et al., (2014) conducted a multi-agent simulation to compare the Physical Internet -enabled interconnected and integrated distribution systems also the consequences for inventory levels. Sarraj et al., (2014) evaluated the sustainability in Physical Internet similar to this study; however, they only considered the specialized containers that are used in Physical Internet. They simulated and analyzed a total of three scenarios, including Road-based Physical Internet, multimodal Physical Internet, and Physical Internet -without Manufacturing. According to their results, the utilization of transport vehicles increases by almost 17% with the use of Physical Internet. Also, the share of rail transport significantly increases and leads to a 60% reduction in CO_2 without increasing lead times or operational costs. In their results, the total cost was significantly lower in Physical Internet scenarios. Oktaei et al., (2014) also concentrated on the Physical Internet transit centers. They provided business models to prospective service providers for the functionality of implementing the Physical Internet. Pach et al., (2014) suggested a routing strategy for PI-hub railroad by analyzing the effect of various parameters on the evacuation time without internal system interruption. Loading was charged to be the system's bottleneck. Pan and Ballot (2015) assessed the perspectives of the application of open tracing container in FMCG supply chains by comparing the scenarios of with and without the use of open tracing containers. Their study showed that open tracing container reduces average inventory levels, daily transportation distances, and the number of rotation per open tracing container. Pan et al., (2015) proposed a simulation model to analyze the resource levels in a Physical Internet structure, however, unlike this study; their main purpose is to assess the inventory management policies for Physical Internet. Their results showed that Physical Internet can help to reduce the total logistics costs, inventory levels, transportation costs and holding costs while maintaining the same service level to the customers. Yang et al., (2015) studied inventory management problems in the Physical Internet for FMCG supply chain by identifying the optimal replenishment policies for hubs in order to minimize the total logistics costs. Their results showed that total cost and average inventory levels may reduce with the Physical Internet. Crainic & Montreuil (2015) conducted a Physical Internet research by focusing on interconnected city logistics. This was the first study of the connection between these two notions. In the context of FMCG logistics, Landschützer et al., (2015) researched containers within the concept of Physical Internet. As a consequence, they proposed the solutions which would allow the supply chain greater versatility. Montreuil et al., (2015) presented a review of the emerging products encapsulation transition and identified important prospects and obstacles for both business and academics in science and technology. Sallez et al., (2015) addressed the control of cross docking PI-hubs by focusing on the simulation of the problem of container routing. The study revealed that the proposed approach is effective for such problems. Tretola et al., (2015) mainly focused on a proposal to exchange data model to enable modular containers to be exploited interoperable. Ballot & Montreuil (2016) investigated a comparison analysis about equipment for transportation process of Physical Internet such as handling boxes. Analysis demonstrated that Physical Internet equipment provides a more efficient improvement. Chakroun et al., (2016) performed a case study of the city of Casablanca by proposing the concept of adopting current systems and transport systems by utilizing the widespread network of nearby agencies in the big city to boost the last mile deliveries. Kong et al., (2016) presented the first paper in the Auction logistics centre of Physical Internet to systematically propose a scheduling approach for trolley loading and auction trading by presenting an analysis of operational problems and work limitations prior to the implementation of Physical Internet -enabled scheduling. Qiao et al., (2016) explored a less-than-truckload decision-making problem through Physical Internet by introducing a dynamic pricing strategy to refine the carrier's offer price to increase predicted profit. Sallez et al., (2016) concentrated on Physical Internet containers with a case study in a road-rail PI-hub. The study's findings demonstrated the definition of activity in reality and its importance to usefulness. Treiblmaier et al., (2016) conducted a systematic literature study of the Physical Internet's most relevant elements, performance indicators, priorities, prospects and threats, promoting further gradual and thorough work with some main avenues for prospective study. Venkatadri et al., (2016) established a traditional and Physical Internet network system model as an arrangement of feasible point-to - point dispatch models among city pairs based on key performance indicators. Findings showed that the Physical Internet's gains were considered to be in minimizing the cost of the inventory and the total cost of the logistics. Wang et al., (2016) mainly focused on the emerging features of the Physical Internet-based manufacturing system through the analysis of centralized and decentralized operation modes. Zhong et al., (2016) conducted a case study to introduce a Physical Internet-enabled Manufacturing Executive System (PIMES) that is based on RFID for real-time data collection for Mass-Customized workshop. An excellent performance appears as the result. Sternbereg & Norman (2017) carried out an analysis of the literature to thoroughly examine the definition and formulate a work agenda. They also offered a viewpoint for outsider and industry acceptance of Physical Internet research, as well as significant consequences for policy makers and researchers. Yang et al., (2017a) suggests a novel vendor-managed inventory approach by designing a non-linear, simulation-based optimization model that uses the Physical Internet with stochastic demands. The findings indicate that the Physical Internet may minimize the overall cost of logistics while providing a similar or superior quality of service to target consumers. Yang et al., (2017b) explores the adaptability of inventory systems in the Physical Internet utilizing interconnected logistics services by suggesting a simulation-based optimization method. The findings indicate that the Physical Internet inventory model outperforms the existing classic inventory models in terms of strength, with greater flexibility. Ji et al., (2019) conducted a simulation study and measure the advantages of Physical Internet from a cost performance perspective. The results of computational experiments show that it can provide significant cost savings while achieving a comparable or better service level. Treiblemainer (2019) presented a conceptual paper on a combination of blockchain and the Physical Internet including a theory-based research agenda proposal. Matusiewicz (2020) defined the systematic planning of the European Union for the Physical Internet framework as well as the identified initiatives, projects and resources that already operate in the logistics sense as samples of the Physical Internet model. Chargui et al. (2020) considered the Road-Rail PI-hub sustainable truck scheduling and PI-containers grouping problem by developing multi-agent system based model. They proposed a mixed integer linear programming model to evaluate the performance of the multi-agent system based model developed. Qiao et al. (2020) investigated a less-than-truckload request pricing and selection problem by developing an optimization model coupling dynamic programming and integer programming.

Information sharing is a significant feature of Physical Internet. Thus, the following chapter explains the summaries of the information sharing publications in Table 2.2. in Chapter 2.2. The publications start from 2001 to 2020.

2.2. Information Sharing

The studies about information sharing strategies in the literature are indicated in Table 2.2. Li et al., (2001) examine the impact of information sharing strategies on performance in the supply chain. The strategies they concentrated on are (1) order information sharing where every stage of the supply chain only knows the orders from its immediate downstream stage; (2) demand information sharing where every stage has full information about consumer demand; (3) inventory information sharing where each stage shares its inventory levels and demand information with its immediate upstream stage; and (4) shipment information sharing where every stage shares its shipment data with its immediate upstream stage. The findings show that information sharing increases the efficiency of the supply chain total product cost and fill rate while the volatility in demand is small. Merkuryev et al., (2002) used simulation to analyze the impacts of two types of information sharing strategies that are decentralized and centralized information. In addition to the information sharing strategies, they also compared min-max and stock-to-demand inventory control policies on the bullwhip effect on a four-echelons supply chain. Fawcett et al., (2009) performed case study interviews to analyze the growth and comparative impact of information-sharing capability in a supply chain over time. Connectivity and ability have seen to lead to better results. Yang et al., (2011) practiced the simulated beer game to analyze the robustness of several information-sharing strategies in multiple uncertain environments. As a result of the analysis, e-shopping obtained to be the most robust output in uncertain environments. The effect of RFID information sharing strategies on a decentralized supply chain of reverse logistics processes was analyzed by Nativi & Lee (2012). With the creation of further returns at the end of the analysis the economic gains are substantially improved. Therefore, while economic effects are noted, environmental benefits are much important. To order to improve the quality of corporate success to the manufacturing industry, Lotfi et al., (2013) examined and analyzed the efficacy of information sharing in supply chain management. As a consequence, the advantages and boundaries of information sharing have been established to contribute to enhanced supply chain collaboration between companies. Wu et al., (2014) introduced a novel research model to explore the relationships between variables dependent, information sharing and collaboration, and performance in the supply chains. Constantino et al., (2015) examined the effect of information sharing on ordering policies to enhance the efficiency of the supply chain by comparing two models that are a traditional policy and a mechanism of coordination focused on ordering policy through simulation. Kim & Chai (2017) built a survey to explore the effect of supplier innovativeness on collaboration and agility in the supply chain by adapting innovation theory to diffusion. Prasoon et al., (2017) built a two-echelon supply chain structure using simulation to compare centralized and decentralized supply chains in order to minimize the cost. Cannella et al., (2018) studied a simulation model to analyze two main sources of information inaccuracies that are errors and delays in a supply chain. Their study focused on demand error, demand delay, demand variability and average lead times. They used bullwhip effect, inventory variability and average inventory level as the performance indicators. Yoon et al., (2020) performed a research on procurement decisions and information sharing in a supply chain under three-tiered disruption risk. The findings revealed that information sharing allows the procurement choices of the supplier more cautious, i.e. bringing more inventories, but the decision to buy the first-tier is based on the efficiency of the second-tier.

Another significant feature of Physical Internet is lateral shipment. Thus, the following chapter focuses on the literature review of lateral shipment. The summaries of the publications in Table 2.2. are explained in Chapter 2.3.

2.3. Lateral Shipment

Simulation and lateral shipment studies that are demonstrated in Table 2.2 are explained in this chapter. Banerjee et al., (2003) simulated a two-echelon supply chain network that includes different operating circumstances to examine the effects of two lateral shipment approaches that are Lateral shipments based on availability (TBA) policy and Lateral shipments for inventory equalization (TIE) policy. Similar to Banerjee et al., (2003), Tiacci and Saetta (2011) implemented a simulation of two-echelon supply chain network to analyze the relative effectiveness of TBA and TIE policies to reduce the mean supply delay of a non-repairable item. They also compared their results with a classic policy of no lateral shipments. Tlili et al., (2012) proposed an empirical simulation of an inventory model based on three components: the optimization inventory model, the shipment policy and the rationing policies to minimize total system cost to define the effective parameters on shipment benefits. Nasiri et al., (2015) analyzed the impact on place, distribution and inventory decisions of distribution network centers of the lateral shipments by performing a nonlinear mixed-integer programming model. The findings revealed that lateral shipment may improve supply chain efficiency in terms of process costs, safety stock, and warehouse capacity. In the framework of a lateral shipment study inside an inventory network, Salehi et al., (2015) proposed an efficient heuristic-based memetic algorithm by modeling as a nonlinear mixed-integer programming model. Firouz et al., (2016) considered a problem considering multi-sourcing, supplier selection, and inventory problem with lateral shipments by a decomposition based heuristic algorithm, along with a simulation model to minimize total cost. Yan and Liu (2017) conducted simulations of multi-echelon supply chains to analyze by comparing them respect to average stock level, customer satisfaction rate, and transshipment cost. Agarwal (2018) presented two models of a single-echelon supply chain to compare continuous and periodic inventory policies, by using a discrete-event simulation on SimPy. Zhi & Keskin (2018) proposed two approach algorithms that center on theoretical annealing heuristics and GRASP. They studied a multi-product, three-stage network of direct and lateral shipments to assess the most effective network structure to minimize the total fixed facilities and transport costs. The findings of the experiment indicate that the simulated annealing and GRASP algorithms surpass the best heuristic in the literature based on the distributed scope for both the efficiency and duration of the option, especially for more rigorous capability large-scale problems situations. A heuristic, theoretical graph algorithm was proposed by Rabbani et al., (2018) to identify a multi-echelon supply chain structure including lateral shipments. The results demonstrate that in a brief period of time, the proposed algorithm generates responses of decent quality. Yan & Liu (2018) utilized the network dynamics methodology to create a multi-echelon supply chains-focused product distribution model, involving manufacturers, retailers, and retailers. Evaluation demonstrated that the average inventory level from the single- to four-chain models has altered relatively and deteriorated. With rising shipping rates, the typical customer satisfaction rating's shrinking range is steadily decreasing. Additionally, Avci (2019) carried out a simulation-based modeling of a retail chain comprising numerous distribution centers and multiple retailers. In the context of disruptions, she investigated the effect of lateral transshipment and significantly increased shipments on supply chain performance. Yan et al., (2019) conducted a case study by designing a continuous inventory review model with two echelons and multi-location without time restrictions. The purpose is to minimize total costs while being motivated by the penalty system on placing orders, including both limited with queuing time limitations. Aside from the stock-outs, lateral shipments and emergency deliveries further maintain supply and demand. The literature review of information sharing and lateral shipment which are also the features of the Physical Internet are summarized. As the result of these features, the Physical Internet can contribute sustainability. Thus, the following chapter focuses on the literature review of sustainability. The summaries of the publications in Table 2.2. are explained in Chapter 2.4.

2.4. Sustainability

The studies of greenhouse gas reduction and sustainability in transport are also demonstrated in Table 2.2, Woensel et al., (2001) focused on environmental sustainability and evaluated GHG emissions of road vehicles in the context of traffic with a simulation model. Results show that traffic flow emissions depend mainly on the speed and number of vehicles. Chaabane et al., (2008) carried out operation research by implementing a mathematical programming model for the structure of an eco-friendly supply chain system also with the content validity of carbon emission costs. The new model provides decision-makers with a quantitative decision support tool for identifying the tradeoffs among total logistics costs and minimizing carbon footprints. Halldórsson et al., (2009) claimed that, rather than a feasible alternative, SCM should be viewed as one of the sources of the sustainability problem. Three common techniques are introduced as an answer to explain this challenge: "(1) enhancing the use of current SCM approaches, (2) aligning SCM with social and environmental concerns and (3) rejecting SCM in its current fashion to address environmental and social concerns and suggesting a replacement strategy." Byrne et al., (2010) identified the techniques already utilized in the analysis of the environmental supply chain and explored the prospective utilization discrete event simulation as a method to capture the dynamic nature of modern SC development and implementation. As a result, the proposed model demonstrated the ability of discrete simulation of activities to conveniently correspond CO_2 emission reductions to potential financial gains, making it a great method for experimentation in decision making. Ramudhin et al., (2010) clarified the supply chain structure to assess the trade-offs for both total logistics costs and carbon-reducing applying a multi-objective mixed-integer linear programming method that is solved through goal programming. Chaabane et al., (2011) presented a systematic approach to tackle sustainable supply chain management problems where greenhouse emissions and overall logistics costs are addressed, such as the selection of suppliers and subcontractors, technology development and the range of modes of transport, via the application of a multi-objective mixed-integer linear programming method to assess the trade-off between economic and environmental concerns. Dey et al., (2011) performed a literature review to evaluate the present state of sustainable practices in the field of supply chain management, more precisely supply chain logistics activities, as well as to generate ideas and guidelines for businesses to pursue sustainable products and services. Lee (2011) performed a case study to increase the perception of carbon emissions within the automotive supply chain management. The findings demonstrate that an organization will define and calculate the overall benefit of the carbon footprint for each car unit by defining and calculating the carbon footprint of the key elements and goods from the major suppliers. Plambeck (2012) presented details of how explicitly and indirectly regulated businesses would efficiently mitigate greenhouse gas emissions. Businesses will mitigate the consequences of climate change by intervening quickly to decrease greenhouse gas emissions. The scale of profitably reducing emissions, nonetheless, remains likely to be inadequate. Chaabane et al., (2012) implemented a mixed-integer linear programming dependent method to assess the tradeoffs among economic and environmental targets within varying cost and operational approaches in the aluminum industry. The findings indicate strengthening existing regulations and Emissions Trading Schemes. Additionally, to push a practical sustainability policy, the global level should also be harmonized. Pan et al., (2013) focused on environmental and economical sustainability and studied the effect on reducing CO_2 emissions from transport with rail and road modes. Finally, the results show a relative reduction in CO_2 emissions of only 14% by road transport and 52% by joint road and rail transport. Lee & Wu (2014) concentrated on environmental sustainability, particularly carbon emissions, to define eco-efficient freight transport alternatives in the logistics system through a case study of Westgate Ports, based in Melbourne, Australia, through a multi-methodological methodology that allows businesses to effectively catch and evaluate various alternatives in the use of eco-efficient logistics. In an effort to minimize greenhouse gas emissions, Dadhich et al., (2015) showed how different intervention strategies throughout the supply chain can be utilized to define and evaluate the source of emissions during the product life-cycle by applying a hybrid life cycle assessment technique. Kellner & Igl (2015) also focused on economical sustainability and analyzed CO_2 performance of different freight forwarder networks and found that the reduction of GHG emissions is efficient as decentralized consolidation of shipments is applied. Tidy et al., (2016) studied the influence of supplier relationship management in reducing greenhouse gas emissions from food supply chains in the UK supermarket sector with a supplier engagement. Findings clarify that improvement is being made in Sustainable Supply Chain Management but variable in practice is the usage of Supplier Relationship Management for emission mitigation. When resource efficiencies can be obtained across the route, carbon emissions can be minimized and gains can be made financially, the resultant gains pass to manufacturers, customers and community. Kaur & Singh (2018) proposed an eco-friendly procurement and logistics model for a supply chain that is primarily focused on real-time data and provides an optimal decision on sustainable procurement and transport. Mangina et al., (2020) evaluated road freight activities in Europe on the basis of two indicators that are efficiency of truck usage or truck loading each route and sustainable CO_2 emissions each route. They implemented various algorithms, namely Horizontal Cooperation, Pooling and

Physical Internet. This study shows that a holistic view could be provided for logistics and supply chain management through implementing advanced algorithms and helping to enhance sustainability, lessen inventory costs and accelerate the time-to-market of the products with a greater environmental result, decrease waste in supply chains and contribute to the Sustainable Development Goals. The publications found in the research for the literature review is examined and a research gap is discovered.

In the next chapter, this research gap is defined and the contributions of this study to the literature while fulfilling this gap are explained.

2.5. Contribution of the Thesis

The classic supply chain is inadequate in the context of sustainability that contains social, environmental, and economic pillars; however, Physical Internet is designed to enhance the classic supply chain in that manner. The necessity of the possible answer to these sustainability issues is continuing to grow with the increasing emphasis on sustainability due to the increasing global warming. In this study, the Physical Internet concept has been compared with the existing supply chain in terms of sustainability to help prevent this global warming. In addition, sustainability cannot be accomplished unless the three pillars of sustainability are present. For this reason, all three pillars of sustainability must be taken into consideration. However, while the literature review of the Physical Internet is conducted, it is observed that only the environmental and economic sustainability are focused on, but the social sustainability is not been underlined. Furthermore, the lateral shipment is examined only among PI-hubs in the studies that focus on the Physical Internet. Unlike the publications in the literature, this study addresses the social pillar of sustainability as well as the economic and environmental pillars. Supply chain network models of classic supply chain and Physical Internet concepts were created and compared with a hypothetical but realistic supply chain case study. Two simulation models were created for this case study using Arena Simulation Software.

Often the open global and transparent network provided by the features of the Physical Internet provides a solution to supply chain sustainability issues. Thus, this study has many contributions. First, this study reveals that if the Physical Internet system is implemented to the supply chain, the shipping duration can be reduced and the social pillar of sustainability could be strengthened. Furthermore, this study also indicates that the lateral shipment between PI-hubs in the Physical Internet system may be generalized and implemented between retailers. This approach can further increase the decisive aspect of Physical Internet on sustainability. In addition, the environmental part of this approach is that the damage inflicted by transportation to environment (seen in Figure 1.1.) can be decreased without adjusting the quantity of vehicles and also the cost for the economic pillar.

In the following chapter, the concept of Physical Internet is explained in detail and illuminated together with the foundations' framework of the Physical Internet.

CHAPTER 3
PHYSICAL INTERNET

The Physical Internet was presented by Montreuil (2011) as a response to the "Global Logistics Sustainability Grand Challenge" (Meller et al., 2012). Physical Internet implements internet policies in the physical environment. The Internet transfers data across the world by separating it into information packets with header information that relays how separated packets have to be re-assembled, regarding Transmission Control Protocol/Internet Protocol (TCP/IP) (Zacharia, 2017). Standardized protocols mean the process is platform-independent such as Mac, Linux, Microsoft Windows, etc. Zacharia (2017) provides an example, "If a 25MB photo from Bethlehem, Pa., to Sydney, Australia, that file will be broken into separate packets that are automatically routed through the most efficient network path. One packet may go through New York, London, and Dubai and arrive in Sydney, while another packet of information may route through Los Angeles to Tokyo to Sydney. Once the individual packets arrive, the image is reconstructed and you get a full picture. This happens seamlessly." How information flows over the internet is an excellent example to show why the Physical Internet is needed to adapt to the logistics industry into a lower emission future model. The Physical Internet does not transmit information: it transmits packets with embedded information (Montreuil, 2011). Critical business processes are already done with technological advances over the internet. The logistics industry can take the internet model and incorporate into their business practices for more efficient physical ordering and delivery services. For example, it would make logical sense that products should be leaving a hub that is closest to the drop off destination point. The Physical Internet also allows multiple users within the network resulting in full horizontal and vertical collaboration. Instead of having multiple separate users or supply chains business process efficiency can be optimized together into one model reducing order errors, distance challenges, load capacity, and overall emissions. Recognition of the importance of the Physical Internet has already begun around the world. For example in Europe, the roadmap to success includes interoperability between networks by 2020, a fully visible supply chain by 2030, a fully functional and operating open logistics network by 2040, and culminating with the new reality of Physical Internet by 2050 (ALICE, 2015).

As cities and urban areas continue to develop along with increasing population levels, they have begun implementing specific restrictions, particularly within the city centers. This has caused the logistics industry to reassess business operations to now require consolidation to reduce the number of trucks and delivery points to maximize efficiency on routes. Collaboration is also achieved with goods, distribution hubs, and competitors. This could potentially also lead to better land use and city planning efforts (ALICE, 2015).

Physical Internet embraced three pillars of sustainability, which are environmental, economic, and social, by handling the signs of today's logistics operation as confirmation of the existing system's unsustainability (Meller et al., 2012). The Physical Internet introduced the concept of interconnection (Ballot et al., 2016; Montreuil et al., 2012a). Physical Internet uses the Internet of Things to construct information interaction through the network (Ballot, 2019). Physical Internet enables the transition from an exclusive supply network to an open global procurement web, although, the existing logistics organizations, manufacturers, distributors, and retailers often rely on private supply chains (Montreuil, 2011). The purpose of the Physical Internet is the interconnection between highly diverse and separate logistics channels and the creation of a growing decentralized logistics network (Pan et al., 2013b). Figure 3.1. demonstrates the framework of Physical Internet foundations (Montreuil et al., 2012a). The Physical Internet is the logical development and integration of container standardization and smart technologies, internet service communication, cloud computing (Ballot et al., 2011). The Physical Internet has been enabled by the environmental, economic, social efficiency, and sustainability of the method physical items are moved, stored, realized, supplied, and used worldwide, even in the widest context of logistics (Montreuil, 2011). Physical Internet intends to empower the web of logistics increasingly accessible and international at the same time while being accurate, sustainable, and responsive (Hakimi et al., 2012).

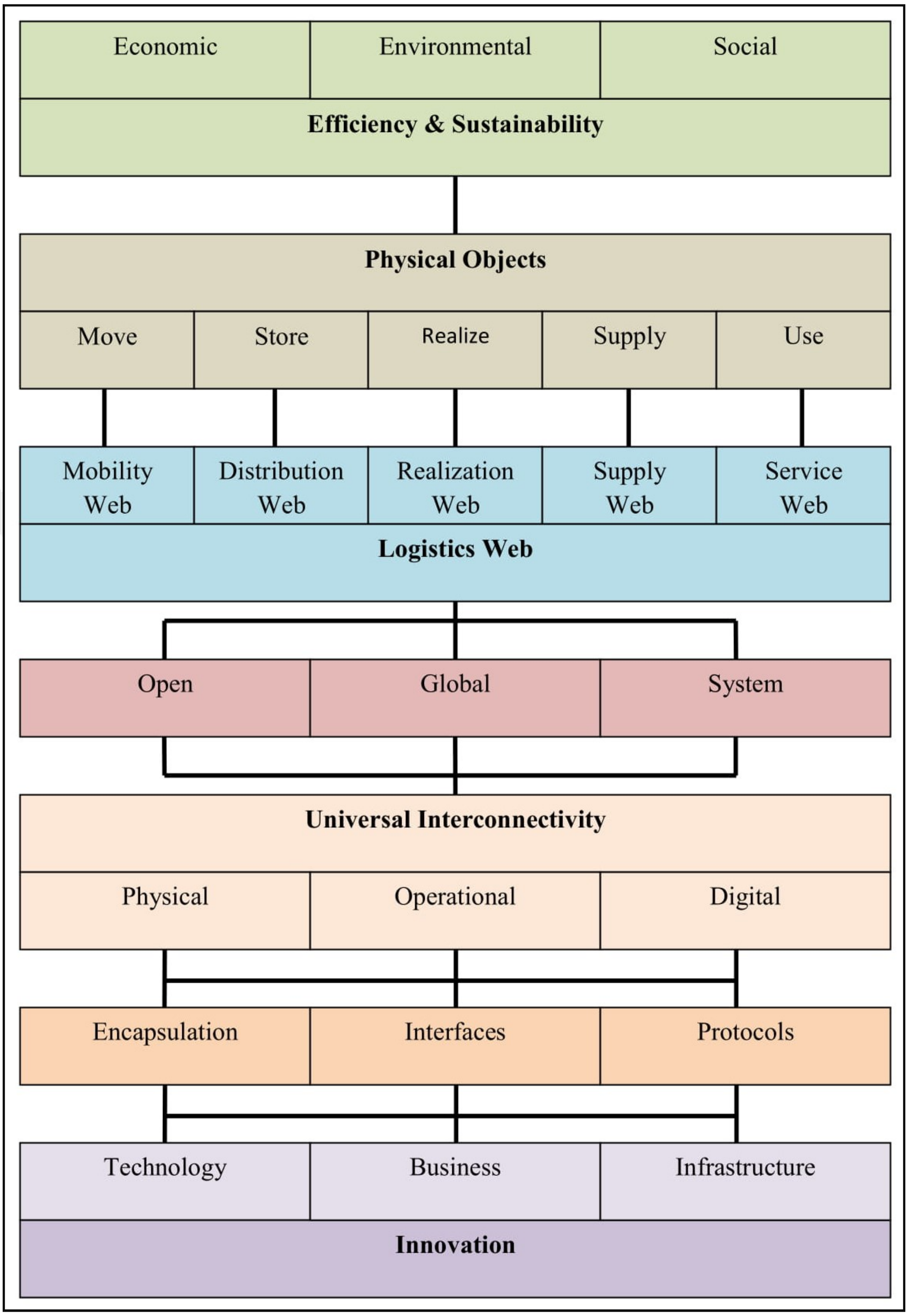

Figure 3.1. Physical Internet Foundations Framework (Montreuil et al., 2012a)

Moreover, as logistics is, therefore, a wide term, Montreuil et al., (2012a) mentioned logistics with its five component webs:

1. Mobility Web: The primary objective of a mobility web is to represent the movement (transport, handling) requirements, including people and other living beings and also physical objects including such goods and materials.

2. Distribution Web: The objective of a distribution web is to meet the requirements of physical product delivery. These products are contained in modular, renewable, smart, global standard PI-containers in a Physical Internet sense.

3. Realization Web: Realization involves the manufacture and dismantling of physical products, from materials to components and modules to products and systems. The Realization Web is intended in the context of digital cloud computing to allow physical products to be realized in a centralized manner utilizing accessible centers of realization from all over the globe.

4. Supply Web: The objective of a supply web is to complete the requirements for supplying physical products by sourcing, receiving, purchasing, and ensuring entrance to materials, parts, assemblies, products, as well as systems.

5. Service Web: Service Web tends to concentrate on the availability of physical products services. Specialists are often expected to be present remotely through mobile phones; the availability of sensor-fed data, and physical (evaluation) equipment held on the Mobility Web and managed just-in-time by staff members.

The transparency of the Physical Internet simply means that all its constituents, enablers, and operators have to contemplate and function in terms of transparency for an open global system (Montreuil et al., 2012a). Information flow is transparent and each tier can reach information on any tire's inventory level. Unlike classic supply chain understanding, PI-hubs provide the stock replenishment from any point in the chain, including inventory relocation between other PI-hubs within the Physical Internet. PI-hubs are open to all users and reachable. In addition, retailers can order from any available PI-hub, not from a fixed PI-hub, unlike the classic supply chain. In other words, retailers have multiple resources (i.e., PI-hub options) when ordering (Pan et al., 2015). Next, universal interconnectivity is the main factor for an open, global, efficient, and sustainable Physical Internet system with high performance with its three components that are encapsulation, interfaces, and protocols (Montreuil, 2011).

Physical Internet encapsulates physical products in modular and smart PI-containers instead of dealing directly with physical products (Montreuil et al., 2012a; Montreuil, 2011). As seen in Figure 3.2., PI-containers vary widely from large to small in modular dimensions (Pach et al., 2014) and each is smart and secured (Sarraj et al., 2014). These smart and modular containers have also increased an informational, communicational, and decisional capacity that assists to play an active role in processes (Pach et al., 2014).

Figure 3.2. Physical Internet Containers

Another level of universal connectivity is interfaces that Physical Internet contains four: fixtures, devices, nodes, and platforms (Montreuil, 2011). Montreuil et al., (2012a) defined the four interfaces as follows:

Fixtures: Operationally normal and standardized physical fixtures are required at the simple practical level to insure that PI-containers can function seamlessly across the Physical Internet.

Devices: Devices are crucial interfaces at prior level of information and communication. Any smart PI-container has a smart tag to serve as its representation linked to the Internet of Things.

Nodes: The logistics PI-nodes are essential interfaces at a greater operating stage. For instance, PI-hubs allow the seamless shipment of PI-containers from transporters to transporters through all the Physical Internet.

Platforms: Digital middleware platforms are principal interfaces to empower the routing of PI-containers through the Physical Internet from origin to final destination.

In the next chapter, the simulation model of the transparent and fully technological Physical Internet concept created with the information given in this chapter while explaining definition of the problem.

CHAPTER 4
PROBLEM DEFINITION

There are several problematic inefficiencies in the classic supply chain such as high backorders due to long lead times, high inventory levels, and cost caused by inadequate information flow. These inefficient factors are the main cause of the sustainability problems of the supply chain. As explained in Chapter 1, a radical change in supply chain structures is required due to the increasing importance of sustainability. This change should affect all three pillars of sustainability: environmental, economic, and social. It is seen that Physical Internet, which is explained in detail in Chapter 3, can be a comprehensive solution to this sustainability problem. Thus, the main focus is the transparent information sharing of the Physical Internet between PI-hubs and PI-containers to see the difference between the supply chain structures in the broad concept of sustainability because these are the features that make Physical Internet effective in the field of sustainability. In response to the supply chain unsustainability, a comparison is required to analyze the difference between the classic supply chain structure and the Physical Internet structure in terms of three pillars of sustainability. A hypothetical case study which is also realistic was created to make this comparison. The supply chains in this case study consist of four-echelons. The most preferred facilities were selected by researching the literature to find realistic solutions to the sustainability problem. Accordingly, the preferred facilities for the classic supply chain include the producer, warehouse, distribution center, and retailer. Also, the Physical Internet consists of manufacturers, PI-hubs, and retailers. Production time is set as 1.5 minutes in the produces for each item in the structures. Moreover, the Physical Internet performs very efficiently inside the FMCG supply networks (Sarraj et al., 2014). Furthermore, the cost of FMCG inventories corresponds to 40% of the total logistics cost (Pan et al., 2013b). Thus, the product type is determined as FMCG because it contributes to both the Physical Internet focus and the economic pillar of sustainability. The three products that cover the product flow in the models are the same type of products but from different companies. The products come from different producers and are collected in the same warehouse and distribution centers or PI-hubs in the supply chains. The delivery process can be started if the load is equal to or greater than the minimum truckload that is calculated according to the load factor value on the experimental factors that are 0.50, 0.75, and 1.00. 3^{rd} party logistics service is used for the delivery process to evaluate transportation which is the second biggest contributor to the environmental pillar as demonstrated in Figure 1.1. Moreover, the transportation mode that is utilized throughout delivery processes in the case study is road transportation since Kellner & Igl (2015) stated that only road transport alone generates approximately 20% of the overall EU CO_2 emissions and also 28% of total GHG emissions in the USA. Two simulation models are created for the case study: the classic supply chain and Physical Internet.

In the next chapter, the classic supply chain model is detailed. In addition, in Chapter 4.2, simulation model created for Physical Internet is explained in detail with algorithm flowcharts.

4.1. Classic Supply Chain Model

The classic supply chain model is a multi-tier supply chain that consists of four-echelons that are three producers, one warehouse, two distribution centers, and six retailers. This simulation model shows a hierarchy that starts with producer facilities to retailers. Each tier is informed by its next tier and each tier can reach only information of the previous tier. Production flow starts with producers. After products are ready, the warehouse keeps stock and delivers it to each distribution center for their orders. Distribution centers can only send an order to the warehouse and cannot reach inventory information before ordering. Each retailer is assigned to a specific distribution center and only can send an order to the distribution center that it is assigned. Figure 4.1. indicates the classic supply chain model. In the figure, retailers 1, 2, and 3 are assigned to distribution center 1; retailers 4, 5, and 6 are assigned to distribution center 2. This figure also shows the distance between the facilities. These distances are calculated on the coordinate plane symmetrically and hypothetically, inspired by real-life examples. The facility positions and numbers in proportion to the distances are also harmonized according to the most common real-life examples. In case of insufficient inventory at the warehouse and distribution centers, the waiting orders are assumed as backorders.

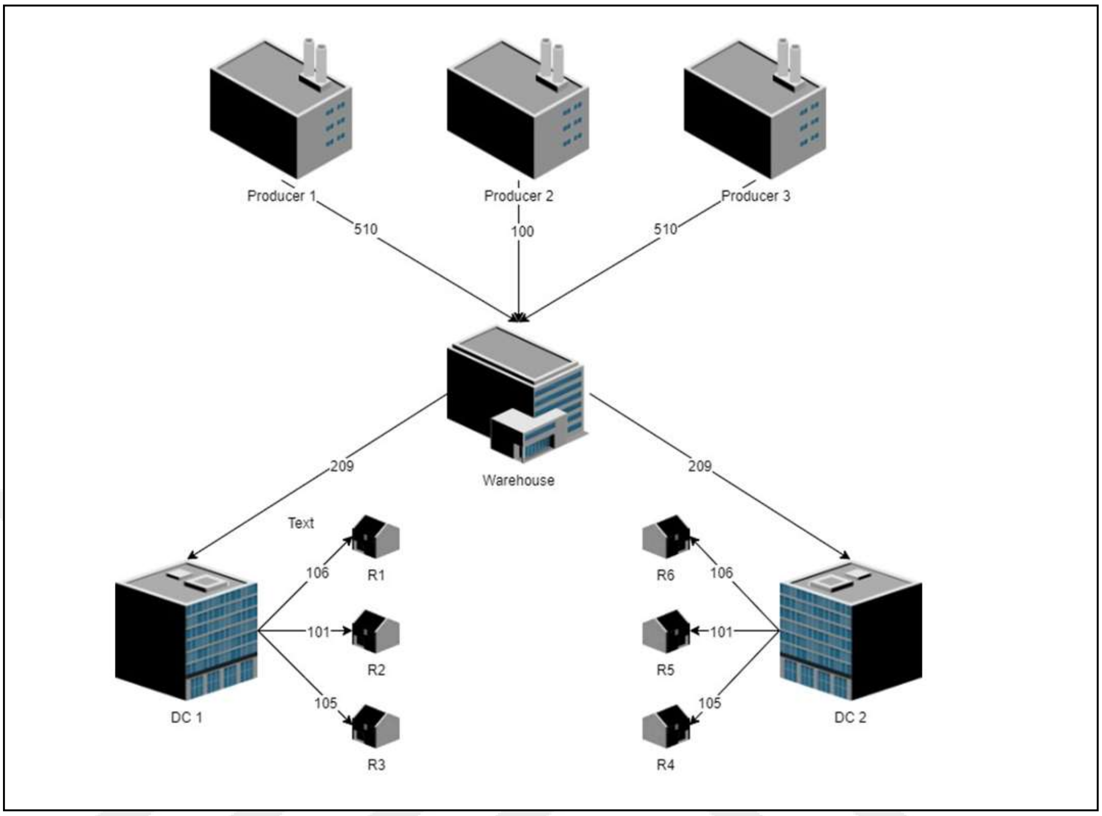

Figure 4.1. Classic Supply Chain Model

In Chapter 4.2, simulation models created for Physical Internet are explained in detail with algorithm flowcharts.

4.2. Physical Internet Model

Physical Internet is a technology-powered transparent chain that is very different from the classic model as stated in Chapter 3. Thus, there is transparent information and product sharing between each facility. For this reason, more distance details are given in Figure 4.2. than Figure 4.1. because all three PI-hubs can order products from the producer and also provide lateral shipment between each other. The distance values shown are calculated according to the same coordinate plane as the classic supply chain model. The figure also demonstrates that the distances and structural positioning in the Physical Internet model are identical to the classic supply chain model. However, the Physical Internet model contains three PI-hubs instead of a warehouse and two distribution centers.

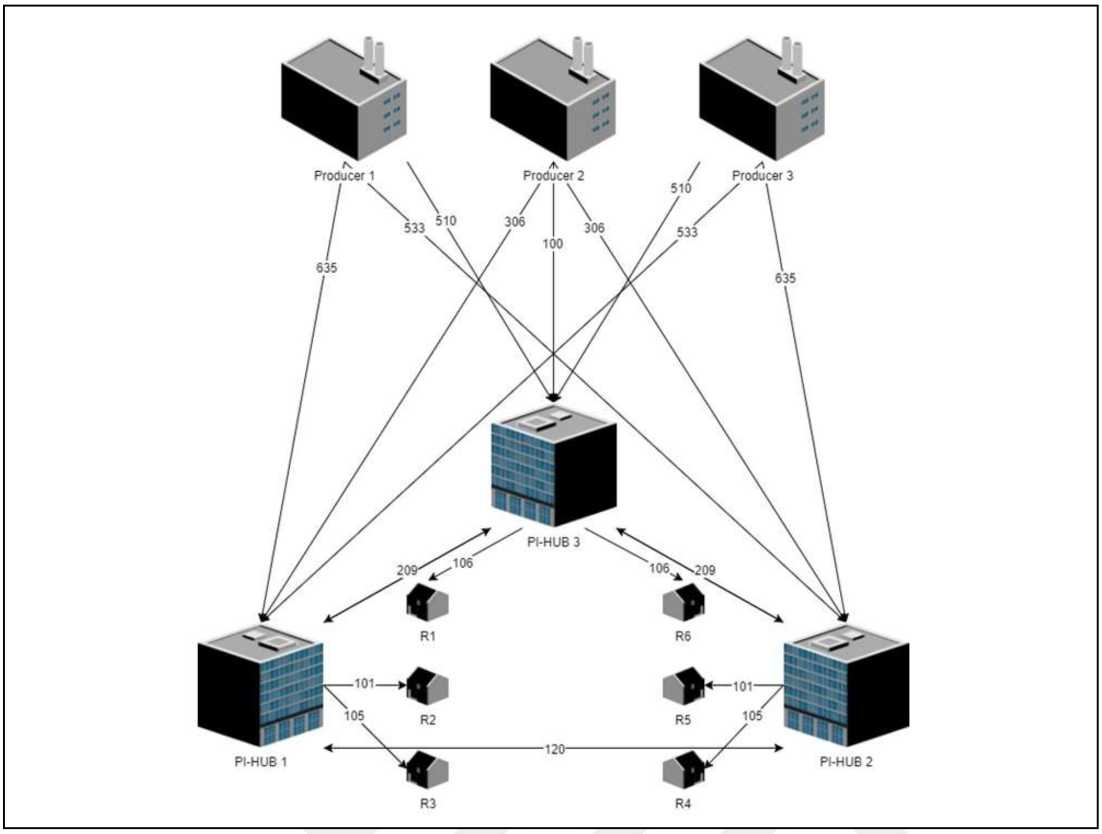

Figure 4.2. Physical Internet Model

The simulation model starts with the first arriving customer to the retailers. Upon the arrival of the first customer, the process order fulfillment process is visualized in Figure 4.3. If inventory of $retailer_i$ for t type of product ($INV_{p_t r_i}$) is sufficient to meet the demand arriving to $retailer_i$ for t type of product ($demand_{p_t r_i}$), the request is met and the process is completed. Otherwise, however, Total backorder amount for t type of product at $retailer_i$ ($B_{p_t r_i}$) is increased by $demand_{p_t r_i}$. Later, the adequacy of total expected order amount from the producer of t type of product to $retailer_i$ ($\sum EOA_{p_t r_i}$) to $B_{p_t r_i}$ at that moment is measured. If the amount is insufficient, the flowchart in Figure 4.4. starts. If $\sum EOA_{p_t r_i}$ is insufficient for $B_{p_t r_i}$ or if $INV_{p_t r_i}$ is equal to or less than reorder point of retailers (ROP^r), the flowchart specified in Figure 4.4. is started and an order is sent to the PI-hub with the minimum estimated time of arrival of the order of $retailer_i$ for the t type of product from $PI - hub_s$ ($ETA_{h_s p_t r_i}$). When sufficient conditions are not provided for ordering, the estimated time for the next order period is calculated to be shared with PI-hubs. PI-hubs use this information before deciding on the lateral shipment by taking advantage of the transparency provided by Physical

Internet. Meanwhile, orders registered as backorder are put on hold until inventory reaches a sufficient amount. The waiting period ends when the order is received and the inventory reaches a sufficient amount. At the same time, the inventory control process is started while the request is met and the order fulfillment process at retailers ends.

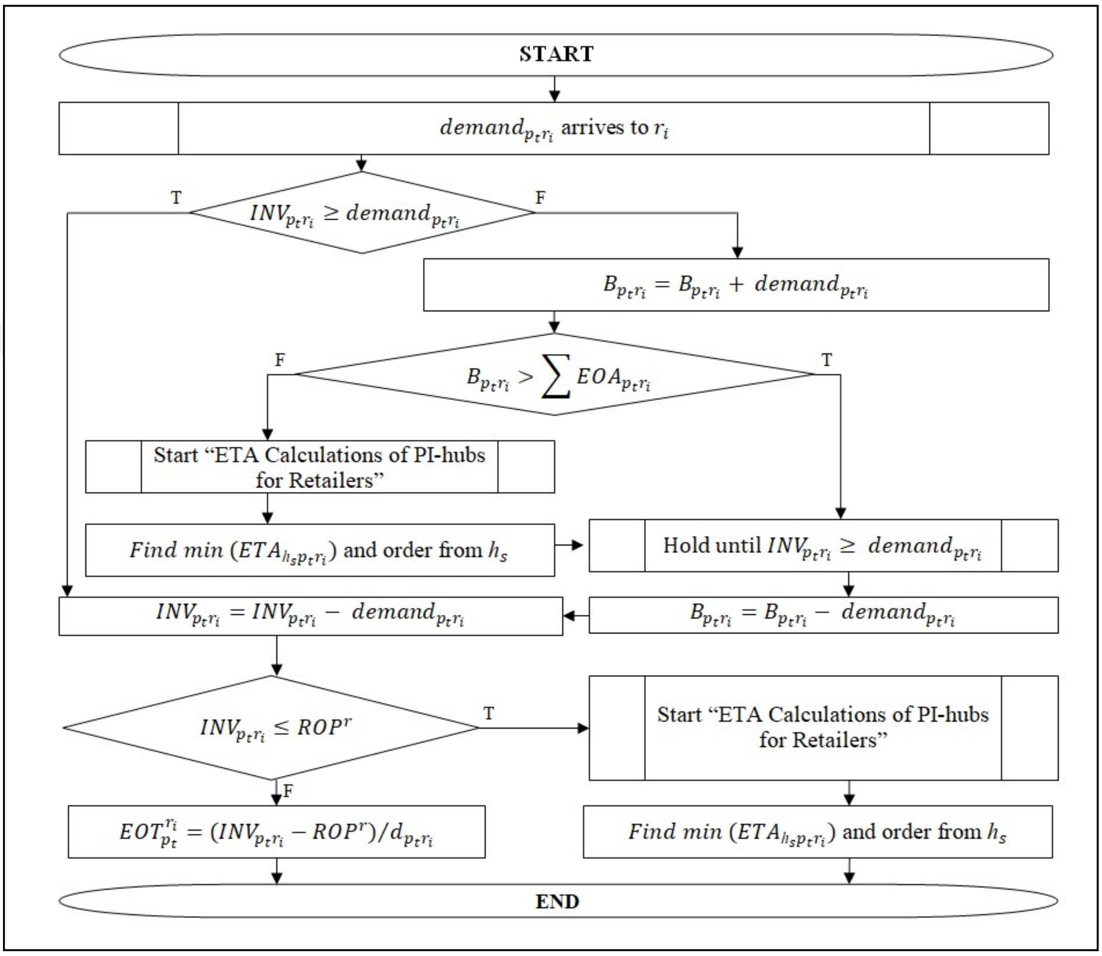

Figure 4.3. Order Fulfillment Process at Retailers for Physical Internet

The facilities in the structure of the Physical Internet simulation model benefit from the interconnection feature within the scope of Physical Internet during the ordering process as seen in Figure 4.4. When the process is started, estimated ordering time of $retailer_i$ for the t type of product ($EOT_{p_t}^{r_i}$) is reset. PI-hubs start to be evaluated from PI-hub1 until all PI-hubs are evaluated. Once inventory of $PI - hub_s$ for t type of product ($INV_{h_s p_t}$) is sufficient for order amount of $retailer_i$ for t type of product ($OA_{p_t r_i}$), estimated supply time of the order of $retailer_i$ for the k type of product from $PI - hub_s$ ($EST_{h_s p_t r_i}$) is determined as current time in simulation ($TNOW$). In the next step, containers and order being prepared at the facilities of h_s are evaluated. Estimated time of arrival of $container_a$ for the t type of product arriving to $PI - hub_s$ ($ETA_{c_a h_s p_t}$) and the order being prepared for t type of product of $PI - hub_s$ with the n^{th} early estimated time of arrival ($ETA^{n}_{h_s p_t}$) are sorted in ascending order. This process continues until the sufficient amount is found. When sufficient amount is obtained, $EST_{h_s p_t r_i}$ is determined. If all containers and orders being prepared are evaluated and no sufficient amount is found, $\widehat{ETA}_{h_s p_t r_i}$is determined as the final termination time of simulation ($TFIN$). Afterward, vehicle competence is observed. The reason is that after the order has been supplied, the order gets stuck in minimum truckload ($MinTL$) obstacle due to the load factor. This hurdle creates a bottleneck, causing a delay in delivery. For this reason, vehicle occupancy helps to determine $\widehat{ETA}_{h_s p_t r_i}$ by participating in the examination in this process. First, after the order is supplied and loaded on the vehicle, the part of the order that cannot be loaded is calculated by defining it as remaining load after orders are loaded on the vehicle at $PI - hub_s$ (RL_{h_s}). The current waiting truckload in the vehicle at $PI - hub_s$ (WTL_{h_s}), total backorder amount that will be supplied before $OA_{p_t r_i}$ for t type of product at $PI - hub_s$($B^{B}_{h_s}$) and $OA_{p_t r_i}$ are summed. Next, it is divided by vehicle capacity (VC) and the result is rounded down to find the number of vehicles required. The number of vehicles required is multiplied by VC. RL_{h_s} is obtained as an absolute value by subtracting the result of this multiplication from the sum of WTL_{h_s}, $B^{B}_{h_s}$ and $OA_{p_t r_i}$. If there is no RL_{h_s} or greater than or equal to $MinTL$, $\widehat{ETA}_{h_s p_t r_i}$ is found by summing the delivery time with $EST_{h_s p_t r_i}$. Otherwise, how much load is required to start the delivery of RL_{h_s} is calculated. For this, RL_{h_s} is subtracted from $MinTL$ and the result is defined as required space for vehicle to departure from $PI - hub_s$ (RS_{h_s}). The required number of orders is found as m by dividing RS_{h_s} by economic order quantity of retailers (EOQ^r). Order supply is adjusted by product type because inventory is separate for each product. For this reason, an examination is made for each product. If the product examined is the same as the product type to be ordered, the order quantity is removed from the inventory because it will be supplied later in any case. If the λ value is enough to meet the EOQ^r, the estimated supply time of the k type of product at $PI - hub_s$ ($EST_{h_s p_k}$) is set to zero. The reason it matches to zero is for the order to appear available later at the order time. λ is also defined as available amount to meet required space for k type of product of $PI - hub_s$ ($ARS_{h_s p_k}$). In case of unavailability of λ, total backorder amount that will be supplied after $OA_{p_t r_i}$ for k type of product at $PI - hub_s$ ($B^A_{h_s p_k}$) is checked. Because due to FIFO, it is inefficient to wait for another order if there is enough $B^A_{h_s p_k}$. In this case, the efficiency of $B^A_{h_s p_k}$ is measured by ordering $B^{A_n}_{h_s p_k}$ from the smallest to the largest, and $EST_{B^{Aa}_{h_s p_k}}$ is taken as $EST_{h_s p_k}$. Next, containers and order being prepared at the facilities of h_s are evaluated. Estimated time of arrival of $container_a$ for the k type of product arriving to $PI - hub_s$ ($ETA_{c_a h_s p_k}$) and the order being prepared for k type of product of $PI - hub_s$ with the n^{th} early estimated time of arrival ($ETA^n_{h_s p_k}$) are sorted in ascending order. This process proceeds until the adequate quantity is obtained. When adequate quantity is reached, $EST_{h_s p_k}$ is finalized. If all containers and orders being prepared are evaluated and no adequate quantity is detected, $\widehat{ETA}_{h_s p_t r_i}$is $TFIN.$ n^{th} earlier estimated ordering time of $retailer_l$ for the z type of product ($EOT^n_{p_z r_l}$) are listed in ascending order and the investigation is started initiating from the retailer who will give the first order. If there is total after backorder amount for z type of product at $PI - hub_s$ ($B^A_{h_s p_z}$) of the closest $EOT^n_{p_z r_l}$, if the backorder amount can meet RS_{h_s}, $\widehat{ETA}_{h_s p_t r_i}$ is calculated by adding delivery time to estimated supply time of the z type of product at $PI - hub_s$ ($EST_{h_s p_z}$). Unlike the product type (p_z) of $EOT^n_{p_z r_l}$, there is also the possibility of having sufficient $B^A_{h_s p_z}$ in other product type; For this reason, considering $B^A_{h_s p_z}$ in all product types, this possibility is examined based on the one with $\min(EST_{B^{Aa}_{h_s p_k}})$. Then only $EOT^n_{p_z r_l}$ are examined and $\widehat{ETA}_{h_s p_t r_i}$ is determined by considering the orders that come after $EST_{h_s p_z}$. If $EOT^n_{p_z r_l}$ is not found, $\widehat{ETA}_{h_s p_t r_i}$ is determined as TFIN.

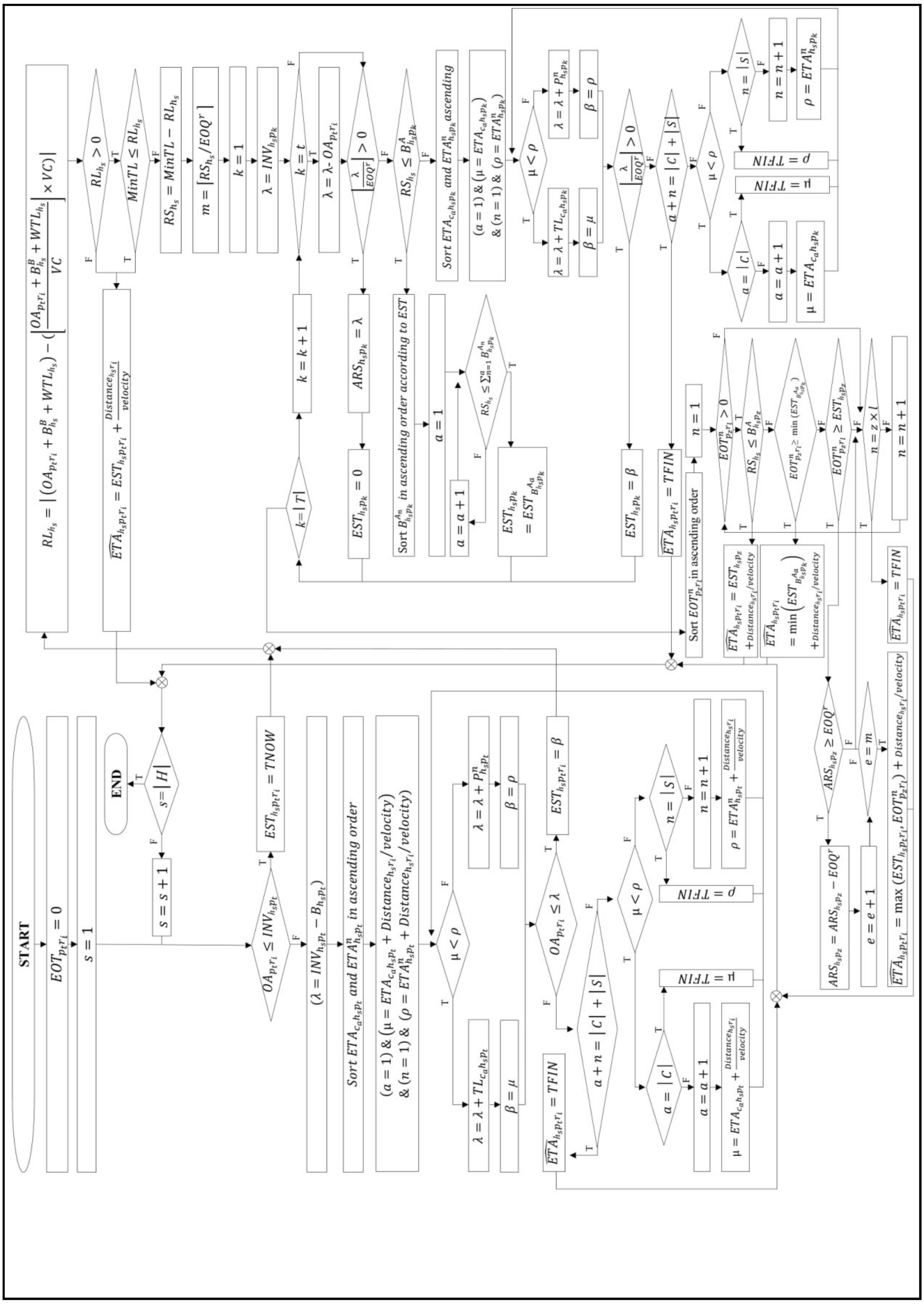

Figure 4.4. Process of ETA Calculations of PI-hubs for Retailers

As seen in Figure 4.5., the order fulfillment process in PI-hubs starts with the order arrives at PI-hub. First, it is determined who sent the order. After checking the inventory adequacy according to the following decision mechanism, the facility sending the order is determined as destination (d) to be added to the destination set (D) as one of the points where the vehicle will deliver. At this stage, through the smart technologies within the structure of PI-container, the destination, product details are entered and exchanged with the interconnection when the vehicle moves for delivery. Then, if order amount of destination_d for t type of product (OA_{dp_t}) can be met, it is deducted from $INV_{h_sp_t}$, but it is processed as a backorder amount for t type of product at $PI-hub_s$ ($B_{h_sp_t}$) when $INV_{h_sp_t}$ is not sufficient. After OA_{dp_t} is subtracted from the sufficient $INV_{h_sp_t}$, the facility sending the order (d) is added to the vehicle's destination (D) set. Moreover, available space in the vehicle for loading at $PI-hub_s$ (AS_{h_s}) is calculated. OA_{dp_t} is placed on the vehicle and $MinTL$ is set to depart the vehicle is checked for shipment. In cases where OA_{dp_t} comes from PI-hubs, even if the vehicle does not meet $MinTL$, it leaves for delivery within thirty minutes. Delivery starts from the nearest facility and continues to the farthest. The last process demonstrated in Figure 4.5., supplier selection at PI-hubs begins after $INV_{h_jp_t}$ is less than or equal to reorder point of PI-hubs (ROP^h). Subsequently, production as the amount of economic order quantity of PI-hubs (EOQ^h) is started immediately. Later, it is checked if there is a possibility that retailer the PI-hub is assigned as its main PI-hub can send orders until the products ordered for production are received. If a retailer with the potential to place an order is detected, the order amount of $PI-hub_j$ for t type of product ($OA_{h_jp_t}$) is calculated. The number of suppliers to search for is calculated based on the ratio of $OA_{h_jp_t}$ to EOQ^h, because effective use of total inventory is one of the features of Physical Internet. Depending on the nearness of the branches the process is initiated in an ascending order as in Figure 4.6. And after that, the suitability of branch inventory is evaluated. It is verified that $B_{h_sp_t}$ and $OA_{h_jp_t}$ are sufficient to make potential complications noticeable. After this assessment, the order will be sent if $INV_{h_sp_t}$ is adequate however if it is not adequate, the second stage will be proceeded. Target is to send orders as many as number of lateral shipments required ($NumLS$) with the order amount of $OA_{h_jp_t}$. The estimated time of arrival of the order of $PI-hub_j$ for the t

type of product from $PI - hub_s$ ($\widehat{ETA}_{h_j h_s p_t}$) values that are smaller than the estimated time of arrival of the order of $PI - hub_s$ from for the producer of t type of product ($ETA_{h_j p_t}$) are detected and sent the order.

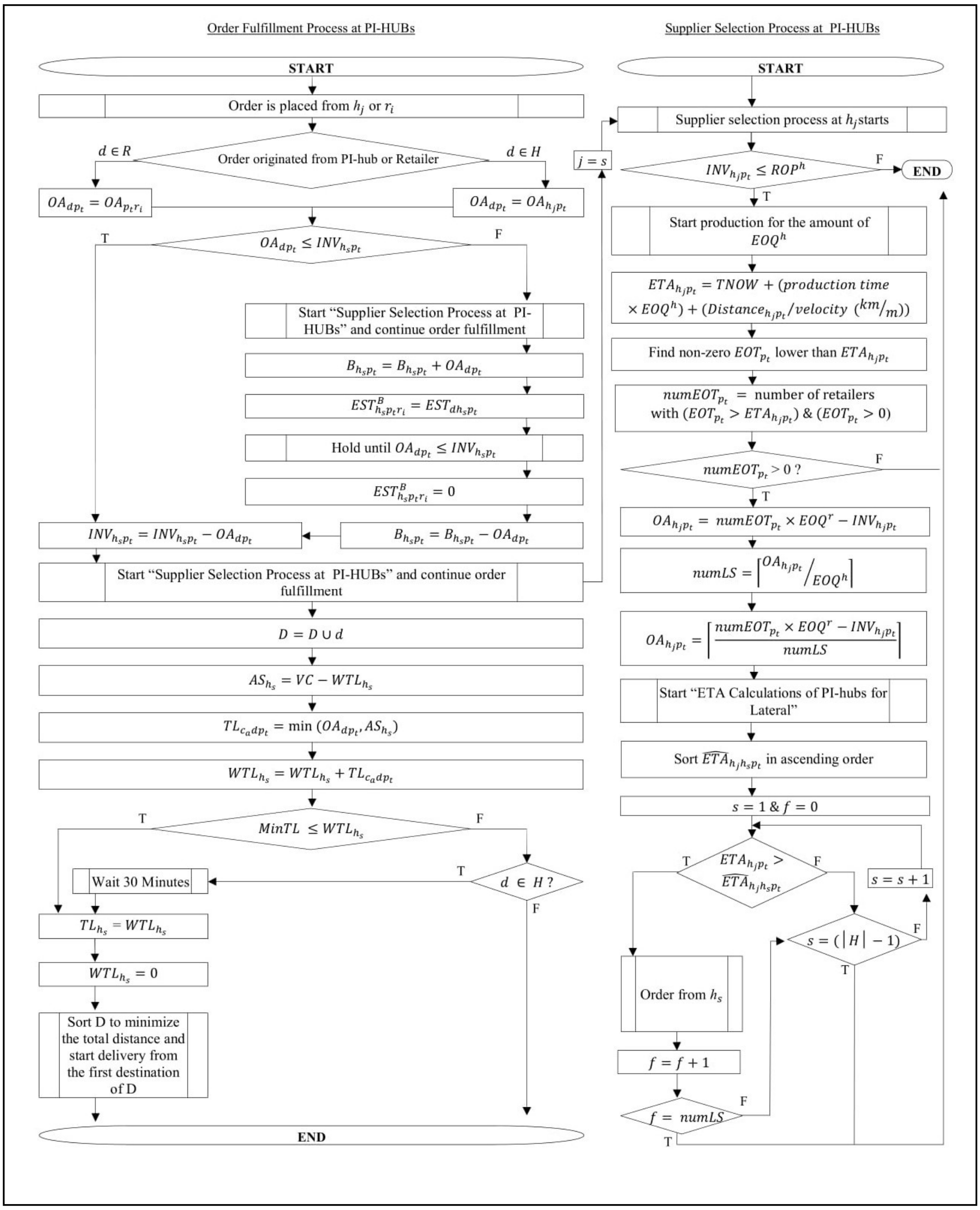

Figure 4.5. Flowchart of Order Fulfillment Processes and Supplier Selection in the Physical Internet Model

PI-hubs begin to be assessed from PI-hub1 once all PI-hubs are assessed in Figure 4.6. When $INV_{h_s p_t}$ is acceptable to meet $OA_{h_j p_t}$, $\widehat{ETA}_{h_j h_s p_t}$ is ascertained as $TNOW$. Afterward, containers and order being prepared at the facilities of h_s are assessed. $ETA_{c_a h_s p_t}$ and $ETA^n_{h_s p_t}$are sorted in rising order. This process continues as far as the agreeable quantity is acquired. When agreeable quantity is acquired, $\widehat{ETA}_{h_j h_s p_t}$ is calculated. If all containers and orders being prepared are evaluated and no agreeable quantity is acquired, $\widehat{ETA}_{h_j h_s p_t}$is decided to be set as $TFIN$.

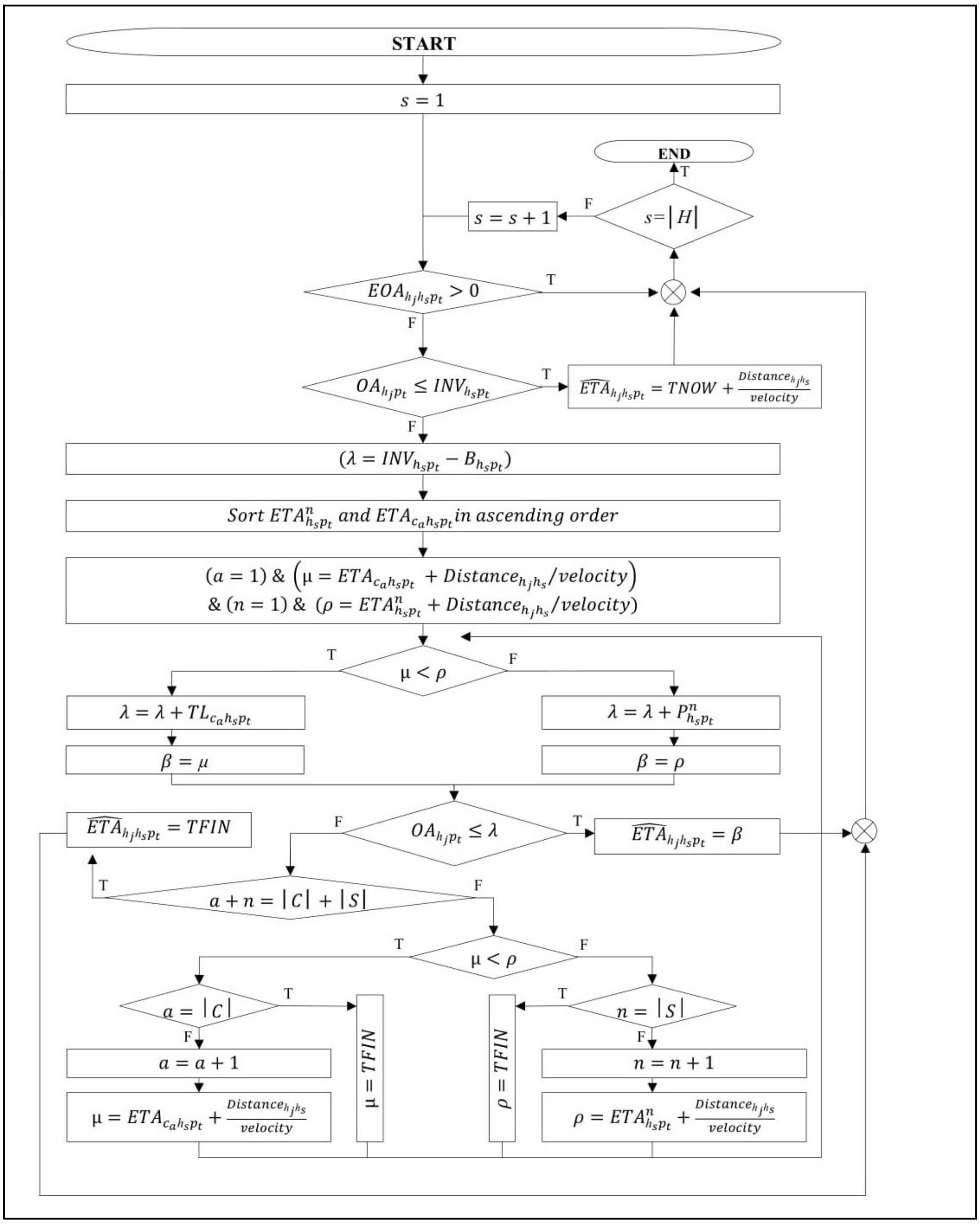

Figure 4.6. Process of ETA Calculations of PI-hubs for Lateral Shipment

Production process starts when one of the PI-hubs order prom the producer. $Total\ production\ time_{h_j p_t}$ is calculated as the first step. Then, production starts and continues as long as the $total\ production\ time_{h_j p_t}$. When production is completed, truckload that $container_a$ carries for the order of $PI - hub_j$ for t type of product ($TL_{c_a h_j p_t}$) is set as min ($VC, OA_{h_j p_t}$) to ensure that truckload does not exceed vehicle capacity and vehicle is requested.

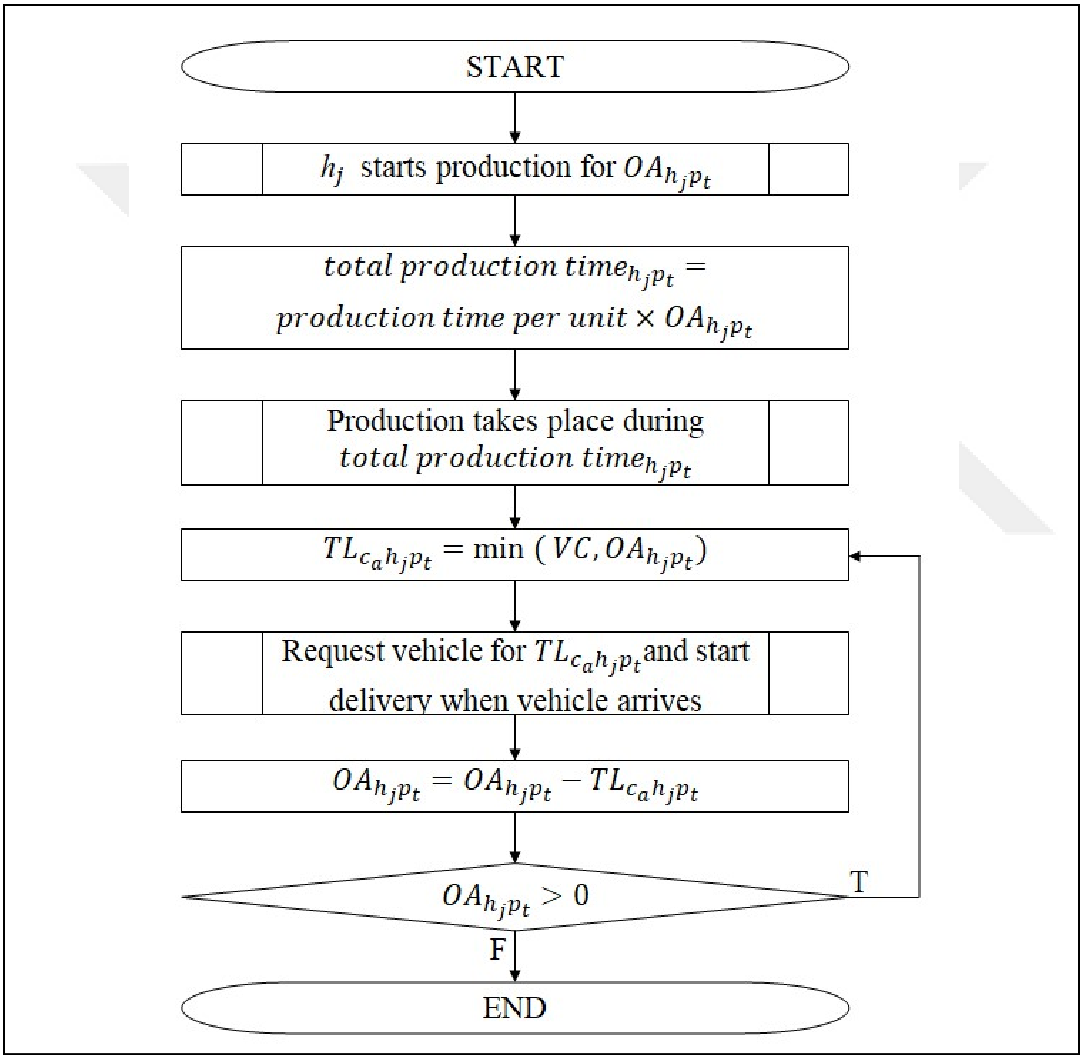

Figure 4.7. Production Process

The last flowchart is demonstrated in Figure 4.8. The flowchart includes the product arrival process for PI-hubs and retailers. Initially, when the vehicle arrives to a PI-hub, $INV_{h_j p_t}$ increases as many as $TL_{c_a h_j p_t}$. Later, $TL_{c_a h_j p_t}$ is subtracted from truckload departed from $PI-hub_s$ (TL_{h_s}). If there are products remained in the vehicle, delivery process continues for the next destination. $TL_{c_a h_j p_t}$ is reset. In the next step, "Supplier Selection Process for PI-hubs" is started. For retailers, when the vehicle arrives, $INV_{p_t r_i}$ increases as many as truckload that $container_a$ carries for the order of $retailer_i$ for t type of product ($TL_{c_a p_t r_i}$). Later, $TL_{c_a p_t r_i}$ is subtracted from TL_{h_s}. If there are products remained in the vehicle, delivery process continues for the next destination. $TL_{c_a p_t r_i}$ is reset. Inventory is checked. If $INV_{p_t r_i}$ is less than or equal to ROP^r, "ETA Calculations of PI-hubs for Retailers" is started and $min\ (ETA_{h_j p_t r_i})$ is found then order is placed from h_j. Otherwise, $EOT_{p_t}^{r_i}$ is calculated.

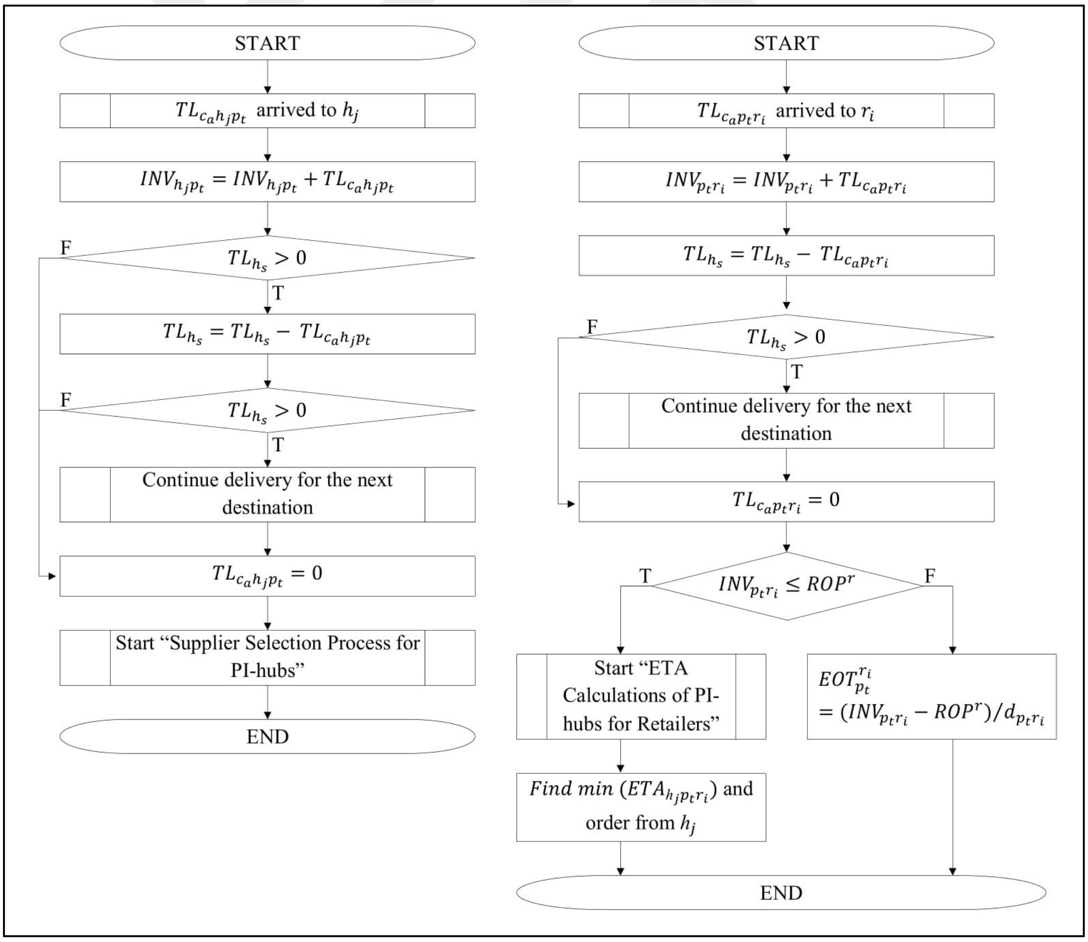

Figure 4.8. Product Arrival Process

4.3. Inventory Control Policies

The same inventory control policy was used in the supply chains of the two models created in this study. This inventory control policy used in all is continuous review policy (s, S). The closeness of the inventory level to the ROP amount is checked after each reduction in the inventory in all facilities in this simulation. In other saying, inventory is reviewed continuously and order is placed when inventory level is less than or equal to ROP. The amount of ROP is calculated considered the formula in Equation 1 (Tek & Karaduman, 2012) and taking into account the simulation dynamics. When this situation is seen, the order is made as much as the amount of EOQ. These values are calculated by utilizing Microsoft Office Excel 2007.

$$ROP = \bar{d}LT \qquad (1)$$

Where

$\bar{d}$ = Average daily demand

LT = Lead Time

Order quantity is calculated with EOQ formula (Grubbström, 1995). The formula is shown in Equation 2. Details about ROP and EOQ quantities are given in Chapter 7.1.

$$EOQ = \sqrt{\frac{2 * K * \bar{d}}{h}} \qquad (2)$$

Where

k = Fixed cost per order

$\bar{d}$ = Average daily demand

h = holding cost per item

In the classic supply chain model, facilities do not have other alternatives than the assigned suppliers that they can order. This situation differs in Physical Internet models. Dynamic source selection is one of the main characteristics of Physical Internet thus the orders can be fulfilled by distinct source points depending on the real-time situation of the alternative suppliers and the criteria of selection (Pan et al., 2013b). Also, source substitution is applied to select the supplier. PI-hubs are fully interconnected and source substitution strategy which is a Physical Internet inventory control model is applied.

Source substitution is the source with the lowest distance (km) and also has sufficient inventory to meet the order (Pan et al., 2015). Pan et al., (2013b) also said that source substitution is the simplest and the most efficient criterion of other strategies. This strategy enables lateral shipment among PI-hubs that are members of the same echelon (Yang et al., 2015). As seen in Figure 4.4., this approach is further elaborated, with the address information that can be accessed from the PI-container and the outgoing loads to the facility under consideration.

In the next chapter, simulation is explained as the solution method of the problem definition explained in Chapter 4.

CHAPTER 5
METHOD: SIMULATION

Simulation is a method that models a mechanism in such a manner that the interpretation represents or replicates the entire system related to external properties. The major intention of a simulation model is to enable measurements to be collected as a theoretical concept of a specific structure (Rossetti, 2015). The simulation contains three dimensions, which are deterministic vs. stochastic, static vs. dynamic, and continuous vs. discrete (Kelton, 2002). Stochastic simulations are commonly known to model time-evolving random phenomena e.g. delivery sources, service hours, and routing assessments, etc; if not, then they are called deterministic (Altiok and Melamed, 2010). Static simulations do not involve natural functions of time however dynamic models involve (Kelton, 2002). Continuous simulation necessitates the ongoing selection of measurements at each moment in time (Rossetti, 2015). The widely known computer simulation techniques incorporate a theory method, named the model for discrete event simulation (Altiok and Melamed, 2010). Discrete event models represent only those time steps at which change occurs by leaving out the irrelevant behavior, for the model, between the events while simulating the behavior and performance of a real-life process (Groenewoud, 2011). The system direction over time is derived as a chapteral-stationary mechanism in discrete event simulations, the jumps, or discontinuities, which are initiated by distinct occurrences (Altiok and Melamed, 2010).

A major advantage of simulation is that it has the potential to simulate the actual structure including dynamic complexities. The analytical capability of the simulation generates adaptable modeling which is requested to catch complicated procedures (Rossetti, 2015). Since actual world structures are too expensive to be assessed explicitly, simulation models generate low-cost experiments to make inferences on how the particular system operates (Rossetti, 2015). In addition, simulation allows for the creation of procedures without requiring costly functional applications. It is also an outstanding method for confirming the accuracy of current procedures and principles because of volatile demand, considering rising situations and variability (Balogh et al., 2020).

5.1. Arena Simulation Software

Rockwell Arena is discrete event simulation and automation software developed by Systems Modeling and acquired by Rockwell Automation in 2000. Arena Simulation Software 14.0 uses SIMAN simulation language as the latest version. Arena Simulation Software 14.0 is used to build the two simulation models Arena integrates the simplicity of use contained with the versatility of high-level simulation languages (Kelton, 2002). Along with the study, simulation models are conducted to compare the classic supply chain and Physical Internet supply chain in terms of sustainability in all three pillars, which are environmental, social, and economic. Two models were created on the Arena software using a supply chain structure with four-echelon. The comparison was performed with the simulation models generated.

Arena simulation requires creating a system in order to fully replicate the real system. Some pieces are utilized during this replicating process. These pieces are entities, attributes, variables, resources and queues. In the next section, entities from these pieces are explained.

5.1.1. Entities

Entities are the parts to be processed and act dynamically in the simulation. They move around, change status and are disposed (Kelton et al., 2002). In this model, the entities vary according to the facility where they are located. Entities created for this case in the simulation are:

- Customer arriving at retailer,
- Order placed from warehouse, distribution centers and PI-hubs,
- Raw materials producers use for production process,
- Truckloads to be delivered to facilities.

5.1.2. Attributes

An attribute is a particular characteristic which can vary from one entity to another (Kelton et al., 2002). The entity that started the model is the customer that reaches the retailer. Attributes assigned to the customer entity:

- Product type: More than one product type was preferred in a retailer using real life examples and the number of product types was determined as three.
- Demand: The amount of product that is assigned to customers and desired to be purchased.
- Backorder: When the inventory is not sufficient, the backorder is attributed to the entity and put on hold.

Order which is another entity reaches warehouse, distribution center, PI-hub and facilities. Attributes assigned to each order entity are seen as following:

- Owner: Where the order came from is assigned to each order for processing to the PI-container.
- Order quantity: The quantity of products ordered by retailer and PI-hubs as a result of lateral shipment on Physical Internet models.
- Order arrival time: The time that the order arrive the facility is assigned as an attribute to the each order entity in order to measure the lead time.
- Backorder: When the inventory is not sufficient, the backorder is attributed to the entity and put on hold.

The entity of raw materials arrives to the producer facilities. This entity is used in production. It passes through the process module and creates the requested product type. Attributes specified to each entity truckload are known as:

- Order arrival time: The time that the order arrive the facility is assigned as an attribute to the each raw material entity in order to measure the lead time.

- Order quantity: The amount of product ordered by the customer is processed as an attribute. This attribute is used to calculate the total production time.

After loading the order entity to the vehicles, the entity type is changed to truckload. It is assumed that the Truckload entity is loaded on vehicles in the classic model, while in the Physical Internet model it is assumed on the PI-containers. Attributes specified to each entity truckload are known as:

- Truckload: The amount of the order loaded on the vehicle is processed on the truckload entity.
- Departure: The previous location of the vehicle.
- Destination: The location where truckload entity will be delivered.

5.1.3. Variables

Variables also vary according to facility. Unlike attributes, the variables are not assigned to any particular entity. There are two forms of variables: built-in variables for the arena and user-defined variables (Kelton et al., 2002). The variables described in this chapter are user-defined variables.

- Work-In-Process (WIP): The total number of products handled over a certain period of time is indicated by this variable for each facility.
- Inventory: It is the amount of product stocked by each facility.
- Total backorder current amount: Total backorder amount of each facility. When the backorder is met, the amount met is deducted from the total amount.
- Total backorder during simulation: The total number of entities that received the backorder attribute during the simulation. These variables are used to calculate backorder cost.
- Amount of product being prepared: This variable is the amount of product that is prepared according to the order owner in a specific facility.
- Available space: The volume available for loading in the vehicle.

- Waiting truckload: The amount of product loaded on the vehicle and hold for the vehicle to move for delivery.
- Destination oriented truckload: The amount of product to be delivered to a particular destination in the vehicle.
- Vehicle truckload: The total amount of product in the vehicle.
- CO_2: The amount of CO_2 that vehicles release to reach the destinations. It is calculated cumulatively.
- Transportation cost: The cost of fuel vehicles uses to reach destinations. It is calculated cumulatively.

5.1.4. Resources

A resource may refer to a group of multiple single virtual machines (Kelton et al., 2002). The resource module is available only to producers in the simulation models for this case study. This module can be explained as follows:

Resource Manufacturing Cell: Where available, the raw material entity seizes the resource and releases it once it is completed.

5.1.5. Queues

If an entity is unable to continue due to a busy resource, it requires a spot to stand in line, which is a queue's main objective (Kelton et al., 2002). Queues in simulation models occur during specific processes. These specific processes are specified as follows:

- Production: While resource is occupied during production.
- Backorder: If the entry is attributed as a backorder, it is held in queue until the inventory is sufficient.
- Waiting truckload: Prepared orders are held until the vehicle reaches the minimum truckload where it can start delivery.

- Request vehicle: If the loads are sufficient for the delivery time, the vehicle is requested. In cases where no vehicle is available, the loads are kept until the vehicle is available.
- Loading vehicle: During the loading of the vehicle, the product that comes first is loaded while the other products that come after it are held.

Some assumptions are identified in the following chapter. The assumptions are adopted for all the scenarios when generating the two models by using simulations.

5.2. Assumptions

Some assumptions are identified to apply in the system of the two models generated by using simulations. The following common assumptions were adopted for all the scenarios when creating the simulation model in Arena:

(a) Distribution centers, warehouse, PI-hubs and retailers apply a continuous review policy (s, S) where an order with its quantity is placed when the inventory level drops below or is equal to a ROP. Each value is calculated by using the formulas as seen in Equation 1 and Equation 2.

(b) Orders are delivered on a FIFO basis.

(c) The weight of products is same for all of the three product types.

(d) The production time is valid for every item.

(e) The velocity of the vehicles is 60 km\h and assumed to remain still during the delivery.

(f) Loading process occupies zero time units.

(g) In cases where the inventory of the retailer is insufficient to fulfill the customer's order, it is assumed that the customers wait until the order is fulfilled.

(h) No storage capacity is defined.

(i) It is assumed that the homogeneous vehicle type is always used in the delivery process.

5.3. Verification of the Simulation Model

Verification is the process of comparing two or more results to ensure the accuracy of the model. In this process, the model's implementation and the associated data with the conceptual description and specifications have to be compared. The simulation model output is checked by using various input combinations to conduct verification. The process is completed on Microsoft Office Excel 2007. The summary of the verification is shown in Figure 5.1. A total of seven scenarios were created to test all responses, and verification was achieved by obtaining the results shown above. In the first scenario, ten vehicles with 3000 capacity were selected as 0.50 minimum truckload limit, maximum demand 10, and production time 1.5 minutes. Based on this scenario, one value was changed in the remaining scenarios and the rest was kept constant. In the second scenario, no minimum truckload limit is set. While the expected increase in CO_2, transportationcost, holding cost and average inventory level increase as expected; backorders, which are expected to decrease, also decreased cost and lead time values. In the third scenario, the number of vehicles was reduced to 5 by taking the minimum truckload limit as in the first scenario. Along with this change, transportation cost decreased meanwhile CO_2 increased by providing the expectation. In the fourth scenario, the production time is reset. In this scenario, while holding cost and average inventory level increased, cost and lead time decreased, and provided verification. In the fifth scenario, the maximum demand reaching the retailer has been reduced to 2. However, transportation cost, lead time, holding cost and average inventory level have increased; backorder cost has also decreased. In the sixth scenario, the maximum demand is doubled and taken as 20. The cost of backorders and CO_2, which were predicted to rise to ensure verification, increased; The transportation cost, holding cost, average inventory level, which are estimated to decrease, have also decreased. In the seventh scenario which is the last scenario, the production time was doubled to 3 minutes per item. As a result, while the holding cost and average inventory level declined, backorders and lead time rose. Verification of the model is provided with these values.

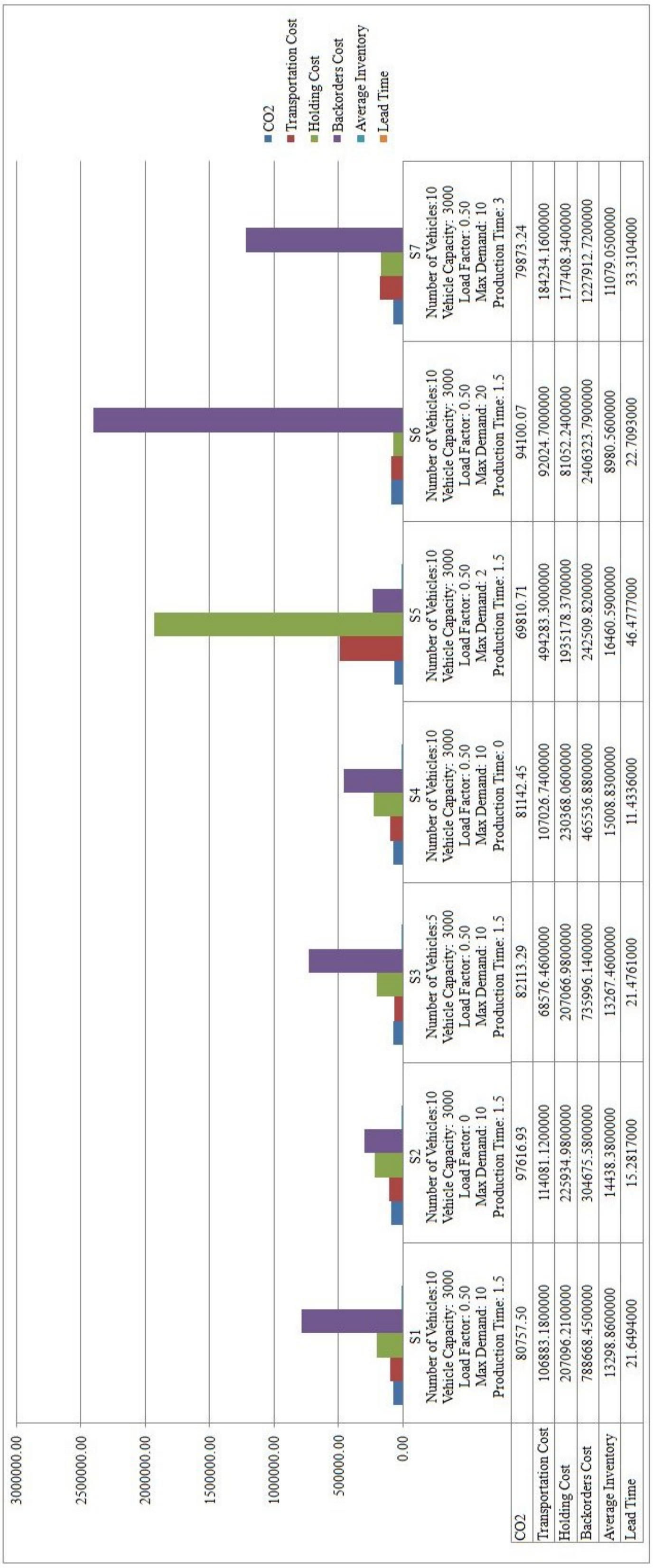

Figure 5.1. Verification of the Model

The performance metrics determined based on the three pillars of sustainability with the hypotheses in Chapter 4.4. are described in the next chapter.

5.4. Performance Metrics

Physical Internet's objective is to improve the environmental, economic, and social efficiency of logistics assets, which include transport, storage, material processing and procurement (Montreuil et al., 2010). The concept also encourages the growth of a coordinated, systematic framework that can offer potentially sustainable approaches to old and new methods (Montreuil, 2011). Montreuil (2012) described objectives of Physical Internet goal in the sense of the three sustainability pillars as follows,

- Environmental sustainability aim of Physical Internet: Sustainably reduce GHG production, electricity use, pollution, and resource waste globally.
- Economic sustainability aim of Physical Internet: Reduce the global economic cost of logistics sustainably, and thus to make substantial company performance improvement.
- Social sustainability aim of Physical Internet: Significantly and sustainably boost the living conditions of the logistics sector and the global population by improving the fast and effective usability and mobility of physical products. Also, Wood (1991) defined socially sustainable practices as the product and process aspects that determine human safety, welfare and wellness.

Simulation models of classic supply chain and Physical Internet concepts are generated and evaluated via a theoretical and therefore realistic case study of the supply chain in the context of sustainability. Key performance indicators are prime indicators to observe the performance of accomplishing objectives (Gözaçan & Lafcı, 2020). Because of the reasons mentioned above and the hypotheses that are explained in Chapter 4.4, there are six performance metrics in this study to compare the models in the objective of sustainability with its three pillars. These performance metrics are CO_2 emissions caused during transportation process, transportation cost, holding cost (*h*), backorder cost that are caused by insufficient inventory, average inventory levels, lead time of deliveries to each facility. GHG emissions for the environmental pillar of the performance metrics because it corresponds to “sustainably reduce GHG production”. In addition, average inventory level can be considered for environmental purpose since an efficient reduction in inventory may prevent resource waste. Moreover, the costs including transportation, holding, and backorder for the economic pillar because it represents “reduce the global economic cost of logistics sustainably” by increasing profitability which also equaled to “economic performance improvement”. Lastly, for the social pillar, backorder and lead time are examined because a decline in the two performance metrics represents “fast and effective usability and mobility of physical products”.

The GHG emissions identified to examine the environmental pillar of sustainability, along with its formula, are described in the following chapter.

5.4.1. GHG Emissions

Supply chain should aim to reduce GHG emissions of vehicles from a perspective of environmental sustainability for transport and supply chains (Lee & Wu, 2014). And also, the transportation sector appears as the second major contributor to GHG emissions after the energy supply sector from 1994 to 2019 according to the EU Climate Action Progress Report published for the year 2019. The transportation sector was the fourth sector that produced GHG emissions before 1994 according to the same report. The growing effect of the transportation sector on GHG emissions remains as can be demonstrated by this particular report. The environmental impact of GHG emissions and the contribution of transportation to the increase of GHG emissions reveal the reality of a problem that requires to be solved instantly.

The main contributing factor of global warming is GHG emissions, particularly CO_2 (Chaabane et al., 2008; Intergovernmental Panel on Climate Change, 2007). During transportation, vehicles produce CO_2 as a result of the burning of fuel. The transportation mode for delivery process in the simulation models is determined as road transportation. This statistic was recorded as time-persistent. To calculate CO_2 emission during the transportation process, the formula given in Equation 3 is used.

$$GHG_{TO} = EC_{ve} + \left(EC_{vf} - EC_{ve}\right) * LF/distance * EF \qquad (3)$$

Where

EF = The energy conversion factor (in kg CO_2 per liter fuel)

EC_{vf} = Energy consumption while vehicle is full

EC_{ve} = Energy consumption while vehicle is empty

LF = Load factor which is the weight-based capacity utilization of the vehicle

EF is multiplied by total energy consumption during the delivery process to calculate CO_2, emissions. EF, Energy Conversion Factor, is taken as 2.6 kg CO_2 per liter as it is recommended by Kellner and Igl (2015). EC_{vf} and EC_{ve} values that are used in the formula are shown in Table 5.1. Energy consumption while the vehicle is full and empty values per kilometers, are 0.11 and 0.20 liters for small vehicles, respectively, 0.14 and 0.25 liters for large vehicles. LF is calculated by dividing the freight mass (measured in tones or kilograms) by the maximum weight-based carrying capacity of the vehicle.

Table 5.1. EC_{vf} & EC_{ve} Values per kilometers (Kellner and Igl, 2015)

Vehicle Type	EC_{ve}	EC_{vf}
Small	0.11 lt	0.20 lt
Large	0.14 lt	0.25 lt

In the next chapter, transportation cost, one of the performance metrics of the economic pillar of sustainability, is explained in detail.

5.4.2. Transportation Cost

Transportation cost is one of the performance metrics to analyze the economic sustainability of the simulation models. Transportation cost is calculated for per truck that is used for delivery as time-persistent. The formula is shown in Equation4. The equation consists of the sum of fixed cost that includes vehicle purchase or rental, driver's salary, insurance, registration, vehicle taxes and depreciation. The variable cost of transport is determined according to the distance and quantity for each delivery being transported. Vehicle capacities are identified as large and small vehicles and taken as levels of experimental factors. In this case, the fixed cost per hour for each vehicle is $5 (Jorgensen, 2019). Furthermore, it assumed to be $4.4 for the small vehicle and also, $5.09 for large vehicle. In the formula, "b" stands for the cost of fuel consumption per kilometers (km) per vehicle,

$$Transportation\ Cost = fixed\ cost * TFIN + km * b * fuel\ price\ per\ litre \quad (4)$$

The cost of fuel consumption per kilometers per vehicle is shown in Table 5.2. In the formula, "b" stands for the liter of fuel consumption of a vehicle per km. The liter of fuel consumption per km for each vehicle is shown in Table 1. Thus, fuel price per liter is equal to $0.762.

Table 5.2. The Liter of Fuel Consumption Per Km (Kellner and Igl, 2015)

Vehicle Load	**Small**	**Large**
Full	0.235	0.371
Empty	0.193	0.227

In the next chapter, holding cost which is one of the performance metrics of the economic pillar of sustainability is explained in detail with its formula.

5.4.3. Holding Cost

Holding costs were determined as one of the performance metrics to examine sustainability's economic pillar. The changes in total cost of holding inventories are explained as a result of movements of the average level of inventory. Inventory holding cost is recorded time-persistent by calculating the daily cost of the average inventory level. U.S. Dollar is used as the currency in this study while calculation the costs. Inventory holding cost is calculated by using the formula in Equation 5. In the formula, "a" stands for the cost of holding a product per item per hour and is taken as $0.19 for retailers, and $0.13 for warehouse, DCs and PI-hubs (Pan et al., 2013b).

$$h = average\ inventory * TFIN * a \qquad (5)$$

In the next chapter, backorders cost, the last performance metric of the economic pillar of sustainability, is explained in detail with its formula.

5.4.4. Backorders Cost

Backorders cost is also one of the performance metrics for assessment of the simulation models' economic and also social pillars of sustainability. When an order is delivered and inventory is insufficient or in other saying, the amount in the inventory is less than the amount of the order, it is assumed that order waits to be delivered until inventory is replenished and every order what is under this situation is recorded as backorder. In order to calculate the backorders cost, the backorders cost is determined as $20. This statistic was recorded as time-persistent. The next chapter describes the average inventory level.

5.4.5. Average Inventory Level

Average inventory level is among the most broadly utilized performance metrics in simulation models (Altiok & Melamed, 2010). For two models, average inventory levels for each product at each member of echelons are recorded as the length of the simulations. This statistic was recorded as time-persistent over the entire simulation length to obtain average values. Lead time, the performance metric of the social pillar of sustainability, is described in detail in the next chapter.

5.4.6. Lead Time

Lead time is the time between initiation of an order and delivery of the total order amount. Lead times are recorded for each member of the echelons and recorded in two categories: lead time for retailers and lead time for facilities that are warehouse, distribution centers and PI-hubs. Lead time is the last performance metric. It is identified to measure the social sustainability of the simulation models since it is an indicator of the fast and effective usability and mobility of physical products by measuring delivery times.

The numerical study begins in the next chapter, after completing the explanation of all performance metrics in Chapter 6.

CHAPTER 6
NUMERICAL STUDY

This chapter conducts the numerical study of the comparison of Physical Internet model and classic supply chain model in the context of sustainability. The first model which is the classic supply chain model is explained in Chapter 4.1.The first model consists of three producers, one warehouse, two distribution centers and six retailers. There is no alternative option for supplier selection. Physical Internet models are mentioned in Chapter 4.2. The second model is Physical Internet model. The second model includes three producers, three PI-hubs and six retailers. There are alternative options in this models and lateral shipment between PI-hubs is enabled. The facility can reach the inventory data and product information in the PI-containers during the supplier selection process.

The performance metrics to be based on in comparison of these two models were determined in a coordinated manner with the hypotheses explained in Chapter 4.4. and explained in Chapter 6. Previously identified performance metrics are CO_2 emissions of the vehicles, cost which includes transportation, holding (h) and backorder that is caused by insufficient inventory, lead time of deliveries to each facility, average inventory levels.

An experimental design is the design of any task aimed at describing and explaining the variability of the information under circumstances that are assumed to reflect the variability. Thus, an experimental design has been created to calculate and analyze these predetermined performance metrics on all two models. In total, 24 scenarios and 720 runs completed for the analysis.

The input data used during this numerical study is described in the next chapter.

6.1. Input Data

Identifying input data is an essential stage towards a feasible simulation project, since the process is guided by the data. Using the simulation method, supply chain network models of classic supply chain and Physical Internet concepts were created and compared in terms of sustainability using a hypothetical but realistic supply chain case study. The values of EOQ and ROP were taken as items and calculated on Microsoft Office Excel 2007, Equation 1 and 2 are taken into account. In order to compare the results, the same input data for all scenarios is used. The input data of this study consists of,

- ROP (retailer): 200
- ROP (distribution center): 690
- ROP (warehouse): 980
- ROP (PI-hub): 500
- EOQ (retailer): 500
- EOQ (distribution center): 1500
- EOQ (warehouse): 3000
- EOQ (PI-hub): 900
- The velocity of vehicles: 60 km/h
- The production time per item: 1.5 minutes.
- Demand at retailers is set as Uniform (0, 10) items per hour.

Distance between the members of the supply chain models is shown in Table 6.1.

Table 6.1. Distance Between the Members of Supply Chain Models

	P1	P2	P3	HUB- DC 1	HUB - DC 2	HUB - DC 3	R1	R2	R3	R4	R5	R6
P1	0	500	1000	635	533	510	550	556	547	538	529	532
P2	500	0	500	306	306	100	206	211	211	211	211	206
P3	1000	500	0	533	635	510	532	529	538	547	556	550
HUB - DC 1	635	306	533	0	120	209	106	101	105	110	117	117
HUB – DC 2	533	306	635	120	0	209	117	117	110	105	101	106
HUB - DC 3	510	100	510	209	209	0	106	111	111	111	111	106
R1	550	206	532	106	117	106	0	6	7	16	25	20
R2	556	211	529	101	117	111	6	0	10	20	30	25
R3	547	211	538	105	110	111	7	10	0	10	20	16
R4	538	211	547	110	105	111	16	20	10	0	10	7
R5	529	211	556	117	101	111	25	30	20	10	0	6
R6	532	206	550	117	106	106	20	25	16	7	6	0

The scenarios that will be applied during the numerical study using these defined input data are explained in detail in the next chapter as experimental design.

6.2. Experimental Design

The two simulation models that are built are classic, Physical Internet. Each are respectively first and second levels of network structure factor as it is seen in Table 6.2. Vehicle capacity consists of two levels: 1500 and 3000. Load factor includes three levels each level are 0.50, 0.75 and 1.00 respectively. Number of vehicles is determined according to the facility number in the model by considering the potential maximum number of vehicle requirements during the simulations for all of the simulation models. After observing the simulation models, the levels of number of homogeneous vehicles are identified as 10 and 20.

Table 6.2. Experimental Design

Factors		Factors Level		
		1	**2**	**3**
A	**Network Design**	Classic	Physical Internet	
B	**Vehicle Capacity (item)**	1500	3000	
C	**Load Factor**	0.50	0.75	1.00
D	**Number of Vehicles**	10	20	

The experimental design results of the scenarios that will be applied during the numerical study utilizing these defined input data are explained in the next chapter.

6.3. Result Analysis

The analysis was first started from sustainability's environmental pillar, and then economic and social analyzes were performed, respectively. First of all, when the results are examined, it is seen that 2 % of the total orders in the Physical Internet model are lateral shipments. The factors are determined as network structure, vehicle capacity, number of vehicles and load factor to evaluate the results of the simulation. The responses are CO_2 emissions, average inventory level, holding cost, transportation cost, backorders cost and lead time to analyze sustainability with its three pillars. In total, 24 scenarios and 720 runs completed for the analysis for the two simulation models. Terminating condition is to complete 1000 deliveries. Warm-up is 30 days and 30 replications applied. The results are analyzed on Minitab® 14 Software. The results are analyzed with full factorial DOE. In statistics, a full factorial DOE is an experiment that consists of two or more factors, each with discrete possible values or "levels", and whose experimental units take on all possible combinations of these levels across all such factors. While analyzing full factorial DOE, the purpose is to obtain main effects and interaction that have statistically significant influence on response variable. Main effects plots are examined as first. The main effect test would simply investigate whether there's anything in a single aspect that creates an impact altogether. Next, interaction plots are evaluated. Minitab by design shows one plot for the interaction of every pair of factors.

6.3.1. Results for GHG Emissions

All of the factors are statistically important. The important two way interactions are Network Structure*Vehicle Capacity, Network Structure*Load Factor and Vehicle Capacity*Load Factor. To achieve the validation of the model for the current response, the condition of $R^2 > 80\%$ is usually used. For CO_2, R^2 is equal to 99.74%. Thus, it can be said that the factors of the model response well.

Source	DF	MS	F-Value	P-Value
Model	23	3957957223	11706.07	**0.000**
Linear	5	6862804893	20297.46	**0.000**
Network Structure	1	8349964569	24695.89	**0.000**
Number of Vehicles	1	22509863	66.58	**0.000**
Vehicle Capacity	1	22277359241	65887.61	**0.000**
Load Factor	2	1832095396	5418.61	**0.000**
2-Way Interactions	9	6280696728	18575.81	**0.000**
Network Structure*Number of Vehicles	1	184100	0.54	0.461
Network Structure*Vehicle Capacity	1	55679312266	164677.36	**0.000**
Network Structure*Load Factor	2	379653357	1122.86	**0.000**
Number of Vehicles*Vehicle Capacity	1	1771818	5.24	0.022
Number of Vehicles*Load Factor	2	78900	0.23	0.792
Vehicle Capacity*Load Factor	2	42768928	126.49	**0.000**
3-Way Interactions	7	27524271	81.41	**0.000**
Network Structure*Number of Vehicles*Vehicle Capacity	1	7666	0.02	0.880
Network Structure*Number of Vehicles*Load Factor	2	82147	0.24	0.784
Network Structure*Vehicle Capacity*Load Factor	2	96234549	284.62	**0.000**
Number of Vehicles*Vehicle Capacity*Load Factor	2	14417	0.04	0.958
4-Way Interactions	2	25605	0.08	0.927
Network Structure*Number of Vehicles*Vehicle Capacity*Load Factor	2	25605	0.08	0.927
Error	696	338112		
Total	719			
Model Summary				
S	R-sq	R-sq(adj)	R-sq(pred)	
581.474	99.74%	99.73%	99.72%	

Table 6.3. ANOVA Table for CO_2

Figure 6.1. demonstrates that the classic supply chain model causes much higher absorption of CO_2 than Physical Internet. Physical Internet model shows a decrease of 11%. Moreover, vehicle with large capacity can contain more items than small capacity so it releases less CO_2 . Next, the figure explains that as the number of vehicle increases CO_2 emissions decreases because as the number of vehicles per area increases, the possibility of finding a vehicle closer to the point of need increases. There is an inverse proportion between load factor and CO_2 emissions because as the load factor increases, the CO_2 decreases.

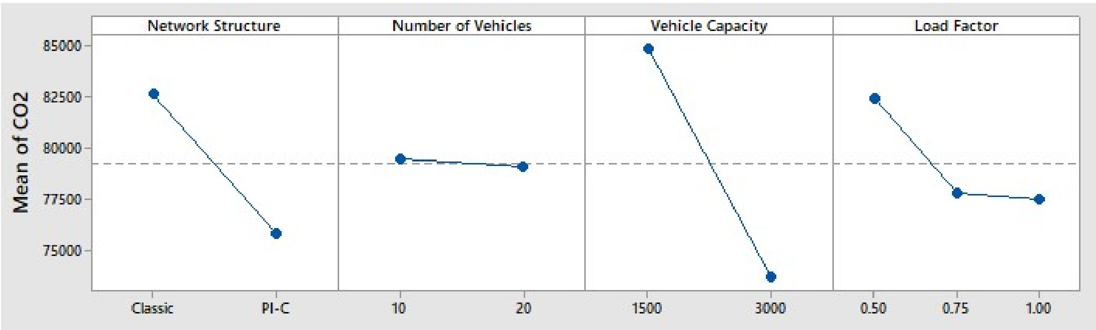

Figure 6.1. Main Effects Plot for CO_2

As can be understood from the interaction plot in Figure 6.2., an interaction occurs and the greater the strength of the interaction for network structures. Load factor of 0.5 causes the highest amount of CO_2. As can be seen from the CO_2 results, Physical Internet in network structure factor; 20 for the number of vehicles factor; 3000 for vehicle capacity factor; 1.00 should be selected for load factor.

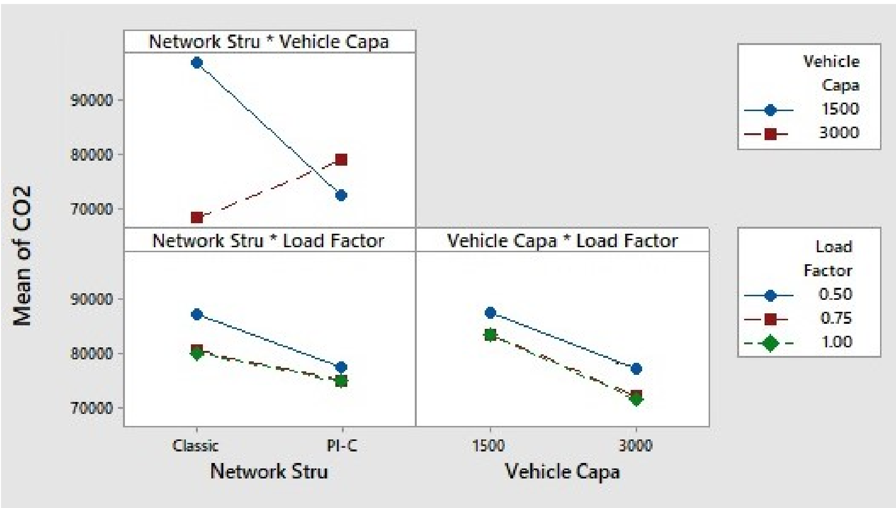

Figure 6.2. Interaction Plot for CO_2

6.3.2. Results for Transportation Cost

When Table 6.4. is examined, it is observed that all one-way factors are statistically important for transportation cost. Moreover, all two-way interactions are important apart from Number of Vehicles*Load Factor. The factors of the model response well since R^2 is equal to 99.99%.

Source	DF	MS	F-Value	P-Value
Model	23	76954545243	394156.91	**0.000**
Linear	5	3.46218E+11	1773310.82	**0.000**
Network Structure	1	2.12977E+11	1090858.62	**0.000**
Number of Vehicles	1	1.30569E+12	6687648.95	**0.000**
Vehicle Capacity	1	2.12041E+11	1086061.74	**0.000**
Load Factor	2	193755240	992.40	**0.000**
2-Way Interactions	9	4289474417	21970.45	**0.000**
Network Structure*Number of Vehicles	1	30720343464	157347.89	**0.000**
Network Structure*Vehicle Capacity	1	558310580	2859.64	**0.000**
Network Structure*Load Factor	2	58674291	300.53	**0.000**
Number of Vehicles*Vehicle Capacity	1	7029920389	36006.86	**0.000**
Number of Vehicles*Load Factor	2	175685	0.90	0.407
Vehicle Capacity*Load Factor	2	89497683	458.40	**0.000**
3-Way Interactions	7	36824978	188.62	**0.000**
Network Structure*Number of Vehicles*Vehicle Capacity	1	180859084	926.35	**0.000**
Network Structure*Number of Vehicles*Load Factor	2	14230	0.07	0.930
Network Structure*Vehicle Capacity*Load Factor	2	38359128	196.47	**0.000**
Number of Vehicles*Vehicle Capacity*Load Factor	2	84524	0.43	0.649
4-Way Interactions	2	40034	0.21	0.815
Network Structure*Number of Vehicles*Vehicle Capacity*Load Factor	2	40034	0.21	0.815
Error	696	195238		
Total	719			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
441.858	99.99%	99.99%	99.99%

Table 6.4. ANOVA Table for Transportation Cost

Figure 6.3. demonstrates the main effects for the performance metric of transportation cost. When network structures are analyzed, transportation cost

declines for Physical Internet because the facility that places an order can access vehicle occupancy rate information while selecting its own orderer. In Vehicle capacity, it is seen that the big vehicle causes more costs because the fixed cost of the large vehicle is higher than that of the small vehicle. The highest increase is seen in the number of vehicles. As the number of vehicles increases, the cost of each vehicle is added to the transportation cost. In the load factor, the inverse ratio is observed.

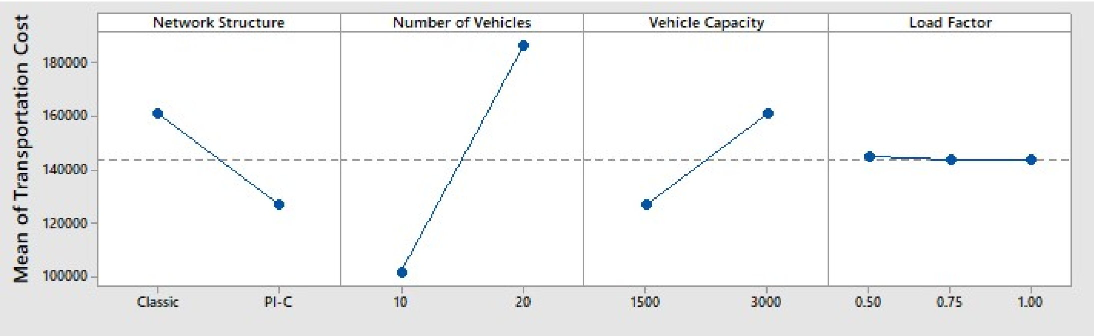

Figure 6.3. Main Effects Plot for Transportation Cost

When Figure 6.4. is examined, transportation cost has been reduced in the Physical Internet network structure compared to the classic model. Moreover, the large vehicle costs more, while the small vehicle is less. This is due to the change in fixed cost. According to the transportation cost results, Physical Internet in the network structure factor; 10 for the number of vehicles factor; 1500 for vehicle capacity factor; 1.00 should be selected for load factor.

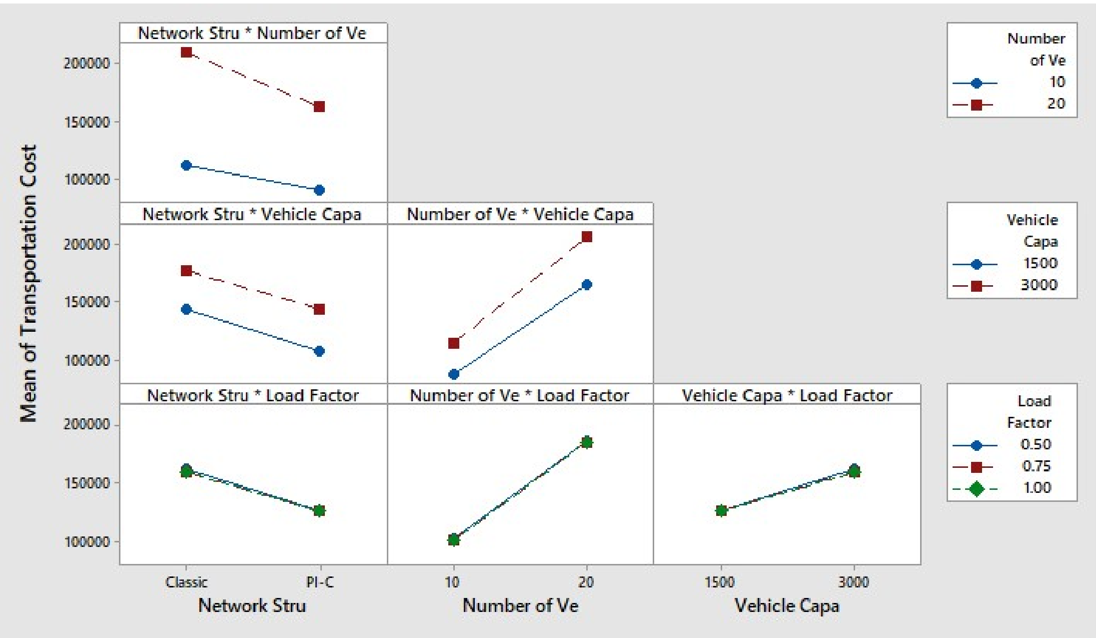

Figure 6.4. Interaction Plot for Transportation Cost

6.3.3. Results for Holding Cost

When Table 6.5. is reviewed, it is recognized that all one-way factors are statistically important for holding cost. Furthermore, all two-way interactions are necessary except Number of Vehicles*Vehicle Capacity and Number of Vehicles*Load Factor. The factors of the model reply properly because R^2 is equal to 99.94%.

Source	DF	MS	F-Value	P-Value
Model	23	31033E+13	51652.21	**0.000**
Linear	5	6.02500E+13	237500.66	**0.000**
Network Structure	1	3.00817E+14	1185796.36	**0.000**
Number of Vehicles	1	3377505565	13.31	**0.000**
Vehicle Capacity	1	2.61162E+11	1029.48	**0.000**
Load Factor	2	84244155992	332.08	**0.000**
2-Way Interactions	9	12507298776	49.30	**0.000**
Network Structure*Number of Vehicles	1	3567817534	14.06	**0.000**
Network Structure*Vehicle Capacity	1	22596927179	89.08	**0.000**
Network Structure*Load Factor	2	6610775374	26.06	**0.000**
Number of Vehicles*Vehicle Capacity	1	49056750	0.19	0.660
Number of Vehicles*Load Factor	2	32152946	0.13	0.881
Vehicle Capacity*Load Factor	2	36533015439	144.01	**0.000**
3-Way Interactions	7	1945167445	7.67	**0.000**
Network Structure*Number of Vehicles*Vehicle Capacity	1	19852171	0.08	0.780
Network Structure*Number of Vehicles*Load Factor	2	51714012	0.20	0.816
Network Structure*Vehicle Capacity*Load Factor	2	6696954858	26.40	**0.000**
Number of Vehicles*Vehicle Capacity*Load Factor	2	49491102	0.20	0.823
4-Way Interactions	2	14396122	0.06	0.945
Network Structure*Number of Vehicles*Vehicle Capacity*Load Factor	2	14396122	0.06	0.945
Error	696	253683619		
Total	719			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
15927.4	99.94%	99.94%	99.94%

Table 6.5. ANOVA Table for Holding Cost

As demonstrated in Figure 6.5., in the Physical Internet model, a approximately 80% decrease in holding cost is revealed. Inventory levels can be accessed through the transparent structure on the Physical Internet and orders are placed accordingly. As the number of vehicles increases, the holding cost also increases. This is because as the orders delivered increase, they are added to the inventory. Load factor has an inverse ratio with a small difference. As the load factor increases, holding cost decreases, because the load factor affects the delivered order quantity.

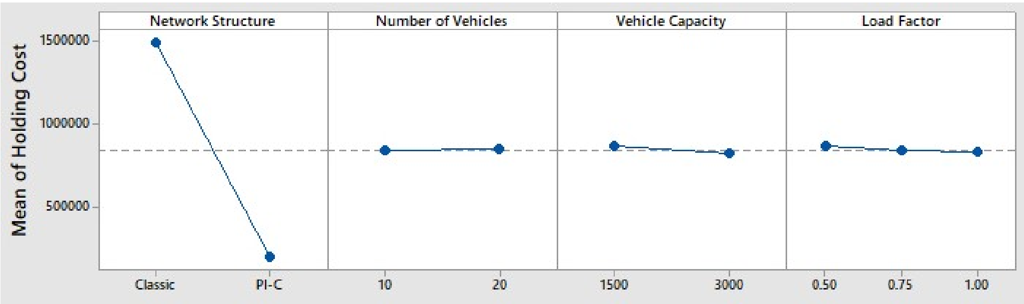

Figure 6.5. Main Effects Plot for Holding Cost

Physical Internet has significantly less holding costs than the classic model. As indicated in Figure 6.6., there is a direct proportion between the number of vehicles and holding cost, the opposite is observed in the load factor. As can be understood from the holding cost outputs, Physical Internet in network structure factor; 10 for the number of vehicles factor; 3000 for vehicle capacity factor; 1.00 should be prefered for load factor.

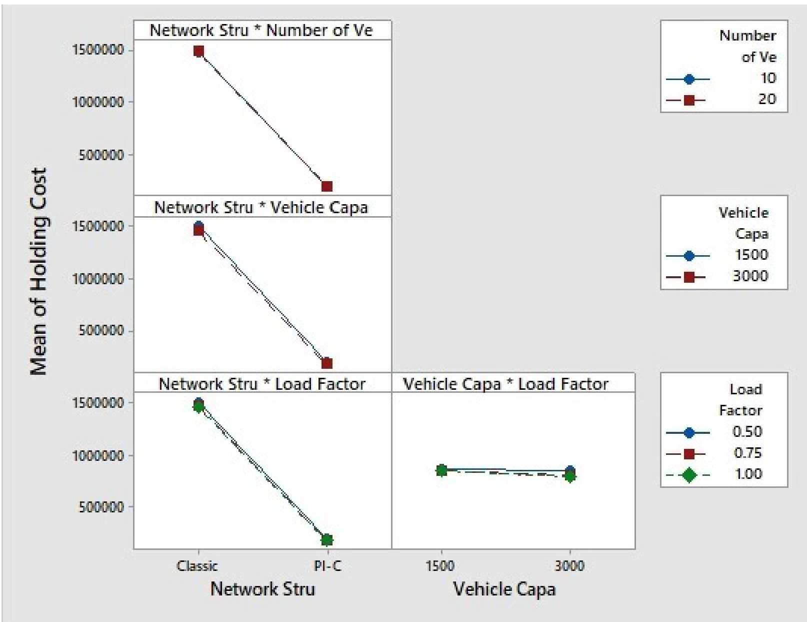

Figure 6.6. Interaction Plot for Holding Cost

6.3.4. Results for Backorders Cost

As demonstrated in Table 6.6. all one-way factors are statistically significant for backorders cost except number of vehicles. Also, the insignificant 2-way interactions are Network Structure*Number of Vehicles, Number of Vehicles*Vehicle Capacity and Number of Vehicles*Load Factor. The factors of the model respond suitably because R^2 is equal to 95.81% which is above 80% as well.

Source	DF	MS	F-Value	P-Value
Model	23	2.07373E+13	691.86	**0.000**
Linear	5	8.90868E+13	2972.21	**0.000**
Network Structure	1	3.23546E+14	10794.48	**0.000**
Number of Vehicles	1	9167008255	0.31	0.580
Vehicle Capacity	1	7.60839E+13	2538.39	**0.000**
Load Factor	2	2.28975E+13	763.93	**0.000**
2-Way Interactions	9	3.45619E+12	115.31	**0.000**
Network Structure*Number of Vehicles	1	623072377	0.02	0.885
Network Structure*Vehicle Capacity	1	6.80116E+12	226.91	**0.000**
Network Structure*Load Factor	2	1.77300E+12	59.15	**0.000**
Number of Vehicles*Vehicle Capacity	1	74585772089	2.49	0.115
Number of Vehicles*Load Factor	2	38380022720	1.28	0.279
Vehicle Capacity*Load Factor	2	1.03033E+13	343.75	**0.000**
3-Way Interactions	7	51836399683	1.73	0.099
Network Structure*Number of Vehicles*Vehicle Capacity	1	14313223780	0.48	0.490
Network Structure*Number of Vehicles*Load Factor	2	15973726964	0.53	0.587
Network Structure*Vehicle Capacity*Load Factor	2	1.47125E+11	4.91	0.008
Number of Vehicles*Vehicle Capacity*Load Factor	2	11172504285	0.37	0.689
4-Way Interactions	2	27791472700	0.93	0.396
Network Structure*Number of Vehicles*Vehicle Capacity*Load Factor	2	27791472700	0.93	0396
Error	696	29973263569		
Total	719			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
173128	95.81%	95.67%	95.52%

Table 6.6. ANOVA Table for Backorders Cost

According to Figure 6.7., it is seen that the backorder cost in the Physical Internet structure is approximately 60% less than the classic structure. In addition, it is observed that as the vehicle capacity increases, the number of backorders increases. This is because it takes longer to fill the large vehicle and causes delay in orders. When the load factor is examined, a right proportion is seen.

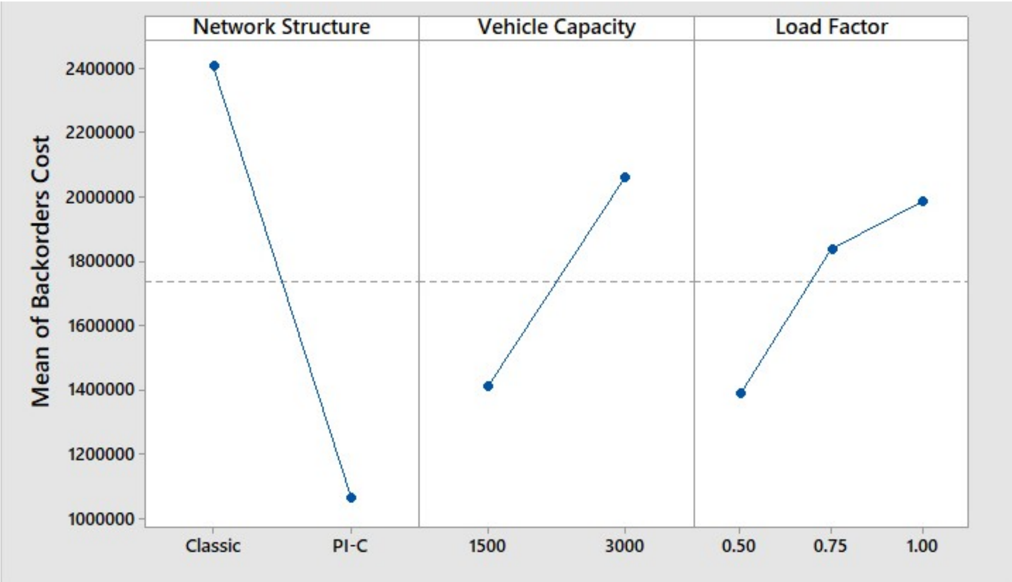

Figure 6.7. Main Effects Plot for Backorders Cost

Physical Internet is the network structure with the lowest backorder cost for all factors as shown in Figure 6.8. In addition to this information, small fluctuations are also observed in other factors. First of all, as the vehicle capacity increased, the backorder cost in the two models increased, while the difference was preserved. The increase in the load factor also causes an increase in backorder because delivery may take longer than planned. Although there is a difference between vehicle capacity factors, it is observed that this difference may decrease in certain situations. A similar situation is seen in network structure factors. While this difference is visible in Physical Internet, it is very small in classic model. In load factor, the large vehicle strengthens the backorder cost increasing effect of the 1.00 factor. As the backorders cost findings indicate, Physical Internet in network structure factor; 1500 for vehicle capacity factor; 0.50 should be applied for the load factor.

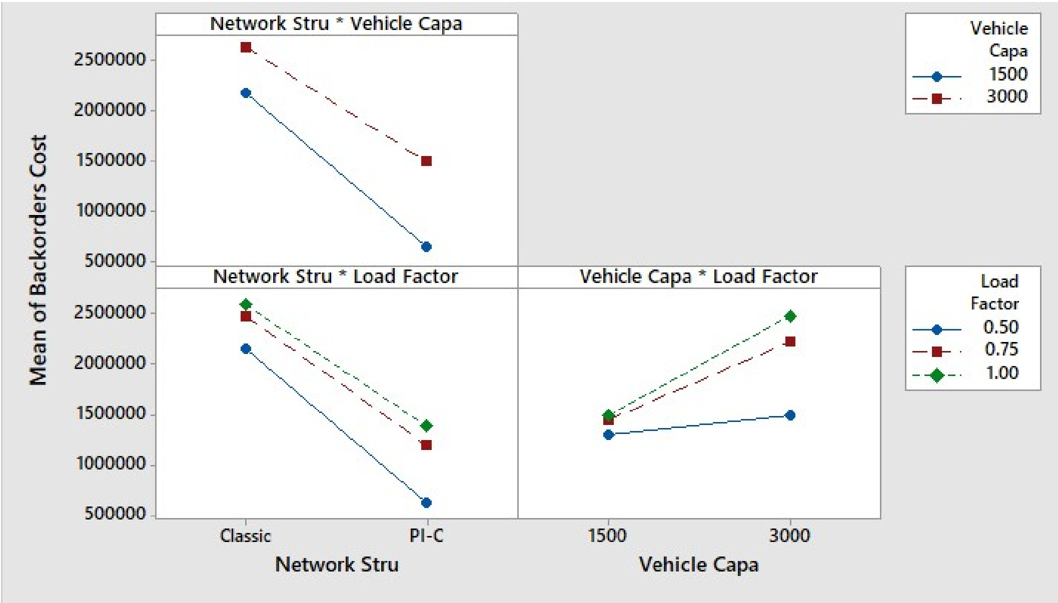

Figure 6.8. Interaction Plot for Backorders Cost

6.3.5. Results for Total Cost

All one-way factors are statistically significant for total cost in Table 6.7. Also, 2-way interactions that are not statistically important are Network Structure*Number of Vehicles, Number of Vehicles*Vehicle Capacity and Number of Vehicles*Load Factor. The factors of the model answer well because R^2 is equal to 98.19% which is also above 80%.

Source	DF	MS	F-Value	P-Value
Model	23	1.95906E+13	1643.67	**0.000**
Linear	5	8.80607E+13	7388.38	**0.000**
Network Structure	1	3.93775E+14	33038.08	**0.000**
Number of Vehicles	1	5.92612E+11	49.72	**0.000**
Vehicle Capacity	1	3.00750E+13	2523.32	**0.000**
Load Factor	2	7.93065E+12	665.39	**0.000**
2-Way Interactions	9	1.13059E+12	94.86	**0.000**
Network Structure*Number of Vehicles	1	10752767261	0.90	0.343
Network Structure*Vehicle Capacity	1	2.40231E+12	201.56	**0.000**
Network Structure*Load Factor	2	6.28941E+11	52.77	**0.000**
Number of Vehicles*Vehicle Capacity	1	19643622793	1.65	0.200
Number of Vehicles*Load Factor	2	9505084927	0.80	0.451
Vehicle Capacity*Load Factor	2	3.23285E+12	271.24	**0.000**
3-Way Interactions	7	12346134858	1.04	0.404
Network Structure*Number of Vehicles*Vehicle Capacity	1	11089205892	0.93	0.335
Network Structure*Number of Vehicles*Load Factor	2	3303459527	0.28	0.758
Network Structure*Vehicle Capacity*Load Factor	2	32063869068	2.69	0.069
Number of Vehicles*Vehicle Capacity*Load Factor	2	2299540463	0.19	0.825
4-Way Interactions	2	9596068357	0.81	0.447
Network Structure*Number of Vehicles*Vehicle Capacity*Load Factor	2	9596068357	0.81	0.447
Error	696	11918808789		
Total	719			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
109173	98.19%	98.13%	98.07%

Table 6.7. ANOVA Table for Total Cost

According to Figure 6.9., it is seen that the total cost in the Physical Internet structure is approximately 60% less than the classic structure. In the next factor, it is seen that as the number of vehicle increases, total cost increases as well. In addition, it is observed that as the vehicle capacity increases, the total cost increases. When the load factor is examined, a right proportion is seen.

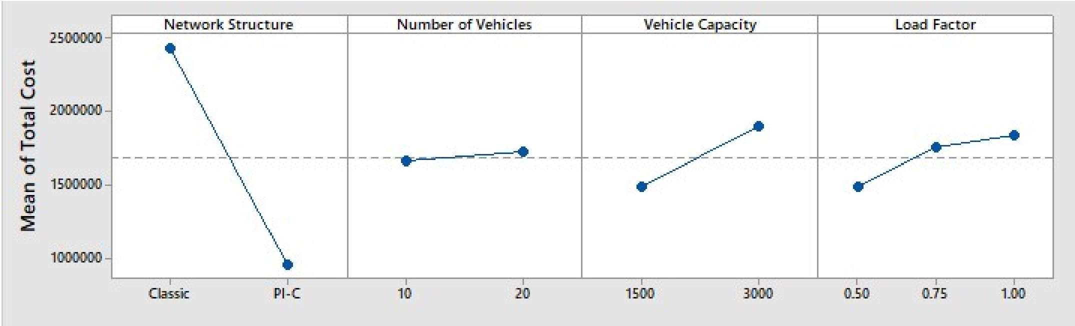

Figure 6.9. Main Effects Plot for Total Cost

Figure 6.12. visualizes the interaction plot for total cost. An obvious decrease is seen in the Physical Internet level of the network structure factor. The total cost generated by the load factor of 1.00 and 0.75 seem close to each other meanwhile the load factor of 0.5 causes the minimum total cost. Also, small vehicle with the load factor of 0.50 causes the less total cost as large vehicle with the load factor of 1.00 causes the greatest total cost. The total cost results show that Physical Internet in the network structure factor; 10 for the number of vehicles factor; 1500 for vehicle capacity factor; 0.50 should be chosen for the load factor.

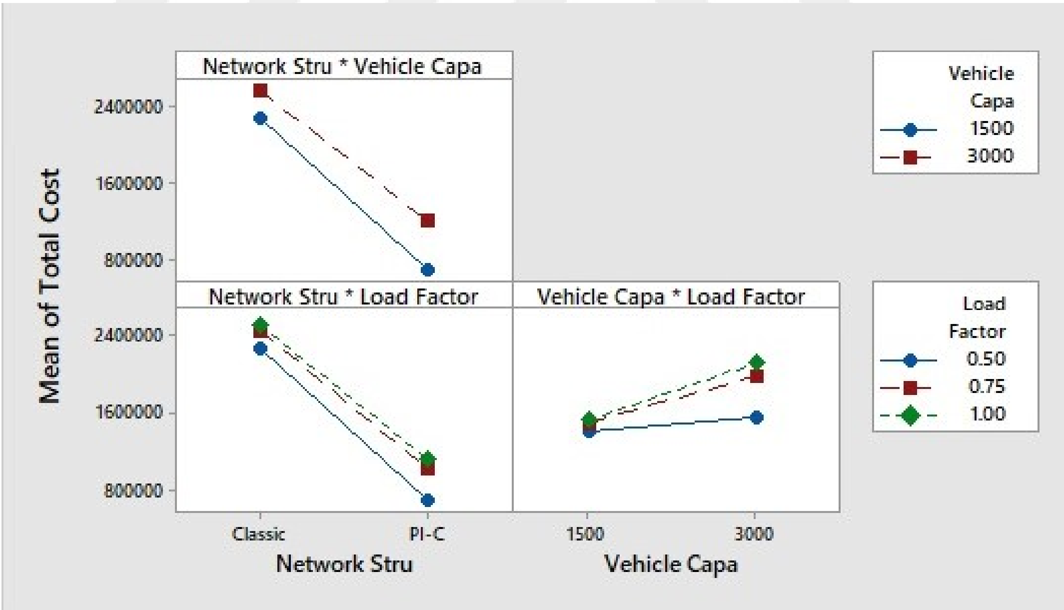

Figure 6.10. Interaction Plot for Total Cost

6.3.6. Results for Average Inventory level

As indicated in Table 6.8., all one-way factors are statistically important for average inventory level. Furthermore, 2-way interactions that are not statistically necessary are Number of Vehicles*Vehicle Capacity and Number of Vehicles*Load Factor. The factors of the model answer well because R^2 is equal to 99.93%.

Source	DF	MS	F-Value	P-Value
Model	23	16169656829	45100.25	**0.000**
Linear	5	74342428423	207355.17	**0.000**
Network Structure	1	3.70684E+11	1033907.28	**0.000**
Number of Vehicles	1	5416625	15.11	**0.000**
Vehicle Capacity	1	620720421	1731.31	**0.000**
Load Factor	2	201162183	561.08	**0.000**
2-Way Interactions	9	19684830	54.90	**0.000**
Network Structure*Number of Vehicles	1	6021933	16.80	**0.000**
Network Structure*Vehicle Capacity	1	12787429	35.67	**0.000**
Network Structure*Load Factor	2	3092748	8.63	**0.000**
Number of Vehicles*Vehicle Capacity	1	241221	0.67	0.412
Number of Vehicles*Load Factor	2	30966	0.09	0.917
Vehicle Capacity*Load Factor	2	75932729	211.79	**0.000**
3-Way Interactions	7	1819803	5.08	**0.000**
Network Structure*Number of Vehicles*Vehicle Capacity	1	146012	0.41	0.524
Network Structure*Number of Vehicles*Load Factor	2	60686	0.17	0.844
Network Structure*Vehicle Capacity*Load Factor	2	6204254	17.30	**0.000**
Number of Vehicles*Vehicle Capacity*Load Factor	2	31365	0.09	0.916
4-Way Interactions	2	31429	0.09	0.916
Network Structure*Number of Vehicles*Vehicle Capacity*Load Factor	2	31429	0.09	0.916
Error	696	358527		
Total	719			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
598.771	99.93%	99.93%	99.93%

Table 6.8. ANOVA Table for Average Inventory Level

Figure 6.11. shows the main effects plot for the average inventory level. It is seen that the average inventory level decreases approximately 80% in the Physical Internet model compared to the classic model. This decrease has been caused by the transparent information flow created by the technological hardware of Physical Internet. Numerous vehicles make more available vehicles, and with this, instant delivery becomes more possible. For this reason, this increase in the second level of the number of vehicles factor is due to this. In the same way, as the load factor increases, the departure time of the vehicle is delayed, so the average inventory level decreases.

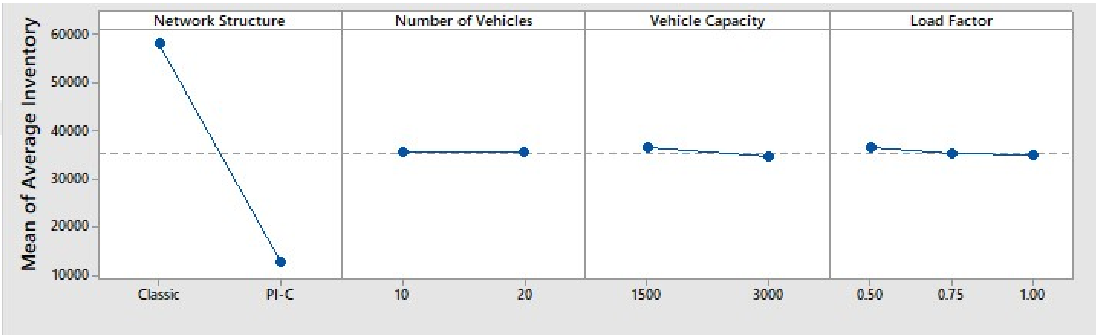

Figure 6.11. Main Effects Plot for Average Inventory Level

Figure 6.12. indicates the interaction plot for average inventory level. A serious average inventory level decrease is observed in the Physical Internet level of the network structure factor. In load factor, the large vehicle declines average inventory level increasing effect of the load factor of 1.00. Small vehicle has an increasing the effect since it requires a shorter period of time to fill the vehicle than large vehicle. As understood from the average inventory level results, Physical Internet in the network structure factor; 10 for the number of vehicles factor; 3000 for vehicle capacity factor; 1.00 should be selected for load factor.

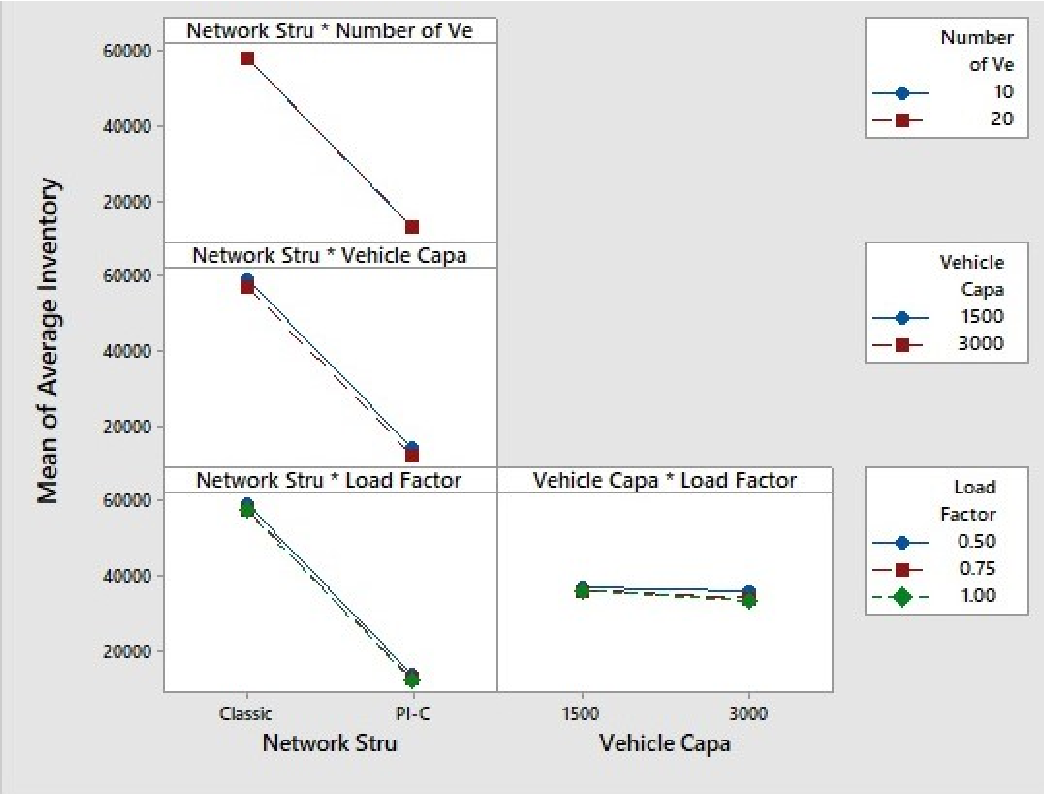

Figure 6.12. Interaction Plot for Average Inventory Level

6.3.7. Results for Lead Time

As Table 6.9. visualizes ANOVA for Lead time-Facilities, the only factor which is not statistically significant is number of vehicles. Also, 2-way interactions that are not statistically significant are Network Structure*Number of Vehicles, Number of Vehicles*Vehicle Capacity and Number of Vehicles*Load Factor. The factors of the model answer well because R^2 is equal to 97.79%.

Source	DF	MS	F-Value	P-Value
Model	23	1397.3	1340.13	**0.000**
Linear	5	5820.5	5582.52	**0.000**
Network Structure	1	27039.1	25933.79	**0.000**
Number of Vehicles	1	1.0	0.91	0.340
Vehicle Capacity	1	1415.3	1357.41	**0.000**
Load Factor	2	323.5	310.24	**0.000**
2-Way Interactions	9	274.3	310.24	**0.000**
Network Structure*Number of Vehicles	1	1.6	1.51	0.219
Network Structure*Vehicle Capacity	1	1280.3	1227.92	**0.000**
Network Structure*Load Factor	2	293.0	280.98	**0.000**
Number of Vehicles*Vehicle Capacity	1	1.0	1.00	0.319
Number of Vehicles*Load Factor	2	0.0	0.01	0.987
Vehicle Capacity*Load Factor	2	299.8	287.50	**0.000**
3-Way Interactions	7	80.8	77.54	**0.000**
Network Structure*Number of Vehicles*Vehicle Capacity	1	1.4	1.33	0.249
Network Structure*Number of Vehicles*Load Factor	2	0.0	0.03	0.970
Network Structure*Vehicle Capacity*Load Factor	2	282.0	270.49	**0.000**
Number of Vehicles*Vehicle Capacity*Load Factor	2	0.2	0.19	0.824
4-Way Interactions	2	0.1	0.13	0.876
Network Structure*Number of Vehicles*Vehicle Capacity*Load Factor	2	0.1	0.13	0.876
Error	696	1.0		
Total	719			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
1.02109	97.79%	97.72%	97.64%

Table 6.9. ANOVA Table for Lead Time – Facilities

As seen in Figure 6.13., lateral shipment feature of Physical Internet can strongly influence lead time to PI-hubs. Lead time of Physical Internet network structure is approximately 30% percent lower than classic network structure. Moreover, large vehicle causes longer lead times compared to small vehicle because minimum truckload is calculated via vehicle capacity. The load factor has the correct proportion because as the load factor increases, the minimum truckload increases and causes delays in delivery.

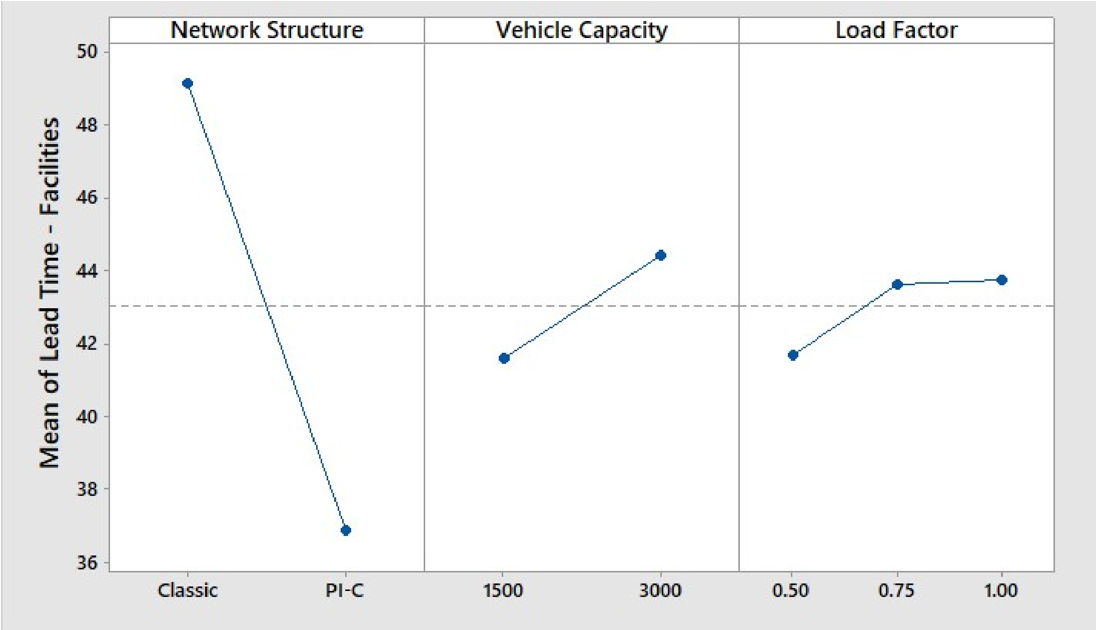

Figure 6.13. Main Effects Plot for Lead Time - Facilities

As seen in Figure 6.14., the difference between the levels of vehicle capacity is bigger for the classic network structure. Also, when the vehicle capacity and load factor increase at the same time, there is an increase in lead time. While there is no obvious fluctuation in the Physical Internet level of the network structure, this situation is different in the classic model. Because, the inventory relocation on the Physical Internet prevents this situation.

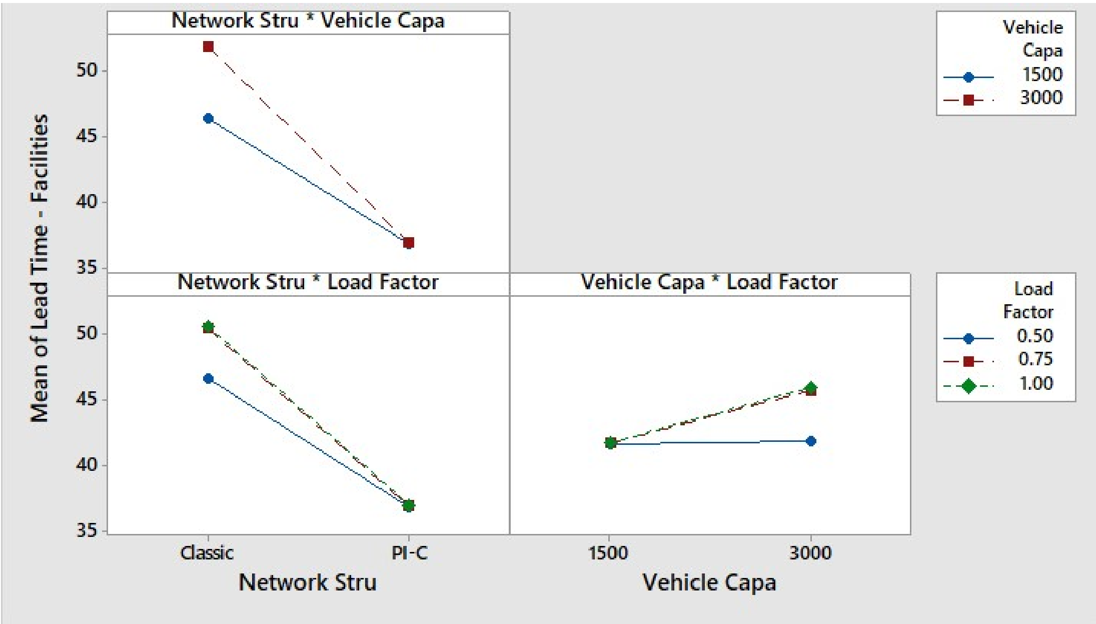

Figure 6.14. Interaction Plot for Lead Time – Facilities

ANOVA for Lead time-Retailers is visualized in Table 6.10. The only factor which is not statistically significant is number of vehicles as well as Table 6.9. Also, 2-way interactions that are not statistically significant are Network Structure*Number of Vehicles, Number of Vehicles*Vehicle Capacity and Number of Vehicles*Load Factor which is also similar to Table 6.9. The factors of the model answer well because R^2 is equal to 98.76%.

Source	DF	MS	F-Value	P-Value
Model	23	3913.1	2401.15	**0.000**
Linear	5	15260.1	9363.79	**0.000**
Network Structure	1	584.0	358.34	**0.000**
Number of Vehicles	1	6.0	3.66	0.056
Vehicle Capacity	1	44612.6	27374.81	**0.000**
Load Factor	2	15549.0	9541.07	**0.000**
2-Way Interactions	9	1452.5	891.29	**0.000**
Network Structure*Number of Vehicles	1	2.8	1.70	0.192
Network Structure*Vehicle Capacity	1	824.9	506.16	**0.000**
Network Structure*Load Factor	2	217.0	133.14	**0.000**
Number of Vehicles*Vehicle Capacity	1	0.8	0.48	0.489
Number of Vehicles*Load Factor	2	0.8	0.95	0.387
Vehicle Capacity*Load Factor	2	5903.6	3622.54	**0.000**
3-Way Interactions	7	89.5	54.89	**0.000**
Network Structure*Number of Vehicles*Vehicle Capacity	1	0.7	0.45	0.505
Network Structure*Number of Vehicles*Load Factor	2	2.1	1.27	0.281
Network Structure*Vehicle Capacity*Load Factor	2	310.4	190.49	**0.000**
Number of Vehicles*Vehicle Capacity*Load Factor	2	0.2	0.14	0.867
4-Way Interactions	2	1.3	0.79	0.454
Network Structure*Number of Vehicles*Vehicle Capacity*Load Factor	2	1.3	0.79	0.454
Error	696	1.6		
Total	719			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
1.27660	98.76%	98.71%	98.67%

Table 6.10. ANOVA Table for Lead Time - Retailers

Figure 6.15. demonstrates that Physical Internet decreases lead time to retailers roughly by 20% and this can be related to the source substution feature of the Physical Internet network structure. Large vehicle increases lead time by

approximately 50% because of the minimum truckload limit. The load factor has the correct proportion because as in the previous figure, the minimum truckload increases as the load factor increases and causes delays in delivery.

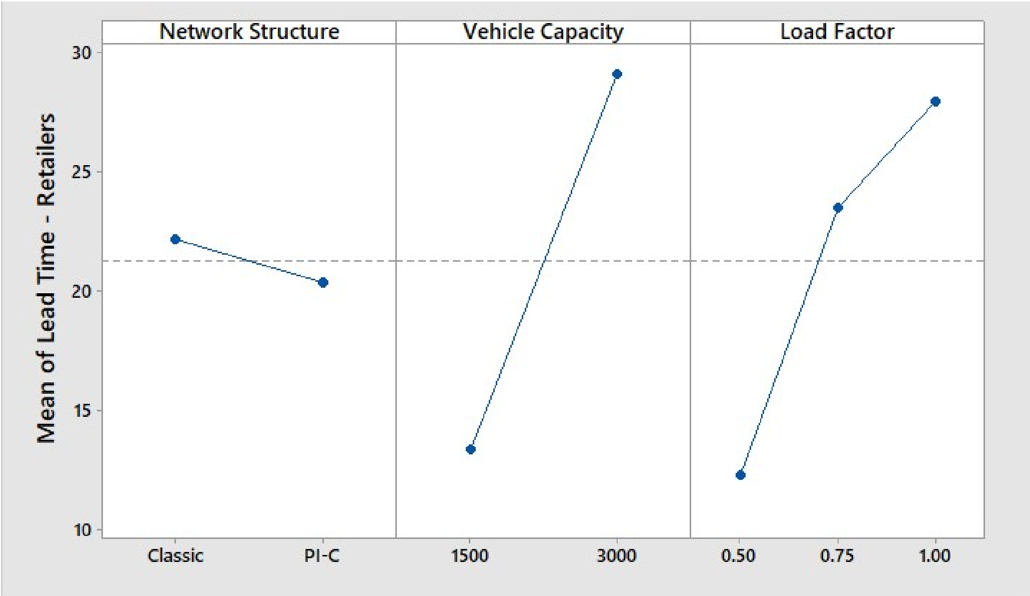

Figure 6.15. Main Effects Plot for Lead Time - Retailers

Figure 6.16. indicates the interaction plot for lead time to retailers. In this figure, fluctuations increased in both network structures. While the classic network structure is greatly affected by the increase in vehicle capacity, this difference is less in Physical Internet. Because Physical Internet prevents this fluctuation by interacting with transparent information flow and can offer a more stable lead time. In the 2-way interaction of vehicle capacity with the load factor, the fluctuation in a large vehicle is greater than in a small one. As seen from the lead time findings, Physical Internet in the network structure factor; 1500 for vehicle capacity factor; 0.50 should be preferred for the load factor.

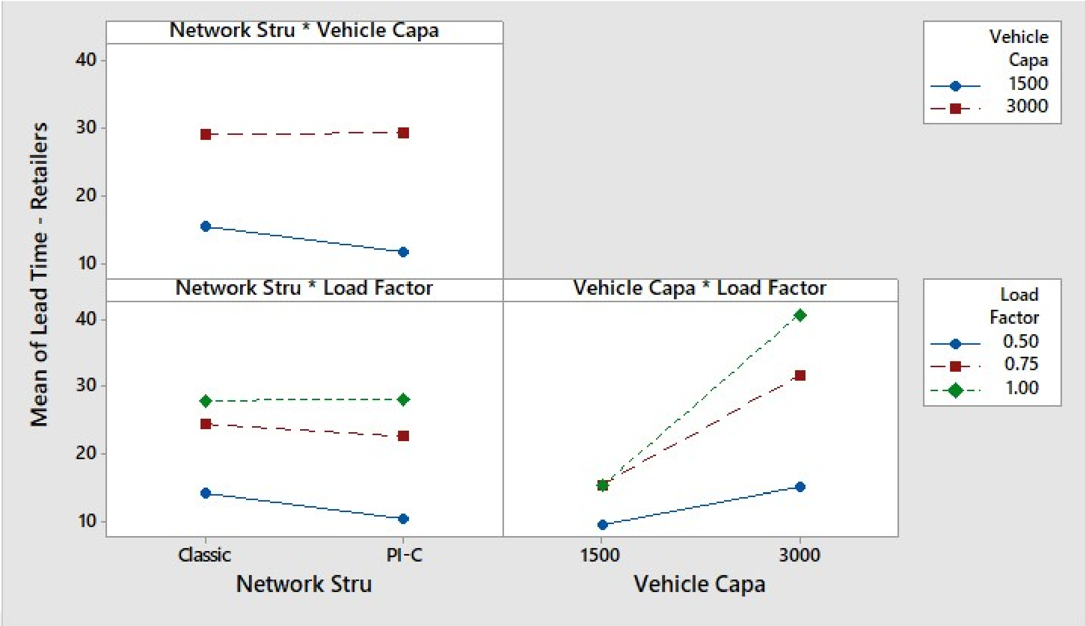

Figure 6.16. Interaction Plot for Lead Time -Retailers

6.4. Discussion

The results obtained according to the conducted case study conditions were examined in the previous chapter. The effects of factors on responses, in other words performance metrics, will be examined in this chapter. Table 7.1. indicates the final results of performance metrics for each factors and the suitability of the results with the hypotheses. The hypotheses are determined as below,

H1: Physical Internet generates less GHG Emissions than the classic model.

H2: Physical Internet produces lower transportation costs than the classic model.

H3: Physical Internet causes less holding costs than the classic model.

H4: Physical Internet obtains less backorders cost than the classic model.

H5: Physical Internet creates less average inventory levels than the classic model.

H6: Physical Internet provides shorter lead times than the classic model.

When the environmental pillar of sustainability starts to be examined, the first response is CO_2. When the network structure levels are examined, it is seen that the classic model and the Physical Internet have interactions under the title of vehicle capacity. However, when the main effects plot is examined, it is seen that Physical Internet corresponds to the minimum level which corresponds to 1st hypothesis. This is related to that PI-hubs provide the stock replenishment from any point in the chain, including inventory relocation between other PI-hubs within the Physical Internet. In other saying, PI-hubs are open to all users and reachable structure as well as lateral shipment helps to minimize environmental damage. This feature creates the shortest route for delivery. When the number of vehicles factor is examined, it is seen that 20 vehicles cause the least CO_2 emission. This is because the number of available vehicles in the immediate vicinity of the location that will deliver the product is proportional to the number of vehicles used.

	Network Structure	Number of Vehicles	Vehicle Capacity	Load Factor
CO_2	Physical Internet	20	3000	1.00
Transportation Cost	Physical Internet	10	1500	1.00
Holding Cost	Physical Internet	10	3000	1.00
Backorders Cost	Physical Internet	-	1500	0.5
Total Cost	Physical Internet	10	1500	0.5
Average Inventory Level	Physical Internet	10	3000	1.00
Lead Time	Physical Internet	-	1500	0.5

Table 7.1. Best Factor Level Combinations

In the vehicle capacity, the large vehicle, which can carry the most products at once, emitted the least emission. In the load factor, 1.0 caused the least CO_2. Thus, previous explanation provides the result which is seen on Table 7.1. When average inventory level is observed, Physical Internet includes a more efficient level than the classic model since PI-hubs have the ability to request inventory when the need is recognized via its transparency. 10 vehicles cause lower inventory levels and prevent waste and also load factor of 1.00 that proves 5th hypothesis.

Cost is under examination for the cost part corresponding to the economic pillar. Table 7.1. indicates that the three costs that are transportation, holding and backorders are at the lowest amount when the network structure is Physical Internet. In addition, the number of vehicles factor reduced the cost of 10 vehicles since the factor is not statistically significant for backorders cost meanwhile 10 vehicles cause the least transportation and holding costs. Meanwhile, large vehicle capacity should be preferred for lower holding cost, small vehicle is seen as the least total cost generator. Load factor of 1.00 should be chosen for the minimum value of transportation and holding cost. However, load factor of 0.5 has a declining effect when it is observed in a broader perspective which is total cost. It is seen that the factor of the network structure with the lowest total cost is Physical Internet that answers 2nd, 3rd and 4th hypotheses.

For the social pillar of sustainability, lead times are evaluated. Physical Internet creates the shortest lead times for all scenarios comparing to the classic model that proves 6th hypothesis. Physical Internet optimizes workflows and lead times reduce by enhancing the quick and efficient accessibility and mobility of physical items. Moreover, small vehicle capacity and load factor of 0.5 causes the shortest lead times since these conditions fastens the loading process. In these conditions, Physical Internet provides more reliable supply, and less lead time and improves the performance of suppliers in a supply chain.

This study studies compares the two levels of the network structure factor in terms of the three pillars of sustainability. As it is mentioned in the previous paragraphs, Physical Internet accomplishes all of the sustainability pillars. Also, when the number of vehicles values are analyzed by considering three pillars, it is seen that 10 vehicles reach more minimum results. According to this case study, Physical Internet with 10 small vehicles and load factor of 0.5 achieves a complete sustainability with the three pillars.

CHAPTER 7
CONCLUSION

The concept of Physical Internet was investigated in this study using the simulation method on Arena Simulation Software. The supply chain network models of classic supply chain and Physical Internet concepts were created and compared in terms of sustainability using a hypothetical but realistic supply chain case study. Two simulation models have been created, namely classic supply chain and Physical Internet. The results from 24 scenarios and 720 run according to the experimental design were examined in Minitab. There are six performance metrics in this study to compare the models in the context of sustainability with its three pillars. These performance metrics are cost which includes transportation cost, holding cost (*h*), lead time of deliveries to each facility, CO_2 emissions caused during transportation process, backorders that are caused by insufficient inventory, average inventory levels. GHG emissions for the environmental pillar of the performance metrics; costs including transportation, holding, and backorder for the economic pillar; for the social pillar, average inventory level and lead times were examined by sustainability. As it can be understood from the main effects and interaction plots, GHG emissions are reduced in Physical Internet models compared to the classic model. There is also a drop in the backorder and average inventory levels performance metrics, which means that resource waste, is reduced. Thus, it can be said that Physical Internet provides the environmental pillar of sustainability. When analyzing data on holding costs, backorders cost, transportation cost and total cost; it is acknowledged that Physical Internet is more sustainable unlike classic supply chain system. It can be remarked that by observing the results of the lead time, the Physical Internet satisfies the purpose of the fast movement of physical products. In addition, the lower average inventory level and backorder rates show that Physical Internet effectively accomplishes its goal of effective usability of products. Thus, this study addresses the social pillar of sustainability as well as the economic and environmental pillars, and investigates all pillars at the same time by employing simulation. In this case study, Physical Internet achieves sustainability with its three pillars with the conditions of 10 vehicles with small capacity and load factor of 0.5.

As a summary, this study has many contributions. First, this study reveals that if the Physical Internet system is implemented to the supply chain, the shipping duration can be reduced and the social pillar of sustainability could be strengthened. In today's age, while global warming has become even more dangerous, small vehicles of 10 should be preferred with the Physical Internet structure in order to ensure full sustainability and achieve optimum results. Another part of ensuring this sustainability is to calculate the estimated time of vehicle filling. In this case study, the transparent information sharing of PI-hubs and PI-containers was sufficient to complete this calculation. This approach can further increase the decisive aspect of Physical Internet on sustainability. In addition, the environmental part of this approach is that the damage inflicted by transportation to environment can be decreased without adjusting the quantity of vehicles and also the cost for the economic pillar.

In addition to its theoretical contribution to the literature, this study also has contributions as a managerial implication. Minitab results also show that the open web structure and inventory transparency of Physical Internet show a great improvement on sustainability. According to the main effects and interaction plots, the transparent structure of Physical Internet can supply the flexible supply chain model required to meet the customer's requests by addressing the social part of sustainability with the fast movement of physical products. The change in customer demand is immediately noticeable thanks to the transparent technological system of Physical Internet. In addition, the sharing of information provided by PI-containers also speeds up the supplier selection process, reducing lead time and this positively affects customer satisfaction with the increase in customer service level. Lateral shipment contributes to customer satisfaction by reducing the lead time further. In addition, there is an interaction in terms of the economic pillar of sustainability. While customer satisfaction rises, inventory also reaches the optimum level. Vehicle utilization is affected by this circumstance and the mileage declines and reaches the optimum level. This change in inventory and vehicle utilization circumstances additionally diminishes the cost. This decline in cost means improved profitability for companies. This positive change in vehicle utilization and optimum inventory level replies to the environmental part by showing the same effect in the environmental pillar of sustainability, Physical Internet clearly shows the positive effects that can change the way transportation is the most environmentally harmful transportation mode. In addition, the Physical Internet model contributes to the reduction of waste in the supply chain, as it reaches the optimum level in inventory. This research provides meaningful insights for academics and industry by filling an important gap in the literatures and showing managers the positive impact of supplier innovativeness in order to facilitate collaborations in the supply chain. This study can be extended in a few directions as a future work. For further studies, heterogeneous fleet should be taken into consideration with various vehicle types. Also, lateral shipment can be applied between retailers in a branch perspective.

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