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A Sustainability Comparison of Traditional Supply Chains and Physical Internet Supply Chains Using Simulation

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Abstract

Sustainability is one of the most important topics that should be considered by every sector because it helps to reduce the harmful environmental effects of operations. Supply chain operations have significant impacts on environmental, social and economic issues, and therefore, sustainable supply chains have become an important issue for the companies. Also, Physical Internet (PI) is one of the recent research topics in supply chain literature and it helps to provide sustainability. The contribution of this study to the literature is the comparison of traditional supply chain and PI structures with simulation in terms of sustainability. The simulation models are tested on realistic but hypothetical case studies. Each simulation model consists of three echelons (supplier, distribution center and retailer) and is developed by using ARENA 14.0 software. The PI and the traditional are compared according to carbon emissions, and the results are discussed in detail. The results show that the emission level of PI is significantly lower than the emission level of traditional supply chain structures. Also, larger vehicle capacity reduces the total carbon emissions in both traditional supply chains and PI due to the reduced number of trips.

Keywords: Logistics, Physical Internet, Simulation, Supply Chain Management, Sustainability.

1. Introduction

Profit and cost-oriented studies have been the focus of the majority of the firms; however, there has been an increase in the number of studies focused on the sustainability and environmental aspects of the operations. In supply chain management, sustainability is even more important because it has a global impact on the environment. Therefore, Sustainable Supply Chain Management (SSCM) has become one of the most popular topics in the supply chain literature. Sustainable Supply Chain Management 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." [1]. Sustainability cannot be reached in an environment where one of these three sustainability elements that were mentioned SSCM definition is missing in a supply chain [2]. Traditional logistics and supply chain management are not sustainable in terms of these three aspects of sustainability that are social, environmental, and economic [3]. In Sustainable Supply Chain Management, global energy consumption, direct and indirect pollution and greenhouse gas (GHG) emissions are minimized to provide a sustainable logistics and supply chain network. Also, additional gains in logistics and supply chain processes can be obtained by efficient communication flow and accessible also accurate data sharing [4].

In this paper, the traditional supply chains and PI are compared in terms of sustainability using a hypothetical but realistic supply chain case study. Arena Simulation Software is used to build simulation models. This study extends the cost-based comparisons of PI and traditional supply chains in the literature and compares them in terms of carbon emissions.

This paper is organized as follows. The relevant literature of PI and Sustainable Supply Chains are summarized in Section 1. The problem definition and methodology are explained in Section 3. The case study and results are presented in Section 4. Conclusion and future work are summarized in Section 5.

2. Literature Review

There are various studies on the PI in the literature. Similar to our study, Hakimi, Montreuil, Sarraj, Ballot, & Pan [6] developed the first simulators of PI-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 PI-enabled environments to non-PI environments. As a result of their simulations with the real data, the overall traveled distance is significantly reduced in the PI scenario. However, unlike our study, they did not consider sustainability. Similarly, Furtado, Fakhfakh, Frayret, & Biard [7] studied on PI and explored a PI-based transport model, but they focused on consolidation. Their simulation proved that the current traditional supply chain of their case study is unsustainable, and PI helps to ensure sustainability by improving efficiency, reducing costs, and also reducing GHG emissions. Sarraj, Ballot, Pan, Hakimi, & Montreuil [8] evaluated the sustainability in PI similar to our paper, however, they only considered the specialized containers that are used in PI. They simulated and analyzed a total of three scenarios, including Road-based PI, multimodal PI, and PI-without Manufacturing. According to their results, the utilization of transport vehicles increases by almost 17% with the use of PI. 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 PI scenarios. Pan and Ballot [9] assessed the perspectives of the application of open tracing container (OTC) in FMCG supply chains by comparing the scenarios of with and without the use of OTCs. Their study showed that OTC reduces average inventory levels, daily transportation distances, and the number of rotation per OTC. Pan, Nigrelli, Ballot, Sarraj, & Yang [10] proposed a simulation model to analyze the resource levels in a PI structure, however, unlike our study, their main purpose is to assess the inventory management policies for PI. Their results showed that PI 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, Pan, & Ballot [11] studied inventory management problems in the PI for the 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 PI.

Aside from the studies on PI, there are some studies in the literature compared to different supply chain structures using simulation. However, unlike our study, they did not consider sustainability. For example, Merkuryev, Petuhova, Van Landeghem, & Vansteenkiste [12] 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-echelon

supply chain. Prasoon, Agarwal, & Kumar[13] built a two-echelon supply chain structure using simulation to compare centralized and decentralized supply chains in order to minimize the cost. Cannella, Dominguez, Framinan, & Bruccoleri [14] 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. Agarwal [15] presented two models of a single echelon supply chain to compare continuous and periodic inventory policies, by using a discrete-event simulation on SimPy. Banerjee, Burton, & Banerjee [16] simulated a two-echelon supply chain network that includes different operating circumstances to examine the effects of two lateral transshipment approaches that are Lateral transshipments based on availability (TBA) policy and Lateral transshipments for inventory equalization (TIE) policy. Similar to Banerjee et al. [16], Tiacci and Saetta [17] implemented a simulation of a 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 classical policy of no lateral shipments. Tlili, Moalla, & Campagne [18] proposed an empirical simulation of an inventory model based on three components: the optimization inventory model, the transshipment policy and the rationing policies to minimize total system cost to define the effective parameters on transshipment benefits. Firouz, Keskin, & Melouk [19] considered a problem considering multi-sourcing, supplier selection, and inventory problem with lateral transshipments by a decomposition-based heuristic algorithm, along with a simulation model to minimize total cost. Yan and Liu [20] conducted simulations of multi-echelon supply chains to analyze by comparing them with respect to the average stock level, customer satisfaction rate, and transshipment cost. Although there are studies comparing PI and traditional supply chains, far too little attention has been paid to analyze sustainability. Our study differs from the ones in the literature by focusing on sustainability. The next section defines the problem in detail.

3. Problem Definition and Methodology

Sustainability is an essential topic in the management of a supply chain because it has a global environmental influence. Distribution activities in a supply chain contribute to a significant amount of GHG emissions within the supply chain. In a sustainable supply chain, GHG emissions are reduced in order to provide sustainable logistics and preserve the environment. However, traditional logistics and supply chain management are not sustainable [3]. The most studies in the supply chain literature are focused on cost minimization, lead time minimization or profit

maximization. However, the sustainability of a supply chain has become one of the major research areas for the last decade. With the recent developments in the global communications and information system technologies, a new distribution system, PI, has emerged. PI is structured to promote sustainability by encouraging the creation of a systematic and extensive mindset that can offer genuinely sustainable alternatives to current methods and symptomatic problems caused by existing practices that support the future initiatives for sustainability [4]. For example, in a recent study, specialized containers are suggested to be used in PI by Sarraj, Ballot, Pan, Hakimi, & Montreuil [8]. They noticed a 60% reduction in CO_2 emissions without increasing lead times. Pan and Ballot [9] analyzed the perspective for the application of OTC in the FMCG supply chain, and the findings showed a decrease in daily transport distance and rotation. These studies show us new opportunities for reducing carbon emissions within supply chains. Therefore, our study investigates the sustainability of PI and compares its performance with the traditional supply chains in terms of GHG emissions.

In this study, a realistic hypothetical distribution scenario with three retailers and three producers are used to compare traditional supply chains and PI in terms of GHG emissions using. The structure of the traditional supply chain is shown in Figure 1. This traditional supply chain network includes three producers, one distribution center (DC) and three retailers. Each tier (retailer, distribution, or producer) is informed only by its next tier and each tier can reach only information of the previous tier. The product flow is also provided only vertically. DC receives products only from producers. There are three retailers and these retailers receive products only from DC. This traditional distribution structure increases the distance traveled.
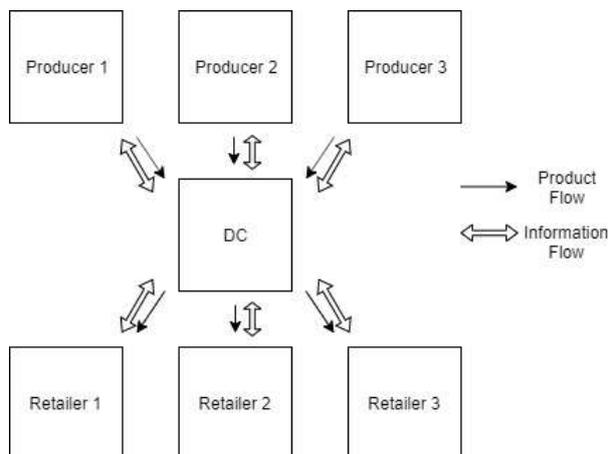

Figure 1. The simulation model of the traditional supply chain network.

According to Equation 3, the energy conversion factor (EF; in kg CO_2 per liter fuel) is multiplied by total fuel consumption during the delivery process to calculate

The distribution network structure of PI includes three producers (each produces different products), three physical internet hubs (PI-HUBs) and three retailers as shown in Figure 2. Each tier can reach information on any tier in the supply chain. At this stage, the features of the PI-HUB concept should be explained briefly. Unlike traditional supply chain understanding, PI-HUBs provide the stock replenishment from any point in the supply chain, including inventory relocation between other PI-HUBs within the PI. PI-HUBs are open (and also reachable) to all users in the PI model. In addition, retailers can order from any available PI-HUB, not from a fixed PI-HUB, unlike the traditional supply chain. In other words, retailers have multiple resource options (i.e., PI-HUB options) while making orders [10]. This feature of the PI model changes the total distribution distance and this affects total GHG emissions. Therefore, traditional supply chain and PI models, are compared in terms of GHG emissions to measure sustainability. The formulas for GHG emissions are explained as follows.
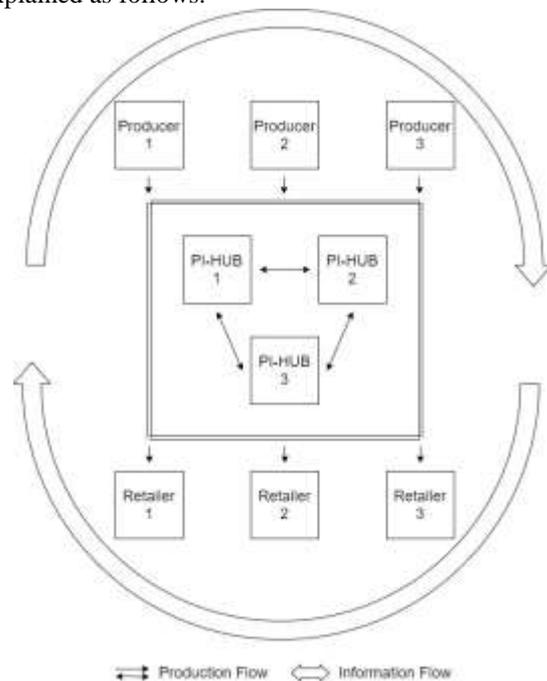

Figure 2. The simulation model of the PI network.

This study focuses on sustainability. Thus, both models are compared in terms of the total amount of carbon dioxide released during transportation. To calculate the total carbon dioxide (CO_2) emission during the transportation processes, the formula given in Equation 1 is used. This formula is adopted from [21].

$$GHG_{TO} = \frac{(EC_{ve} + (EC_{vf} - EC_{ve}) * LF)}{100} * distance * EF \text{ (3.1)}$$

CO_2 emissions. EC stands for total energy consumption in liters fuel. EC_{vf} is the fuel consumption while the vehicle is full, EC_{ve} is the energy consumption while the

vehicle is empty. *EF*, Energy Conversion Factor, is taken as 2.6 kg CO_2 per lt as it is recommended by Kellner and Igl [21]. EC_{vf} and EC_{ve} values that are used in the formula are shown in Table 1. *LF* stands for Load Factor, which is the weight-based capacity utilization of the vehicle and it is calculated by dividing the freight mass (measured in tones or kilograms) by the maximum weight-based carrying capacity of the vehicle.

Table 1. Total fuel consumption (liters per 100 km) of vehicles.

Vehicle Type	EC_{ve}	EC_{vf}
Small	11 lt	20 lt
Large	14 lt	25lt

4. Results

To compare the traditional supply chain and PI, two simulation models are built as in Figures 1 and 2, respectively. One simulation model for the traditional supply chain of the three-echelon supply chain that includes three producers and each of them produces different products, one DC and three retailers that are competitors. The PI model shares the same three echelon structure as the traditional supply chain model. However, the PI model includes three PI-HUBs so that each retailer can be assigned to a specific PI-HUB but can order from any of them. PI-HUBs are different from

the DC that is in the traditional supply chain model. PI-HUBs do not have to order to producers for the stock replenishment. It is possible to provide stock replenishment to one of the other PI-HUBs, including inventory relocation between other PI-HUBs within the PI. Therefore, lateral shipment is possible between PI-HUBs. In this study, the main goal is to compare the traditional supply chains and PI in terms of GHG emissions.

The main hypothesis of this study is that the application of the PI in supply chains produces less GHG emissions.

Table 2. Experimental design

Factors	Description	Factor Levels	
		Level 1	**Level 2**
A	Network Structure	Traditional	PI
B	Vehicle Capacity	1,000 kg	3,000 kg

The experimental factors are given in Table 2. Two experimental factors are considered with two levels each. The first level of the network structure is the traditional supply chain, whereas the second level is the PI. The second factor is vehicle capacity, which is determined by the vehicle type. The small vehicle has a capacity of 1,000 kg, and the large vehicle has a capacity of 3,000 kg.

Table 3. Parameters of the traditional supply chain model

No.	Parameters	Unit	Type	Value	
				Min	**Max**
1	Demand At Retailer 1 For Product 1	Units/5 mins	Uniform	1	2
2	Demand At Retailer 1 For Product 2	Units/5 mins	Uniform	1	5
3	Demand At Retailer 1 For Product 3	Units/20 mins	Uniform	1	5
4	Demand At Retailer 2 For Product 1	Units/5 mins	Uniform	1	5
5	Demand At Retailer 2 For Product 2	Units/15 mins	Uniform	1	10
6	Demand At Retailer 2 For Product 3	Units/30 mins	Uniform	1	5
7	Demand At Retailer 3 For Product 1	Units/5 mins	Uniform	1	4
8	Demand At Retailer 3 For Product 2	Units/10 mins	Uniform	1	5
9	Demand At Retailer 3 For Product 3	Units/45 mins	Uniform	1	5
10	Batch Size At Producer 1	-	Fixed	100	
11	Batch Size At Producer 2	-	Fixed	100	
12	Batch Size At Producer 3	-	Fixed	100	
13	ROP For Product 1 At Retailer 1	-	Fixed	200	
14	ROP For Product 2 At Retailer 1	-	Fixed	200	
15	ROP For Product 3 At Retailer 1	-	Fixed	200	
16	ROP For Product 1 At Retailer 2	-	Fixed	200	
17	ROP For Product 2 At Retailer 2	-	Fixed	200	
18	ROP For Product 3 At Retailer 2	-	Fixed	200	
19	ROP For Product 1 At Retailer 3	-	Fixed	200	
20	ROP For Product 2 At Retailer 3	-	Fixed	150	
21	ROP For Product 3 At Retailer 3	-	Fixed	200	
22	ROP For Product 1 Of DC	-	Fixed	400	
23	ROP For Product 2 Of DC	-	Fixed	400	
24	ROP For Product 3 Of DC	-	Fixed	400	

Table 4. The distances (km) between DC and retailers.

	Retailer1	Retailer 2	Retailer 3
DC	100	200	300

The inventory policy of the traditional supply chain model is a continuous review. When the inventory of the DC is lower than or equal to the reorder point (ROP), the production process starts at the producer. Production quantity is determined according to the quantity of the DC ordered. If the order quantity is greater than the batch size of the production, production continues with the batch size, however, if it is lower than the batch size, production continues with order quantity. When the inventory of one of the retailers is lower than or equal to the ROP, an order is made to the DC. If there is sufficient inventory, the order is met by sending the products from the DC, however, if the inventory is not sufficient, the order is recorded as a backorder and met when inventory is available. Table 3 shows the parameters of the traditional supply chain model. Parameters 1 through 9 are distributed with uniform distribution. 10 to 27 are fixed values. The distances between the DC and retailers of the traditional supply chain model are shown in Table 4.

The inventory policy of PI-HUBs in the PI model is source substitution. Source Substitution is picking the closest source with sufficient inventory [10]. When the inventory of the PI-HUB is lower than or equal to its ROP, an order is sent to the closest PI-HUB, thus, this enables lateral shipment. If PI-HUBs do not have sufficient inventory to meet the order, the order is made to producers and production starts. Table 5 shows the parameters of the PI model. Parameters from 1 to 9 are distributed with uniform distribution, and the rest are constant values. The distances between PI-HUBs and retailers of the PI model are shown in Table 6.

Table 5. Parameters of the PI model.

No.	Parameters	Unit	Type	Value Min	Max
1	Demand At Retailer 1 For Product 1	Units/5 mins	Uniform	1	2
2	Demand At Retailer 1 For Product 2	Units/5 mins	Uniform	1	5
3	Demand At Retailer 1 For Product 3	Units/20 mins	Uniform	1	5
4	Demand At Retailer 2 For Product 1	Units/5 mins	Uniform	1	5
5	Demand At Retailer 2 For Product 2	Units/15 mins	Uniform	1	10
6	Demand At Retailer 2 For Product 3	Units/30 mins	Uniform	1	5
7	Demand At Retailer 3 For Product 1	Units/5 mins	Uniform	1	4
8	Demand At Retailer 3 For Product 2	Units/10 mins	Uniform	1	5
9	Demand At Retailer 3 For Product 3	Units/45 mins	Uniform	1	5
10	Batch Size At Producer 1	-	Fixed	100	
11	Batch Size At Producer 2	-	Fixed	100	
12	Batch Size At Producer 3	-	Fixed	100	
13	ROP For Product 1 At Retailer 1	-	Fixed	200	
14	ROP For Product 2 At Retailer 1	-	Fixed	200	
15	ROP For Product 3 At Retailer 1	-	Fixed	200	
16	ROP For Product 1 At Retailer 2	-	Fixed	200	
17	ROP For Product 2 At Retailer 2	-	Fixed	200	
18	ROP For Product 3 At Retailer 2	-	Fixed	200	
19	ROP For Product 1 At Retailer 3	-	Fixed	200	
20	ROP For Product 2 At Retailer 3	-	Fixed	150	
21	ROP For Product 3 At Retailer 3	-	Fixed	200	
22	ROP For Product 1 Of HUB1	-	Fixed	700	
23	ROP For Product 2 Of HUB1	-	Fixed	700	
24	ROP For Product 3 Of HUB1	-	Fixed	700	
25	ROP For Product 1 Of HUB2	-	Fixed	500	
26	ROP For Product 2 Of HUB2	-	Fixed	500	
27	ROP For Product 3 Of HUB2	-	Fixed	500	
28	ROP For Product 1 Of HUB3	-	Fixed	150	
29	ROP For Product 2 Of HUB3	-	Fixed	150	
30	ROP For Product 3 Of HUB3	-	Fixed	150	

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Table 6. The Distances (km) Between PI-HUBs and Retailers.

	Retailer1	Retailer 2	Retailer 3
HUB1	100	200	300
HUB2	300	100	200
HUB3	200	300	100

A 2-factor factorial design with two levels was used for the experiments. Note that the factors were defined in Table 2. For each scenario 10 replications were used and a total of 40 test instances were run. Each simulation runs 30 days. According to the ANOVA test, all factors are significant. In other words, the structure of the supply chain, vehicle capacity and the interaction of these two main factors are found significant as shown in Figure 3.
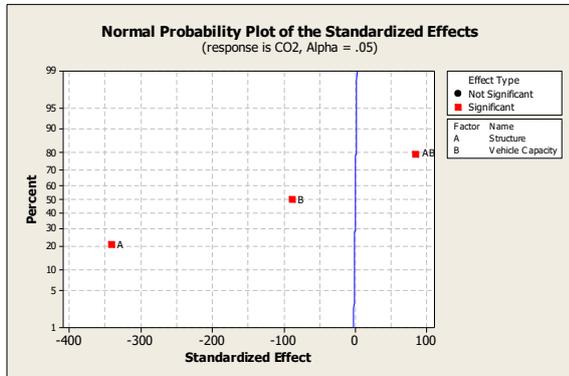

Figure 3. Normal Probability Plot of the Standardized Effects.

Note that, statistical analysis has been performed using Minitab Software. According to the Pareto chart for the standardized effect, as shown in Figure 4, the structure of the supply chain factor has the largest effect.
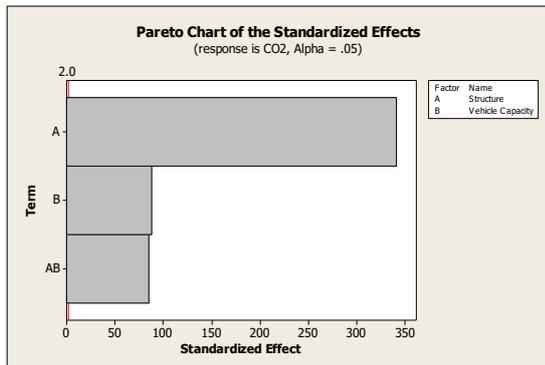

Figure 4. Pareto Chart of the Standardized Effects.

Figure 5 shows the significant main effects of CO_2 emissions. Similarly, Figure 6 shows the interaction plot. According to Figures 5 and 6, the PI yields significantly lower CO_2 emissions than the traditional supply chain. Also, the large vehicle with a capacity of 3,000 kg helps to reduce carbon emissions.
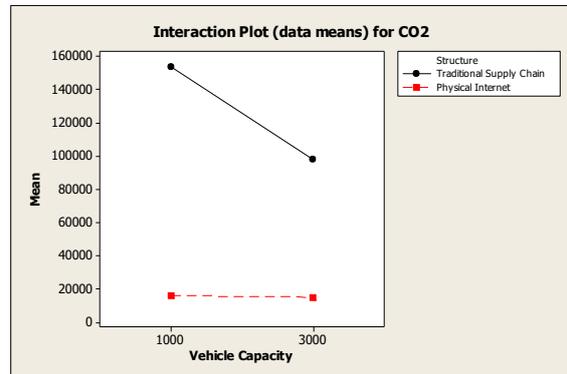

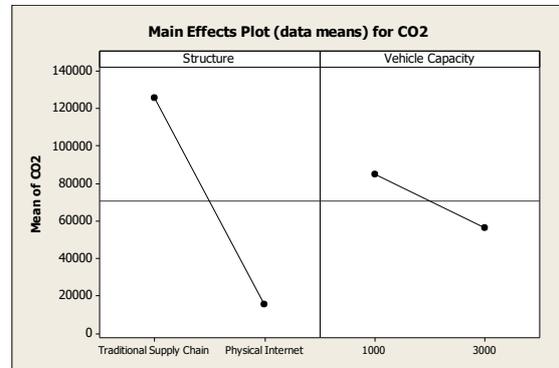**Figure 5.** Significant main effects for CO_2 Emissions.

Figure 6. Interaction Effect of Structure and Vehicle Capacity for CO_2 emissions.

4.1 Discussion

As it is already known, the traditional supply chains are not sustainable. Our study showed that the emission level of PI is significantly lower than the emission level of traditional supply chain structures. With consideration of the features of the PI, such as information sharing and inventory sharing, sustainability in supply chains can be improved. Also, the PI provides transparency in information sharing and allows access to information anywhere in the supply chain. This transparency is very useful in accessing the inventory information of other PI-HUBs and prevents a great deal of time and a large portion of carbon dioxide emissions.

The inventory policy applied in PI simulation is source substitution. Source substitution enables inventory relocation between PI-HUBs, unlike the traditional supply chain. While the traditional supply chain focuses only on vertical shipment, the PI's inventory policy allows for lateral shipment. Instead of ordering from a manufacturer at a remote location, the option to order from a closer PI-HUB significantly increases the supply chain's sustainability.

5. Conclusion

Sustainability has become one of the most important topics in logistics and supply chain for the last decade. Reducing the harmful effects on the environment by redesigning operations is crucial for maintaining sustainable supply chains.

This paper focuses on the comparison of the traditional chain and PI in terms of sustainability. The simulation models are structured as three-echelon supply chain networks and modeled using ARENA Simulation Software. Our study compared PI and traditional supply chains on a hypothetical but realistic supply chain case study using simulation. The results of the simulation study highlighted that PI has a significant effect on decreasing CO_2 emissions of a supply chain during logistics and supply chain processes. Moreover, the increase in vehicle capacity has significantly reduced carbon emissions.

In the future work, other performance factors, such as total cost with transportation and inventory holding costs, lead time, and average inventory levels, will be included in this study. In the PI, retailers are assumed to be competitors in this study, however, like other future work, retailers can be structured as branches and lateral shipment can be enabled between retailers as well so retailers will be able to apply source substitution among them. Also, different vehicle types using electric or alternative fuel sources can be investigated as a future study.

Abbreviations

PI:	Physical Internet
PI-HUB:	Physical Internet Hub
GHG:	Greenhouse Gas
DC:	Distribution Center
ROP:	Reorder Point
EF:	Energy Conversion Factor
EC:	Total Energy Consumption
EC_{ve}:	EC when Vehicle Empty
EC_{vf}:	EC when Vehicle Full
FMCG:	Fast Moving Consumer Goods
LF:	Load Factor
SSCM:	Sustainable Supply Chain Management

Ethics

There are no ethical issues after the publication of this manuscript.

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