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Research Article

Analyses on the Effects of Time Window Choices on Sustainable Vehicle Allocation Problems

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Abstract
This study aims to analyze the effects of the time window choices on Vehicle Allocation Problems with respect to economic, social, and environmental indicators. To the best of our knowledge, such an attempt does not exist in the related literature. We present a Mixed Integer Programming model for a generic Vehicle Allocation Problem with a profit maximization objective under time window constraints. The applicability of the model in practice has been shown in numerical analyses. The model enables to reveal potential effects of the time window choices on economic, social, and environmental outcomes of allocation decisions in Vehicle Allocation Problems. The numerical results show that loosened time windows have the potential to provide economic and environmental benefits in the addressed problem. We also propose a collaboration policy attractive to both the transportation company and its customers through price discounts, which improves the economic and social performances of the addressed transportation logistics network.
Keywords: Vehicle Allocation, Time Windows, Mixed Integer Programming, Sustainability.
JEL Classification Codes: C610, L910, M210

Sürdürülebilir Araç Tahsis Problemlerinde Zaman Penceresi Seçimlerinin Etkisi Üzerine Analizler

Öz
Bu çalışma, Araç Tahsis Problemlerinde zaman penceresi seçimlerinin ekonomik, sosyal ve çevresel göstergeler açısından etkilerini incelemeyi amaçlamaktadır. Bildiğimiz kadarıyla ilgili literatürde böyle bir çalışma bulunmamaktadır. Bu çalışmada zaman pencereleri kısıtlamaları altında kar maksimizasyonu hedefi olan genel bir Araç Tahsis Problemi için bir Karma Tam sayılı Programlama modeli sunulmaktadır. Modelin pratikte uygulanabilirliği nümerik analizler üzerinde gösterilmiştir. İlgili model Araç Tahsis Problemlerinde zaman penceresi seçimlerinin tahsis kararlarının ekonomik, sosyal ve çevresel sonuçları üzerindeki potansiyel etkilerini ortaya koyma imkânı tanımaktadır. Sayısal sonuçlar, ele alınan problemde genişletilmiş zaman pencerelerinin ekonomik ve çevresel faydalar sağlama potansiyeline sahip olduğunu göstermektedir. Ayrıca, iskontolu fiyat uygulaması yoluyla hem nakliye şirketi hem de müşterileri için cazip, nakliye lojistik ağının ekonomik ve sosyal performanslarını iyileştiren bir iş birliği politikası önerilmektedir.
Anahtar Kelimeler: Araç Tahsisi, Zaman Penceresi, Karışık Tam Sayılı Programlama, Sürdürülebilirlik.
JEL Sınıflandırma Kodları: C610, L910, M210

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1. Introduction

Vehicle Allocation Problems (VAPs) are one of the decision support problems frequently encountered especially in long-haul transportation. VAPs are usually related to carriers that generate revenue by transporting freight over long distances (Ghiani, Laporte and Musmanno, 2013, pp. 350-352). In a typical VAP, vehicles perform direct shipments between node pairs throughout a finite planning horizon. After a product delivery is fulfilled, each vehicle has three options: taking a new load from the current node, making an empty travel to another node to satisfy future demands, or staying in the current node as idle.

Growing awareness of environmental issues such as global warming or air pollution brings sustainability into the agenda of the freight transport companies. Sustainability comprises three dimensions: economic, social, and environmental. The economic dimension ensures preventing the deterioration of the company's capital (Goodland, 2002). The social dimension measures the ability of the company to address issues that are related to the well-being of its stakeholders, while the environmental dimension measures the company's negative impacts on air, land, water, and ecosystem (Chopra and Meindl, 2015, pp. 498-500). Companies should respect all three aspects of sustainability to ensure their future continuity and to gain a competitive advantage. VAPs are confronted in many sectors subject to sustainability concerns, such as fresh food transportation, home-to-home moving, or direct parcel deliveries. Delivery time management, accordingly time window settings in these fields are crucial since they could affect the main decisions involved in VAPs, such as the number of full and/or empty vehicles or the number of demands that are met or rejected. Therefore, the effects of time window choices on economic, social, and environmental performances of the decisions in VAPs are worth investigating.

The early studies on VAPs address rail freight transportation systems (e.g., White and Bomberault, 1969; Holmberg, Joborn and Lundgren, 1970). In their problems related to the assignment of empty freight wagons, the parameters are deterministic, and the decision-maker has the opportunity to reject the demands. Holmberg et al. (1970) have additionally used heterogeneous wagon capacities in their studies. Another study that is presented by Philip and Sussman (1977) has used inventory control theory to allocate empty freight wagons. Later, in light of these studies, VAPs have been defined for road haulage cases. VAPs may aim to maximize profit, minimize costs/emissions, or achieve these goals simultaneously. To achieve these goals, the movements of both loaded and empty vehicles have to be decided (Kazanç, Soysal and Çimen, 2021). Soft or hard time windows affect distribution plans of the long-haul freight transport companies and related performance indicators.

The term “time window” refers to the time interval with the lower and upper bounds for an activity to take place. In the literature, researchers address two different types (hard and soft) of time windows. If service points have “soft” time windows, vehicles can arrive before the lower bound or after the upper bound, with a penalty cost. If service points have “hard” time windows, vehicles are strictly prevented from violating the given time interval (Ichou, Gendreau and Potvin, 2003). While companies plan their production and distribution activities, they need to consider the time window requests of customers.

Time windows are used as a constraint in various routing and transportation problems. In the fields where businesses work with fixed timelines, time windows arise naturally in problems faced (Solomon, 1987). In this context, there are fields where vehicle routing problems are handled under time windows constraints, such as emergency logistics (e.g. Han, Li, Liu, Liu and Tian, 2020; Wei et al., 2020), distribution of products that must be transported in a certain time interval due to their structural features (e.g. Meng, Lee and Cheu, 2005; Komijan and Delavari, 2017; Martins, Ostermeier, Amorim, Hübner and Almada-Lobo, 2019), and waste collection (e.g. Buhrkal, Larsen and Ropke, 2012; Islam and Rahman, 2012; Campos and Arroyo, 2016). As well as vehicle routing problems, it is seen that traveling salesman problems with time windows are handled with various exact or heuristic algorithms (e.g. Ohlmann and Thomas, 2007; Shi, Wang, Zhou and Liang, 2008; Wang and Regan, 2009; Rimmel, Teytaud and Cazenave, 2011).

This study aims to analyze the effects of the time window choices on economic, social, and environmental indicators in VAPs. As far as we know, such an attempt does not exist in the related literature. A VAP under time windows constraints is formulated as a mixed-integer linear programming model. Employing this model, our analyses comprise the effects of tight and loose time windows on (i) the bottom line of the company (economic pillar), (ii) the number of satisfied customers, under rejection penalty or discounted transportation fee assumptions (social pillar), and (iii) the emissions generated by transportation activities (environmental pillar).

The literature search in the Turkish language on VAPs with time windows and sustainability concerns, conducted by searching the "Google Scholar" index, did not reveal any academic studies. Then, a topic-based search was made using the keyword "vehicle allocation" in the "Web of Science" database, to find articles written in the English language on the topic. The search scope was narrowed by using the keyword "time windows". Additionally, the literature reviews of these articles were also examined. Finally, six studies that address VAP with time windows were obtained. Table 1 presents the summary of the relevant studies, in terms of the type of modeling approach used, the type of time windows (hard or soft) defined, whether rejection of demands is allowed, and whether the effects of time windows on particularly economic, environmental, and social pillars of sustainability, are investigated.

Table 1: Summary of the Reviewed Studies

Article	Model Type	Time Windows		Rejection of Demands	Effects of Time Windows on Sustainability Pillars		
		Soft	Hard		Eco	Soc	Env
Beaujon and Turnquist, 1991	Stochastic Dynamic Programming	√		x	x	x	x
Godfrey and Powell, 2002a	Stochastic Dynamic Programming		√	√	x	x	x
Godfrey and Powell, 2002b	Stochastic Dynamic Programming	√		x	x	x	x
Ongarj and Ongkunaruk, 2013	Integer Programming		√	x	x	x	x
Shi, Song and Powell, 2014	Stochastic Dynamic Programming		√	√	x	x	x
Kaewpuang, Niyato, Tan and Wang, 2016	Stochastic Programming and Linear Programming		√	x	x	x	x
Our Study	**Mixed Integer Linear Programming**		√	√	√	√	√

Eco: Economic sustainability
Soc: Social sustainability
Env: Environmental sustainability

As summarized in Table 1, the time windows assumption in VAPs was first discussed in a study conducted by Beaujon and Turnquist (1991). Godfrey and Powell (2002b) allowed the demands, which could not be met in time, to be met in the next period, by using the soft time windows. Contrary to these two studies, hard time windows were used by Godfrey and Powell (2002a), Ongarj and Ongkunaruk (2013), Shi et al. (2014), and Kaewpuang et al. (2016). According to our brief literature review, there is no study on VAPs which analyzes the effects of time window choices on sustainability. This study may potentially contribute to the sustainable freight transportation management literature by filling the revealed gap.

The rest of this paper is structured as follows. The second section presents problem assumptions and the proposed mixed-integer linear programming model. The third section presents a sample problem that is solved by adding various parameters and the corresponding analyses. The last section presents the conclusions, and suggestions for future research.

2. Problem Description and Model

This study addresses a VAP under hard time windows constraints. Let a freight transportation company serve a number of customers (N = {1, 2, …, |N|}) located in different cities. Arcs refer to potential transportation services that directly connect two nodes. The travel time for each arc is measured in integer multiples of periods and is deterministic. Demands appear as the number of required vehicles to depart from the departure node of each arc in each time period. In other words, customers request to be allocated the number of required vehicles to be used for direct shipment activities between node pairs.

The company does not have to meet all of the demands. Depending on the number of available vehicles and the profit and/or cost, the company can choose the demands to be satisfied. Moreover, the freight transportation company may also partially meet the demands on an arc in a given period.

Vehicle allocation decisions are made for a finite planning horizon (T = {1, 2, …, |T|}). Let d_{ijt} refer to the number of requests on arc (ij) with a departure deadline (the latest time period that a vehicle should start its travel from node i) on period t. Demands with departure deadline t can be satisfied within the time interval $[t - \alpha, t]$, where α refers to the length of time windows (i.e., the number of periods earlier a demand can be met before its due time). Each demand has a different price and therefore profit. The vehicles can also make empty travels to meet future demands with a different starting point than their current node. For the empty travels, the company bears transportation costs without generating any revenue.

The vehicles are assumed to be identical. The number of vehicles located at each node at the beginning of the planning horizon, as well as the number of vehicles entering to and leaving the system (due to maintenance, vacation, leasing contract, etc.) at each node in each period are also known (m_{it}).

The problem aims to maximize the profit obtained through transportation activities. Accordingly, the decisions on the full and empty movements of vehicles and accepted/rejected demands should be optimized. Table 2 presents the notation used in the integer linear programming model of the described VAP which is followed by the corresponding model. Please note that the proposed model has been developed based on a basic VAP model presented by Ghiani et al., 2013.

Table 2: Notation Table for the Model

Symbol	Description
Sets and Parameters	
i, j, k	Indices of nodes
t	Index of time periods
α	Length of time windows in days/periods
N	Set of nodes where loads are taken from and delivered to $N = \{1, \dots, \|N\|\}$
T	Set of time periods $T = \{1, \dots, \|T\|\}$
d_{ijt}	Number of vehicle demands from node i to j with departure deadline in period t
τ_{ij}	Travel time between nodes i and j in periods, in days/periods
p_{ijt}	Price of demand per vehicle for transports from i to j in period t in ₺
c_{ij}	Cost of empty travels from node i to j in ₺
m_{it}	Number of vehicles entered at node i in period t
Decision Variables	
W_{ijt}^{α}	Number of loaded vehicles moved from node i to j in period t to satisfy demand in this arc in period $t + \alpha$
X_{ijt}	Number of loaded vehicles moved from i to j in period t
Y_{ijt}	Number of empty vehicles moved from i to j in period t
Z_{ijt}	Number of unmet demands from i to j in period t

Objective Function:

$$maximize \sum_{t \in T} \sum_{i \in N} \sum_{\substack{j \in N, \\ j \neq i}} \sum_{\substack{a \in \{0, \dots, \alpha\}, \\ t+a \leq |T|}} (p_{ij(t+a)} * W_{ijt}^{a} - c_{ij} * Y_{ijt}) \tag{1}$$

Subject to;

$$\sum_{j \in N} (X_{ijt} + Y_{ijt}) - \sum_{\substack{k \in N, \\ k \neq i : t > \tau_{ki}}} \left(X_{ki(t-\tau_{ki})} + Y_{ki(t-\tau_{ki})}\right) - Y_{ii(t-1)} = m_{it} \qquad i \in N, t \in T \tag{2}$$

$$\sum_{\substack{a \in \{0, \dots, \alpha\}, \\ t+a \leq |T|}} W_{ijt}^{a} = X_{ijt} \qquad i \in N, j \in N, t \in T \tag{3}$$

$$\sum_{\substack{a\in\{0,\ \dots,\ \alpha\},\\ t-a\geq 1}} W^{a}_{ij(t-a)} = d_{ijt} - Z_{ijt} \qquad i \in N, j \in N, t \in T \qquad (4)$$

$$Z_{ijt} \leq d_{ijt} \qquad i \in N, j \in N, t \in T \qquad (5)$$

$$W^{a}_{ijt} \in \mathbb{N} \qquad a \in \{1, \dots, \alpha\}, i \in N, j \in N, t \in T \qquad (6)$$

$$X_{ijt}, Y_{ijt}, Z_{ijt} \in \mathbb{N} \qquad i \in N, j \in N, t \in T \qquad (7)$$

The objective function (1) comprises profit obtained from full vehicles and the cost caused by empty vehicles. The constraint set (2) ensures vehicle flow balance for each period and node. The constraint set (3) determines the vehicles sent in period t to satisfy demands within the time window $[t, \dots, t+\alpha]$ by taking the number of loaded vehicles sent in that period into account. The constraint set (4) indicates that the demands can be delivered up to α periods before the deadline. The constraint set (5) ensures that the unmet demand is less than or equal to the total demand. The constraint sets (6) and (7) define the restrictions on the decision variables.

3. Numerical Analyses

This section shows implementations of the proposed model on an exemplar problem under several scenarios. The analyses aim to demonstrate the applicability of the model in practice and to reveal the potential effects of the time window choices on economic, social, and environmental outcomes of allocation decisions in VAPs. Accordingly, first, tight and loose time window settings are tested in a base case scenario. Then, (i) the results of four different settings of time windows from tight to loose, regarding the bottom line of the company, are presented, (ii) two different policies (price discounts for encouraging customers to comply with loose time window agreements, and penalty cost for unmet demand) are proposed to improve the social sustainability performance of vehicle allocation operations, and (iii) the effect of time window choices on avoidable emissions are presented.

For the numerical analysis, IBM ILOG CPLEX Studio IDE v.12.10 software is used on a machine with Intel® Core ™ i7-8565U CPU @ 1.80 GHz processor and 16 GB RAM to develop and solve the proposed mathematical model.

In what follows, we first explain the experimental design of the analyzes. Then, detailed results of the base case analyses will be presented. Lastly, the results of the analyzes regarding the three pillars of sustainability will be discussed.

3.1. Experimental Design

We assume a freight transportation company that aims to prepare a vehicle allocation plan for serving customers located in the 15 largest cities in Turkey (according to their population density). Distances between the cities are taken from the website of the General Directorate of Highways.[1] Travel times (τ_{ij}) between cities are calculated accordingly by the assumption that the vehicles can travel up to 400 kilometers per day. In total, 15*14=350 arcs are available for allocation requests, over a planning horizon of 25 days. The demand data (d_{ijt}) between city pairs ij with the departure deadline t (i.e., demand values for each of 350*25=8750 ijt tuples) are arbitrarily generated between 0 and 4. The resultant total demand for the whole planning horizon is 2185 vehicles. The freight company has an opportunity to satisfy the demands α periods earlier than their departure deadline, where α is an integer and is set between $[0, 3]$ separately for each demand.

At the beginning of the planning horizon, there are two available vehicles located in each city. The number of vehicles (m_{it}) that will enter or leave the system throughout the planning horizon is assumed to be uniformly distributed between -2 and 2. It is assumed that the freight company uses a homogeneous fleet of heavy load vehicles with 10 wheels and a volume of 60 m^3. This type of vehicle is reported to consume (on average) between 0.27 and 0.32 liters of fuel per kilometer (Man, 2020). We accordingly assume an average 0.3 liters fuel consumption per kilometer. Fuel consumption is converted to emission rates with a fuel conversion factor of 2.63 kg / liter (Defra, 2007). The transportation cost (c_{ij}) generated by empty travels is set arbitrarily as ₺3 per kilometer. Profit (p_{ijt}) to be earned by meeting each demand is randomly generated by a uniform distribution between ₺3.1 and ₺5 per kilometer.

Table 3 shows the summary of the parameter settings described above.

Table 3: Summary of Parameter Settings

Symbols	Values
Sets and Parameters	
N	{1, …, 15}
T	{1, …, 25}
α	{0, 1, 2, 3}
d_{ijt}	Arbitrarily generated between 0 and 4.
τ_{ij}	One day per each 400 kilometers.
p_{ij}	Uniformly distributed between ₺3.1 and ₺5 per kilometer.
c_{ij}	₺3 per kilometer.
m_{it}	$m_{i1} = 2$ for all nodes (i). m_{it} is uniformly distributed between -2 and 2 for all nodes, for all periods except 1.

[1] https://www.kgm.gov.tr/Sayfalar/KGM/SiteTr/Uzakliklar/illerArasiMesafe.aspx, accessed online on 15.07.2020

3.2. Base Solution

This section presents detailed results of the above-described problem under two different settings of time windows (α = 0, α = 3). It takes approximately three seconds to obtain optimal solutions for each setting. Table 4 shows the detailed results of the key performance indicators.

Table 4: Base Solution Results Under Two Time Window Settings (α = 0, α = 3)

<table>
<tr><th colspan="2"></th><th>α = 0</th><th>α = 3</th></tr>
<tr><td colspan="2">Objective Function (Net profit)</td><td>461,192</td><td>697,722</td></tr>
<tr><td colspan="2">Number of loaded vehicles</td><td>185</td><td>285</td></tr>
<tr><td rowspan="4">Number of loaded vehicles that meet demands after ‘a’ periods</td><td>a=0</td><td>185</td><td>97</td></tr>
<tr><td>a=1</td><td>0</td><td>67</td></tr>
<tr><td>a=2</td><td>0</td><td>61</td></tr>
<tr><td>a=3</td><td>0</td><td>60</td></tr>
<tr><td colspan="2">Number of empty vehicles</td><td>94</td><td>9</td></tr>
<tr><td colspan="2">Number of standing (waiting) vehicles</td><td>73</td><td>37</td></tr>
<tr><td colspan="2">Unmet demands</td><td>2,000</td><td>1,900</td></tr>
<tr><td colspan="2">Amount of satisfied demands</td><td>185</td><td>285</td></tr>
</table>

As presented in Table 4, the tight time window setting generates a total profit of ₺461,192 with 185 units of demand met and 94 empty vehicle travels. A loose time window setting enables a higher total profit of ₺697,722. In this setting, 285 units of demand are satisfied and only 9 empty vehicle travels are made. It can be observed from the table that the optimal plan benefits from the opportunity to make earlier shipments. Only 97 demands out of 285 are satisfied on its deadline, whereas 67 units of demand are met one day earlier, 61 are met two days earlier and 60 are met three days earlier.

3.3. Effects of Time Windows on Sustainability Pillars

This section analyses the effects of time window settings on the performance of allocation decisions in VAPs in terms of the three dimensions of sustainability (economic, social, and environmental).

3.3.1. Economic Sustainability

In order to avoid any deterioration in its capital, the company needs to generate as high operating profits as possible. Here we present how changes in time windows may alter the company's operating profit. Therefore, the proposed model is optimized using the base dataset under different α settings and the objective function values are recorded. Figure 1 provides operating profits under each time window setting.

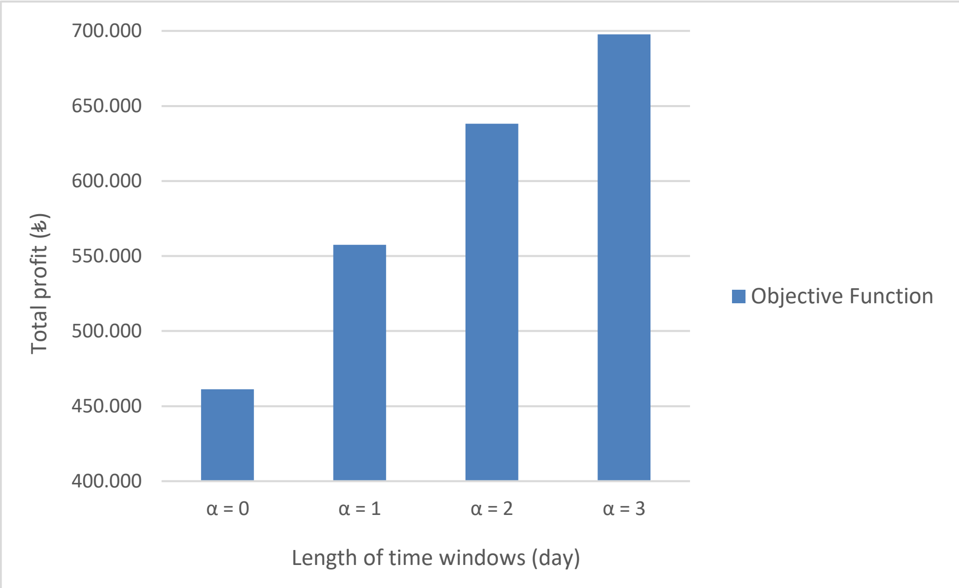

Figure 1: Operating Profits Under Each Time Window Settings (₺)

As can be observed from Figure 1, loosening time windows allows to meet a higher number of demands. It also provides the flexibility of choosing which of the available demands (demands on that arc that have a deadline within [0, α] days) to meet. This flexibility allows the company to choose demands with higher prices. With loosened time windows, the number of empty travels which generate unrequited costs also decreases. Figure 2 shows that these opportunities are realized in every step of increase in the length of time windows. Correspondingly, the

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yielded profits increase by 51% when the length of time windows increases from 0 to 3 days.

The results show the potential economic benefits for freight companies of investing in loose time window agreements with their customers.

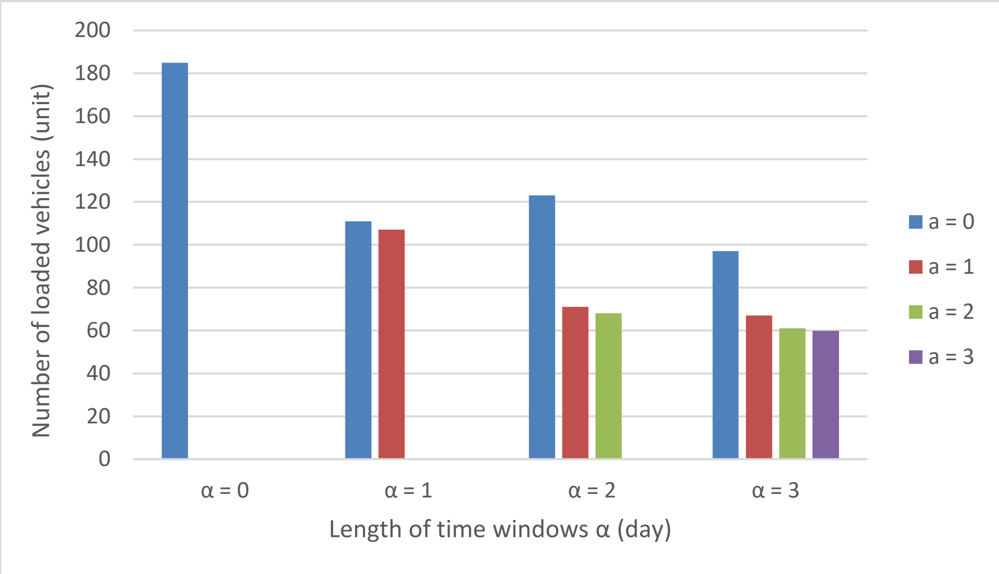

Figure 2: Number of Loaded Vehicles That Meet Demands 'a' Days Earlier Than Its Deadline

3.3.2. Social Sustainability

In a system where companies have the opportunity to select which demands to meet, unmet demands are left to be satisfied by other companies. These unmet demands (which may have a lower revenue/cost ratio, may require a long travel, or may be unattractive for other reasons), however, may potentially affect the well-being of corresponding customers negatively. Other companies might also reject these demands due to similar reasons, which results in a decrease in the number of freight service providers. This reduces the competitiveness in the market which might reduce service quality. In the worst-case scenario, there may be customers which are not able to receive a service within the desired deadlines from any company.

Here, we aim to incorporate the customer point-of-view into the decision process. We first analyze the scenario where a penalty cost is assigned for each unmet demand. Second, we investigate the case where discounted service prices are offered to convince the customers to agree with loosened time windows.

In the first scenario, we simply assign penalty costs to unmet demands. Therefore, the objective function of the proposed model has been changed by adding a parameter of penalty cost (f_{ijt}) and the decision variable for unmet demands (Z_{ijt}).

The proposed model has been run for the base dataset with two different penalty costs settings by using the objective function (8) illustrated below and six constraint sets (2, …,7).

$$maximize \sum_{t \in T} \sum_{i \in N} \sum_{\substack{j \in N, \\ j \neq i}} \sum_{\substack{a \in \{0,\ldots,\alpha\}, \\ t+a \leq |T|}} (p_{ij(t+a)} * W_{ijt}^{a} - c_{ij} * Y_{ijt} - f_{ijt} * Z_{ijt}) \quad (8)$$

Two settings for the unit penalty cost parameter (f_{ijt}) are employed: half of the potential profit that could be earned for each ijt demand tuple, and a sufficiently large number (also known as big M) that will force the company to meet as much demand as possible. Figure 3 shows the resultant key performance indicators under the two penalty cost settings.

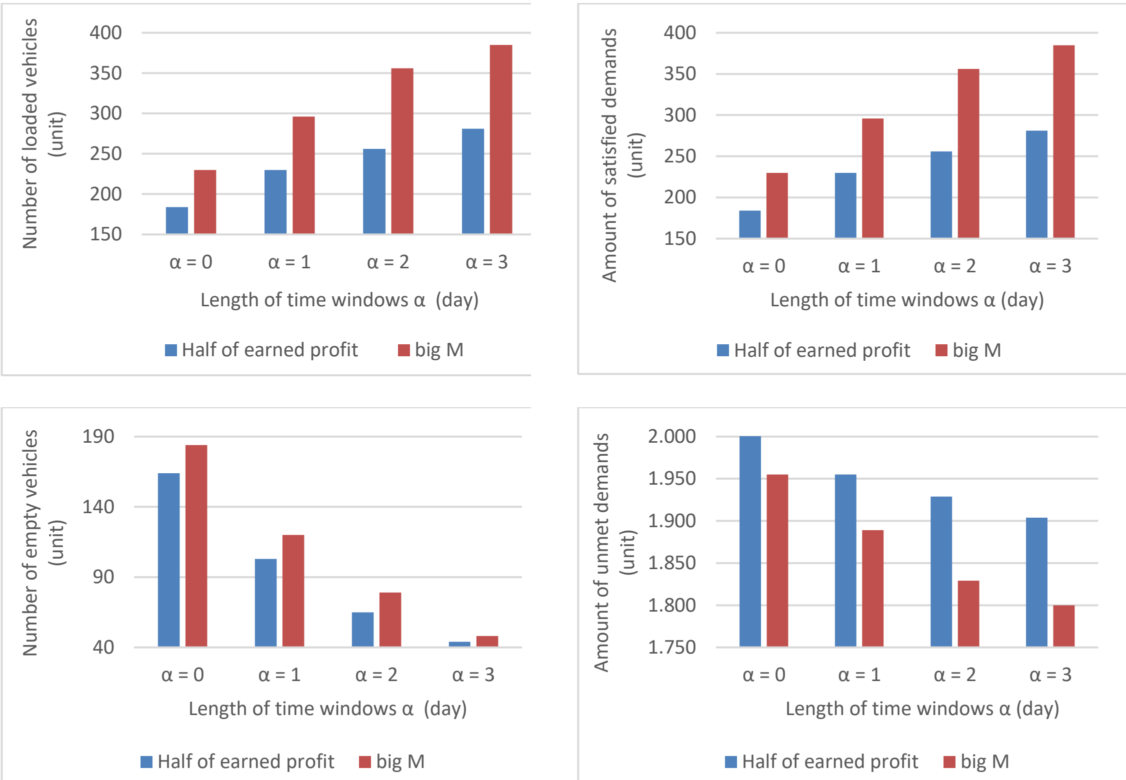

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Figure 3: Key Performance Indicators Under the Two Penalty Cost Settings

The results show that employing penalty costs helps to increase the number of satisfied demands and to decrease the number of unmet demands and empty travels. Loosened time windows also contribute to this improvement. However, incorporating the penalty costs might lead to end up with significantly altered delivery plans with poor economic performance. Therefore, the decision-makers might hesitate to employ such an approach while making allocation decisions. Loose time windows, also, is not a desirable option for customers, since leaving delivery time decisions to the supplier might disturb their operations or complexify their decision-making processes.

The second setting focuses on a different scenario where both parties (the company and the customers) could benefit from reducing the number of unmet demands. We assume that the customers are reluctant to agree to loosen time windows without any incentives. The company, however, may have an opportunity to convince the customers for loosened time windows by means of discounted prices. To demonstrate this, the proposed model has been re-run with different values of price parameter, which is changed according to discount rates, for each value of α. For this purpose, it is assumed that a discount has been applied on the service price for those customers who accept a delivery out of their specified time window. Figure 4 shows the results of the scenarios where regular prices and three different price discount rates of 5%, 15% and 25% are analyzed.

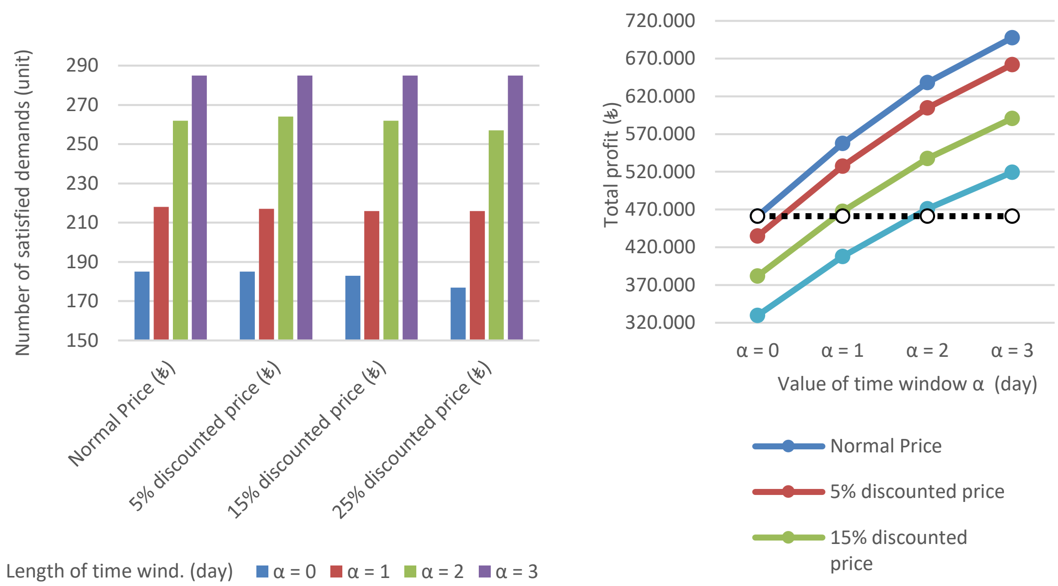

Figure 4: Changes of the Objective Function by Applying Various Discount Rates in Different Time Window Lengths (α)

Figure 4 shows that if the customers insist on tight time windows, the maximum attained profit (without any discounts) is ₺461,192 and the total number of unmet demands is 2,000. This performance could be improved for both sides via loosened time windows and discounted prices. If the customers accept to be allocated vehicles one day earlier than the deadline, a 5% or even 15% discount could yield a higher profit for the freight company (₺527,508 and ₺467,570, respectively) and a smaller number of unmet demands (1,968 and 1,969 units, respectively) which also means a greater number of satisfied demands (217 and 216 units, respectively). If the length of time windows could be expanded to three days, all three discount level offerings enable the company to obtain a higher profit than that where early vehicle allocations are not allowed (₺662,056, ₺590,725, and ₺519,394, respectively) with again a smaller number of unmet demands (1,900 in all discount levels) (a greater number of satisfied demands (285 in all discount levels)).

In summary, a socially sustainable collaboration policy can be proposed to freight companies that serve customers reluctant to loosen time windows without any incentives. The results show that a win-win scenario can be attained by price discounts which improve the economic and social sustainability performances of vehicle allocation decisions through increased profit and demands satisfied.

3.3.3. Environmental Sustainability

Most researches on environmental sustainability in the field focus on emitted CO_2 emissions to nature. In VAPs, customers request direct shipments between specific arcs, meaning that there is a necessity to make the loaded travels of vehicles. The emissions generated by these vehicle movements can be reduced only by using different vehicle types or technologies or eliminating demands; which are beyond the scope of our research. Yet, the empty travels do not reflect the same necessity and could be eliminated. Reducing the number of empty travels would reduce the amount of “avoidable” carbon emissions released. Here we observe the change in the amounts of emission which is obtained by multiplying the number of empty vehicles (found by running the proposed model with the base dataset and different alphas) with the emission coefficients. Thus, we present the effects of tight and loose time windows on the amount of avoidable carbon emissions generated by empty vehicle travels. Figure 5 summarizes the corresponding findings.

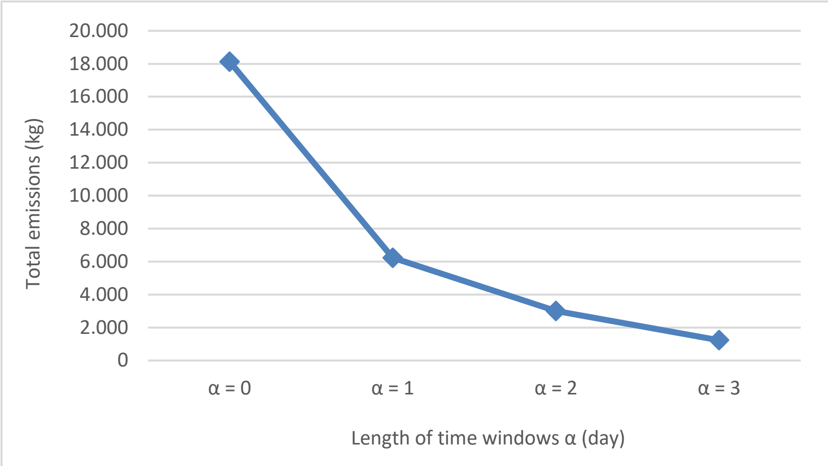

Figure 5: Avoidable Emission Amount (kg) Generated by Empty Vehicles

As seen in Figure 5, the levels of CO_2 which is produced by the movements of the empty vehicles can be decreased by loosening the time windows. When α = 3, the avoidable emissions amount generated by movements of the empty vehicles are decreased by 93% compared to the tight time window setting (α = 0). These results imply that investing in loosening time windows does not only provide economic and social benefits, but also has the potential to contribute to the environmental performance of the logistics system.

4. Conclusion

In this paper, we have modeled and analyzed a VAP under hard time window constraints. As distinct from the traditional attempts on the problem, we revealed the potential effects of time window settings in a logistics system in terms of economic, social and environmental outcomes. To the best of our knowledge, this study is the first attempt to analyze the effects of the time window choices on economic, environmental, and social pillars of sustainability in the field of VAPs.

The added value of the proposed model is presented through several numerical examples. The analyses on the base case show that when customers agree to a more flexible deadline structure, the number of loaded trucks in logistics operations increases by 54%, the number of empty vehicles decreases by 72%, and the amount of unmet demand decreases by 5%. Accordingly, profits (51%) and the amount of satisfied demand (54%) have grown. Besides, when the length of the time windows is expanded (from α=0 to α=3), the economic sustainability performance improves due to a 51% rise in profit and a 54% rise in the number of loaded vehicles. Moreover, it has been observed that by loosening the time windows, a 25% discount rate can be applied to customers, and the satisfied demand amount (61%) and the logistics company's profit (58%) can be enhanced. Consequently, the loosened time window setting has contributed to social sustainability performance. Additionally, loosening time windows reduces the levels of CO_2 emissions produced due to empty vehicle movements by 93% and thus has a positive effect on environmental sustainability performance.

Our findings reveal that loosened time windows have the potential to increase the economic and environmental returns of freight transportation companies' vehicle allocation decisions. Furthermore, loosened time windows tend to generate better results for both the transportation firm and its consumers. In this context, we offer a partnership policy that is appealing to both the transportation firm and its consumers through price reductions, therefore improving the economic and social performance of the targeted transportation logistics network. The suggested model, as well as the data and insights supplied, may be employed in the managerial decision-making processes of freight businesses in a variety of practical applications.

One possible extension of the paper is to consider uncertainty in travel times and demands. Another future research direction could be optimizing the amounts of price discounts on a customer basis. Also, a better estimation of the fuel consumption (such as load-dependent energy calculation) could improve the value of the suggested model.

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