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Impact of the Integration of First-Mile and Last-Mile Drone-Based Operations from Trucks on Energy Efficiency and the Environment

Tamás Bányai

Institute of Logistics, University of Miskolc, 3515 Miskolc, Hungary; alttamas@uni-miskolc.hu

Abstract: Supply chain solutions are based on first-mile and last-mile deliveries; their efficiency significantly influences the total cost of operation. Drone technologies make it possible to improve first-mile and last-mile operations, but the design and optimization of these solutions offers new challenges. Within the frame of this article, the author focuses on the impact of integrated first-mile/last-mile drone-based delivery services from trucks, analyzing the impact of solutions on energy efficiency, the environmental impact and sustainability. The author describes a novel model of drone-based integrated first-mile/last-mile services which makes it possible to analyze the impact of different typical solutions on sustainability. As the numerical examples and computational results show, the integrated first-mile-last-mile drone-based service from trucks could lead to a significant reduction in energy consumption and a reduction in virtual greenhouse gas (GHG) emissions, which would lead to a more sustainable logistics system. The numerical analysis of the scenarios shows that the increased application of drones and the integration of first-mile and last-mile delivery operations could decrease energy consumption by about 87%. This reduction in energy consumption, depending on the generation source of electricity, significantly increases the reduction in greenhouse gas emission.

Keywords: energy efficiency; GHG emission; delivery services; drone technology; optimization; routing; scheduling; supply chain

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1. Introduction

The fast, reliable and cost-efficient delivery of goods is logistically a challenging problem. The application of Industry 4.0 technologies has led to revolutionary new solutions in the field of supply chain solutions. Buy-online-and-pickup-in-store, smart locker and drone delivery solutions are the most representative [1]. The integration of emerging technologies with existing ones has improved the performance of logistics and supply chain solutions, among which the joint truck–drone delivery services are the most promising [2]. Many firms are looking for ways to cut delivery times and costs by exploring opportunities to take advantage of drone technology. The coronavirus outbreak has led to extraordinary pressure to offer contactless services, which has also led to the forced application of drones in the field of parcel delivery, especially in the food industry [3].

The global drone package delivery business has grown from USD 0.68 billion in 2020 to about USD 1 billion in 2021, which means an annual growth rate of about 47%. This remarkable growth is mainly due to the pandemic situation, which led to the increased demand for contactless deliveries. As the research of BusinessWire has predicted, the expected growth of the drone package delivery business is about USD 4.4 billion until 2025 [4].

The advantages of truck–drone joint delivery systems can be described from the technological, logistics, sustainability and financial aspects. Case studies have shown that drone-based last-mile delivery solutions can lead to a significant reduction in customer waiting times of up to 60% compared to truck-only delivery solutions [5].

The use of drones is not limited to the transportation and logistics fields. The utilization of cellular-enabled drones as aerial base stations in next-generation cellular networks is also an extensively researched scientific field [6]. Another interesting research direction of the delivery of heavy parcel delivery solutions is the design of robot-assisted last-mile delivery systems [7]. The extended application of Industry 4.0 technologies in urban areas offers new opportunities for the multi-purpose application of drones, where the drone can perform parcel delivery operations, data collection from Internet of Things devices, security surveillance or wireless power transfer [8].

The truck–drone joint delivery systems have generally focused on last-mile delivery operations, but the integration of first-mile and last-mile operations can increase the efficiency of drone-based delivery service processes. In this research, we address this gap and introduce a new methodology to support the analysis of the impact of different truck-drone joint delivery solutions on energy efficiency and greenhouse gas emission.

This paper is organized as follows. Section 2 presents a systematic literature review to summarize the available research background and research results published. Section 3 presents the model framework and mathematical model of different drone-based delivery services including the following three models: first-mile/last-mile delivery by e-trucks; first-mile delivery by drones from e-trucks; last-mile delivery by e-trucks; and integrated first-mile/last-mile delivery by drones from e-trucks. Section 4 presents the results of the numerical analysis of scenarios. Conclusions and future research directions are discussed in the last section.

2. Literature Review

The drone routing problems have been discussed from different aspects. In the major part of the models, only last-mile delivery operations are taken into consideration [9,10] and only a few of them include first-mile delivery aspects [11]. The drone-based delivery services from trucks can be modelled as flying sidekick travelling salesman problems, where the milk run solutions are represented by multiple drops [12]. The collaboration of e-trucks and drones increases the flexibility of the services, especially in the case of flexible launch and recovery sites [13]. In the integration of scheduling models into the design and drone-based delivery services, it is important to take the predefined time windows of delivery tasks into consideration [14]. The Piggyback Transportation Problem is also a suitable approach for the optimization of truck–drone cooperation, where a large vehicle moves small vehicles near the delivery stations [15]. The routing problems can be combined using trucks, vans and drones. In this approach, the trucks are responsible for the transportation of packages and vans are responsible for the transportation of drones near the delivery locations, while drones are responsible for the physical delivery [16].

The routing problems can be extended with various logistics-related aspects as follows: the optimization of parking lots for trucks and vans [17]. The drones can fly to fulfil delivery tasks from these optimized parking lots. In the case of the assignment and scheduling task of multi-drone solutions, the variable drone speed has a great impact on the complexity of the optimization problem [18]. The optimal solution of drone-based delivery services is limited by the allowed traffic density from a drone-based delivery in very low-level urban airspaces [19].

The objective function of the optimization of drone-based delivery services is generally the operation cost [20], total transportation cost [14], environmental and social impact [21] and minimal time route [22]. Integrated approaches extend the routing and scheduling problems with inventory-related aspects (optimal order quantity) to improve the cost-efficiency of the optimized solutions [23]. The optimization of drone-based delivery becomes an especially complex problem in the case of uncertain energy consumption [24]. This uncertainty can be influenced, for example, by weather conditions.

The available charging technologies also represent a significant influencing factor on the efficiency of drone-based services. The optimal design and location of static and moving charging stations has a great impact on the logistics performance of the delivery services [9]. The operation range of drones can be extended through the optimization of the location of intermediate recharge stations [25]. Previous studies have shown that the used batteries of drones can be also swapped with a newly charged one, and in this way the charging time of the drones can be minimized [26]. The swapping process of batteries can be automatized [27].

The last-mile delivery problems can be solved with a wide range of methods, including heuristic and analytical approaches [28]. The solution algorithms of drone-based delivery services are generally heuristics and metaheuristics including hybrid algorithms [20], random walk based ant colony optimization [29], the Monte-Carlo simulation [30], Fuzzy models [31], combinatorial optimization [26], multi-start tabu search with tailored neighborhood structure [32], an extension of the ranch-and-price approach with dynamic programming recursions [33], a combination of the branch-and-cut algorithm and the column generation procedure [34,35], the non-dominated sorting genetic algorithm [36] and the integrated MILP and branch-and-cut algorithm [37], but simple mixed integer linear programming can also be used [14,38].

The research regarding drone-based delivery services includes not only technological, IT and engineering aspects, but also social impacts which have to be taken into consideration [39]. These social aspects are the following: privacy risk and perceptions [40], consumers' usage behavior [1] and the authentication of consumers [41] with both social and technological aspects. The legal aspects of drone-based parcel services include international, national and local UAV flight regulations [42].

The case studies have validated the use of drones for parcel delivery services, as shown in the following cases: parcel delivery in Milan [21], the Amazon project in the United Kingdom focusing on long-range cargo transport by drones [43], last-mile delivery in Belgrade [31], last-mile drone logistics operations in India's urban cities [44], freight logistics in the city center of Pamplona [45], the integrated application of drones and ground autonomous delivery devices in Paris and Barcelona [46] and the optimization of blood delivery with fuzzy goal programming [47].

As review articles of drone-based delivery research have shown [48], the most popular models are the multi-visit multi-drone pure-play drone-based delivery models and the synchronized multi-modal delivery models, but in these cases the operation or transportation costs are the focus, and the sustainability aspect of the integration of first-mile and last-mile operations are not taken into consideration in relation to the sustainability aspects.

Figure 1 shows the conceptual framework of the published articles demonstrating the most important models, methods, objectives, constraints and case studies.

The consequences of the literature review are the following:

- More than 50% of the articles regarding drone-based delivery services were published in the last four years. This result indicates the scientific potential of the design and optimization of drone-based first-mile/last-mile delivery;
- The articles that addressed the optimization of drone-based parcel services focused on last-mile delivery operations and only a few of them described the first-mile delivery services;
- A wide range of research articles discussed the logistics-related aspects of drone-based last-mile service processes, but the energy efficiency and the environmental impacts of the integrated solutions of first-mile/last-mile drone-based delivery services is a research gap. Therefore, this research topic still needs more attention and research;
- It was found that mathematical models and algorithms are important tools for the design and control of drone-based delivery systems. According to that, the main focus of this research is the sustainability-based analysis of the impact of drone-based delivery services with integrated first-mile/last-mile operations from an energy efficiency and greenhouse gas emission reduction point of view.

The main contributions of this article include: (1) a methodology to define the typical models of truck–drone joint parcel delivery systems; (2) a methodology to describe the impact of logistics parameters on energy efficiency and greenhouse gas emissions; (3) a comparative analysis of conventional truck-based delivery systems with truck–drone joint delivery systems; and (4) the computational results of different scenarios to validate the developed methodology.

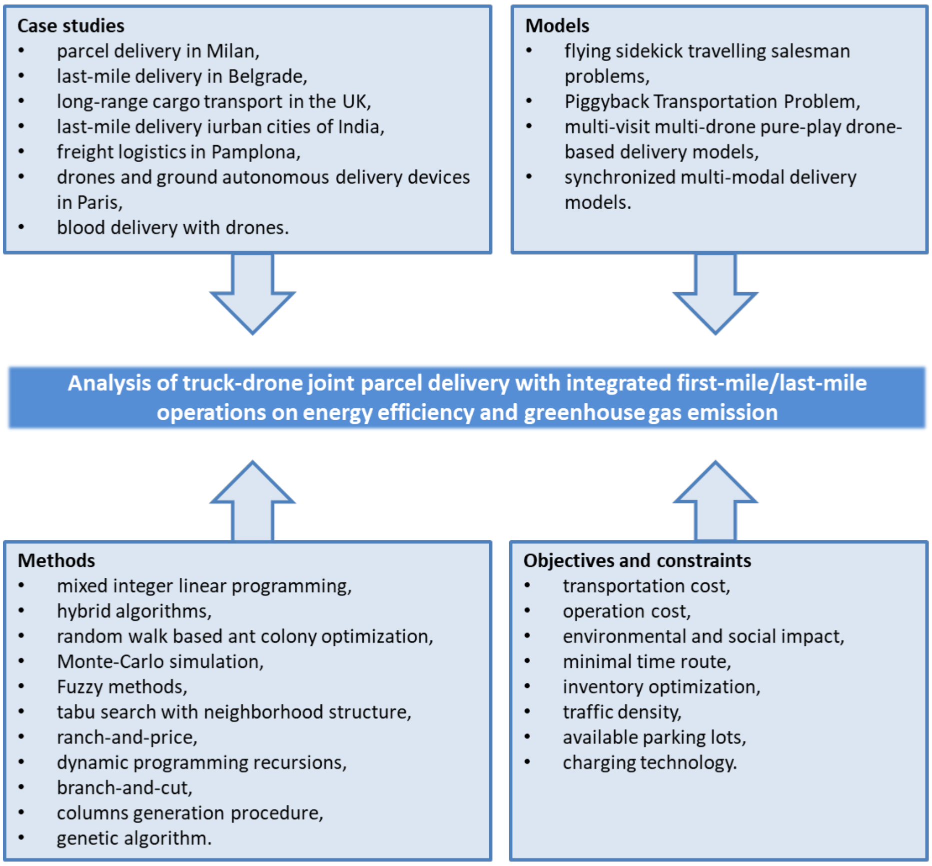

Figure 1. The scientific framework of the research based on analyzed articles [9,12,14,15,17,19–23,29–36,38,43–48].

3. Materials and Methods

Within the frame of this chapter, the mathematical models of different drone-based package delivery systems will be described. The chapter discusses (1) the general input parameters of package delivery services; (2) the methodology of the generation of special models from the general input parameters; and (3) the description of typical drone-based delivery services including objective functions, constraints and decision variables. Within the frame of this chapter the following typical models are discussed:

- Truck-based delivery without drones;
- Drone-based first-mile operations from trucks;
- Integrated first-mile/last-mile drone-based shuttle operations from trucks;
- Integrated first-mile/last-mile drone-based milk run operations from trucks.

The input parameters of the energy efficiency and emission-related design of drone-based package delivery systems are the following:

- lat_i and lon_i: latitude and longitude of first-mile and last-mile delivery tasks;
- q_i: weight of first-mile/last-mile delivery task i in [kg];
- v_i: volume of first-mile/last-mile delivery tasks in [l];
- z_i: type of delivery task i;
- q_{max}^D: maximum payload of drones in [kg];
- q_{max}^T: maximum payload of trucks in [kg];
- BAT^T : available energy of trucks in [kWh];

- BAT^D : available energy of drones in [kWh];
- ρ^T: specific energy consumption of trucks in [kWh/km];
- ρ^D: specific energy consumption of drones [kWh/km];
- $\varepsilon_{x,y}$: specific GHG emission depending on the generation source of electricity [g/kWh];
- x: generation source of used electricity.

Based on these input data, the first step of the modelling is the definition of different service tasks depending on the payload and volume-related constraints to define the typical service relations of the delivery routes and typical service tasks.

If the constraints related to weight and geometry make it possible to fulfill the deliver demand by drones, while the pick-up point is on the delivery route and the departure is the depot, then the delivery belongs to the first set of delivery tasks (first-mile delivery–depot relation with drone):

$$q_i \leq q_{max}^D \ \wedge \ v_i \leq v_{max}^D \ \wedge \ z_i = FD \rightarrow q_i \in Q^{DFD}, \tag{1}$$

where q_i is the weight of the package i to be delivered, q_{max}^D is the loading capacity (weight) of the drone, v_i is the volume or other geometrical parameter of the package i to be delivered, v_{max}^D is the upper limit of volume or other geometric parameter of the package to be transported by drones, Q^{DFD} is the set of first-mile delivery tasks from the delivery route to the depot suitable for drone-based delivery and z_i is the type of delivery task, where $z_i \in [FD,\ DL,\ FI,\ IL]$ and *FD* are for first-mile–depot relation, *LD* is for depot–last-mile relation, *FI* is for first-mile delivery within the delivery route and *IL* is for last-mile delivery within the delivery route. The cardinality of the set of delivery tasks in the case of first-mile–depot relation is $\left|Q^{DFD}\right| = \beta_1$.

If the constraints related to weight and geometry make it possible to fulfill the delivery demand by drones, while the pick-up point is the depot and the departure location is on the delivery route, then the delivery belongs to the second set of delivery tasks (depot–last-mile delivery relation with drone):

$$q_i \leq q_{max}^D \ \wedge \ v_i \leq v_{max}^D \ \wedge \ z_i = DL \rightarrow q_i \in Q^{DDL}, \tag{2}$$

where Q^{DDL} is the set of last-mile delivery tasks from the depot to the departure location on the delivery route suitable for drone-based delivery. The cardinality of the set of delivery tasks in the case of first-mile–depot relation is $\left|Q^{DDL}\right| = \beta_2$.

If the constraints related to weight and geometry make it possible to fulfill the deliver demand by drones, while the pick-up point and the delivery point are on the same delivery route, then the delivery belongs to the third set of delivery tasks (internal first-mile–last-mile relation with drone):

$$q_i \leq q_{max}^D \ \wedge \ v_i \leq v_{max}^D \ \wedge \ z_i \in [FI, IL] \rightarrow q_i \in Q^{DFL}, \tag{3}$$

where Q^{DFL} is the set of integrated first-mile–last-mile delivery tasks on the same delivery route suitable for drone-based delivery. The cardinality of the set of delivery tasks in the case of first-mile–depot relation is $\left|Q^{DFI}\right| = \beta_3$. The positive values of the Q^{DFL} set represent pick-up tasks, while the negative values are for delivery operations.

If the constraints related to weight and geometry do not allow the delivery demand to be performed by drones but do allow it to be performed by trucks, while the pick-up point is on the delivery route and the departure is the depot, then the delivery belongs to the fourth set of delivery tasks (first-mile delivery–depot relation with truck):

$$\left(q_i > q_{max}^D \ \vee \ v_i > v_{max}^D\right) \ \wedge \ z_i = FD \rightarrow q_i \in Q^{TFD}, \tag{4}$$

where Q^{TFD} is the set of first-mile delivery tasks from the delivery route to the depot suitable for truck-based delivery. The cardinality of the set of delivery tasks in the case of truck-based first-mile–depot relation is $\left|Q^{TFD}\right| = \beta_4$.

If the constraints related to weight and geometry do not allow the delivery demand to be performed by drones but do allow it to be performed by trucks, while the pick-up point is the depot and the departure location is on the delivery route, then the delivery belongs to the second set of delivery tasks (depot–last-mile delivery relation with truck):

$$\left(q_i > q_{max}^D \vee v_i > v_{max}^D\right) \wedge z_i = DL \rightarrow q_i \in Q^{TDL}, \tag{5}$$

where Q^{TDL} is the set of last-mile delivery tasks from the depot to the departure location on the delivery route suitable for truck-based delivery. The cardinality of the set of delivery tasks in the case of truck-based first-mile–depot relation is $\left|Q^{TDL}\right| = \beta_5$.

If the constraints related to weight and geometry do not allow the delivery demand to be performed by drones but do allow it to be performed by trucks, while the pick-up point and the delivery point are on the same delivery route, then the delivery belongs to the third set of delivery tasks (internal first-mile–last-mile relation with truck):

$$\left(q_i > q_{max}^D \vee v_i > v_{max}^D\right) \wedge z_i \in [FI, IL] \rightarrow q_i \in Q^{TFL}, \tag{6}$$

where Q^{DFL} is the set of integrated first-mile–last-mile delivery tasks on the same delivery route suitable for truck-based delivery. The cardinality of the set of delivery tasks in the case of truck-based first-mile–depot relation is $\left|Q^{TFI}\right| = \beta_6$. The positive values of the Q^{TFL} set represent pick-up tasks, while the negative values are for delivery operations.

Based on the above-mentioned sets, it is possible to define different models of drone-based delivery services from trucks.

3.1. Modeling of Truck-Based Delivery

In this case, all delivery operations are performed by trucks. Using the Q^{DFD}, Q^{DDL}, Q^{DFL}, Q^{TFD}, Q^{TDL}, and Q^{TFL} matrices, we can define the basic parameters of the truck-based delivery model as follows. The matrix of the available delivery tasks can be calculated as follows:

$$q_i^T = \begin{cases} \forall i \in [1, \ldots, \vartheta_1] : q_i^T = q_i^{DFD} \\ \forall i \in [1 + \vartheta_1, \ldots, \vartheta_2] : q_i^T = q_{i-\vartheta_1}^{DDL} \\ \forall i \in [1 + \vartheta_2, \ldots, \vartheta_3] : q_i^T = q_{i-\vartheta_2}^{DFL} \\ \forall i \in [1 + \vartheta_3, \ldots, \vartheta_4] : q_i^T = q_{i-\vartheta_3}^{TFD} \\ \forall i \in [1 + \vartheta_4, \ldots, \vartheta_5] : q_i^T = q_{i-\vartheta_4}^{TDL} \\ \forall i \in [1 + \vartheta_5, \ldots, \vartheta_6] : q_i^T = q_{i-\vartheta_5}^{TFL} \end{cases}, \tag{7}$$

where $\vartheta_s = \sum_{j=1}^{s} \beta_j$. The objective function of the optimization is the minimization of energy consumption and GHG emissions. Within the frame of this article, e-trucks are taken into consideration; therefore, the emissions will be defined as virtual GHG emissions using the emission rates of the generation source of electricity.

3.1.1. The Objective Function

Within the frame of this model, two objective functions are used: the energy consumption and the virtual GHG emission. However, the GHG emission depends on the energy consumption, but we define both objective functions.

The minimization of the energy consumption as an objective function can be defined depending on the different sections of the delivery route:

$$C^1 = C^{1TD\rightarrow} + C^{1TR} + C^{1T\rightarrow D} \rightarrow min., \tag{8}$$

where C^1 is the energy consumption of the whole truck-based delivery model, $C^{aTD\rightarrow}$ is the energy consumption of the e-truck within the initial section of the delivery route from the depot to the first delivery location in the case of model a, C^{aTR} is the energy consumption of the e-truck within the delivery route between the first and last delivery location in the case of model a and $C^{aT\rightarrow D}$ is the energy consumption of the e-truck within the closing section of the delivery route from the last delivery location to the depot in the case of model a (e.g., $C^{1T\rightarrow D}$ is for the first model). The explanations of superscripts regarding energy consumption are shown in Nomenclature. The energy consumption within the initial section of the delivery route from the depot to the first delivery location can be calculated depending on the length of the transportation between the depot and the first delivery location, the loading of the delivery truck and the specific energy consumption:

$$C^{1TD\rightarrow} = \left(q^{TINI} + \sum_{i=1,z_i^*=DL}^{\vartheta_6} q_{p_i}^{*T}\right) \cdot l_{D,p_1} \cdot \rho^T, \tag{9}$$

where q^{TINI} is the net weight of the e-truck, l_{D,p_1} is the length of transportation route between the depot and the first delivery location, ρ^T is the specific energy consumption of the truck $[kWh/(kg \cdot km)]$ and $\overline{p} = [p_i]$ is the permutation matrix of the optimal solution. Based on the permutation matrix, we can define the weight of delivery tasks for each scheduled delivery as follows:

$$\forall i \in \left[1, \ldots, \sum_{j=1}^{6} \beta_j\right] : q_{p_i}^{*T} = q_i^T. \tag{10}$$

The energy consumption within the delivery route between the first and last delivery location can be calculated depending on the length of the transportation between the pick-up and delivery locations between the initial and closing section of the delivery route, the loading of the delivery truck and the specific energy consumption:

$$C^{1TR} = \sum_{k=1}^{\vartheta_6-1} \left(q^{TINI} + \sum_{i=k,z_i^*=DL}^{\vartheta_6} q_{p_i}^{*T} + \sum_{i=1,z_i^*\in[FI,IL]}^{k} q_{p_i}^{*T}\right) \cdot l_{p_k,p_{k+1}} \cdot \rho^T. \tag{11}$$

where $l_{p_k,p_{k+1}}$ is the length of the transportation route between the scheduled delivery location k and $k+1$.

The energy consumption within the closing section of the delivery route from the last delivery location to the depot can be calculated depending on the length of the transportation between the last delivery location and the depot, the loading of the delivery truck and the specific energy consumption:

$$C^{1T\rightarrow D} = \left(q^{TINI} + \sum_{i=1,z_i^*=FD}^{\sum_{j=1}^{6}\beta_j} q_{p_i}^{*T}\right) \cdot l_{D,p_1} \cdot \rho^T. \tag{12}$$

In this case the loading weight of internal pick-up and delivery tasks within the delivery route has no impact on the closing payload of the e-truck because all of these pick-up and delivery tasks are performed before the closing section of the delivery route.

The minimization of the GHG emission can be calculated depending on the energy generation source and the type of GHG as follows:

$$E_{x,y}^1 = E_{x,y}^{1TD\rightarrow} + E_{x,y}^{1TR} + E_{x,y}^{1T\rightarrow D} \rightarrow min., \tag{13}$$

where $E_{x,y}^1$ is the energy consumption of the first model including only e-truck-based delivery operations, $E_{x,y}^{aTD\rightarrow}$ is the GHG emissions within the initial section of the delivery route from the depot to the first delivery location in the case of model a, $E_{x,y}^{aTR}$ is the GHG emissions within the delivery route between the first and last delivery location in the case of model a, $E_{x,y}^{aT\rightarrow D}$ is the GHG emissions within the closing section of the delivery route from the last delivery location to the depot in the case of model a, x is for the generation source of electricity (lignite, coal, oil, natural gas, photovoltaic, biomass, nuclear, water, wind) and y is for the type of GHG (CO_2, SO_2, CO, HC, NO_X, PM).

The GHG emissions within the initial section of the delivery route from the depot to the first delivery location can be calculated depending on the energy consumption and the specific emission rate depending on the electricity generation source and type of GHG:

$$E_{x,y}^{1TD\rightarrow} = \left(q^{TINI} + \sum_{i=1,z_i^*=DL}^{\vartheta_6} q_{p_i}^{*T}\right) \cdot l_{D,p_1} \cdot \rho^T \cdot \varepsilon_{x,y}, \quad (14)$$

where $\varepsilon_{x,y}$ is the specific GHG emission in the case of electricity generation source x and GHG y.

The GHG emissions within the delivery route between the first and last delivery location can be calculated depending on the energy consumption and the specific emission rate depending on the electricity generation source and type of GHG:

$$E_{x,y}^{1TR} = \sum_{k=1}^{\vartheta_6-1}\left(q^{TINI} + \sum_{i=k,z_i^*=DL}^{\vartheta_6} q_{p_i}^{*T} + \sum_{i=1,z_i^*\in[FI,IL]}^{k} q_{p_i}^{*T}\right) \cdot l_{p_k,p_{k+1}} \cdot \rho^T \cdot \varepsilon_{x,y}. \quad (15)$$

The GHG emission within the closing section of the delivery route from the last delivery location to the depot can be calculated depending on the energy consumption and the specific emission rate depending on the electricity generation source and type of GHG:

$$E_{x,y}^{1T\rightarrow D} = \left(q^{TINI} + \sum_{i=1,z_i^*=FD}^{\vartheta_6} q_{p_{\vartheta_6}}^{*T}\right) \cdot l_{\vartheta_6,D} \cdot \rho^T \cdot \varepsilon_{x,y}. \quad (16)$$

3.1.2. The Constraints

We can define three constraints for this model including capacity- and loading-related aspects. The first constraint focuses on the allowed maximal payload of e-trucks. The delivery route must be planned and scheduled so that it is not allowed to exceed this predefined maximal payload of the e-truck:

$$q_{p_i}^L \leq q^{Tmax}, \quad (17)$$

where q^{Tmax} is the maximum payload of the truck and

$$q_{p_i}^L = q^{INI} + \sum_{i=k,z_i^*=DL}^{\vartheta_6} q_{p_i}^{*T} + \sum_{i=1,z_i^*\in[FI,IL]}^{k} q_{p_i}^{*T}, \quad (18)$$

where $q_{p_i}^L$ is the weight of the load of the e-truck at delivery location p_i.

The second constraint focuses on the maximal volume of e-trucks. The delivery route must be planned and scheduled so that it is not allowed to exceed this predefined maximal loading volume of the e-truck:

$$v_{p_i}^L \leq v^{Tmax}, \quad (19)$$

where

$$v_{p_i}^L = \sum_{i=k,z_i^*=DL}^{\vartheta_6} v_{p_i}^{*T} + \sum_{i=1,z_i^*\in[FI,IL]}^{k} v_{p_i}^{*T}. \quad (20)$$

where $v_{p_i}^{*T}$ is the volume of the scheduled package p_i, $v_{p_i}^L$ is the total volume of scheduled packages on the e-truck at the pick-up or delivery location p_i and v^{Tmax} is the maximum loading volume of the e-truck.

The third constraint defines the upper limit of available energy of the e-truck's battery. It is not allowed to consume more energy than available:

$$C^1 \leq BAT^T, \quad (21)$$

where BAT^T is the capacity of the e-truck's battery.

3.1.3. Decision Variables

The decision variable of the above-mentioned conventional e-truck-based delivery problem is the $\overline{p} = [p_i]$ permutation matrix describing the optimal solution, where the value of p_i defines the ID of the pick-up or delivery task to be scheduled as pick-up or delivery task i.

3.2. Modeling of First-Mile Drone-Based Operations from Trucks

In this model, the pick-up operations can be performed by the drones depending on the weight and volume of the packages, while last-mile delivery tasks are assigned to the e-trucks. The basic operations are the following:

- The first-mile delivery tasks from the first-mile delivery location to the depot are performed in the relation pick-up operation location–truck–depot if the capacity-related constraints make it possible. Between the pick-up operation location and the e-truck the transportation is performed by the drone, while in the case of the truck–depot location, the package is transported by the truck;
- The last-mile delivery tasks from the depot to the delivery location are performed by the e-truck;
- The first-mile operations with a delivery location within the same delivery route are performed in the following way: the first-mile delivery operation is performed by the drone if the capacity-related constraints make it possible in relation to the pick-up operation location–truck, and the last mile delivery is performed by the truck.

Using the Q^{DFD}, Q^{DDL}, Q^{DFL}, Q^{TFD}, Q^{TDL} and Q^{TFL} matrices, we can define the basic parameters of the drone-based and truck-based delivery model as follows. The matrices of the available delivery tasks can be calculated both for the drones and the trucks as follows:

$$q_i^T = \begin{cases} \forall i \in [1, \ldots, \beta_2] : q_i^T = q_i^{DDL} \\ \forall i \in [1 + \beta_2, \ldots, \beta_2 + \beta_3] : q_i^T = q_{i-\beta_2}^{DFL} \\ \forall i \in [1 + \beta_2 + \beta_3, \ldots, \vartheta_4 - \beta_1] : q_i^T = q_{i-\beta_2+\beta_3}^{TFD} \\ \forall i \in [\vartheta_4 - \beta_1 + 1, \ldots, \vartheta_5 - \beta_1] : q_i^T = q_{i-\vartheta_4-\beta_1}^{TDL} \\ \forall i \in [\vartheta_5 - \beta_1 + 1, \ldots, \vartheta_6 - \beta_1] : q_i^T = q_{i-\vartheta_5-\beta_1}^{TFL} \end{cases}, \tag{22}$$

and

$$q_g^D = \begin{cases} \forall g \in [1, \ldots, \vartheta_1] : q_g^D = q_g^{DFD} \\ \forall g \in [1 + \vartheta_1, \ldots, \vartheta_1 + \vartheta_3 - \vartheta_2] : q_g^D = q_{g-\vartheta_3}^{DFL} \end{cases}. \tag{23}$$

3.2.1. The Objective Function

Within the frame of this model the energy consumption and the virtual GHG emissions of both drones and e-trucks are taken into consideration. The minimization of the energy consumption as an objective function can be defined depending on the different sections of the delivery route:

$$C^2 = C^{2TD\rightarrow} + C^{2TR} + C^{2T\rightarrow D} + C^{2DR} + C^{2D\rightarrow D} \rightarrow min., \tag{24}$$

where C^2 is the energy consumption of the whole truck-based delivery route including the energy consumption of drones and e-trucks, C^{aDR} is the energy consumption of the drone within the delivery route between the pick-up operation locations and the e-truck in the case of model a and $C^{aD\rightarrow D}$ is the energy consumption of the drone within the closing section of the delivery route from the last delivery location to the depot in the case of model a.

The energy consumption within the initial section of the delivery route from the depot to the first delivery location can be calculated depending on the length of the transportation between the depot and the first delivery location, the loading of the delivery truck and the specific energy consumption:

$$C^{2TD\rightarrow} = \left(q^{TINI} + \sum_{i=1+\vartheta_1, z_i^*=DL}^{\vartheta_6} q_{p_i}^{*T} \right) \cdot l_{D,p_1} \cdot \rho^T. \tag{25}$$

The energy consumption of the truck within the delivery route between the first and last delivery location can be calculated depending on the length of the transportation between the pick-up and delivery locations between the initial and closing section of the delivery route, the loading of the delivery truck and the specific energy consumption:

$$C^{2TR} = \sum_{k=1+\vartheta_1}^{\vartheta_6-1} \left(q^{TINI} + \sum_{i=k,z_i^*=DL}^{\vartheta_6} q_{p_i}^{*T} + \sum_{i=1+\vartheta_1,z_i^*\in[FI,IL]}^{k} q_{p_i}^{*T} \right) \cdot l_{p_k,p_{k+1}} \cdot \rho^T. \quad (26)$$

The energy consumption within the closing section of the delivery route from the last delivery location to the depot can be calculated depending on the length of the transportation between the last delivery location and the depot, the loading of the delivery truck and the specific energy consumption:

$$C^{2T\to D} = \left(q^{TINI} + \sum_{i=1+\vartheta_1,z_i^*=FD}^{\vartheta_6} q_{p_1}^{*T} \right) \cdot l_{D,p_1} \cdot \rho^T. \quad (27)$$

The energy consumption of the drone within the delivery route between the first and last delivery location performing pick-up operations can be calculated as follows:

$$C^{2DR} = \sum_{k=1+\vartheta_1,z_k^*\in[FI]}^{\vartheta_1+\vartheta_3-\vartheta_2} \left(q^{DINI} + q_{p_k}^{*D} \right) \cdot 2 \cdot l_{p_{k,}p_{TR}} \cdot \rho^D. \quad (28)$$

where $l_{p_{k,}p_{TR}}$ is the travelling distance between the pick-up delivery location p_k and the current position of the e-truck, and ρ^D is the specific energy consumption of the drone.

The energy consumption of the drone between pick-up operations on the delivery route and the depot can be calculated as follows:

$$C^{2D\to D} = \sum_{k=1,z_k^*\in[FI]}^{\vartheta_1} \left(q^{DINI} + q_{p_k}^{*D} \right) \cdot 2 \cdot l_{p_{k,}D} \cdot \rho^D. \quad (29)$$

The minimization of GHG emissions can be calculated depending on the energy generation source and the type of GHG as a sum of the energy consumption of the e-truck and the drone as follows:

$$E_{x,y}^2 = E_{x,y}^{2TD\to} + E_{x,y}^{2TR} + E_{x,y}^{2T\to D} + E_{x,y}^{2DR} + E_{x,y}^{2D\to D} \to min \quad (30)$$

where $E_{x,y}^{aDR}$ is the GHG emission of the drone within the delivery route between the first and last delivery location in the case of model a and $E_{x,y}^{aD\to D}$ is the GHG emission of the drone between pick-up operations on the delivery route and the depot in the case of model a.

The GHG emission within the initial section of the delivery route from the depot to the first delivery location in the case of the e-truck can be calculated as follows:

$$E_{x,y}^{2TD\to} = \left(q^{TINI} + \sum_{i=1+\vartheta_1,z_i^*=DL}^{\vartheta_6} q_{p_i}^{*T} \right) \cdot l_{D,p_1} \cdot \rho^T \cdot \varepsilon_{x,y}. \quad (31)$$

The GHG emission within the delivery route between the first and last delivery location in the case of e-trucks can be calculated as follows:

$$E_{x,y}^{2TR} = \sum_{k=1+\vartheta_1}^{\vartheta_6-1} \left(q^{TINI} + \sum_{i=k,z_i^*=DL}^{\vartheta_6} q_{p_i}^{*T} + \sum_{i=1+\vartheta_1,z_i^*\in[FI,IL]}^{k} q_{p_i}^{*T} \right) \cdot l_{p_k,p_{k+1}} \cdot \varepsilon_{x,y}. \quad (32)$$

The GHG emission within the closing section of the delivery route from the last delivery location to the depot in the case of the e-truck can be calculated as follows:

$$E_{x,y}^{2T\to D} = \left(q^{TINI} + \sum_{i=1+\vartheta_1,z_i^*=FD}^{\vartheta_6} q_{p_1}^{*T} \right) \cdot l_{D,p_1} \cdot \rho^T \cdot \varepsilon_{x,y}. \quad (33)$$

The GHG emission of the drone within the delivery route between the first and last delivery location can be calculated as follows:

$$E_{x,y}^{2DR} = \sum_{k=1+\vartheta_1, z_k^* \in [FI]}^{\vartheta_1+\vartheta_3-\vartheta_2} \left(q^{DINI} + q_{p_k}^{*D} \right) \cdot 2 \cdot l_{p_k, p_{TR}} \cdot \rho^D \cdot \varepsilon_{x,y}. \quad (34)$$

The GHG emission of the drone between pick-up operations on the delivery route and the depot can be calculated as follows:

$$E_{x,y}^{2D \to D} = \sum_{k=1, z_k^* \in [FI]}^{\vartheta_1} \left(q^{DINI} + q_{p_k}^{*D} \right) \cdot 2 \cdot l_{p_k, D} \cdot \rho^D \cdot \varepsilon_{x,y}. \quad (35)$$

3.2.2. The Constraints

We can define constraints for both the e-truck-related pick-up and delivery operations and for the drone-based pick-up and delivery operations. The pick-up and delivery operations of e-trucks are the following. The first constraint focuses on the allowed maximal payload of e-trucks. The delivery route must be planned and scheduled so that it is not allowed to exceed this predefined maximal payload of the e-truck:

$$\forall i \in [\vartheta_6 - \beta_1] : q_{p_i}^L \leq q^{Tmax}, \quad (36)$$

where

$$\forall i \in [\vartheta_6 - \beta_1] : q_{p_i}^L = q^{TINI} + \sum_{i=k, z_i^* = DL}^{\vartheta_6 - \beta_1} q_{p_i}^{*T} + \sum_{i=1, z_i^* \in [FI, IL]}^{k} q_{p_i}^{*T}. \quad (37)$$

The second constraint focuses on the maximal volume of e-trucks. The delivery route must be planned and scheduled so that it is not allowed to exceed this predefined maximal loading volume of the e-truck:

$$\forall i \in [\vartheta_6 - \beta_1] : v_{p_i}^L \leq v^{Tmax}, \quad (38)$$

where

$$\forall i \in [\vartheta_6 - \beta_1] : v_{p_i}^L = q^{TINI} + \sum_{i=k, z_i^* = DL}^{\vartheta_6 - \beta_1} v_{p_i}^{*T} + \sum_{i=1, z_i^* \in [FI, IL]}^{k} v_{p_i}^{*T}. \quad (39)$$

The third constraint defines the upper limit of available energy of the e-truck's battery. It is not allowed to consume more energy than available:

$$C^{2TD \to} + C^{2TR} + C^{2T \to D} \leq CAP^T. \quad (40)$$

In the case of the drone-based service we can define the following constraints. The first constraint focuses on the allowed maximal payload of the drone. If no milk runs are performed by the drones (no collection or distribution routes), then this constraint can be written in a quite simple form:

$$\forall i \in [\vartheta_1 + \vartheta_3 - \vartheta_2] : q_{p_i} \leq q^{Dmax}, \quad (41)$$

where q^{Dmax} is the maximal payload of the drone. If the collection or distribution route are performed by the drone, the weight of the collected packages cannot exceed the maximum payload of the drone:

$$\forall i : \sum_{i \in \theta} q_{p_i} \leq q^{Dmax}, \quad (42)$$

where θ is the set of collection or distribution routes of the drone.

In the case of the second constraint, the maximum available volume of the drone is not allowed. If no milk runs are performed by the drones (no collection or distribution routes), then this constraint can be written in a quite simple form:

$$\forall i \in [\vartheta_1 + \vartheta_3 - \vartheta_2] : v_{p_i} \leq v^{Dmax}, \quad (43)$$

where v^{Dmax} is the maximal loading volume of the drone. If collection or distribution routes are performed by the drone, the weight of the collected packages cannot exceed the maximum payload of the drone:

$$\forall i : \sum_{i \in \theta} v_{p_i} \leq v^{Dmax}. \tag{44}$$

The third constraint defines the upper limit of available energy of the drone's battery. It is not allowed to consume more energy than available:

$$\forall i : \sum_{i \in \theta} C_i^{*2DR} \leq BAT^D \wedge \forall i : \sum_{i \in \theta} C_i^{*2D \to D} \leq BAT^D, \tag{45}$$

where BAT^D is the capacity of the drone's battery.

3.2.3. Decision Variables

The decision variable of the above-mentioned model including drone-based pick-up operations from e-truck is the $\overline{p} = [p_i]$ permutation matrix, as shown in the case of the conventional truck-based delivery service.

3.3. Modeling of the Integrated First-Mile/Last-Mile Drone-Based Operations from Trucks

In this model both the pick-up and the delivery operations can be performed by drones if the weight-, volume- and energy-related constraints make it possible.

Using the Q^{DFD}, Q^{DDL}, Q^{DFL}, Q^{TFD}, Q^{TDL} and Q^{TFL} matrices, we can define the basic parameters of the drone-based and truck-based delivery model as follows. The matrices of the available delivery tasks can be calculated as follows:

$$q_g^D = \begin{cases} \forall i \in [1, \ldots, \vartheta_1] : q_g^D = q_g^{DFD} \\ \forall i \in [1 + \vartheta_1, \ldots, \vartheta_2] : q_g^D = q_{g-\vartheta_1}^{DDL} \\ \forall i \in [1 + \vartheta_2, \ldots, \vartheta_3] : q_g^D = q_{g-\vartheta_2}^{DFL} \end{cases}, \tag{46}$$

and

$$q_i^T = \begin{cases} \forall i \in [1, \ldots, \vartheta_4 - \vartheta_3] : q_i^T = q_i^{TFD} \\ \forall i \in [\beta_4 + 1, \ldots, \beta_4 + \beta_5] : q_i^T = q_{i-\beta_4}^{TDL} \\ \forall i \in [\beta_4 + \beta_5 + 1, \ldots, \vartheta_6 - \vartheta_3] : q_i^T = q_{i-\beta_4-\beta_5}^{TFL} \end{cases}. \tag{47}$$

3.3.1. The Objective Function

Within the frame of this model the energy consumption and the virtual GHG emission of both drones and e-trucks are taken into consideration. The minimization of the energy consumption as an objective function can be defined depending on the different sections of the delivery route performed by the e-truck and the drone:

$$C^3 = C^{3TD\to} + C^{3TR} + C^{3T\to D} + C^{3DD\to} + C^{3DR} + C^{3D\to D} \to min., \tag{48}$$

where C^3 is the energy consumption of the whole integrated, drone- and truck-based delivery route including the energy consumption of drones and e-trucks.

The energy consumption within the initial section of the delivery route from the depot to the first delivery location can be calculated depending on the length of the transportation between the depot and the first delivery location, the loading of the delivery truck and the specific energy consumption:

$$C^{3TD\to} = \left(q^{TINI} + \sum_{i=\beta_4+1, z_i^*=DL}^{\beta_4+\beta_5} q_{p_i}^{*T} \right) \cdot l_{D,p_1} \cdot \rho^T. \tag{49}$$

The energy consumption of the truck within the delivery route between the first and last delivery location can be calculated depending on the length of the transportation between the pick-up and delivery locations between the initial and closing section of the delivery route, the loading of the delivery truck and the specific energy consumption:

$$C^{3TR} = \sum_{k=\beta_4+\beta_5+1}^{\vartheta_6-\vartheta_3} \left(q^{TINI} + \sum_{i=k, z_i^*=DL}^{\vartheta_6-\vartheta_3} q_{p_i}^{*T} + \sum_{i=\beta_4+\beta_5+1, z_i^* \in [FI,IL]}^{k} q_{p_i}^{*T} \right) \cdot l_{p_k,p_{k+1}} \cdot \rho^T. \quad (50)$$

The energy consumption within the closing section of the delivery route from the last delivery location to the depot can be calculated depending on the length of the transportation between the last delivery location and the depot, the loading of the delivery truck and the specific energy consumption:

$$C^{3T\to D} = \left(q^{TINI} + \sum_{i=\beta_4+1, z_i^*=FD}^{\beta_4+\beta_5} q_{p_1}^{*T} \right) \cdot l_{D,p_1} \cdot \rho^T. \quad (51)$$

The energy consumption of the drone within the delivery route between the first and last delivery location performing pick-up operations can be calculated as follows:

$$C^{3DR} = \sum_{k=\beta_4+\beta_5+1, z_k^* \in [FI]}^{\vartheta_6-\vartheta_3} \left(q^{DINI} + q_{p_k}^{*D} \right) \cdot 2 \cdot l_{p_k,p_{TR}} \cdot \rho^D. \quad (52)$$

where $l_{p_k,p_{TR}}$ is the travelling distance between the pick-up delivery location p_k and the current position of the e-truck, and ρ^D is the specific energy consumption of the drone.

The energy consumption of the drone between pick-up operations on the delivery route and the depot can be calculated as follows:

$$C^{3D\to D} = \sum_{k=1, z_k^* \in [FI]}^{\vartheta_4-\vartheta_3} \left(q^{DINI} + q_{p_k}^{*D} \right) \cdot 2 \cdot l_{p_k,D} \cdot \rho^D. \quad (53)$$

The energy consumption within the initial section of the delivery route from the depot to the first delivery location for the drone can be calculated as follows:

$$C^{3DD\to} = \left(q^{DINI} + \sum_{i=\beta_4+1, z_i^*=DL}^{\beta_4+\beta_5} q_{p_i}^{*T} \right) \cdot l_{D,p_1} \cdot \rho^T. \quad (54)$$

The minimization of the GHG emissions can be calculated depending on the energy generation source and the type of GHG as a sum of the energy consumption of the e-truck and the drone as follows:

$$E_{x,y}^3 = E_{x,y}^{3TD\to} + E_{x,y}^{3TR} + E_{x,y}^{3T\to D} + E_{x,y}^{3DD\to} + E_{x,y}^{3DR} + E_{x,y}^{3D\to D} \to min. \quad (55)$$

The GHG emission within the initial section of the delivery route from the depot to the first delivery location in the case of the e-truck can be calculated as follows:

$$E_{x,y}^{3TD\to} = \left(q^{TINI} + \sum_{i=\beta_4+1, z_i^*=DL}^{\beta_4+\beta_5} q_{p_i}^{*T} \right) \cdot l_{D,p_1} \cdot \rho^T \cdot \varepsilon_{x,y}. \quad (56)$$

The GHG emission within the delivery route between the first and last delivery location in the case of e-trucks can be calculated as follows:

$$E_{x,y}^{3TR} = \sum_{k=\beta_4+\beta_5+1}^{\vartheta_6-\vartheta_3} \left(q^{TINI} + \sum_{i=k, z_i^*=DL}^{\vartheta_6-\vartheta_3} q_{p_i}^{*T} + \sum_{i=\beta_4+\beta_5+1, z_i^* \in [FI,IL]}^{k} q_{p_i}^{*T} \right) \cdot l_{p_k,p_{k+1}} \cdot \rho^T \cdot \varepsilon_{x,y}. \quad (57)$$

The GHG emission within the closing section of the delivery route from the last delivery location to the depot in the case of the e-truck can be calculated as follows:

$$E_{x,y}^{3T\to D} = \left(q^{TINI} + \sum_{i=\beta_4+1, z_i^*=FD}^{\beta_4+\beta_5} q_{p_1}^{*T} \right) \cdot l_{D,p_1} \cdot \rho^T \cdot \varepsilon_{x,y}. \quad (58)$$

The GHG emission of the drone within the delivery route between the first and last delivery location can be calculated as follows:

$$E_{x,y}^{3DR} = \sum_{k=\beta_4+\beta_5+1, z_k^* \in [FI]}^{\vartheta_6-\vartheta_3} \left(q^{DINI} + q_{p_k}^{*D} \right) \cdot 2 \cdot l_{p_k,p_{TR}} \cdot \rho^D \cdot \varepsilon_{x,y}. \quad (59)$$

The GHG emission of the drone between pick-up operations on the delivery route and the depot can be calculated as follows:

$$E_{x,y}^{3D\to D} = \sum\nolimits_{k=1,z_k^*\in[FI]}^{\vartheta_4-\vartheta_3}\left(q^{DINI}+q_{p_k}^{*D}\right)\cdot 2\cdot l_{p_k,D}\cdot\rho^D\cdot\varepsilon_{x,y}. \quad (60)$$

The GHG emission of the drone within the initial section of the delivery route from the depot to the first delivery location for the drone can be calculated as follows:

$$E_{x,y}^{3DD\to} = \left(q^{DINI}+\sum\nolimits_{i=\beta_4+1,z_i^*=DL}^{\beta_4+\beta_5} q_{p_i}^{*T}\right)\cdot l_{D,p_1}\cdot\rho^T\cdot\varepsilon_{x,y}. \quad (61)$$

3.3.2. The Constraints

We can define constraints for both the e-truck-related pick-up and delivery operations and for the drone-based pick-up and delivery operations. In the case of this model the pick-up and delivery operations of e-trucks are the following. The first constraint focuses on the allowed maximal payload of e-trucks. The delivery route must be planned and scheduled so that it is not allowed to exceed this predefined maximal payload of the e-truck:

$$\forall i\in[1,\ldots,\vartheta_6-\vartheta_3]: q_{p_i}^L \le q^{Tmax}, \quad (62)$$

where

$$\forall i\in[1\ldots\vartheta_6-\vartheta_3]: q_{p_i}^L = q^{TINI}+\sum\nolimits_{i=k,z_i^*=DL}^{\vartheta_6-\vartheta_3} q_{p_i}^{*T}+\sum\nolimits_{i=1,z_i^*\in[FI,IL]}^{k} q_{p_i}^{*T}. \quad (63)$$

The second constraint focuses on the maximal volume of e-trucks. The delivery route must be planned and scheduled so that it is not allowed to exceed this predefined maximal loading volume of the e-truck:

$$\forall i\in[1,\ldots,\vartheta_6-\vartheta_3]: v_{p_i}^L \le v^{Tmax}, \quad (64)$$

where

$$\forall i\in[1,\ldots,\vartheta_6-\vartheta_3]: v_{p_i}^L = q^{TINI}+\sum\nolimits_{i=k,z_i^*=DL}^{\vartheta_6-\vartheta_3} v_{p_i}^{*T}+\sum\nolimits_{i=1,z_i^*\in[FI,IL]}^{k} v_{p_i}^{*T}. \quad (65)$$

The third constraint defines the upper limit of available energy of the e-truck's battery. It is not allowed to consume more energy than available:

$$C^{3TD\to}+C^{3TR}+C^{3T\to D}\le CAP^T. \quad (66)$$

In the case of the drone-based we can define the following constraints. The first constraint focuses on the allowed maximal payload of the drone. If no milk runs are performed by the drones (no collection or distribution routes), then this constraint can be written in a quite simple form:

$$\forall i\in[1,\ldots,\vartheta_3]: q_{p_i}\le q^{Dmax}, \quad (67)$$

where q^{Dmax} is the maximal payload of the drone. If the collection or distribution route are performed by the drone, the weight of the collected packages cannot exceed the maximum payload of the drone:

$$\forall i: \sum\nolimits_{i\in\theta} q_{p_i}\le q^{Dmax}, \quad (68)$$

where θ is the set of collection or distribution routes of the drone.

In the case of the second constraint, the maximum available volume of the drone is not allowed. If no milk runs are performed by the drones (no collection or distribution routes), then this constraint can be written in a quite simple form:

$$\forall i\in[1,\ldots,\vartheta_3]: v_{p_i}\le v^{Dmax}, \quad (69)$$

where v^{Dmax} is the maximal loading volume of the drone. If collection or distribution route are performed by the drone, the weight of the collected packages cannot exceed the maximum payload of the drone:

$$\forall i : \sum_{i \in \theta} v_{p_i} \leq v^{Dmax}. \quad (70)$$

The third constraint defines the upper limit of available energy of the drone's battery. It is not allowed to consume more energy than available:

$$\forall i : \sum_{i \in \theta} C_i^{*2DR} \leq BAT^D \wedge \forall i : \sum_{i \in \theta} C_i^{*2D \to D} \leq BAT^D, \quad (71)$$

where BAT^D is the capacity of the drone's battery.

3.3.3. Decision Variables

The decision variable of the above-mentioned model including drone-based pick-up operations from the e-truck is the $\overline{p} = [p_i]$ permutation matrix, as shown in the case of the conventional truck-based delivery service.

In the next chapter the above-mentioned models will be analyzed through scenario analysis and numerical studies to validate the model and show the impact of the application of drones on the energy efficiency and greenhouse gas emissions. The above-mentioned models were optimized using the Excel's Solver add-in.

4. Results

Within the frame of this chapter, the proposed models of different drone-based delivery services are analyzed. The scenario analysis focused on the following four main models:

- Truck-based delivery without drones: in the case of this model, the pick-up and delivery tasks can be performed either by e-truck or by drone from the truck, but in this scenario only the conventional truck-based delivery is taken into consideration;
- Drone-based first-mile operations from trucks: in this model the suitable pick-up (first-mile) operations are performed by the drone from the e-truck;
- Integrated first-mile/last-mile drone-based shuttle operations from trucks: in this model all suitable pick-up (first-mile) and delivery (last-mile) operations are performed by the drone and the integrated delivery tasks within the delivery route can be also performed by the drone;
- Integrated first-mile/last-mile drone-based milk run operations from truck: in this model all suitable pick-up (first-mile) and delivery (last-mile) operations are performed by the drone and the integrated delivery tasks within the delivery route can also be performed by the drone.

The input parameters of the scenario were the following: location of pick-up and delivery tasks (see Table 1), weight and volume of pick-up and delivery tasks (see Table 2), maximum payload of e-trucks and drones, maximum capacity of battery in e-trucks and drones, specific energy consumption of e-trucks and drones and specific GHG emissions depending on the electricity generation source.

Table 1. Location of pick-up and delivery tasks in the case of the analyzed four scenarios.

Task ID	Name of Pick-Up and Delivery Locations	Latitude	Longitude
01	2505 167-151, Miskolc, 3535	48.112034	20.668218
02	2519, Miskolc, 3533	48.086944	20.715982
03	Black Bontó, Miskolc, Besenyői u. 24, 3527	48.125582	20.797602
04	Danlos, Miskolc, 3510	48.111775	20.738653
05	DINAS Mérnökiroda Kft., Miskolc 3533	48.092708	20.736762
06	Mátyás király u. 16, Felsőzsolca, 3561	48.112274	20.855699

Table 1. *Cont.*

Task ID	Name of Pick-Up and Delivery Locations	Latitude	Longitude
07	Sajószigeti utca 19, Miskolc, 3527	48.118469	20.807808
08	Tatár u. 11, Miskolc, 3531	48.095782	20.752215
09	Vereckei u. 15, Miskolc, 3527	48.120301	20.798316
10	Vörösbérc utca, Miskolc, 3533	48.077806	20.721317

Table 2. Weight and volume of pick-up and delivery tasks in the case of the analyzed four scenarios.

Task ID	Weight [kg]	Volume [Liter]	Type of Delivery *
01	12.57	14.3	LM Truck (from D)
02	8.40	17.0	LM Truck (from D)
03	0.55	0.2	FM Drone (to 05)
04	1.40	0.04	FM Drone (to D)
05	0.55	0.2	LM Drone (from 03)
06	8.70	22.1	FM Truck (to D)
07	16.20	30.0	LM Truck (from D)
08	11.12	6.65	LM Truck (from D)
09	0.40	0.5	LM Drone (from D)
10	1.80	0.25	FM Drone (to D)

* FM Truck = First-mile delivery by truck. LM Truck = Last-mile delivery by truck. FM Drone = First-mile delivery by drone from. LM Drone = Last-mile delivery by drone from truck. from D = Last-mile delivery task from the depot. to D = First-mile delivery task to the depot.

The maximum payload of e-trucks was 500 kg, while the carrying capability of the drone was 3 kg. The energy consumption for the e-truck was about 250 Wh/km, for the drone it was 30 Wh/km and for a diesel van it was about 1100 Wh/km [49]. The specific greenhouse gas emission depending on the generation source of electricity used by the drones and e-trucks is defined in Table 3 [50,51].

Table 3. Specific greenhouse gas (GHG) emission depending on the electricity generation source in CO_2 emission in g/kWh [50,51].

EGS [1]	Emission					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	1054	0.032	0.880	0.480	4.760	0.040
Coal	888	0.028	0.733	0.400	3.960	0.030
Oil	733	0.022	0.615	0.335	3.324	0.028
Natural gas	499	0.016	0.418	0.228	2.226	0.019
Photovoltaic	85	0.002	0.073	0.040	0.396	0.003
Biomass	45	0.001	0.038	0.021	0.205	0.002
Nuclear	29	$<10^{-3}$	0.024	0.013	0.132	0.001
Water	26	$<10^{-3}$	0.022	0.012	0.119	0.001
Wind	26	$<10^{-3}$	0.022	0.012	0.119	0.001

[1] EGS = Electricity Generation Source.

4.1. Results of the Analysis of Truck-Based Delivery

The total length of the optimized delivery route (see Table 4 and Figure 2) performed by the e-truck was 40.2 km, the required transportation time was 79 min, the required additional handling time for loading, unloading, paying and billing was 24 min (8 times 3 min as an average handling time).

Table 4. The scheduled and performed delivery route of the e-truck including GPS coordinates and delivery types in the case of the first scenario, where all pick-up and delivery operations are performed by the e-truck.

Name of Pick-Up and Delivery Locations	Latitude	Longitude	Type of Delivery *	Weight [kg]
Mátyás király u. 16, Felsőzsolca, 3561	48.112274	20.855699	FM Truck	12.57
Sajószigeti utca 19, Miskolc, 3527	48.118469	20.807808	LM Truck	8.40
Black Bontó, Miskolc, Besenyői u. 24, 3527	48.125582	20.797602	FM Drone	2.55
Vereckei u. 15, Miskolc, 3527	48.120301	20.798316	LM Drone	1.40
Tatár u. 11, Miskolc, 3531	48.095782	20.752215	LM Truck	18.50
Danlos, Miskolc, 3510	48.111775	20.738653	FM Drone	0.70
2519, Miskolc, 3533	48.086944	20.715982	LM Truck	6.20
Vörösbérc utca, Miskolc, 3533	48.077806	20.721317	FM Drone	1.12
DINAS Mérnökiroda Kft., Miskolc 3533	48.092708	20.736762	LM Drone	0.40
2505 167-151, Miskolc, 3535	48.112034	20.668218	LM Truck	22.80

* FM Truck = First-mile delivery by truck. LM Truck = Last-mile delivery by truck. FM Drone = First-mile delivery by drone from. LM Drone = Last-mile delivery by drone from truck.

Based on the length of the performed delivery route we can calculate the energy consumption of the e-truck and the virtual GHG emissions. The energy consumption of the e-truck was 10.05 kWh. This energy consumption in the case of a diesel truck would be 44.22 kWh. The virtual GHG emission depending on the generation source of the electricity is shown in Table 5.

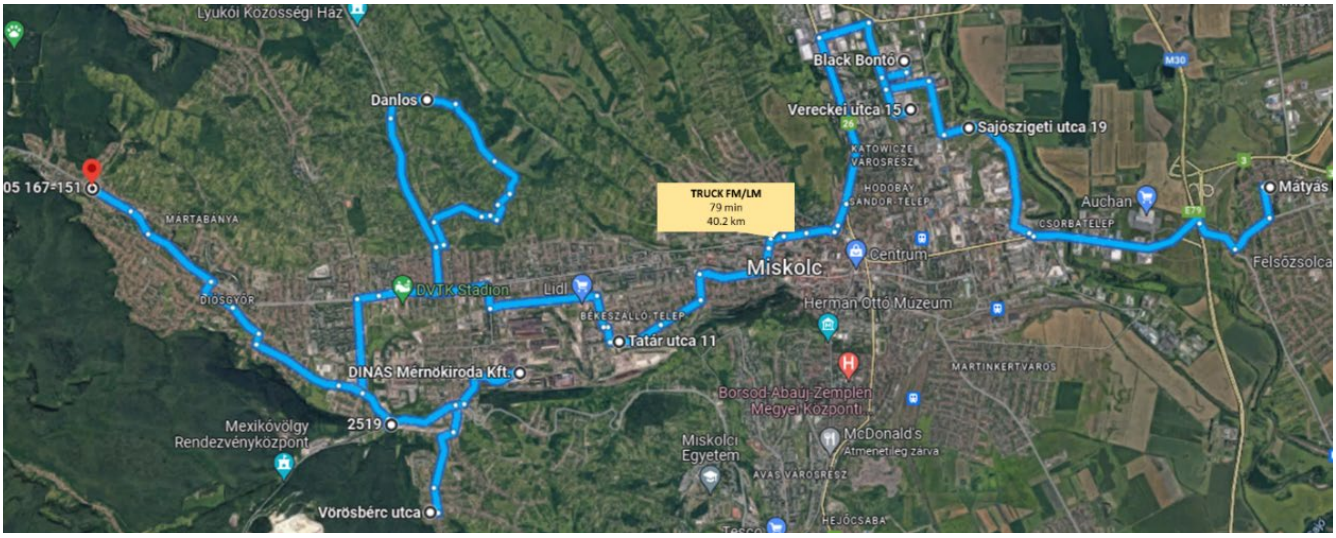

Figure 2. The scheduled and performed delivery route of the e-truck.

Table 5. The greenhouse gas (GHG) emission of the e-truck depending on the electricity generation source in CO_2 emission in g in the case of e-trucks.

EGS [1]	Emission					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	10,592.7	0.3216	8.844	4.824	47.838	0.402
Coal	8924.4	0.2814	7.36665	4.02	39.798	0.3015
Oil	7366.65	0.2211	6.18075	3.36675	33.4062	0.2814
Natural gas	5014.95	0.1608	4.2009	2.2914	22.3713	0.19095
Photovoltaic	854.25	0.0201	0.73365	0.402	3.9798	0.03015
Biomass	452.25	0.01005	0.3819	0.21105	2.06025	0.0201
Nuclear	291.45	$<10^{-4}$	0.2412	0.13065	1.3266	0.01005
Water	261.3	$<10^{-4}$	0.2211	0.1206	1.19595	0.01005
Wind	261.3	$<10^{-4}$	0.2211	0.1206	1.19595	0.01005

[1] EGS = Electricity Generation Source.

4.2. Results of the Analysis of Drone-Based First-Mile Operations from Trucks

The total length of the delivery route (see Table 6 and Figure 3) performed by the e-truck was 27.5 km, the required transportation time was 49 min, the required additional handling time for loading, unloading, paying and billing was 15 min (5 times 3 min as an average handling time). The total length of the delivery route performed by the drone (see Table 7 and Figure 3) from the e-truck was 8.95 km and the required transportation time was 19.51 min, including average additional handling time.

Table 6. The scheduled and performed delivery route of the e-truck including GPS coordinates and delivery types in the case of the second scenario, where suitable pick-up operations (first-mile) were performed by the drone from the e-truck.

Name of Pick-Up and Delivery Locations	Latitude	Longitude	Type of Delivery *
Mátyás király u. 16, Felsőzsolca, 3561	48.112274	20.855699	FM Truck
Sajószigeti utca 19, Miskolc, 3527	48.118469	20.807808	LM Truck
Vereckei u. 15, Miskolc, 3527	48.120301	20.798316	LM Drone
Tatár u. 11, Miskolc, 3531	48.095782	20.752215	LM Truck
2519, Miskolc, 3533	48.086944	20.715982	LM Truck
DINAS Mérnökiroda Kft., Miskolc 3533	48.092708	20.736762	LM Drone
2505 167-151, Miskolc, 3535	48.112034	20.668218	LM Truck

* FM Truck = First-mile delivery by truck. LM Truck = Last-mile delivery by truck. LM Drone = Last-mile delivery by drone from truck.

Table 7. The scheduled and performed delivery route of the drone from the e-truck including GPS coordinates and delivery types in the case of the second scenario, where suitable pick-up (first-mile) operations were performed by the drone from the e-truck.

Name of Pick-Up and Delivery Locations	Latitude	Longitude	Time and Distance *
TP ** Sajószigeti utca 19, Miskolc, 3527	48.118469	20.807808	2.38 min 0.25 km
Black Bontó, Miskolc, Besenyői u. 24, 3527	48.125582	20.797602	
TP Sajószigeti utca 19, Miskolc, 3527	48.118469	20.807808	

Table 7. *Cont.*

Name of Pick-Up and Delivery Locations	Latitude	Longitude	Time and Distance *
TP Kiss Ernő u. Miskolc, 3531	48.099665	20.733654	11.3 min 6.15 km
Danlos, Miskolc, 3510	48.111775	20.738653	
TP Kiss Ernő u. Miskolc, 3531	48.099665	20.733654	
TP 2505 Miskolc, 3533	48.087144	20.721217	5.83 min 2.55 km
Vörösbérc utca, Miskolc, 3533	48.077806	20.721317	
TP 2505 Miskolc, 3533	48.087144	20.721217	

* The time and distance in Table 7 is for the drone from the Truck Point through the location of the first-mile delivery location back to the Truck Point. ** TP = Truck Point (the starting and arrival location of the drone from/to the e-truck).

Figure 3. The scheduled and performed delivery route of the e-truck and the drone in the case of Scenario 2, where all suitable first-mile operations were performed by the drone.

The energy consumption of the e-truck was 6.875 kWh. This energy consumption in the case of a diesel truck would be 30.25 kWh. The virtual GHG emission depending on the generation source of the electricity is shown in Table 8.

Table 8. The greenhouse gas (GHG) emission of the e-truck depending on the electricity generation source in CO_2 emission in g in the case of e-trucks.

EGS [1]	Emission					
	CO_2	SO_2	CO	HC	NO_X	PM [2]
Lignite	7246.25	0.22	6.05	3.3	32.725	0.275
Coal	6105	0.1925	5.039375	2.75	27.225	0.20625
Oil	5039.375	0.15125	4.228125	2.303125	22.8525	0.1925
Natural gas	3430.625	0.11	2.87375	1.5675	15.30375	0.130625
Photovoltaic	584.375	0.01375	0.501875	0.275	2.7225	0.020625
Biomass	309.375	0.006875	0.26125	0.144375	1.409375	0.01375
Nuclear	199.375	$<10^{-4}$	0.165	0.089375	0.9075	0.006875
Water	178.75	$<10^{-4}$	0.15125	0.0825	0.818125	0.006875
Wind	178.75	$<10^{-4}$	0.15125	0.0825	0.818125	0.006875

[1] EGS = Electricity Generation Source. [2] PM = Particulate matter.

The energy consumption of the drone was 0.2685 kWh. The virtual GHG emission depending on the generation source of the electricity is shown in Table 9.

Table 9. The greenhouse gas (GHG) emission of the drone depending on the electricity generation source in CO_2 emission in g in the case of e-trucks.

EGS [1]	Emission					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	282.999	0.008592	0.23628	0.12888	1.27806	0.01074
Coal	238.428	0.007518	0.1968105	0.1074	1.06326	0.008055
Oil	196.8105	0.005907	0.1651275	0.0899475	0.892494	0.007518
Natural gas	133.9815	0.004296	0.112233	0.061218	0.597681	0.0051015
Photovoltaic	22.8225	0.000537	0.0196005	0.01074	0.106326	0.0008055
Biomass	12.0825	0.0002685	0.010203	0.0056385	0.0550425	0.000537
Nuclear	7.7865	$<10^{-3}$	0.006444	0.0034905	0.035442	0.0002685
Water	6.981	$<10^{-3}$	0.005907	0.003222	0.0319515	0.0002685
Wind	6.981	$<10^{-3}$	0.005907	0.003222	0.0319515	0.0002685

[1] EGS = Electricity Generation Source.

4.3. Results of the Analysis of the Integrated First-Mile/Last-Mile Drone-Based Shuttle Operations from Trucks

The total length of the delivery route performed by the e-truck (see Table 10 and Figure 4) was 21.6 km, the required transportation time was 38 min, the required additional handling time for loading, unloading, paying and billing was 9 min (3 times 3 min as an average handling time).

Table 10. The scheduled and performed delivery route of the e-truck including GPS coordinates and delivery types in the case of the third scenario, where all suitable pick-up and delivery operations were performed by drones.

Name of Pick-Up and Delivery Locations	Latitude	Longitude	Type of Delivery *
Mátyás király u. 16, Felsőzsolca, 3561	48.112274	20.855699	FM Truck
Sajószigeti utca 19, Miskolc, 3527	48.118469	20.807808	LM Truck
Tatár u. 11, Miskolc, 3531	48.095782	20.752215	LM Truck
2519, Miskolc, 3533	48.086944	20.715982	LM Truck
2505 167-151, Miskolc, 3535	48.112034	20.668218	LM Truck

* FM Truck = First-mile delivery by truck. LM Truck = Last-mile delivery by truck. FM Drone = First-mile delivery by drone. LM Drone = Last-mile delivery by drone from truck.

The total length of the delivery route performed by the drone (see Table 11 and Figure 4) from the e-truck was 15.43 km and the required transportation time was 32.35 min, including average additional handling time.

Table 11. The scheduled and performed delivery route of the drone from e-truck including GPS coordinates and delivery types in the case of the third scenario, where pick-up and delivery operations were performed by drones.

Name of Pick-Up and Delivery Locations	Latitude	Longitude	Time and Distance *
TP ** Sajószigeti utca 19, Miskolc, 3527	48.118469	20.807808	2.38 min 0.25 km
Black Bontó, Miskolc, Besenyői u. 24, 3527	48.125582	20.797602	
TP Sajószigeti utca 19, Miskolc, 3527	48.118469	20.807808	

Table 11. *Cont.*

Name of Pick-Up and Delivery Locations	Latitude	Longitude	Time and Distance *
TP Gömöri, Miskolc, Állomás u., 3526	48.104893	20.800836	6.95 min 3.33 km
Vereckei u. 15, Miskolc, 3527	48.120301	20.798316	
TP Gömöri, Miskolc, Állomás u., 3526	48.104893,	20.800836	
TP Kiss Ernő u. Miskolc, 3531	48.099665	20.733654	11.3 min 6.15 km
Danlos, Miskolc, 3510	48.111775	20.738653	
TP Kiss Ernő u. Miskolc, 3531	48.099665	20.733654	
TP Kiss Ernő u. Miskolc, 3531	48.099665,	20.733654	4.62 min 1.75 km
DINAS Mérnökiroda Kft., Miskolc, 3533	48.092708	20.736762	
TP Kiss Ernő u. Miskolc, 3531	48.099665,	20.733654	
TP 2505 Miskolc, 3533	48.087144	20.721217	5.83 min 2.55 km
Vörösbérc utca, Miskolc, 3533	48.077806	20.721317	
TP 2505 Miskolc, 3533	48.087144	20.721217	

* The time and distance are for the drone from the Truck Point through the location of the first-mile delivery location back to the Truck Point. ** TP=Truck Point (the starting and arrival location of the drone from/to the e-truck).

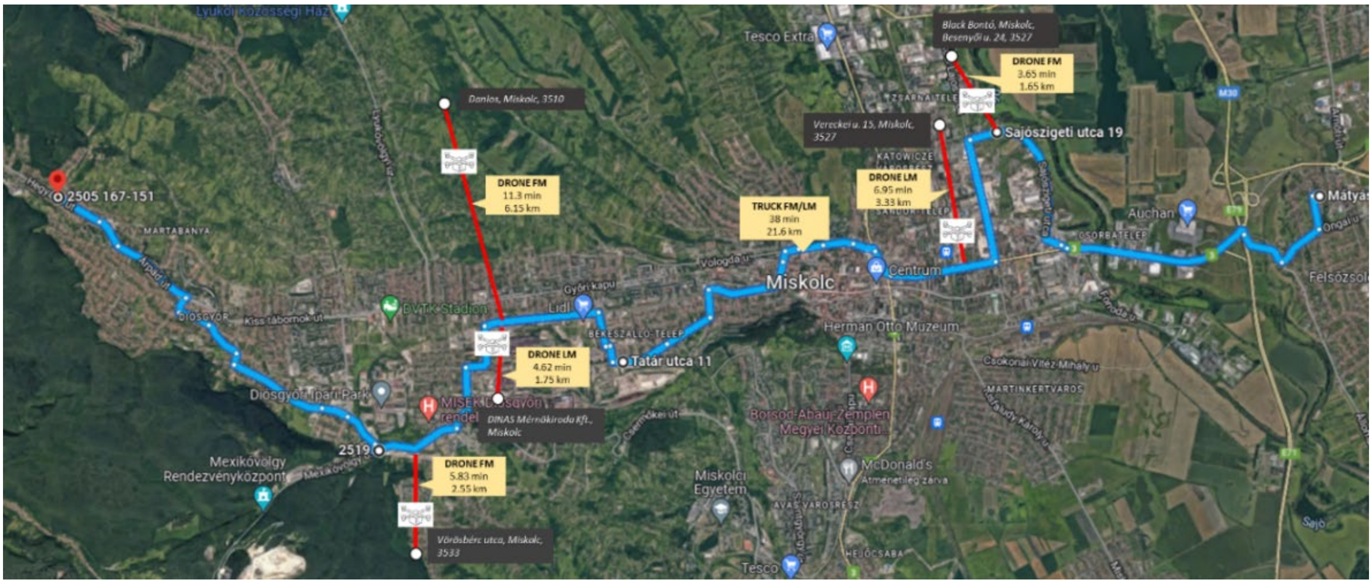

Figure 4. The scheduled and performed delivery route of the e-truck and the drone in the case of the third scenario, where all suitable pick-up and delivery operations were performed by the drone.

The energy consumption of the e-truck was 5.4 kWh. This energy consumption in the case of a diesel truck would be 23.76 kWh. The virtual GHG emission depending on the generation source of the electricity is shown in Table 12.

Table 12. The greenhouse gas (GHG) emission of the e-truck depending on the electricity generation source in CO_2 emission in g in the case of e-trucks.

EGS [1]	Emission					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	5691.6	0.1728	4.752	2.592	25.704	0.216
Coal	4795.2	0.1512	3.9582	2.16	21.384	0.162
Oil	3958.2	0.1188	3.321	1.809	17.9496	0.1512
Natural gas	2694.6	0.0864	2.2572	1.2312	12.0204	0.1026
Photovoltaic	459	0.0108	0.3942	0.216	2.1384	0.0162
Biomass	243	0.0054	0.2052	0.1134	1.107	0.0108
Nuclear	156.6	$<10^{-3}$	0.1296	0.0702	0.7128	0.0054
Water	140.4	$<10^{-3}$	0.1188	0.0648	0.6426	0.0054
Wind	140.4	$<10^{-3}$	0.1188	0.0648	0.6426	0.0054

[1] EGS = Electricity Generation Source.

The energy consumption of the drone was 0.4629 kWh. The virtual GHG emission depending on the generation source of the electricity is shown in Table 13.

Table 13. The greenhouse gas (GHG) emission of the drone depending on the electricity generation source in CO_2 emission in g.

EGS [1]	Emission					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	487.8966	0.0148128	0.407352	0.222192	2.203404	0.018516
Coal	411.0552	0.0129612	0.3393057	0.18516	1.833084	0.013887
Oil	339.3057	0.0101838	0.2846835	0.1550715	1.5386796	0.0129612
Natural gas	230.9871	0.0074064	0.1934922	0.1055412	1.0304154	0.0087951
Photovoltaic	39.3465	0.0009258	0.0337917	0.018516	0.1833084	0.0013887
Biomass	20.8305	0.0004629	0.0175902	0.0097209	0.0948945	0.0009258
Nuclear	13.4241	$<10^{-3}$	0.0111096	0.0060177	0.0611028	0.0004629
Water	12.0354	$<10^{-3}$	0.0101838	0.0055548	0.0550851	0.0004629
Wind	12.0354	$<10^{-3}$	0.0101838	0.0055548	0.0550851	0.0004629

[1] EGS = Electricity Generation Source.

4.4. Results of the Analysis of the Integrated First-Mile/Last-Mile Drone-Based Milk Run Operations from Trucks

The scheduled and performed delivery route of the e-truck was the same as in the case of the third scenario; therefore, the total length of the delivery route performed by the e-truck was 21.6 km, the required transportation time was 38 min and the required additional handling time was 9 min.

The total length of the delivery route performed by the drone from the e-truck (see Table 14 and Figure 5) was 12.96 km and the required transportation time was 29.51 min, including average additional handling time.

The energy consumption of the e-truck and the virtual GHG emissions were the same as in the case of Scenario 3 (see Table 12).

The energy consumption of the drone was 0.3888 kWh. The virtual GHG emission depending on the generation source of the electricity is shown in Table 15.

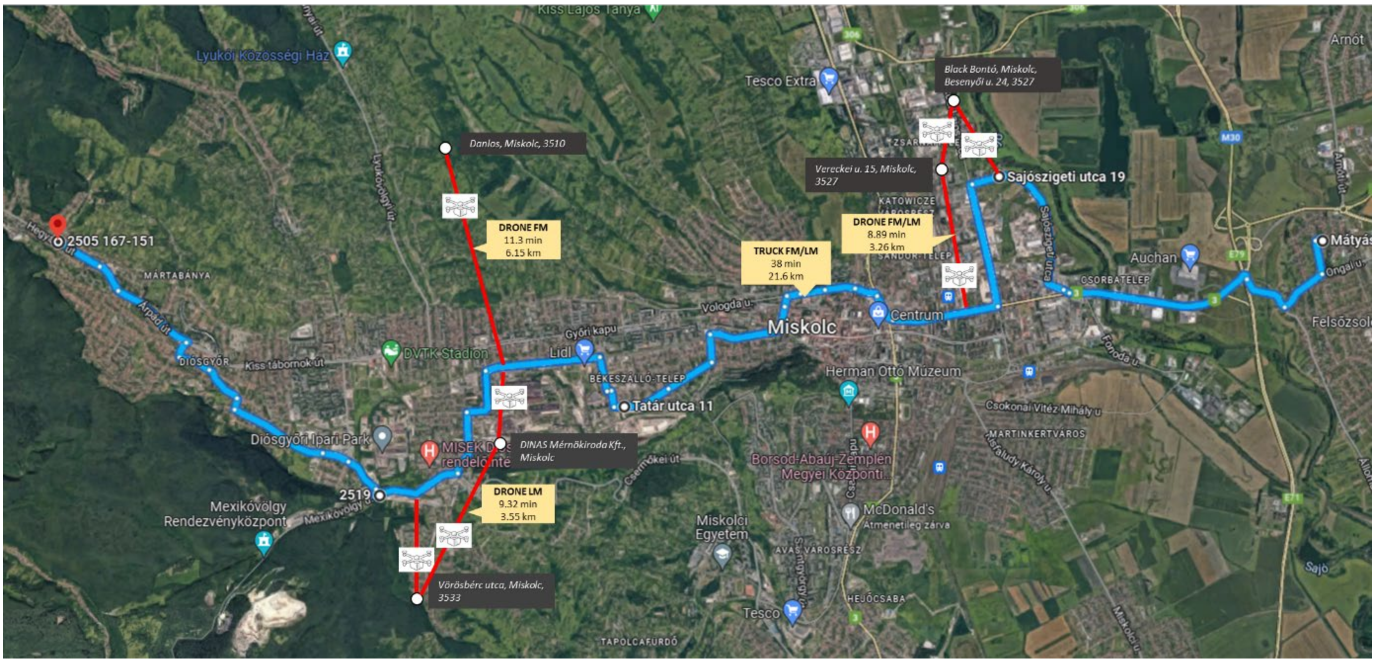

Figure 5. The scheduled and performed delivery route of the e-truck and the drone in the case of the fourth scenario, where all suitable pick-up and delivery operations were performed by the drone with milk runs.

Table 14. The scheduled and performed delivery route of the drone from e-truck including GPS coordinates and delivery types in the case of the fourth scenario, where pick-up and delivery operations were performed by drones with milk runs.

Name of Pick-Up and Delivery Locations	Latitude	Longitude	Time and Distance *
TP ** Sajószigeti utca 19, Miskolc, 3527	48.118469	20.807808	8.89 min 3.26 km
Black Bontó, Miskolc, Besenyői u. 24, 3527	48.125582	20.797602	
Vereckei u. 15, Miskolc, 3527	48.120301	20.798316	
TP Eperjesi u. 1 Miskolc, 3526	48.104643	20.799189	
TP Kiss Ernő u. Miskolc, 3531	48.099665	20.733654	11.3 min 6.15 km
Danlos, Miskolc, 3510	48.111775	20.738653	
TP Kiss Ernő u. Miskolc, 3531	48.099665	20.733654	
TP Kiss Ernő u. Miskolc, 3531	48.099665,	20.733654	9.32 min 3.55 km
DINAS Mérnökiroda Kft., Miskolc, 3533	48.092708	20.736762	
Vörösbérc utca, Miskolc, 3533	48.077806	20.721317	
TP 2505 Miskolc, 3533	48.087144	20.721217	

* The time and distance is for the drone from the Truck Point through the location of the first-mile delivery location back to the Truck Point. ** TP = Truck Point (the starting and arrival location of the drone from/to the e-truck).

Table 15. The greenhouse gas (GHG) emission of the drone depending on the electricity generation source in CO_2 emission in g.

EGS [1]	Emission					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	409.7952	0.0124416	0.342144	0.186624	1.850688	0.015552
Coal	345.2544	0.0108864	0.2849904	0.15552	1.539648	0.011664
Oil	284.9904	0.0085536	0.239112	0.130248	1.2923712	0.0108864
Natural gas	194.0112	0.0062208	0.1625184	0.0886464	0.8654688	0.0073872
Photovoltaic	33.048	0.0007776	0.0283824	0.015552	0.1539648	0.0011664
Biomass	17.496	0.0003888	0.0147744	0.0081648	0.079704	0.0007776
Nuclear	11.2752	$<10^{-3}$	0.0093312	0.0050544	0.0513216	0.0003888
Water	10.1088	$<10^{-3}$	0.0085536	0.0046656	0.0462672	0.0003888
Wind	10.1088	$<10^{-3}$	0.0085536	0.0046656	0.0462672	0.0003888

[1] EGS = Electricity Generation Source.

4.5. Comparison of the Results of the Four Scenarios

Within the frame of this chapter, the comparison of the numerical analysis of the different delivery service models from the energy efficiency and environmental aspects (GHG emission) has been discussed. As the above scenarios show, the application of drones led to an increased energy efficiency, while the greenhouse gas emissions also significantly decreased. Table 16 shows the results of the comparison of the analyzed service models from the energy efficiency point of view.

Table 16. Comparison of scenarios from the energy efficiency point of view.

Model ID	Model Description	Energy Consumption [kWh]		
		Truck	Drone	Total
Scenario 1a	Truck-based delivery without drones (truck: diesel truck)	44.22	-	44.22
Scenario 1b	Truck-based delivery without drones (truck: e-van)	10.05	-	10.05
Scenario 2a	Drone-based first-mile operations from trucks (truck: diesel truck)	30.25	0.2685	30.5185
Scenario 2b	Drone-based first-mile operations from trucks (truck: e-van)	6.875	0.2685	7.1435
Scenario 3a	Integrated first-mile/last-mile drone-based shuttle operations from truck (truck: diesel truck)	23.76	0.4629	24.2229
Scenario 3b	Integrated first-mile/last-mile drone-based shuttle operations from truck v	5.4	0.4629	5.8629
Scenario 4a	Integrated first-mile/last-mile drone-based milk run operations from truck (truck: diesel truck)	23.76	0.3888	24.1488
Scenario 4b	Integrated first-mile/last-mile drone-based milk run operations from truck (truck: e-van)	5.4	0.3888	5.7888

Figure 6 shows the energy saving of the different scenarios compared to the diesel truck-based conventional delivery system. Depending on the used drone-based delivery model, almost 90 percentage of the energy consumption could be saved and this energy consumption reduction has a great impact on the GHG emissions.

The comparison of GHG emission reductions can be also calculated depending on the electricity generation source for each model. Table 17 shows the CO_2 emission reduction compared to the diesel truck-based conventional service solution, where 2629 g/liter CO_2 emission is taken into consideration with an average fuel consumption of 27 L/100 km [52].

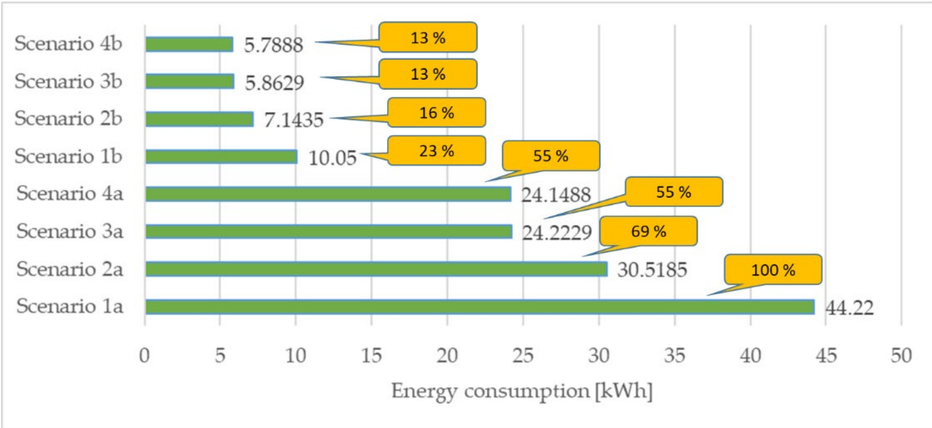

Figure 6. The energy consumption of the different delivery models compared to the energy consumption of the conventional diesel truck-based delivery model.

Table 17. Comparison of CO_2 emissions.

Model ID	Model Description	CO_2 Emission [g]		
		Truck	**Drone**	**Total**
	Basic model			
Scenario 1a	Truck-based delivery without drones (truck: diesel truck)	28,535	-	28,535
	Comparison to the basic model			
		CO_2 emission reduction [g]		
		truck	**drone**	**total**
Scenario 1b	Truck-based delivery without drones (truck: e-van)	17,943	0	17,943
Scenario 2a	Drone-based first-mile operations from trucks (truck: diesel truck)	9015	−283	8732
Scenario 2b	Drone-based first-mile operations from trucks (truck: e-van)	21,109	−283	20,826
Scenario 3a	Integrated first-mile/last-mile drone-based shuttle operations from truck (truck: diesel truck)	13,203	−487.9	12,715.1
Scenario 3b	Integrated first-mile/last-mile drone-based shuttle operations from truck v	22,844	−487.9	22,356.1
Scenario 4a	Integrated first-mile/last-mile drone-based milk run operations from truck (truck: diesel truck)	17,583	−409.8	17,173.2
Scenario 4b	Integrated first-mile/last-mile drone-based milk run operations from truck (truck: e-van)	22,844	−409.8	22,434.2

As the analysis of the above-mentioned scenarios shows, the application of drones can lead to significant reduction in energy consumption and greenhouse gas emissions. Depending on the weight and volume of the packages to be delivered, it is possible to perform more delivery operations from trucks. The analysis shows that depending on the intensity of the application of drone-based deliveries, it is possible to reach an energy consumption reduction of about 87 percent. However, research articles have stated that drones can have up to 94% lower energy consumption per package than other vehicles [53], but in the case of drones from truck deliveries, the energy consumption of trucks has to be taken into consideration.

5. Discussion

Within the frame of this research work, the author developed a novel model to analyze the impact of the integration of drone-based first-mile and last-mile operations from trucks on energy efficiency and greenhouse gas emissions. This model makes it possible to describe the influence of different types of drone-based delivery services on sustainability aspects focusing on energy consumption and the environment. More generally, this paper has focused on the mathematical description of drone-based first-mile/last-mile services from trucks, including the assignment of first-mile and last-mile operations to e-trucks and drones and the routing of these vehicles. A comparative table contrasted the proposed methodology in front of the related analyzed research works, where the relationship between this solution and the past literature was discussed. The existing studies included the optimization of routing problems, while only a few of them considered the sustainability-related aspects of drone-based services from the point of view of the integration of first-mile and last-mile delivery operations.

The added value of the paper is in the description of the impact of the application of drones on energy efficiency and greenhouse gas emissions, while logistics-related constraints (payload capacity of vehicles, routing, scheduling) are taken into consideration. The scientific contribution of this paper for researchers in this field is the mathematical modelling of the relationship between sustainability aspects and logistics parameters. The results can be generalized because the model can be applied for different drone-based services (e.g., stock inventory using drones [54]).

Managerial decisions can be influenced by the results of this research because the described method makes it possible to analyze the available solutions of package delivery systems and strategic decisions can be supported by the results of the analyzed scenarios especially in relation to energy efficiency and greenhouse gas emissions.

However, there are also limitations of the study and the described model, which provides direction for further research. Within the frame of this model, the energy efficiency and the generation of electricity was taken into consideration and the environmental impact of production of batteries for e-trucks and drones was not included. In further studies, the model can be extended to a more complex model including other environmental aspects of drone applications.

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Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

GHG	Greenhouse Gas
GPS	Global Positioning System
PM	Particulate Matter (complex mixture of small liquid droplets and solid particulates suspended in the air)
MILP	Mixed Integer Linear Programming
UAV	Unmanned Aerial Vehicle
FM	First-mile
LM	Last-mile
EGS	Electricity Generation Source
TP	Truck Point

Nomenclature

Description of superscripts for energy consumptions and emissions.

$C^{1TD\rightarrow}$	Energy consumption of the e-truck within the initial section of the delivery route from the depot to the first delivery location in the case of the truck-based delivery model.
C^{1TR}	Energy consumption of the e-truck within the delivery route between the first and last delivery location in the case of the truck-based delivery model.
$C^{1T\rightarrow D}$	Energy consumption of the e-truck within the closing section of the delivery route from the last delivery location to the depot in the case of the truck-based delivery model.
$E_{x,y}^{1TD\rightarrow}$	GHG emission within the initial section of the delivery route from the depot to the first delivery location in the case of the truck-based delivery model.
$E_{x,y}^{1TR}$	GHG emission within the delivery route between the first and last delivery location in the case of the truck-based delivery model.
$E_{x,y}^{1T\rightarrow D}$	GHG emission within the closing section of the delivery route from the last delivery location to the depot in the case of the truck-based delivery model.
$C^{2TD\rightarrow}$	Energy consumption of the e-truck within the initial section of the delivery route from the depot to the first delivery location in the case of the drone-based first-mile delivery model.
C^{2TR}	Energy consumption of the e-truck within the delivery route between the first and last delivery location in the case of the drone-based first-mile delivery model.
$C^{2T\rightarrow D}$	Energy consumption of the e-truck within the closing section of the delivery route from the last delivery location to the depot in the case of the drone-based first-mile delivery model.
C^{2DR}	Energy consumption of the drone within the delivery route between the pick-up operation locations and the e-truck in the case of the drone-based first-mile delivery model.
$C^{2D\rightarrow D}$	Energy consumption of the drone within the closing section of the delivery route from the last delivery location to the depot in the case of the drone-based first-mile delivery model.
$E_{x,y}^{2TD\rightarrow}$	GHG emission within the initial section of the delivery route from the depot to the first delivery location in the case of the drone-based first-mile delivery model.
$E_{x,y}^{2TR}$	GHG emission within the delivery route between the first and last delivery location in the case of the drone-based first-mile delivery model.
$E_{x,y}^{2T\rightarrow D}$	GHG emission within the closing section of the delivery route from the last delivery location to the depot in the case of the drone-based first-mile delivery model.
$E_{x,y}^{2DR}$	GHG emission of the drone within the delivery route between the first and last delivery location in the case of the drone-based first-mile delivery model.
$E_{x,y}^{2D\rightarrow D}$	GHG emission of the drone between pick-up operations on the delivery route and the depot in the case of the drone-based first-mile delivery model.
$C^{3TD\rightarrow}$	Energy consumption of the e-truck within the initial section of the delivery route from the depot to the first delivery location in the case of the integrated first-mile/last-mile drone-based operations.
C^{3TR}	Energy consumption of the e-truck within the delivery route between the first and last delivery location in the case of the integrated first-mile/last-mile drone-based operations.
$C^{3T\rightarrow D}$	Energy consumption of the e-truck within the closing section of the delivery route from the last delivery location to the depot in the case of the integrated first-mile/last-mile drone-based operations.
C^{3DR}	Energy consumption of the drone within the delivery route between the pick-up operation locations and the e-truck in the case of the integrated first-mile/last-mile drone-based operations.
$C^{3D\rightarrow D}$	Energy consumption of the drone within the closing section of the delivery route from the last delivery location to the depot in the case of the integrated first-mile/last-mile drone-based operations.
$E_{x,y}^{3TD\rightarrow}$	GHG emission within the initial section of the delivery route from the depot to the first delivery location in the case of the integrated first-mile/last-mile drone-based operations.
$E_{x,y}^{3TR}$	GHG emission within the delivery route between the first and last delivery location in the case of the integrated first-mile/last-mile drone-based operations.
$E_{x,y}^{3T\rightarrow D}$	GHG emission within the closing section of the delivery route from the last delivery location to the depot in the case of the integrated first-mile/last-mile drone-based operations.

$E_{x,y}^{3DR}$	GHG emission of the drone within the delivery route between the first and last delivery location in the case of the integrated first-mile/last-mile drone-based operations.
$E_{x,y}^{3D\rightarrow D}$	GHG emission of the drone between pick-up operations on the delivery route and the depot in the case of the integrated first-mile/last-mile drone-based operations.

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