Energy-Aware Sequencing and Routing in Green Warehouses by Integrating Energy Management Systems and Renewable Energy

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1 Problem Description

Recently, sustainable supply chain management has gained increasing attention, with a growing focus on economic, environmental, and social objectives. In this context, the environmental impact of logistics facilities and warehouse operations has received particular interest. Several approaches can enhance warehouse sustainability, including the adoption of electric vehicles (EVs), the integration of Renewable Energy Sources (RESs), and the use of Energy Storage Systems (ESSs) to capture and store excess renewable energy for later use [4]. Due to the complexity of coordinating the use of RESs, ESSs, and EVs, the definition of an Energy Management System (EMS) is essential. An EMS monitors and optimizes energy assets within a facility to improve energy efficiency and resource utilization.

Although the integration of EMSs in green warehouse management has been investigated in the literature, it tends to either focus exclusively on the EMS design without modeling the execution of EV warehouse operations [3], or address EV operations without integrating an EMS capable of coordinating recharging schedules and energy flows [2, 5].

This work addresses the design of an EMS for a warehouse equipped with a photovoltaic (PV) system connected to the main grid and supported by an ESS. Energy management decisions are integrated with operational decisions, including storing, picking, task-vehicle assignment, and vehicle routing, using a fleet composed of both electric and conventional vehicles [1].

Specifically, we consider a large warehouse consisting of multiple departments, input points, storage areas arranged along aisles, and a collection area, each with limited capacity. Over a given time horizon, incoming items must be transported from input points to assigned storage locations, while outgoing items are picked from their storage locations and moved to the collection area for shipment. Item handling requests are known in advance, and storage and picking operations follow a strict First-In-First-Out (FIFO) policy, due to the perishability of the products handled. Storing and picking operations are performed by capacitated vehicles, including EVs equipped with lithium-ion batteries and regenerative braking systems. EV batteries are discharged during movement and lifting and may be partially recharged at dedicated stations during operational breaks. To preserve battery health and ensure operational continuity across multiple daily shifts, the state of charge (SOC) of the EVs must remain within predefined limits, and a minimum charge level must be guaranteed at the end of the time horizon. Moreover, safety protocols require that vehicles avoid simultaneous travel to and from the same locations to prevent congestion, delays, and ensure the safety of warehouse workers. The warehouse is connected to the power grid and equipped with a rooftop PV system. PV generation can be directly consumed, stored in the ESS, or injected into the grid. In the latter case, surplus energy is sold to the grid at market price. The base electrical load of the warehouse includes lighting, ventilation, and the power absorbed by conveyor belts, while the EV charging represents the only flexible load.

The aim is to design an EMS to schedule ESS operations, grid exchanges, and EVs charging, while also planning the sequencing operations and the vehicle routing within the warehouse.

2 Problem Modeling

The problem is formulated by means of a Mixed Integer Linear Programming (MILP) model on a space-time network $G = (N, A)$, to capture its dynamics. The time horizon is divided into T periods of equal length, resulting in $T + 1$ time instants. Nodes represent a specific warehouse location i (storage areas, input points, collection area, parking area, and charging stations) at a given time $t = 1, \ldots, T + 1$. The set of arcs includes holding arcs, to model idle time of items or vehicles at a specific location, and moving arcs, to model movements between locations across periods of time.

The model includes several families of decision variables: vehicle routing and item flow variables, variables to enforce FIFO storage and retrieval policies, and variables modeling the energy management, including energy exchanges among the grid, the ESS, and EVs. Constraints regulate vehicle and item flows, storage capacities, safety conditions, and FIFO policies. Energy-related constraints govern grid exchanges, ESS charging and discharging operations, EV battery dynamics, including SOC limits, and overall energy balance between consumption and local generation. The goal is to minimize the warehouse net energy cost, defined as the sum of fuel consumption costs of conventional vehicles and electricity purchase costs from the grid, minus the revenues obtained from selling surplus energy.

3 Matheuristic Approach and Results on Real-Size Instances

Due to the computational complexity of the proposed model, commercial solvers are unable to efficiently handle large-scale instances, such as the real-world cases provided by an industrial partner, which involve an 8-hour planning horizon. To address this limitation, a two-phase matheuristic based on the MILP formulation has been proposed, to obtain high-quality solutions within limited computational times. In the first phase, the time horizon is partitioned into Λ equal-length subperiods, generating smaller subproblems that jointly determine operation sequencing, task-vehicle assignment, routing decisions, and EV charging schedules while enforcing movement, capacity, and SOC constraints. Each subproblem is solved using a commercial solver. The partial solutions obtained by solving the subproblems are then concatenated to build a feasible plan over the full time horizon. In the second phase, the operational plan determined by the first phase is used to optimize the energy management strategy, by determining the ESS operations and the energy exchanges with the grid for each time period. The second phase is solved with a commercial solver as well.

The approach has been tested on real data provided by the reference company. We solved six 8-hour shifts over two consecutive days. The instances include 7 vehicles (3 electric), approximately 40 storage locations, and about 1,200 items to be handled per shift. The computational results show that, in a few minutes, the matheuristic is able to compute high-quality solutions, according to key performance indicators defined in collaboration with the industrial partner, thus enabling the practical application of the proposed approach to real-scale instances.

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