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Energy Efficiency of AGV-Drone Joint In-Plant Supply of Production Lines

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Abstract: Energy efficiency plays an increasingly important role not only in supply chains, but also in in-plant supply systems. Manufacturing companies are increasingly using energy-efficient material handling equipment to solve their in-plant material handling tasks. A new example of this effort is the use of drones for in-plant transportation of small components. Within the frame of this article, a new AGV-drone joint in-plant supply model is described. The joint service of AGV-based milkrun trolleys and drones makes it possible to optimize the in-plant supply in production lines. This article discusses the mathematical description of AGV-drone joint in-plant supply solutions. The numerical analysis of the different AGV-drone joint in-plant supply solutions shows that this new approach can lead to an energy consumption reduction of about 30%, which also has a significant impact on GHG emission.

Keywords: emission reduction; energy efficiency; logistics; optimization; scheduling; service level; vehicle routing

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1. Introduction

Milkrun supply is an extremely popular in-plant supply solution, where a wide range of components has to be picked up and delivered among warehouses, supermarkets, and production resources. The design of milkrun routes represents a problem of dynamic systems; therefore, its processes cannot be planned in advance, but dynamic design and operation methodologies have to be used instead of conventional in-advance design [1].

Milkrun in-plant supply is defined as a supply system including periodically moving vehicles which perform the material supply of manufacturing and assembly cells in different predefined routes. The milkrun supply generally can be taken into consideration as a lean distribution system which standardizes the in-plant logistics processes, the logistics resources, and the strategies. Although there is a wide range of studies focusing on milkrun supply, most of them discuss supply chain-related milkrun solutions and only a few of them discuss in-plant milkrun solutions. The studies generally focus on the optimization of the required resources, and the transportation distances and the potential of using mixed resources (e.g., linked AGV-drone services) are not analyzed [2].

Based on the results of the Fortune Business Insight Study, the unmanned aircraft market has been significantly increased and a Compound Annual Growth Rate of about 43% is expected, while the market size value is growing from USD 13.48 billion in 2022 to USD 232.8 billion by 2029 [3]. The application of drones includes a wide range of services, such as pandemic vaccine distribution [4], as well as local and global supply chain distribution [5]. The application of drones focuses on both single unmanned vehicles and cloud-based supply chain solutions, where not only individual drones, but also drone clusters can be taken into consideration as potential supply solutions [6]. The control of complex drone-based supply solutions is generally based on artificial intelligence methods, which enables the optimization of single echelon and multi-echelon supply chains [7,8]. Most of the literature has discussed the application of drones only in the case of global and local supply chains, and only a few of the studies discuss the in-plant applications of drones.

The design and operation of in-plant milkrun supply solutions can be defined as an NP-hard optimization problem [2]; therefore, most of the optimization-related approaches are using heuristics or metaheuristics. The objective functions of different approaches of the design of milkrun-based in-plant supply integrate the following aspects: minimization of required AGVs, minimization of milkrun trolleys' capacities, minimization of routes of milkruns, minimization of work in process inventories (WIP), minimization of material handling operations, or minimization of inventory cost, number, and capacity of required supermarkets [9].

The impact of milkrun-based in-plant supply can be analyzed using discrete event simulation, where both the resources and the traveling cycles among storages, supermarkets, manufacturing, and assembly cells can be taken into consideration. The simulation makes it possible to analyze the impact of different disturbances on the efficiency of logistics and manufacturing [10].

After this introduction, the remaining part of the paper is divided into three sections. Section 2 presents a literature review to summarize the research background regarding design and optimization of in-plant supply focusing on milkrun solutions. Section 3 presents a new approach, which makes it possible to model and analyze conventional AGV-based and AGV-drone joint in-plant supply solutions from an energy efficiency point of view. Section 4 presents the results of the numerical analysis. Conclusions and future research directions are discussed in the last section.

2. Literature Review

Production processes can be generally described as stochastic flow lines, where storage capacities and limited material supply operations can significantly influence and increase the uncertainties. In the case of an uncertain production environment, the performance analysis and the optimization of stochastic in-plant supply processes play an important role in the efficiency improvement [11]. Holistic approaches can also be used to optimize the in-plant milkrun systems. The planning and dimensioning tasks of in-plant milkrun services can integrate a wide range of logistics operations and logistics-related topics focusing on consignment, storage, time management, and ergonomics [12].

Milkrun solutions are used in a wide range of industries: agricultural machinery [13], food industry [14], automotive supplier [15,16], cable manufacturing [17], or washing machine manufacturing [18].

In the context of Industry 4.0, the application of dynamic simulation models in the optimization of intralogistics processes becomes more and more important. The interactive layout design is an important tool which can have a great impact on the efficiency of milkrun design [19]. As a case study focusing on the transportation of part supply improvement shows, poorly managed in-plant supply processes can lead to increased costs and decreased product quality, while the ability to fulfill customers' demands can also be decreased. Lean tools can support the improvement of in-plant supply processes. As a case study shows, the most important problem of the operation of milkrun supply solutions is the asynchronicity between the demands of production or assembly lines and in-plant supply processes [13].

The design process of in-plant supply solutions is a complex engineering task, where a wide range of influencing factors has to be taken into consideration. The calculation of the intensity of dimensioning parameters can significantly improve the efficiency of milkrun design [20], and it is especially important in the case of AGV-drone joint supply, where the integration of different technologies is a core problem. Milkrun supply can be used both for external logistics and for intralogistics. The design problems of milkrun solutions represent in both cases complex optimization problems. In the case of external logistics, manufacturers, retailers, and suppliers are integrated into a value chain, while in the case of intralogistics, the production and assembly resources are integrated by milkrun solutions. As research by [14] shows, the Analytical Hierarchy Process is a suitable design methodology to optimize milkrun processes. The design tasks of in-plant supply solutions can be solved using analytical methods [21], heuristics [22], and simulation [23,24], but empirical studies also discuss important design aspects [25]. As a 3D micro-simulation of milkruns and pickers in warehouses shows, discrete event simulation and agent-based simulation make it possible to take a wide range of parameters into consideration including storage strategy, quantity of demands, structure of shifts, volume of components, arrival rate of requests, and the available number of milkrun trolleys [26]. As this research shows, milkrun design requires a holistic approach. A new approach focuses on the structural optimization of milkrun-based in-plant supply, where time- and capacity-based constraints are taken into consideration [27]. Merging the payload cycles can also lead to optimized milkrun solutions, as a case study shows in the case of an automotive supplier, where the optimization of loading capacities in the restructuring and rerouting of milkrun routes resulted in a more efficient milkrun-based supply [16].

The design of an intralogistics system integrates different aspects of material handling design including layout planning, vehicle routing, and scheduling. As a black hole heuristics-based optimization approach shows, the integrated solution of milkrun services in production processes can lead to efficient intralogistics operations [28]. One of the first real-time milkrun design approaches was published by [29]. In this research, an in-plant milkrun control methodology is shown focusing on the morphological classification of static and dynamic approaches. Value stream mapping and lean metrics can also support the design of milkrun supply processes. The flexible routing of milkrun trolleys can lead to reduced stocks (inventory in warehouse and work in process inventory), while the lean rate increases [30]. In the case of complex in-plant supply solutions, milkrun routing and scheduling are subject to a trade-off between vehicle fleet size and storage capacity. In this case, periodic distribution policies can support the optimal process, which is based on the identification of the relationship between tact time and the size of replenishment batches [31]. In the case of stochastic processes, probabilities can be added to the predefined schedules and requests, and this model can minimize the order cycle time and the average picking effort [32].

A wide range of methods and tools can be used for the optimization of milkrun supply solutions, such as linear programming [11], Analytical Hierarchy Process [14], Saving Matrix Methods [15], black hole heuristics [28], Linear Temporal Logic [33], and simulation [34]. The application of product allocation in a polling-based milkrun picking system is a complex design problem. As the research results in the case of exhaustive, locally-gated, and globally-gated picking strategies show, the cyclic polling system with simultaneous batch arrivals is a suitable solution for milkrun services [35,36]. Drones can also be used in polling-based milkrun picking systems.

The mentioned mathematical methods, algorithms, and tools are suitable to solve the design and operation problems of various milkrun-based in-plant supply solutions, depending on the complexity of the optimization problem. Linear programming, Analytical Hierarchy Process, and Saving Matrix Methods are generally used for analytical problems, while heuristic methods are suitable for NP-hard optimization problems. Uncertainties can be taken into consideration by using different simulation tools.

The above-mentioned research results indicate the scientific potential of the optimization of in-plant supply solutions. The articles that addressed the design and control problems of in-plant supply solutions focus on AGV-based milkrun services, and only a few of them describe the potential of the application of drones in intralogistics, especially in the field of in-plant supply [37]. According to that, the focus of this research is on the analyses of the impact of AGV-drone joint in-plant supply of production lines on energy efficiency.

As a consequence, the main contributions of this article are the following: (1) model framework of AGV-drone joint in-plant supply solutions; (2) mathematical description of AGV-drone joint in-plant supply solutions; (3) numerical analysis of the impact of different AGV-drone joint in-plant supply solutions on energy efficiency, focusing on both energy consumption and virtual GHG emission.

3. Materials and Methods

Within the frame of this chapter, the mathematical models of different AGV-drone joint in-plant material supply systems will be described. These mathematical models are based on the previous work of Bányai focusing on the evaluation of energy efficiency of integrated first-mile and last-mile drone-based delivery operations [38]. The chapter focuses on the following topics: (i) definition of the input parameters of AGV-drone joint in-plant material supply systems; (ii) definition of specific supply models from the general input parameters depending on the cooperation level of AGV-based milkrun trolley and drone; (iii) mathematical models of typical AGV-drone joint in-plant material supply systems. The structure of the proposed models is demonstrated in Figure 1.

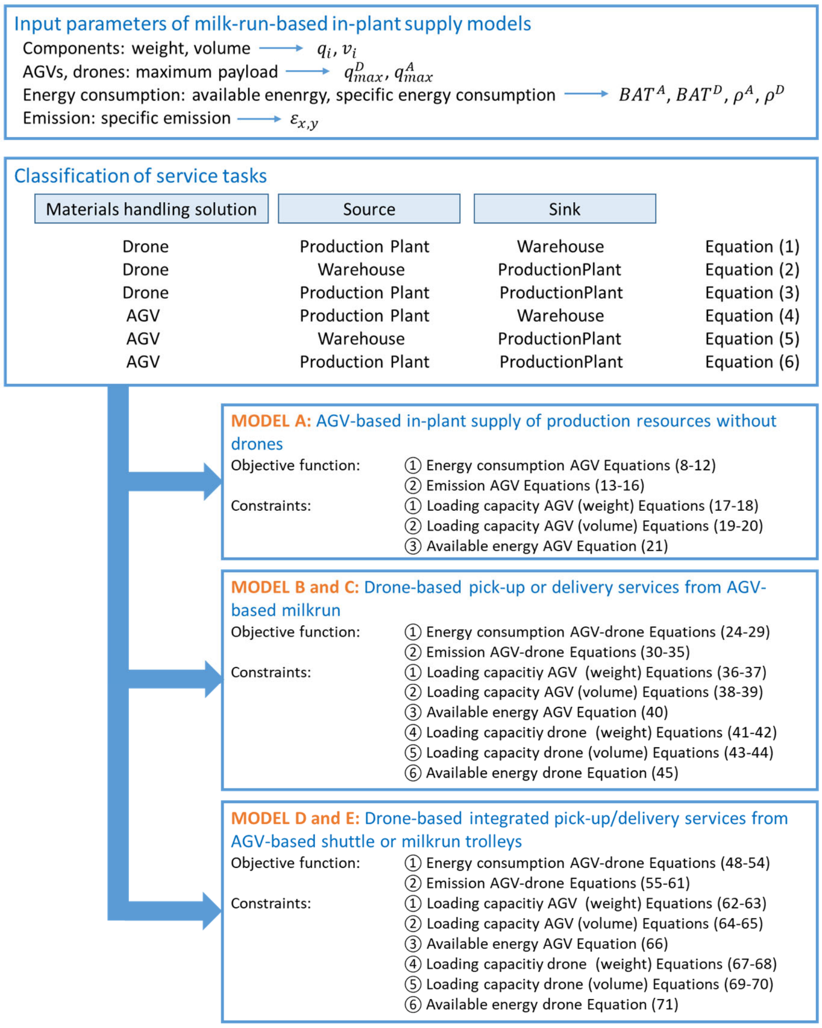

Figure 1. The structure of the proposed models (input parameters, classification of service tasks, typical service models, objective functions, and constraints).

The following typical models are discussed:

- Model A: conventional AGV-based in-plant supply of production resources without drones;
- Model B: drone-based pick-up services from AGV-based milkrun trolleys;
- Model C: drone-based delivery services from AGV-based milkrun trolleys;
- Model D: drone-based integrated pick-up and delivery shuttle services from AGV-based milkrun trolleys;
- Model E: drone-based integrated pick-up and delivery milkrun services from AGV-based milkrun trolleys.

These five service solutions can be integrated into three different mathematical models:

- Modeling of AGV-based in-plant supply of production resources without drones (see Section 3.1);
- Modeling of drone-based pick-up/delivery services from AGV-based milkrun (see Section 3.2);
- Modeling of the drone-based integrated pick-up/delivery shuttle and milkrun services from AGV-based milkrun trolleys (see Section 3.3).

The input parameters for the analysis and optimization of AGV-drone joint in-plant material supply systems are the following:

- q_i: weight of components of pick-up and delivery service i in kg;
- v_i: volume of components of pick-up and delivery service in L;
- z_i: type of material supply service i;
- q^D_{max}: maximum payload of drones in kg;
- q^A_{max}: maximum payload of AGV-based milkrun trolleys in kg;
- BAT^A : available power capacity stored in the battery of AGV-based milkrun trolleys in kWh;
- BAT^D : available power capacity stored in the battery of drones in kWh;
- ρ^A: specific energy consumption of AGV-based milkrun trolleys in kWh/km, which depends on the payload;
- ρ^D: specific energy consumption of drones in kWh/km, which depends on the payload;
- $\varepsilon_{x,y}$: specific emission of CO_2, SO_2, CO, HC, NO_X, and PM, depending on the generation source x of electricity in g/kWh in the case of GHG y.

Depending on the constraints regarding weight and volume of components of service tasks, it is possible to define typical relations in the production plant and typical in-plant service tasks.

If the constraints regarding weight and volume of components to be supplied in the production plant make it possible to fulfill the service for the requested demand by drone, while the location of service location is on the route of the AGV-based milkrun trolley and the departure is the warehouse, where AGV and drone pools are also located, then the service can be assigned to the set of in-plant service operations including pick-up service from production resource to warehouse to be performed by drone:

$$q_i \leq q^D_{max} \wedge v_i \leq v^D_{max} \wedge z_i = PPW \rightarrow q_i \in Q^{DPW}, \quad (1)$$

where q_i is the weight of component i to be picked up, q^D_{max} is the loading capacity of the drone, v_i is the volume of component i to be picked up, v^D_{max} is the upper limit of volume of components suitable for transportation by drone, Q^{DPW} is the set of pick-up service tasks from the production plant to the warehouse suitable for drone-based pick-up supply, and z_i is the type of the delivery tasks, where $z_i \in [PPW, DWP, PP, DP]$ and PPW is for pick-up service from production plant to warehouse, DWP is for delivery from the warehouse to the production plant, PP is for pick-up service in the production plant, and DP is for delivery service in the production plant.

If the constraints regarding weight and volume of components to be supplied in the production plant make it possible to fulfill the service demand by drone, while the location of pick-up is in the warehouse and the departure location is a production resource on the route of the AGV-based milkrun trolley, then the service can be assigned to the set of in-plant service operations including delivery service from warehouse to production resource to be performed by drone:

$$q_i \leq q^D_{max} \wedge v_i \leq v^D_{max} \wedge z_i = DWP \rightarrow q_i \in Q^{DDW}, \quad (2)$$

where Q^{DDW} is the set of delivery service tasks from the warehouse to the production plant suitable for drone-based delivery service.

If the constraints regarding weight and volume of components to be supplied in the production plant make it possible to fulfill the service demand by drone, while the location of pick-up and delivery is a production resource on the route of the AGV-based milkrun trolley, then the service can be assigned to the set of in-plant service operations including delivery service between two production resources to be performed by drone:

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

where Q^{DP} is the set of delivery tasks inside the production plant between production resources suitable for drone-based delivery. If $Q^{DP} > 0$, then the service task is a pick-up operation; otherwise, it is a delivery task between two production resources of the production plant.

If the constraints regarding weight and volume of components to be supplied in the production plant do not make it possible to fulfill the service demand by drone but by AGV-based milkrun trolley, while the location of pick-up is on the route of the AGV-based milkrun trolley and the departure is the warehouse, then the service can be assigned to the set of in-plant service operations including pick-up service from production resource to warehouse to be performed by AGV-based milkrun trolley:

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

where Q^{APW} is the set of pick-up service tasks from the production plant to the warehouse suitable for AGV-based milkrun trolley pick-up supply.

If the constraints regarding weight and volume of components to be supplied in the production plant do not make it possible to fulfill the service demand by drone but by AGV-based milkrun trolley, while the location of pick-up is in the warehouse and the departure location is a production resource on the route of the AGV-based milkrun trolley, then the service can be assigned to the set of in-plant service operations including delivery service from warehouse to production resource to be performed by AGV-based milkrun trolley:

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

where Q^{ADW} is the set of delivery service tasks from the warehouse to the production plant suitable for AGV-based milkrun trolley delivery supply.

If the constraints regarding weight and volume of components to be supplied in the production plant do not make it possible to fulfill the service demand by drone but by AGV-based milkrun trolley, while the location of pick-up and delivery is a production resource on the route of the AGV-based milkrun trolley, then the service can be assigned to the set of in-plant service operations including delivery service between two production resources to be performed by AGV-based milkrun trolley:

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

where Q^{AP} is the set of delivery tasks inside the production plant between production resources suitable for AGV-based milkrun trolley delivery. If $Q^{DP} > 0$, then the service task is a pick-up operation; otherwise, it is a delivery task between two production resources of the production plant. These sets make it possible to define five different models of AGV-drone joint in-plant supply of production lines.

3.1. Modeling of AGV-Based In-Plant Supply of Production Resources without Drones

In this case, all pick-up and delivery services are performed by AGV-based milkrun trolleys. Using the Q^{DPW}, Q^{DDW}, Q^{DP}, Q^{APW}, Q^{ADW}, and Q^{AP} matrices, it is possible to define the input parameters of the AGV-based in-plant supply model. The potential pick-up and delivery tasks of the in-plant supply model are as follows:

$$q_i^A = \begin{cases} \forall i \in [1, \ldots, \vartheta_1] : q_i^A = q_i^{DPW} \\ \forall i \in [1 + \vartheta_1, \ldots, \vartheta_2] : q_i^A = q_{i-\vartheta_1}^{DDW} \\ \forall i \in [1 + \vartheta_2, \ldots, \vartheta_3] : q_i^A = q_{i-\vartheta_2}^{DP} \\ \forall i \in [1 + \vartheta_3, \ldots, \vartheta_4] : q_i^A = q_{i-\vartheta_3}^{APW} \\ \forall i \in [1 + \vartheta_4, \ldots, \vartheta_5] : q_i^A = q_{i-\vartheta_4}^{ADW} \\ \forall i \in [1 + \vartheta_5, \ldots, \vartheta_6] : q_i^A = q_{i-\vartheta_5}^{AP} \end{cases}, \quad (7)$$

where $\vartheta_s = \sum_{j=1}^{s} \beta_j$. The objective function of the optimization is the minimization of energy consumption, which also has a significant impact on the emission of CO_2, SO_2, CO, HC, NO_X, and PM. In this article, automated guided vehicles and drones are performing in-plant supply services; therefore, the emission can be calculated as a virtual emission taking the emission rates of the generation source of electricity, which can be lignite, coal, oil, natural gas, photovoltaic, biomass, nuclear, water, wind, and their mix.

3.1.1. The Objective Function

Within the frame of this model, both the energy consumption of the drone and the AGV-based milkrun trolley, and their virtual GHG emission can be defined.

The minimization of the energy consumption can be defined depending on the different services performed by the AGV-based milkrun trolley:

$$C^1 = C^{1AWP} + C^{1AP} + C^{1APW} \rightarrow min., \quad (8)$$

where C^1 is the energy consumption of AGVs and drones, C^{aAWP} is the energy consumption of the AGV-based milkrun trolley within the first section of the delivery route from the warehouse or AGV pool to the first production resource in model a, C^{aAP} is the energy consumption of the AGV-based milkrun trolley between two production resources of the production plant in model a, and C^{aAPW} is the energy consumption of the AGV-based milkrun trolley within the closing section of the delivery route from the last production resource to the warehouse or AGV depot in the case of model a (e.g., C^{1APW} is the energy consumption of the AGV-based milkrun trolley from the production resources to the warehouse for the first model).

The energy consumption for the first section of the in-plant supply route from the warehouse to the first production plant can be described depending on the route length of the section between the warehouse and the first production plant of the service route, the loading of the AGV-based milkrun trolley, and the specific energy consumption of the AGV-based milkrun trolley:

$$C^{1AWP} = \left(q^{ANET} + \sum_{i=1, z_i^*=DWP}^{\vartheta_6} q_{p_i}^{*A} \right) \cdot l_{D,p_1} \cdot \rho^A, \quad (9)$$

where q^{ANET} is the net weight of the AGV-based milkrun trolley, l_{D,p_1} is the length of the milkrun section between the warehouse and the first production plant, ρ^T is the specific energy consumption of the AGV-based milkrun trolley [kWh/(kg·km)], $\overline{p} = [p_i]$ is the assignment matrix representing the optimal solution as a permutation matrix. This matrix makes it possible to define the weight of components assigned to supply tasks for each scheduled delivery as:

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

The energy consumption among production resources can be defined depending on the length of the milkrun sections between the pick-up and delivery locations, the loading of the AGV-based milkrun trolley, and the specific energy consumption:

$$C^{1AP} = \sum_{k=1}^{\vartheta_6 - 1} \left(q^{ANET} + \sum_{i=k, z_i^*=DWP}^{\vartheta_6} q_{p_i}^{*A} + \sum_{i=1, z_i^* \in [PP,DP]}^{k} q_{p_i}^{*A} \right) \cdot l_{p_k,p_{k+1}} \cdot \rho^A. \quad (11)$$

where $l_{p_k,p_{k+1}}$ is the length of the milkrun section between the scheduled supply operations assigned to production resources k and $k + 1$.

The energy consumption of the transportation in the last section of the milkrun route from the last production resource to the warehouse can be defined depending on the length of the milkrun sections from the last production resource to the warehouse, the loading of the AGV-based milkrun trolley, and the specific energy consumption:

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

The weight of the components assigned to pick-up and delivery tasks between the first and last sections of the milkrun route has no impact on the final payload of the AGV-based milkrun trolley, because all of these operations are finished before the last section of the milkrun.

The minimization of the CO_2, SO_2, CO, HC, NO_X, and PM emission can be expressed as:

$$E_{x,y}^{1} = E_{x,y}^{1AWP} + E_{x,y}^{1AP} + E_{x,y}^{1APW} \rightarrow min., \tag{13}$$

where $E_{x,y}^{1}$ is the energy consumption of the conventional model based on operations performed by the AGV-based milkrun trolley, $E_{x,y}^{aAWP}$ is the virtual GHG emission generated within the first section of the milkrun from the warehouse to the first production resource in model a, $E_{x,y}^{aAP}$ is the virtual GHG emission generated by the milkrun route between the first and last production plant in a, $E_{x,y}^{aAPW}$ is the virtual GHG emission generated within the last section of the milkrun from the last production plant to the warehouse in model a, x defines the type of electricity generation sources, and y defines the type of GHG (CO_2, SO_2, CO, HC, NO_X, PM).

The virtual GHG emission generated in the first section of the milkrun from the warehouse to the first production plant can be written as:

$$E_{x,y}^{1AWP} = \left(q^{ANET} + \sum_{i=1,z_i^*=DWP}^{\vartheta_6} q_{p_i}^{*A}\right) \cdot l_{D,p_1} \cdot \rho^A \cdot \varepsilon_{x,y}. \tag{14}$$

The virtual GHG emission of the milkrun among the first and last production resources of the production plant can be defined as:

$$E_{x,y}^{1AP} = \sum_{k=1}^{\vartheta_6-1} \left(q^{ANET} + \sum_{i=k,z_i^*=DWP}^{\vartheta_6} q_{p_i}^{*T} + \sum_{i=1,z_i^*\in[PP,DP]}^{k} q_{p_i}^{*A}\right) \cdot l_{p_k,p_{k+1}} \cdot \rho^A \cdot \varepsilon_{x,y}. \tag{15}$$

The virtual GHG emission of the last section of the milkrun from the last production resource to the warehouse is as follows:

$$E_{x,y}^{1APW} = \left(q^{ANET} + \sum_{i=1,z_i^*=PPW}^{\vartheta_6} q_{p_{\vartheta_6}}^{*A}\right) \cdot l_{\vartheta_6,D} \cdot \rho^A \cdot \varepsilon_{x,y}. \tag{16}$$

3.1.2. The Constraints

This model takes three constraints regarding available capacities and energies into consideration.

Constraint 1 for AGV-based milkrun trolley: the vehicle routing problem of the AGV-based milkrun trolley must be solved so that it is not allowed to exceed this maximum payload of the AGV-based milkrun trolley:

$$q_{p_i}^{L} \leq q^{Amax}, \tag{17}$$

where q^{Amax} is the maximum payload of the AGV-based milkrun trolley and

$$q_{p_i}^{L} = q^{ANET} + \sum_{i=k,z_i^*=DWP}^{\vartheta_6} q_{p_i}^{*A} + \sum_{i=1,z_i^*\in[PP,DP]}^{k} q_{p_i}^{*A}, \tag{18}$$

where $q_{p_i}^{L}$ is the weight of the load of the AGV-based milkrun trolley at production resource p_i. In the case of this constraint, the weight of the AGV can be calculated as the sum of the net weight of the AGV-based milkrun trolley, the weight of components delivered from the warehouse to the production resources, and the weight of components picked up and delivered between production resources.

Constraint 2 for AGV-based milkrun trolley: it is not allowed to exceed the available loading volume of the AGV-based milkrun trolley:

$$v_{p_i}^{L} \leq v^{Amax}, \tag{19}$$

where

$$v_{p_i}^{L} = \sum_{i=k,z_i^*=DWP}^{\vartheta_6} v_{p_i}^{*A} + \sum_{i=1,z_i^*\in[PP,DP]}^{k} v_{p_i}^{*A}. \tag{20}$$

where $v_{p_i}^{*A}$ is the volume of component p_i, and $v_{p_i}^{L}$ is the volume of components on the AGV-based milkrun trolley at production resource p_i and v^{Amax} is the maximum loading volume of the AGV-based milkrun trolley.

In the case of this constraint, the current volume of the loading can be calculated as the sum of the volume of components transported from the warehouse to the production resources, and the volume of components picked up or delivered between production resources.

Constraint 3 for AGV-based milkrun trolley: the third constraint defines the upper limit of available power capacity stored in the battery of the AGV-based milkrun trolley:

$$C^1 \le BAT^A, \tag{21}$$

where BAT^A is the capacity of the AGV-based milkrun trolley's battery.

3.1.3. Decision Variables

The decision variable of this milkrun supply problem is the $\overline{p} = [p_i]$ permutation matrix, which defines the optimal sequence of production resources to be supplied by required components, where the value of p_i defines the ID of in-plant supply demand of a production resource to be scheduled.

3.2. Modeling of Drone-Based Pick-Up/Delivery Services from AGV-Based Milkrun

In this milkrun-based in-plant supply solution, the pick-up operations can be assigned to a drone depending on their suitability defined by the weight and volume of the component, while delivery tasks are performed by AGV-based milkrun trolley. The basic operations of this type of AGV-drone joint in-plant supply are the following:

- The pick-up service tasks from the first production resource to the warehouse are performed in the relation (production resource—AGV-based milkrun trolley—warehouse), if the capacity-related constraints focusing on weight and volume of the components to be supplied make it possible. Between the production resource and the AGV-based milkrun trolley, the transportation is assigned to a drone, while in the case of the relation (AGV-based milkrun trolley—warehouse), the component is transported by the AGV-based milkrun trolley.
- The delivery services from the warehouse to the production resource are performed by the AGV-based milkrun trolley, because in this model the joint solution means that drones are not performing direct supply from/to the warehouse.
- The pick-up services between two production resources are performed in the following way: the pick-up service is performed by the drone if the capacity-related constraints focusing on weight and volume of the components to be supplied make it possible in the relation (production resource—AGV-based milkrun trolley) and the delivery to the next production resource is performed by the AGV-based milkrun trolley.

In this case, using the Q^{DPW}, Q^{DDW}, Q^{DP}, Q^{APW}, Q^{ADW}, and Q^{AP} matrices, we can define the basic parameters of this model as follows. The potential pick-up and delivery tasks of the in-plant supply model can be written as follows both for the drone and the AGV-based milkrun trolley:

$$q_i^A = \begin{cases} \forall i \in [1,\ldots,\beta_2] : q_i^A = q_i^{DDW} \\ \forall i \in [1+\beta_2,\ldots,\beta_2+\beta_3] : q_i^A = q_{i-\beta_2}^{DP} \\ \forall i \in [1+\beta_2+\beta_3,\ldots,\vartheta_4-\beta_1] : q_i^A = q_{i-\beta_2+\beta_3}^{APW} \\ \forall i \in [\vartheta_4-\beta_1+1,\ldots,\vartheta_5-\beta_1] : q_i^A = q_{i-\vartheta_4-\beta_1}^{ADW} \\ \forall i \in [\vartheta_5-\beta_1+1,\ldots,\vartheta_6-\beta_1] : q_i^A = q_{i-\vartheta_5-\beta_1}^{AP} \end{cases}, \tag{22}$$

and

$$q_g^D = \begin{cases} \forall g \in [1, \ldots, \vartheta_1] : q_g^D = q_g^{DPW} \\ \forall g \in [1 + \vartheta_1, \ldots, \vartheta_1 + \vartheta_3 - \vartheta_2] : q_g^D = q_{g-\vartheta_3}^{DP} \end{cases}. \quad (23)$$

3.2.1. The Objective Function

Within the frame of this model, both the energy consumption of the drone and the AGV-based milkrun trolley, and their virtual GHG emission can be defined. The minimization of the energy consumption performed by the drone and the AGV-based milkrun trolley is as follows:

$$C^2 = C^{2AWP} + C^{2AP} + C^{2APW} + C^{2DP} + C^{2DPW} \to min., \quad (24)$$

where C^2 is the energy consumption of the milkrun supply including energy consumption of the drone and the AGV-based milkrun trolley, C^{aDP} is the energy consumption of the drone between a production resource and the AGV-based milkrun trolley in model a, and C^{aDPW} is the energy consumption of the drone from the last production resource to the warehouse in model a.

The energy consumption of the first section of the milkrun from the warehouse to the first production resource can be defined depending on the length of the milkrun sections between the warehouse and the first production resource, the loading of the AGV-based milkrun trolley, and the specific energy consumption:

$$C^{2AWP} = \left(q^{ANET} + \sum_{i=1+\vartheta_1, z_i^*=DWP}^{\vartheta_6} q_{p_i}^{*A}\right) \cdot l_{D,p_1} \cdot \rho^A. \quad (25)$$

The energy consumption of the AGV-based milkrun trolley generated by the transportation services between the first and last production resource can be defined depending on the length of the milkrun sections between the production resources, the loading of the AGV-based milkrun trolley, and the specific energy consumption:

$$C^{2AP} = \sum_{k=1+\vartheta_1}^{\vartheta_6 - 1} \left(q^{ANET} + \sum_{i=k, z_i^*=DWP}^{\vartheta_6} q_{p_i}^{*T} + \sum_{i=1+\vartheta_1, z_i^* \in [PP,DP]}^{k} q_{p_i}^{*A}\right) \cdot l_{p_k, p_{k+1}} \cdot \rho^A. \quad (26)$$

The energy consumption of the last section of the milkrun from the last production resource of the route to the warehouse can be defined depending on the length of the milkrun sections between the last production resource and the warehouse, the loading of the AGV-based milkrun trolley, and the specific energy consumption:

$$C^{2APW} = \left(q^{ANET} + \sum_{i=1+\vartheta_1, z_i^*=PPW}^{\vartheta_6} q_{p_1}^{*A}\right) \cdot l_{D,p_1} \cdot \rho^A. \quad (27)$$

The energy consumption of the drone within the in-plant supply route between the first and last production resource which results from pick-up services can be formulated as:

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

where $l_{p_k, p_{TR}}$ is the travelling distance between the production resource p_k and the current position of the AGV-based milkrun trolley, and ρ^D is the specific energy consumption of the drone.

The energy consumption of the drone between the production resource and the warehouse can be calculated as:

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

The minimization of the CO_2, SO_2, CO, HC, NO_X, and PM emission can be written in the following form:

$$E_{x,y}^2 = E_{x,y}^{2AWP} + E_{x,y}^{2AP} + E_{x,y}^{2APW} + E_{x,y}^{2DP} + E_{x,y}^{2DPW} \to min. \quad (30)$$

where $E_{x,y}^{aDP}$ is the virtual GHG emission of the drone within the in-plant supply route between the first and last production resource in model a, and $E_{x,y}^{aDPW}$ is the virtual GHG emission of the drone between the production resource and the warehouse in model a.

The virtual GHG emission of the first section of the milkrun from the warehouse to the first production resource in the case of the AGV-based milkrun trolley can be expressed as:

$$E_{x,y}^{2AWP} = \left(q^{ANET} + \sum_{i=1+\vartheta_1, z_i^*=DWP}^{\vartheta_6} q_{p_i}^{*A}\right) \cdot l_{D,p_1} \cdot \rho^A \cdot \varepsilon_{x,y}. \quad (31)$$

The virtual GHG emission of the milkrun between the first and last production resource in the case of the AGV-based milkrun trolley is as follows:

$$E_{x,y}^{2AP} = \sum_{k=1+\vartheta_1}^{\vartheta_6-1} \left(q^{ANET} + \sum_{i=k, z_i^*=DWP}^{\vartheta_6} q_{p_i}^{*A} + \sum_{i=1+\vartheta_1, z_i^* \in [PP,DP]}^{k} q_{p_i}^{*A}\right) \cdot l_{p_k, p_{k+1}} \cdot \varepsilon_{x,y}. \quad (32)$$

The virtual GHG emission of the last section of the in-plant supply route from the last production resource to the warehouse in the case of the AGV-based milkrun trolley can be formulated as:

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

The drone's virtual GHG emission generated between the first and last production resource is as follows:

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

The drone's virtual GHG emission between production resources and warehouse can be expressed as:

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

3.2.2. The Constraints

We can define constraints for in-plant supply services performed by both the AGV-based milkrun trolley and the drone.

Constraint 1 for AGV-based milkrun trolley: the in-plant supply route of the AGV-based milkrun trolley must be designed so that maximum payload must be taken into consideration:

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

where

$$\forall i \in [\vartheta_6 - \beta_1] : q_{p_i}^L = q^{ANET} + \sum_{i=k, z_i^*=DWP}^{\vartheta_6-\beta_1} q_{p_i}^{*T} + \sum_{i=1, z_i^* \in [PP,DP]}^{k} q_{p_i}^{*A}. \quad (37)$$

In the case of this constraint, the weight of the AGV can be calculated as the sum of the net weight of the AGV-based milkrun trolley, the weight of components delivered from the warehouse to the production resources, and the weight of components picked up and delivered between production resources. The difference between constraints (17–18) and (36–37) is that in the case of the conventional, AGV-based model, the payload-related constraint is calculated for all production resources, while in the case of this AGV-drone joint service, only production resources, where no drone is performing a service task, are taken into consideration.

Constraint 2 for AGV-based milkrun trolley: the in-plant supply route must be designed so that maximum loading volume of the AGV-based milkrun trolley must be taken into consideration, and it is not allowed to exceed this value:

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

where

$$\forall i \in [\vartheta_6 - \beta_1] : v_{p_i}^L = q^{ANET} + \sum_{i=k, z_i^*=DWP}^{\vartheta_6-\beta_1} v_{p_i}^{*A} + \sum_{i=1, z_i^* \in [PP,DP]}^{k} v_{p_i}^{*A}. \quad (39)$$

In the case of this constraint, the current volume of the loading can be calculated as the sum of the volume of components transported from the warehouse to the production resources, and the volume of components picked up or delivered between production resources. The difference between constraints (19–20) and (38–39) is that in the case of the conventional, AGV-based model, the volume-related constraint is calculated for all production resources, while in the case of this AGV-drone joint service, only production resources, where no drone is performing a service task, are taken into consideration.

Constraint 3 for AGV-based milkrun trolley: it is not allowed to consume more energy than the available power capacity stored in the battery of the AGV-based milkrun trolley.

$$C^{2AWP} + C^{2AP} + C^{2APW} \leq CAP^{T}. \quad (40)$$

In the case of the drone-based in-plant supply, we can also define three constraints.

Constraint 1 for drone: this constraint defines the maximum payload of the drone. In the case of shuttle service (no milkrun is performed by the drone), this maximum payload of the drone can be written as follows:

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

where q^{Dmax} is the maximum payload of the drone. In the case of milkrun, the weight of the components picked up by the drone has an upper limit, which can be expressed as:

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

where θ is the set of milkrun routes of the drone.

In the case of this constraint, the current payload of the drone can be calculated as the weight of the current payload.

Constraint 2 for drone: it is not allowed to exceed the maximum available loading volume of the drone. In the case of shuttle service (no milkrun is performed by the drone), this constraint can be written as follows:

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

where v^{Dmax} is the maximum loading volume of the drone. In the case of shuttle service (no milkrun is performed by the drone), this constraint can be written as follows:

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

In the case of this constraint, the current volume of the load of the drone can be calculated as the volume of the current payload, because the drone performs only shuttle services.

Constraint 3 for drone: it defines the upper limit of available power capacity stored in the battery of the drone.

$$\forall i : \sum_{i \in \theta} C_i^{*2DP} \leq BAT^{D} \land \forall i : \sum_{i \in \theta} C_i^{*2DPW} \leq BAT^{D}, \quad (45)$$

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

3.2.3. Decision Variables

The decision variable of the above-mentioned AGV-drone joint in-plant supply service with drone-based pick-up operations problem is the $\overline{p} = [p_i]$ matrix.

3.3. Modeling of the Drone-Based Integrated Pick-Up/Delivery Shuttle and Milkrun Services from AGV-Based Milkrun Trolleys

In this model, the drone can perform both the pick-up and the delivery operations suitable for drone-based services.

Using the Q^{DPW}, Q^{DDW}, Q^{DP}, Q^{APW}, Q^{ADW}, and Q^{AP} matrices, we can formulate the input parameters of the AGV-drone joint in-plant supply model as follows. The matrices of the available delivery tasks are as follows:

$$q_g^{D} = \begin{cases} \forall i \in [1, \ldots, \vartheta_1] : q_g^{D} = q_g^{DPW} \\ \forall i \in [1 + \vartheta_1, \ldots, \vartheta_2] : q_g^{D} = q_{g-\vartheta_1}^{DDW} \\ \forall i \in [1 + \vartheta_2, \ldots, \vartheta_3] : q_g^{D} = q_{g-\vartheta_2}^{DP} \end{cases}, \quad (46)$$

and

$$q_i^T = \begin{cases} \forall i \in [1, \ldots, \vartheta_4 - \vartheta_3] : q_i^A = q_i^{APW} \\ \forall i \in [\beta_4 + 1, \ldots, \beta_4 + \beta_5] : q_i^A = q_{i-\beta_4}^{ADW} \\ \forall i \in [\beta_4 + \beta_5 + 1, \ldots, \vartheta_6 - \vartheta_3] : q_i^A = q_{i-\beta_4-\beta_5}^{AP} \end{cases}. \quad (47)$$

3.3.1. The Objective Function

In this milkrun supply model, both the energy consumption of the drone and the AGV-based milkrun trolley, and their virtual GHG emission can be defined. The minimization of the energy consumption performed by the drone and the AGV-based milkrun trolley is as follows:

$$C^3 = C^{3AWP} + C^{3AP} + C^{3APW} + C^{3DPW} + C^{3DP} + C^{3DWP} \rightarrow min., \quad (48)$$

where C^3 is the energy consumption of the whole drone-based integrated pick-up/delivery shuttle and milkrun services from AGV-based milkrun trolleys.

The energy consumption generated in the first milkrun section from the warehouse to the first production resource can be formulated depending on the length of milkrun sections between the warehouse and the first production resource, the loading of the AGV-based milkrun trolley, and the specific energy consumption:

$$C^{3AWP} = \left(q^{ANET} + \sum_{i=\beta_4+1, z_i^*=DWP}^{\beta_4+\beta_5} q_{p_i}^{*A} \right) \cdot l_{D,p_1} \cdot \rho^A. \quad (49)$$

The energy consumption of the AGV-based milkrun trolley within the in-plant supply route between the first and last production resources can be expressed depending on the length of the milkrun sections between the production resources, the loading of the AGV-based milkrun trolley, and the specific energy consumption:

$$C^{3AP} = \sum_{k=\beta_4+\beta_5+1}^{\vartheta_6-\vartheta_3} \left(q^{ANET} + \sum_{i=k, z_i^*=DWP}^{\vartheta_6-\vartheta_3} q_{p_i}^{*T} + \sum_{i=\beta_4+\beta_5+1, z_i^* \in [PP,DP]}^{k} q_{p_i}^{*A} \right) \cdot l_{p_k, p_{k+1}} \cdot \rho^A. \quad (50)$$

The energy consumption of the last milkrun section from the last production resource to the warehouse is a function of the length of the transportation between the last production resource and the warehouse, the loading of the AGV-based milkrun trolley, and the specific energy consumption:

$$C^{3APW} = \left(q^{ANET} + \sum_{i=\beta_4+1, z_i^*=PPW}^{\beta_4+\beta_5} q_{p_1}^{*A} \right) \cdot l_{D,p_1} \cdot \rho^A. \quad (51)$$

The drone's energy consumption generated between the first and last production resource performing pick-up supply services can be written as:

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

where $l_{p_k, p_{TR}}$ is the travelling distance between the pick-up operation assigned to production resource p_k and the current position of the AGV-based milkrun trolley.

The drone's energy consumption between production resources and the warehouse is as follows:

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

The energy consumption in the first section of the in-plant supply route from the warehouse to the first production resource for the drone is as follows:

$$C^{3DPW} = \left(q^{DNET} + \sum_{i=\beta_4+1, z_i^*=DWP}^{\beta_4+\beta_5} q_{p_i}^{*A} \right) \cdot l_{D,p_1} \cdot \rho^A. \quad (54)$$

The emission reduction, as objective function, can be expressed as a function of the source of energy generation and GHG's type:

$$E_{x,y}^3 = E_{x,y}^{3AWP} + E_{x,y}^{3AP} + E_{x,y}^{3APW} + E_{x,y}^{3DPW} + E_{x,y}^{3DP} + E_{x,y}^{3DWP} \rightarrow min. \quad (55)$$

The virtual GHG emission of the first section of milkrun from the warehouse to the first production resource in the case of the AGV-based milkrun trolley is as follows:

$$E_{x,y}^{3AWP} = \left(q^{ANET} + \sum_{i=\beta_4+1, z_i^*=DWP}^{\beta_4+\beta_5} q_{p_i}^{*A} \right) \cdot l_{D,p_1} \cdot \rho^A \cdot \varepsilon_{x,y}. \quad (56)$$

The virtual GHG emission between the first and last production resource in the case of the AGV-based milkrun trolley is as follows:

$$E_{x,y}^{3AP} = \sum_{k=\beta_4+\beta_5+1}^{\vartheta_6-\vartheta_3}\left(q^{ANET} + \sum_{i=k,z_i^*=DWP}^{\vartheta_6-\vartheta_3} q_{p_i}^{*T} + \sum_{i=\beta_4+\beta_5+1,z_i^*\in[PP,DP]}^{k} q_{p_i}^{*A}\right)\cdot l_{p_k,p_{k+1}}\cdot\rho^A\cdot\varepsilon_{x,y}. \quad (57)$$

The virtual GHG emission of the last section of the milkrun from the last production resource to the warehouse in the case of the AGV-based milkrun trolley is expressed as:

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

The drone's virtual GHG emission between the first and last production resource is as follows:

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

The drone's virtual GHG emission between production resources and warehouse is as follows:

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

The drone's virtual GHG emission in the first milkrun section from the warehouse to the first production resource is as follows:

$$E_{x,y}^{3DPW} = \left(q^{DNET} + \sum_{i=\beta_4+1,z_i^*=DWP}^{\beta_4+\beta_5} q_{p_i}^{*A}\right)\cdot l_{D,p_1}\cdot\rho^A\cdot\varepsilon_{x,y}. \quad (61)$$

3.3.2. The Constraints

We can define constraints for in-plant supply services performed by both the AGV-based milkrun trolley and the drone.

Constraint 1 for AGV-based milkrun trolley: the in-plant supply route of the AGV-based milkrun trolley must be designed so that the upper limit of allowed payload must be taken into consideration:

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

where

$$\forall i \in [1\ldots\vartheta_6-\vartheta_3] : q_{p_i}^L = q^{ANET} + \sum_{i=k,z_i^*=DWP}^{\vartheta_6-\vartheta_3} q_{p_i}^{*A} + \sum_{i=1,z_i^*\in[PP,DP]}^{k} q_{p_i}^{*A}. \quad (63)$$

In the case of this constraint, the weight of the AGV can be calculated as the sum of the net weight of the AGV-based milkrun trolley, the weight of components delivered from the warehouse to the production resources, and the weight of components picked up and delivered between production resources. The difference between constraints (17–18), (36–37), and (62–63) is that the set of production resources to be taken into consideration is not the same in the case of the proposed models.

Constraint 2 for AGV-based milkrun trolley: the in-plant supply route must be designed so that the maximum loading volume of the AGV-based milkrun trolley must be taken into consideration:

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

where

$$\forall i \in [1,\ldots,\vartheta_6-\vartheta_3] : v_{p_i}^L = q^{ANET} + \sum_{i=k,z_i^*=DWP}^{\vartheta_6-\vartheta_3} v_{p_i}^{*A} + \sum_{i=1,z_i^*\in[PP,DP]}^{k} v_{p_i}^{*A}. \quad (65)$$

In the case of this constraint, the volume of the AGV can be calculated as the sum of the net weight of the AGV-based milkrun trolley, the weight of components delivered from the warehouse to the production resources, and the weight of components picked up and delivered between production resources. The difference between constraints (19–20), (38–39), and (64–65) is that the set of production resources to be taken into consideration is not the same in the case of the proposed models.

Constraint 3 for AGV-based milkrun trolley: the upper limit of available power capacity stored in the battery of the AGV-based milkrun trolley must be taken into consideration.

$$C^{3AWP} + C^{3AP} + C^{3APW} \leq CAP^{A}. \quad (66)$$

In the case of the drone, we can also define three constraints.

Constraint 1 for drone: in the case of shuttle service (no milkrun is performed by the drone), this constraint can be written as follows:

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

where q^{Dmax} is the maximum payload of the drone. If the drone performs milkrun routes, the weight of the components picked up cannot be higher than the maximum payload:

$$\forall i : \sum_{i \in \theta} q_{p_i} \leq q^{Dmax}, \quad (68)$$

where θ is the set of milkrun routes performed by the drone.

In the case of this constraint, the current weight of the payload of the drone can be calculated as the weight of the current payload. The difference between Constraints (41), (42), (67) and (68) is that the set of production resources to be taken into consideration is not the same in the case of the proposed models.

Constraint 2 for drone: it is not allowed to exceed the maximum available loading volume of the drone. In the case of shuttle service (no milkrun is performed by the drone), this constraint can be written as follows:

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

where v^{Dmax} is the upper limit of the loading. In this case, the weight of the components picked up cannot exceed the maximum payload of the drone:

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

In the case of this constraint, the current volume of the payload of the drone can be calculated as the volume of the current payload. The difference between constraints (43–44) and (69–70) is that the set of production resources to be taken into consideration is not the same in the case of the proposed models.

Constraint 3 for drone: this constraint expresses the upper limit of power capacity stored in the battery of the drone's battery.

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

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

3.3.3. Decision Variables

The decision variable of this drone-based integrated pick-up/delivery shuttle and milkrun services from AGV-based milkrun trolleys problem is the $\overline{p} = [p_i]$ permutation matrix. Within the frame of the next chapter, the above-mentioned models will be analyzed through five scenarios.

4. Results of Numerical Analyses

In this chapter, the above-discussed types of AGV-drone joint in-plant supply solutions are analyzed. The above-mentioned models are solved using the heuristic option of the Excel Solver. The scenario analysis focuses on the following three models:

- AGV-based in-plant supply of production resources without drones: in this in-plant supply model, pick-up and delivery operations are performed by AGV-based milkrun.
- Drone-based pick-up services from AGV-based milkrun: in this model, the suitable pick-up services are performed by the drone from AGV-based milkrun. The suitability depends on the weight constraints of the delivery drone.
- Drone-based delivery services from AGV-based milkrun: in this model, the suitable delivery services are performed by the drone from AGV-based milkrun.

- Integrated pick-up/delivery shuttle services from AGV-based milkrun: in this model, all suitable pick-up and delivery services are performed as shuttle services by the drone from AGV-based milkrun.
- Integrated pick-up/delivery milkrun services from AGV-based milkrun: in this model, all suitable pick-up and delivery services are performed as milkrun services by the drone from AGV-based milkrun.

The input parameters of the AGV-drone joint in-plant supply models are the following: location of production resources (see Table A1), weight and volume of components to be transported from/to production resources (see Table A2), maximum payload of AGV-based milkrun trolleys and drones, available maximum capacity of battery in AGV-based milkrun trolleys and drones, specific energy consumption of AGV-based milkrun trolleys and drones, specific emission of CO_2, SO_2, CO, HC, NO_X, and PM depending on the electricity generation source mix.

The maximum payload of AGV-based milkrun trolley is 80 kg, while the carrying capability of the drone is 5 kg. The average speed of the AGV-based milkrun trolley is about 0.4 m/s; the average loading and unloading time of pick-up and delivery services is 32 s per component. The scenarios take the impact of the weight of components on the loading time into consideration. The standard energy consumption of the AGV-based milkrun trolley is about 120 Wh/km, for the drone it is about 25 Wh/km, but this energy consumption can be influenced by the load of the AGV-based milkrun trolley and the drone. The specific virtual CO_2, SO_2, CO, HC, NO_X, and PM emission is shown in Table A3 [39]. In the analyzed scenarios, there are 25 milkruns per shift, and the analyzed production plan has six production lines. The scenarios show one milkrun in the case of a production line, and the energy consumption and the virtual CO_2, SO_2, CO, HC, NO_X, and PM emission is calculated for a whole shift including 25 milkruns and six production lines.

4.1. Scenario 1: AGV-Based In-Plant Supply of Production Resources without Drones

The total length of the optimized AGV-based in-plant supply (see Table A4 and Figure 2) performed by the AGV-based milkrun trolley is 434.56 m, the required transportation time is 1165 s, and the required loading and unloading time is 754 s.

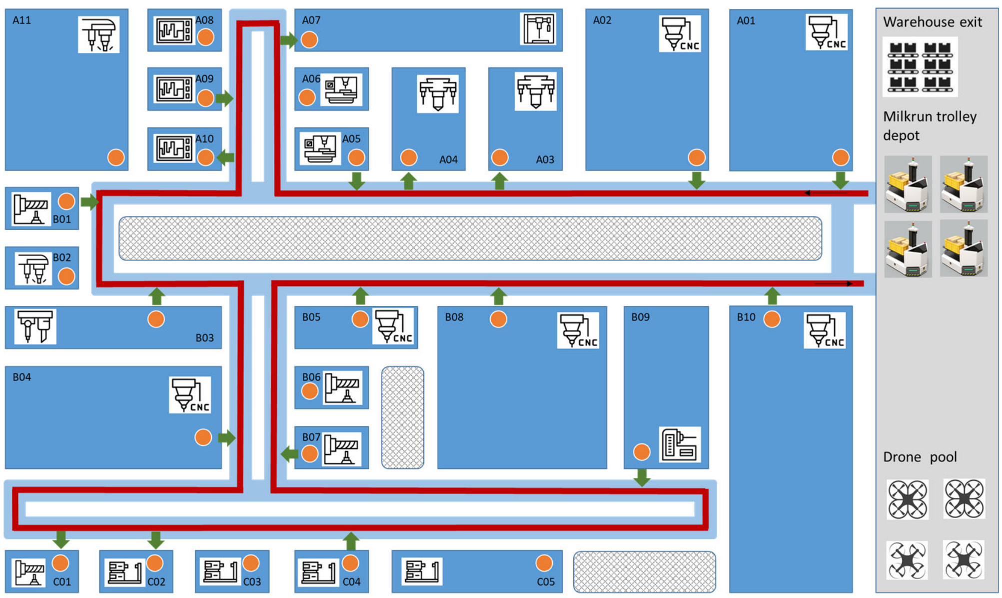

Figure 2. The scheduled and performed in-plant supply operations by AGV-based milkrun trolley in the case of Scenario 1 (green arrow is for pick-up and delivery operations of AGV-based milkrun trolley, black arrow shows the direction of the milkrun route, orange dots are for pick-up and delivery locations of machines).

The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of the AGV-based in-plant supply can be calculated based on the total length of the milkrun routes and the loading of trolleys. The energy consumption of the AGV-based in-plant supply is 156.9 Wh in the case of the analyzed route; the total energy consumption for the shift including 25 milkruns and six production lines is 23.56 kWh. Table 1 shows the virtual CO_2, SO_2, CO, HC, NO_X, and PM emission.

Table 1. The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of AGV-based milkrun trolleys in the case of Scenario 1.

Electricity Generation Source	Emission (g)					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	24,799.485	0.753	20.705	11.294	111.998	0.941
Coal	20,893.684	0.659	17.247	9.412	93.175	0.706
Oil	17,246.701	0.518	14.470	7.882	78.210	0.659
Natural gas	11,740.933	0.376	9.835	5.365	52.375	0.447
Photovoltaic	1999.958	0.047	1.718	0.941	9.317	0.071
Biomass	1058.802	0.024	0.894	0.494	4.823	0.047
Nuclear	682.339	<0.001	0.565	0.306	3.106	0.024
Water	611.752	<0.001	0.518	0.282	2.800	0.024
Wind	611.752	<0.001	0.518	0.282	2.800	0.024
Mix 1: 40% Oil–60%Biomass	7533.961	0.221	6.324	3.449	34.178	0.291
Mix 2: 60% Coal–40%Water	12,780.91	0.395	10.555	5.759	57.024	0.432

4.2. Scenario 2: AGV-Drone Joint In-Plant Supply: Pick-Up Service by Drones

The length of the AGV-based milkrun trolley per milkrun route is 383.04 m, the required transportation time is 957.6 s, and the required loading and unloading time is 669 s (see Table A5 and Figure 3). The length of the drone per milkrun route is 423.4 m, the required transportation time is 201.6 s, and the required loading and unloading time is 84 s (see Table A6 and Figure 3).

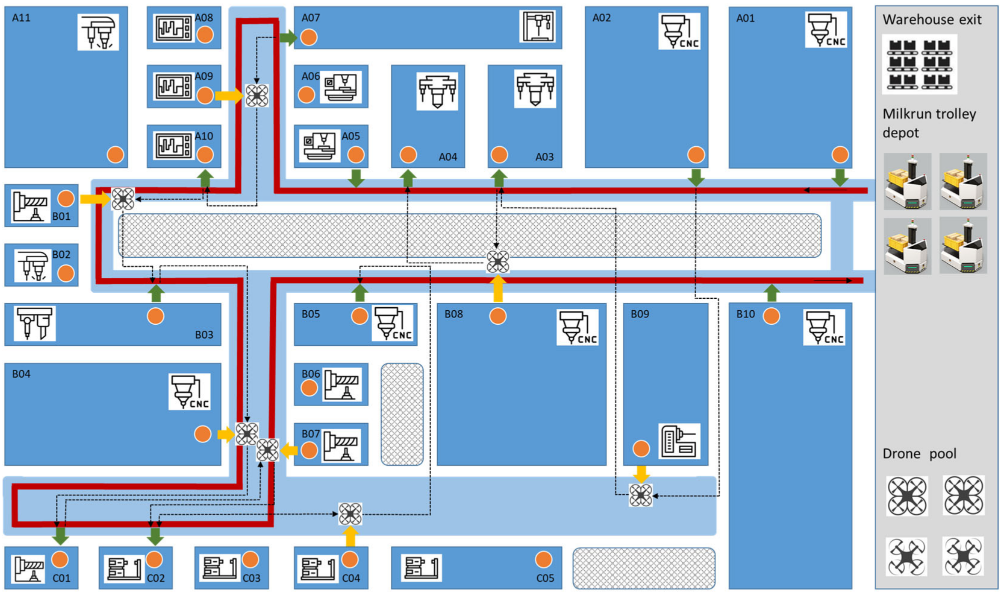

Figure 3. The scheduled and performed in-plant supply operations, where suitable pick-up services are performed by the drone (green arrow is for pick-up and delivery operations of AGV-based milkrun trolley, yellow arrow is for pick-up and delivery operations of drone, black arrow shows the direction of the milkrun route, orange dots are for pick-up and delivery locations of machines).

The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of the AGV-based in-plant supply can be calculated based on the total length of the milkrun routes and the loading of trolleys. The energy consumption of the AGV-based milkrun trolley is 133.9 Wh in the case of the analyzed route; the total energy consumption for the shift including 25 milkruns and six production lines is 20.09 kWh. The energy consumption of the drone is 11.18 Wh in the case of the analyzed route; the total energy consumption for the shift including 25 milkruns and six production lines is 1.67 kWh. The total energy consumption of the AGV-drone joint in-plant supply with pick-up service by drones for the shift including 25 milkruns and six production lines is 21.76 kWh, which means an 8% savings in energy cost. Table 2 shows the virtual CO_2, SO_2, CO, HC, NO_X, and PM emission.

Table 2. The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of AGV-based milkrun trolley and drone in the case of Scenario 2.

Electricity Generation Source	Emission (g)					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	22,944.168	0.697	19.156	10.449	103.619	0.871
Coal	19,330.570	0.610	15.956	8.707	86.204	0.653
Oil	15,956.428	0.479	13.388	7.293	72.359	0.610
Natural gas	10,862.561	0.348	9.099	4.963	48.457	0.414
Photovoltaic	1850.336	0.044	1.589	0.871	8.620	0.065
Biomass	979.590	0.022	0.827	0.457	4.463	0.044
Nuclear	631.291	<0.001	0.522	0.283	2.873	0.022
Water	565.985	<0.001	0.479	0.261	2.590	0.022
Wind	565.985	<0.001	0.479	0.261	2.590	0.022
Mix 1: 40% Oil–60%Biomass	6970.324	0.204	5.851	3.191	31.621	0.269
Mix 2: 60% Coal–40%Water	11,824.736	0.365	9.765	5.328	52.758	0.400

4.3. Scenario 3: AGV-Drone Joint In-Plant Supply: Delivery Service by Drones

The length of the AGV-based milkrun trolley per milkrun route is 414.4 m, the required transportation time is 1036 s, and the required loading and unloading time is 599.4 s (see Table A7 and Figure 4). The length of the drone per milkrun route is 213.9 m, the required transportation time is 101.9 s, and the required loading and unloading time is 48 s (see Table A8 and Figure 4).

The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of the AGV-based in-plant supply can be calculated based on the total length of the milkrun routes and the loading of trolleys. The energy consumption of the AGV-based milkrun trolley is 132 Wh in the case of the analyzed route; the total energy consumption for the shift including 25 milkruns and six production lines is 19.79 kWh. The energy consumption of the drone is 5.53 Wh in the case of the analyzed route; the total energy consumption for the shift including 25 milkruns and six production lines is 0.83 kWh. The total energy consumption of the AGV-drone joint in-plant supply with pick-up service by drones for the shift including 25 milkruns and xix production lines is 20.62 kWh, which means a 12.5% savings in energy consumption cost. Table 3 shows the virtual CO_2, SO_2, CO, HC, NO_X, and PM emission.

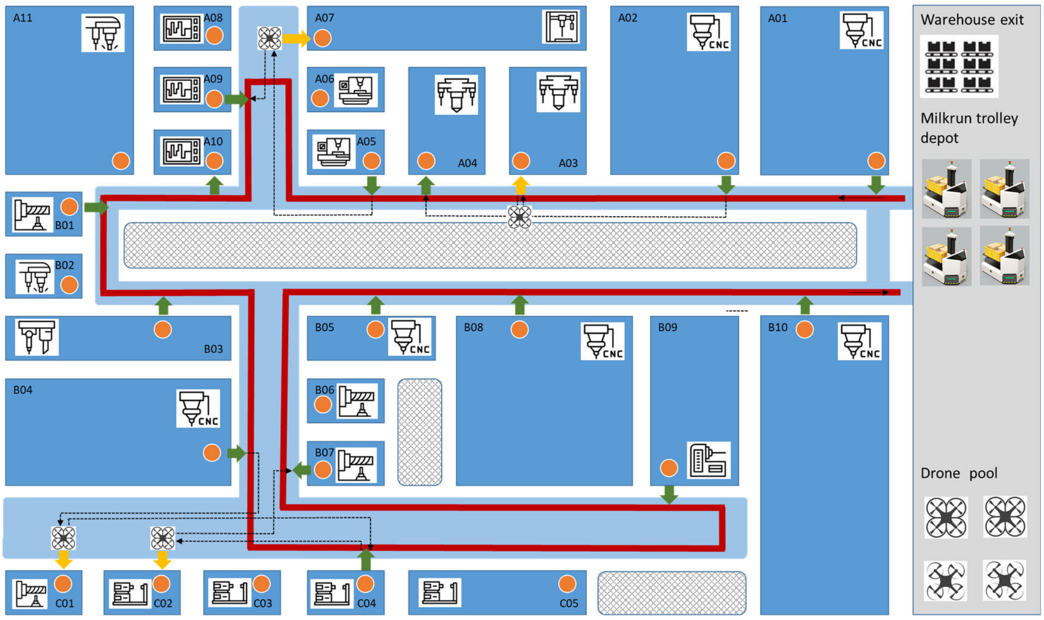

Figure 4. The scheduled and performed in-plant supply operations, where suitable delivery operations are performed by drone (green arrow is for pick-up and delivery operations of AGV-based milkrun trolley, yellow arrow is for pick-up and delivery operations of drone, black arrow shows the direction of the milkrun route, orange dots are for pick-up and delivery locations of machines).

Table 3. The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of AGV-based milkrun trolley and drone in the case of Scenario 3.

Electricity Generation Source	Emission (g)					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	21,738.626	0.660	18.150	9.900	98.174	0.825
Coal	18,314.895	0.577	15.118	8.250	81.675	0.619
Oil	15,118.039	0.454	12.684	6.909	68.557	0.577
Natural gas	10,291.816	0.330	8.621	4.702	45.911	0.392
Photovoltaic	1753.115	0.041	1.506	0.825	8.167	0.062
Biomass	928.120	0.021	0.784	0.433	4.228	0.041
Nuclear	598.122	<0.001	0.495	0.268	2.722	0.021
Water	536.247	<0.001	0.454	0.247	2.454	0.021
Wind	536.247	<0.001	0.454	0.247	2.454	0.021
Mix 1: 40% Oil–60%Biomass	6604.087	0.193	5.543	3.023	29.959	0.255
Mix 2: 60% Coal–40%Water	11,203.435	0.346	9.252	5.048	49.986	0.379

4.4. Scenario 4: AGV-Drone Joint In-Plant Supply: Shuttle Supply Services by the Drone

The length of the AGV-based milkrun trolley per milkrun route is 253.12 m, the required transportation time is 600.8 s, and the required loading and unloading time is 502.9 s (see Table A9 and Figure 5). The length of the drone per milkrun route is 650.7 m, the required transportation time is 309.8 s, and the required loading and unloading time is 96 s (see Table A10 and Figure 5).

The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of the AGV-based in-plant supply can be calculated based on the total length of the milkrun routes and the loading of trolleys. The energy consumption of the AGV-based milkrun trolley is 93.2 Wh in the case of the analyzed route; the total energy consumption for the shift including 25 milkruns and six production lines is 13.98 kWh. The energy consumption of the drone is 17.14 Wh in the case of the analyzed route; the total energy consumption for the shift including 25 milkruns and six production lines is 2.57 kWh. The total energy consumption of the AGV-drone joint in-plant supply with pick-up service by drones for the shift including 25 milkruns and six production lines is 16.55 kWh, which means a 30% savings in energy consumption cost. Table 4 shows the virtual CO_2, SO_2, CO, HC, NO_X, and PM emission.

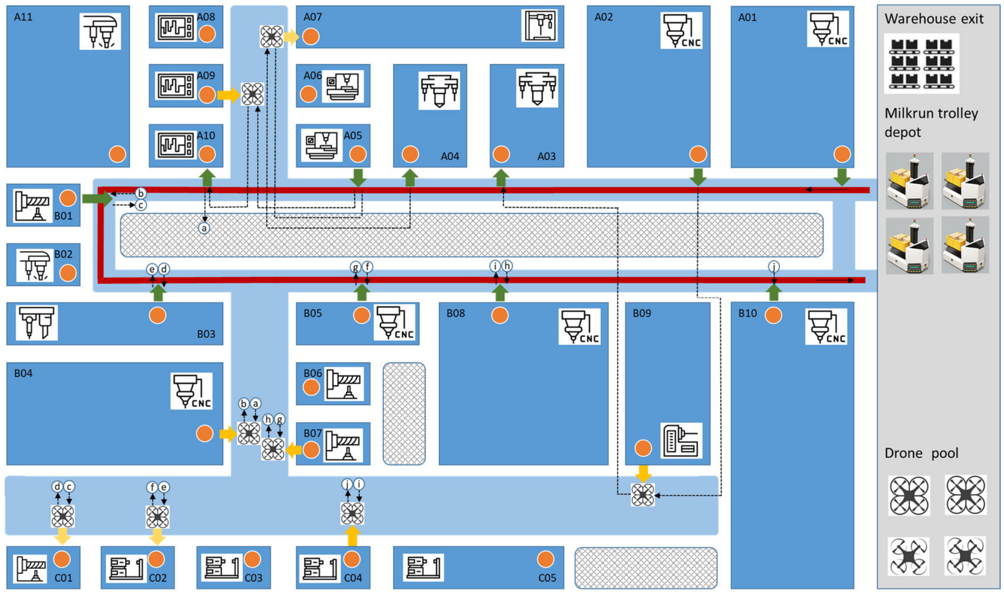

Figure 5. The scheduled and performed in-plant supply operations, where all suitable services are performed by drone as shuttle services (green arrow is for pick-up and delivery operations of AGV-based milkrun trolley, yellow arrow is for pick-up and delivery operations of drone, black arrow shows the direction of the milkrun route, orange dots are for pick-up and delivery locations of machines, letters from a-j represent the routes performed by the drone).

Table 4. The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of AGV-based milkrun trolleys in g in the case of Scenario 5.

Electricity Generation Source	Emission (g)					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	17,459.254	0.530	14.577	7.951	78.848	0.663
Coal	14,709.504	0.464	12.142	6.626	65.596	0.497
Oil	12,141.967	0.364	10.187	5.549	55.061	0.464
Natural gas	8265.814	0.265	6.924	3.777	36.873	0.315
Photovoltaic	1408.004	0.033	1.209	0.663	6.560	0.050
Biomass	745.414	0.017	0.629	0.348	3.396	0.033
Nuclear	480.378	<0.001	0.398	0.215	2.187	0.017
Water	430.684	<0.001	0.364	0.199	1.971	0.017
Wind	430.684	<0.001	0.364	0.199	1.971	0.017
Mix 1: 40% Oil–60%Biomass	5304.035	0.155	4.452	2.428	24.061	0.205
Mix 2: 60% Coal–40%Water	8997.975	0.278	7.430	4.055	40.146	0.304

4.5. Scenario 5: AGV-Drone Joint In-Plant Supply: Milkrun Supply Services by the Drone

The length of the AGV-based milkrun trolley per milkrun route is 253.12 m, the required transportation time is 600.8 s, and the required loading and unloading time is 494.8 s (see Table A11 and Figure 6). The length of the drone per milkrun route is 254.24 m, the required transportation time is 121 s, and the required loading and unloading time is 96 s (see Table A12 and Figure 6).

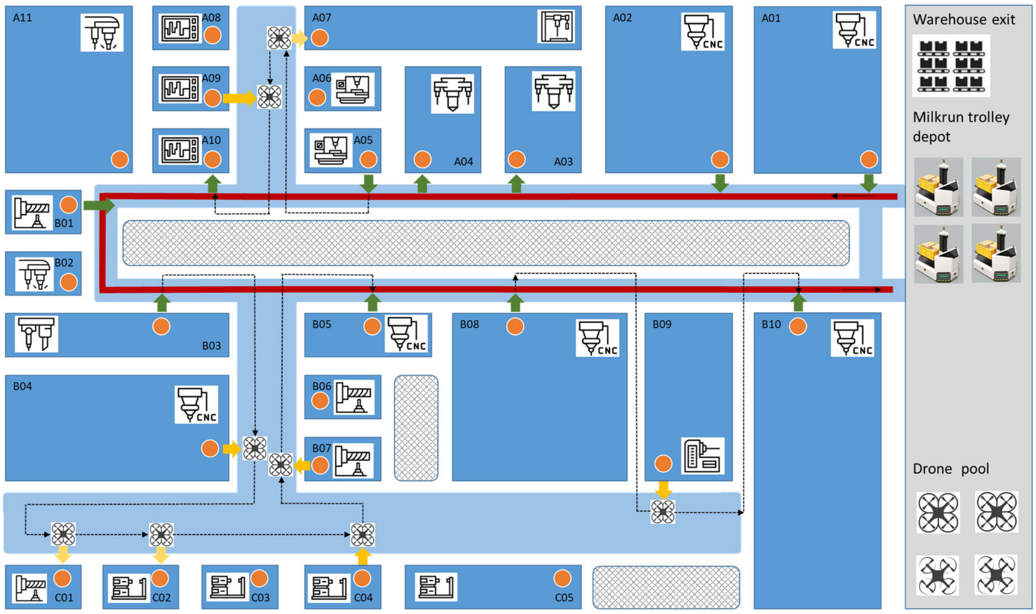

Figure 6. The scheduled and performed in-plant supply operations, where all suitable services are performed by drone as milkruns (green arrow is for pick-up and delivery operations of AGV-based milkrun trolley, yellow arrow is for pick-up and delivery operations of drone, black arrow shows the direction of the milkrun route, orange dots are for pick-up and delivery locations of machines).

The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of the AGV-based in-plant supply can be calculated based on the total length of the milkrun routes and the loading of trolleys. The energy consumption of the AGV-based milkrun trolley is 91.85 Wh in the case of the analyzed route; the total energy consumption for the shift including 25 milkruns and six production lines is 13.77 kWh. The energy consumption of the drone is 7.04 Wh in the case of the analyzed route; the total energy consumption for the shift including 25 milkruns and six production lines is 1.05 kWh. The total energy consumption of the AGV-drone joint in-plant supply with pick-up service by drones for the shift including 25 milkruns and six production lines is 14.82 kWh, which means a 37% savings in energy consumption cost. The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission depending on the generation source of the electricity is shown in Table 5.

Table 5. The virtual CO_2, SO_2, CO, HC, NO_X, and PM emission of AGV-based milkrun trolley and drone depending on the electricity generation source in CO_2 emission in g in the case of Scenario 5.

Electricity Generation Source	Emission					
	CO_2	SO_2	CO	HC	NO_X	PM
Lignite	15,635.705	0.475	13.054	7.121	70.613	0.593
Coal	13,173.156	0.415	10.874	5.934	58.745	0.445
Oil	10,873.787	0.326	9.123	4.970	49.310	0.415
Natural gas	7402.483	0.237	6.201	3.382	33.022	0.282
Photovoltaic	1260.944	0.030	1.083	0.593	5.875	0.045
Biomass	667.559	0.015	0.564	0.312	3.041	0.030
Nuclear	430.204	0.000	0.356	0.193	1.958	0.015
Water	385.701	0.000	0.326	0.178	1.765	0.015
Wind	385.701	0.000	0.326	0.178	1.765	0.015
Mix 1: 40% Oil–60%Biomass	4750.050	0.139	3.988	2.175	21.549	0.184
Mix 2: 60% Coal–40%Water	8058.174	0.249	6.655	3.632	35.953	0.273

5. Discussion

The conventional models of milkrun-based in-plant supply solutions consider only the AGV-based solutions [17,23]. Drones open new perspectives to support the flexible material handling solutions in the case of small-sized components. Within the frame of this article, the new approach focuses on the potentials of AGV-drone joint supply, and this is the superiority of the proposed model.

Within the frame of this research work, the energy efficiency of AGV-drone joint in-plant supply of production lines is discussed. An AGV-drone joint in-plant supply solution is described focusing on the potentials of pick-up and delivery operation of small components suitable for drone-based supply. The mathematical description of AGV-drone joint in-plant supply solutions focuses on the evaluation of different models from the perspective of energy efficiency and GHG emission. The numerical analysis of the different scenarios shows the significant impact of different AGV-drone joint in-plant supply solutions on energy efficiency. As the different scenarios show, the AGV-drone joint in-plant supply solutions can lead to a 5 to 30% energy consumption reduction, depending on the cooperation level of AGV-based milkrun trolley and drone.

The potential implications of the study can be summarized as follows:

- The conventional AGV-based in-plant supply solutions can be improved by the application of drones. The proposed approach makes it possible to model and analyze the joint AGV-drone service of manufacturing and assembly resources.
- In the case of electrical materials handling resources, it is possible to calculate the virtual GHG emission, which depends on the electricity generation source. By taking into account the virtual GHG emission, it is possible to compute the GHG emission caused by electricity generation required for the materials handling operation in the discussed in-plant system, which gives a more realistic picture of the ecological footprint of the logistics process.
- The AGV-drone joint in-plant supply solution can lead to a decreased energy consumption and GHG emission. This energy consumption and GHG emission reduction depends on the type of the service processes (e.g., shuttle or milkrun service by drones, electricity generation source, master schedule of the production plant). In the analyzed scenarios, the energy consumption and emission reduction was 5% in the case of drone-based pick-up operations, while it was about 30% in the case of integrated pick-up delivery services using milkrun drone routes instead of shuttle services of drones.

More generally, this paper focuses on the mathematical description of supply processes of production lines including capacity and energy-related constraints. Why is so much effort being put into this research? The importance of in-plant supply and intralogistics has increased in the last few years from the conventional in-advance design processes to the dynamic, real-time processes, where the parameters of in-plant supply solutions (capacities, resources, scheduling) can be dynamically changed depending on the demands of production resources.

The added value of the paper is the description of the AGV-drone joint in-plant supply solution, which makes it possible to analyze the impact of different solutions on the energy efficiency of the in-plant material handling operations. The scientific contribution of this paper for researchers in this field is the mathematical modelling of the AGV-drone joint in-plant supply solution. The results can be generalized because the model can be applied for different production environments and warehouses [37], and it can also be applied in the case of value chains and supply chains [32]. The described method makes it possible to support managerial decisions, because by depending on the results of analysis of different potential solutions, it is possible to influence the supply strategies and the investment decisions.

However, there are also limitations of the study. This study took capacities and energy consumption-related parameters and deterministic parameters into consideration. Fuzzy models can be used to analyze the impact of stochastic parameters on energy efficiency.

Other future research direction is the integration of milkrun design and the material handling equipment selection for production workplaces [40].

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Data Availability Statement: Not applicable.

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

Appendix A

Table A1. Layout parameters of the production lines: location of production resources.

ID	Name	Coordinate [m]		ID	Name	Coordinate [m]	
		X	Y			X	Y
A01	CNC Milling 012	96	50	B03	Milling 035	19	32
A02	CNC Milling 014	80	50	B04	CNC Milling 048	23	19
A03	CNC Drilling 032	58	50	B05	CNC Milling 048	42	32
A04	CNC Drilling 034	47	50	B06	Turning X26	36	24
A05	CNC Honing 051	42	50	B07	Turning X28	36	17
A06	CNC Honing 052	36	57	B08	CNC Milling 049	58	32
A07	CNC Honing 054	36	65	B09	Turning 217	73	17
A08	Inspection 082	24	65	B10	CNC Milling 126	88	32
A09	Inspection 083	24	57	C01	Finishing C01	8	4
A10	Inspection 084	24	50	C02	Finishing C02	18	4
A11	Shaping 095	14	50	C03	Finishing C03	29	4
B01	Turning X22	8	46	C04	Finishing C04	41	4
B02	Milling 024	8	27	C05	Finishing C05	62	4

Table A2. Weight of components to be picked up or delivered.

ID	Weight [kg]	Type of Service	ID	Weight (kg)	Type of Service
A01	12	PUbAGV [1]	B04	0.5	PUbDRONE [4]
A02	24	PUbAGV [1]	B05	9	DbAGV [3]
A03	2	DbDRONE [2]	B07	2.4	PUbDRONE [4]
A04	8	DbAGV [3]	B08	1	PUbDRONE [4]
A05	12	PUbAGV [1]	B09	5	PUbAGV [1]
A07	1.5	DbDRONE [2]	B10	8	PUbAGV [1]
A09	2.1	PUbDRONE [4]	C01	0.8	DbDRONE [2]
A10	9	DbAGV [3]	C02	2	DbDRONE [2]
B01	1.2	PUbDRONE [4]	C04	1.6	PUbDRONE [4]
B03	25	PUbAGV [1]	-	-	-

[1] PUbAGV = Pick-up service task suitable for AGV. [2] DbDRONE = Delivery service task suitable for drone. [3] DbAGV = Delivery service task suitable for AGV. [4] PUbDRONE = Pick-up service task suitable for drone.

Table A3. Specific CO_2, SO_2, CO, HC, NO_X, and PM emission in CO_2 emission in g/kWh [39].

Electricity Generation Source	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

Appendix B

Table A4. The scheduled and performed in-plant supply operations by AGV-based milkrun trolley in the case of Scenario 1.

ID and Name of Production Resource	Type of Service	TL * (kg)	ID and Name of Production Resource	Type of Service	TL * (kg)
Warehouse	-	226	B04 CNC Milling 048	PUbDRONE [4]	282.3
A01 CNC Milling 012	PUbAGV [1]	238	C01 Finishing C01	DbDRONE [2]	281.5
A02 CNC Milling 014	PUbAGV [1]	262	C02 Finishing C02	DbDRONE [2]	279.5
A03 CNC Drilling 032	DbDRONE [2]	260	C04 Finishing C04	PUbDRONE [4]	281.1
A04 CNC Drilling 034	DbAGV [3]	252	B09 Turning 217	PUbDRONE [4]	286.1
A05 CNC Honing 051	PUbAGV [1]	264	B07 Turning X28	PUbDRONE [4]	288.5
A07 CNC Honing 054	DbDRONE [2]	262.5	B05 CNC Milling 048	DbAGV [3]	279.5
A09 Inspection 083	PUbDRONE [4]	264.6	B08 CNC Milling 049	PUbDRONE [4]	280.5
A10 Inspection 084	DbAGV [3]	255.6	B10 CNC Milling 126	PUbAGV [1]	288.5
B01 Turning X22	PUbDRONE [4]	256.8	Warehouse	-	288.5
B03 Milling 035	PUbAGV [1]	281.8	-	-	-

[1] PUbAGV = Pick-up service task suitable for AGV. [2] DbDRONE = Delivery service task suitable for drone. [3] DbAGV = Delivery service task suitable for AGV. [4] PUbDRONE = Pick-up service task suitable for drone. * TL = total load.

Table A5. The scheduled and performed in-plant supply operations by AGV-based milkrun trolley in the case of Scenario 2.

ID and Name of Production Resource	Type of Service	TL * (kg)	ID and Name of Production Resource	Type of Service	TL * (kg)
Warehouse	-	226	A10 Inspection 084	DbAGV [3]	261.5
A01 CNC Milling 012	PUbAGV [1]	238	B03 Milling 035	PUbAGV [1]	287.8
A02 CNC Milling 014	PUbAGV [1]	262	C01 Finishing C01	DbDRONE [2]	287.5
A03 CNC Drilling 032	DbDRONE [2]	265	C02 Finishing C02	DbDRONE [2]	287.9
A04 CNC Drilling 034	DbAGV [3]	258	B05 CNC Milling 048	DbAGV [3]	280.5
A05 CNC Honing 051	PUbAGV [1]	270	B10 CNC Milling 126	PUbAGV [1]	288.5
A07 CNC Honing 054	DbDRONE [2]	268.5	Warehouse	-	288.5

[1] PUbAGV = Pick-up service task suitable for AGV. [2] DbDRONE = Delivery service task suitable for drone. [3] DbAGV = Delivery service task suitable for AGV. * TL = total load.

Table A6. The scheduled and performed in-plant pick-up services by the drone in the case of Scenario 2.

ID and Name of Production Resource			Type of Service	Weight (kg)
From	Pick-Up Location	To		
A02 CNC Milling 014	B09 Turning 217	A03 CNC Drilling 032	PUbDRONE [1]	5
A03 CNC Drilling 032	B08 CNC Milling 049	A04 CNC Drilling 034	PUbDRONE [1]	1
A07 CNC Honing 054	A09 Inspection 083	A10 Inspection 084	PUbDRONE [1]	2.1
A10 Inspection 084	B01 Turning X22	B03 Milling 035	PUbDRONE [1]	1.2
B03 Milling 035	B04 CNC Milling 048	C01 Finishing C01	PUbDRONE [1]	0.5
C01 Finishing C01	B07 Turning X28	C02 Finishing C02	PUbDRONE [1]	2.4
C02 Finishing C02	C04 Finishing C04	B05 CNC Milling 048	PUbDRONE [1]	1.6

[1] PUbDRONE = Pick-up service task suitable for drone.

Table A7. The scheduled and performed in-plant supply operations by AGV-based milkrun trolley in the case of Scenario 3.

ID and Name of Production Resource	Type of Service	TL * (kg)	ID and Name of Production Resource	Type of Service	TL * (kg)
Warehouse	-	226	B04 CNC Milling 048	PUbDRONE [3]	281.5
A01 CNC Milling 012	PUbAGV [1]	238	C04 Finishing C04	PUbDRONE [3]	281.1
A02 CNC Milling 014	PUbAGV [1]	260	B09 Turning 217	PUbAGV [1]	286.1
A04 CNC Drilling 034	DbAGV [2]	252	B07 Turning X28	PUbDRONE [3]	288.5
A05 CNC Honing 051	PUbAGV [1]	262.5	B05 CNC Milling 048	DbAGV [2]	279.5
A09 Inspection 083	PUbDRONE [3]	264.6	B08 CNC Milling 049	PUbDRONE [3]	280.5
A10 Inspection 084	DbAGV [2]	255.6	B10 CNC Milling 126	PUbAGV [1]	288.5
B01 Turning X22	PUbDRONE [3]	256.8	Warehouse	-	
B03 Milling 035	PUbAGV [1]	281.8	-	-	-

[1] PUbAGV = Pick-up service task suitable for AGV. [2] DbAGV = Delivery service task suitable for AGV. [3] PUbDRONE = Pick-up service task suitable for drone. * TL = total load.

Table A8. The scheduled and performed in-plant delivery services by the drone in the case of Scenario 3.

ID and Name of Production Resource			Type of Service	Weight (kg)
From	Pick-Up Location	To		
A02 CNC Milling 014	A03 CNC Drilling 032	A04 CNC Drilling 034	DbDRONE [1]	2
A05 CNC Honing 051	A07 CNC Honing 054	A09 Inspection 083	DbDRONE [1]	1.5
B04 CNC Milling 048	C01 Finishing C01	C04 Finishing C04	DbDRONE [1]	0.8
C04 Finishing C04	C02 Finishing C02	B07 Turning X28	DbDRONE [1]	2

[1] DbDRONE = Delivery service task suitable for drone.

Table A9. The scheduled and performed in-plant supply operations by AGV-based milkrun trolley in the case of Scenario 4.

ID and Name of Production Resource	Type of Service	TL * (kg)	ID and Name of Production Resource	Type of Service	TL * (kg)
Warehouse	-	226	B01 Turning X22	PUbDRONE [4]	261.5
A01 CNC Milling 012	PUbAGV [1]	238	B03 Milling 035	PUbAGV [1]	284.5
A02 CNC Milling 014	PUbAGV [1]	262	B05 CNC Milling 048	DbAGV [3]	275.5
A03 CNC Drilling 032	DbDRONE [2]	265	B08 CNC Milling 049	PUbDRONE [4]	278.9
A04 CNC Drilling 034	DbAGV [3]	255.5	B10 CNC Milling 126	PUbAGV [1]	288.5
A05 CNC Honing 051	PUbAGV [1]	267.5	Warehouse	-	
A10 Inspection 084	DbAGV [3]	260.6	-	-	-

[1] PUbAGV = Pick-up service task suitable for AGV. [2] DbDRONE = Delivery service task suitable for drone. [3] DbAGV = Delivery service task suitable for AGV. [4] PUbDRONE = Pick-up service task suitable for drone. * TL = total load.

Table A10. The scheduled and performed in-plant supply services by the drone in the case of Scenario 4.

ID and Name of Production Resource			Type of Service	Weight (kg)
From	Pick-Up Location	To		
A02 CNC Milling 014	B09 Turning 217	A03 CNC Drilling 032	PUbDRONE [1]	5
A04 CNC Drilling 034	A07 CNC Honing 054	A05 CNC Honing 051	DbDRONE [2]	1.5
A05 CNC Honing 051	A09 Inspection 083	A10 Inspection 084	PUbDRONE [1]	2.1
A10 Inspection 084	B04 CNC Milling 048	B01 Turning X22	PUbDRONE [1]	0.5
B01 Turning X22	C01 Finishing C01	B03 Milling 035	DbDRONE [2]	0.8
B03 Milling 035	C02 Finishing C02	B05 CNC Milling 048	DbDRONE [2]	2
B05 CNC Milling 048	B07 Turning X28	B08 CNC Milling 049	PUbDRONE [1]	2.4
B08 CNC Milling 049	C04 Finishing C04	B10 CNC Milling 126	PUbDRONE [1]	1.6

[1] PUbDRONE = Pick-up service task suitable for drone. [2] DbDRONE = Delivery service task suitable for drone.

Table A11. The scheduled and performed in-plant supply operations by AGV-based milkrun trolley in the case of Scenario 5.

ID and Name of Production Resource	Type of Service	TL * (kg)	ID and Name of Production Resource	Type of Service	TL * (kg)
Warehouse	-	226	B01 Turning X22	PUbDRONE [4]	256.8
A01 CNC Milling 012	PUbAGV [1]	238	B03 Milling 035	PUbAGV [1]	279
A02 CNC Milling 014	PUbAGV [1]	262	B05 CNC Milling 048	DbAGV [3]	274.5
A03 CNC Drilling 032	DbDRONE [2]	260	B08 CNC Milling 049	PUbDRONE [4]	275.5
A04 CNC Drilling 034	DbAGV [3]	252	B10 CNC Milling 126	PUbAGV [1]	288.5
A05 CNC Honing 051	PUbAGV [1]	262.5	Warehouse	-	
A10 Inspection 084	DbAGV [3]	255.6	-	-	-

[1] PUbAGV = Pick-up service task suitable for AGV. [2] DbDRONE = Delivery service task suitable for drone. [3] DbAGV = Delivery service task suitable for AGV. [4] PUbDRONE = Pick-up service task suitable for drone. * TL = total load.

Table A12. The scheduled and performed in-plant supply operations by the drone in the case of Scenario 5.

ID and Name of Production Resource	Type of Service	Load (kg)	TL * (kg)
Route 1			
A05 CNC Honing 051	DLAGV [1]	1.5	1.5
A07 CNC Honing 054	DbDRONE [2]	−1.5	0
A09 Inspection 083	PUbDRONE [3]	2.1	2.1
A10 Inspection 084	DAAGV [4]	−2.1	0
Route 2			
B03 Milling 035	DLAGV [1]	2.8	2.8
B04 CNC Milling 048	PUbDRONE [3]	0.5	3.3
C01 Finishing C01	DbDRONE [2]	−0.8	2.5
C02 Finishing C02	DbDRONE [2]	−2	0.5
C04 Finishing C04	PUbDRONE [3]	1.6	2.1
B07 Turning X28	PUbDRONE [3]	2.4	4.5
B05 CNC Milling 048	DAAGV [4]	−4.5	0
Route 3			
B08 CNC Milling 049	DLAGV [1]	0	0
B09 Turning 217	PUbDRONE [3]	5	5
B10 CNC Milling 126	DAAGV [4]	−5	0

[1] DLAGV = Drone left AGV. [2] DbDRONE = Delivery service task suitable for drone. [3] PUbDRONE = Pick-up service task suitable for drone. [4] DAAGV = Drone arrived to AGV. * TL = total load.

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