Directed Acyclic Graph Model of AGVs Dispatching Charging and Optimal Scheduling

Chenxiao Jin
Department of Mathematics, Physics and Electrical Engineering
Northumbria University
Newcastle Upon Tyne, United Kingdom
chenxiao.jin@northumbria.ac.uk

Zian Wang
Department of Mathematics, Physics and Electrical Engineering
Northumbria University
Newcastle Upon Tyne, United Kingdom
zian.wang@northumbria.ac.uk

Xuewu Dai
School of Engineering
Northumbria University
Newcastle Upon Tyne, United Kingdom
xuewu.dai@northumbria.ac.uk

Qiang Wu
School of Engineering
Northumbria University
Newcastle Upon Tyne, United Kingdom
qiang.wu@northumbria.ac.uk

Jing Jiang
School of Engineering
Northumbria University
Newcastle Upon Tyne, United Kingdom
jing.jiang@northumbria.ac.uk

***Abstract*—This paper presents a novel service graph model of task assignment and scheduling of Automated Guided Vehicles (AGVs) and its optimisation for smart manufacturing. The studied problem involves the loading sequences and collision avoidance at junctions of a multi-loop route network, complicating the model. In the proposed model, a material transport service in a workshop is formulated as a two-step process comprising a pickup-and-delivery (P&D) task and a backhaul task. A directed acyclic graph (DAG) model is developed to model the task assignment, where the P&D task is modelled as vertices and the backhaul task is modelled as the edges connecting a P&D task and its successive P&D tasks. In the backhaul task, the AGV select whether it will charge at the charging station. Charging and not charging are modelled as two edges (charging edge and non-charging edge) connecting two consecutive P&D nodes. Based on the DAG, a mixed-integer linear programming (MILP) model is developed to optimise the task sequencing and charging constraints for AGVs. Numerical experiments are conducted to evaluate the performance of the proposed AGV dispatching, scheduling and charging strategy.**

***Index Terms*—Automated Guided Vehicles, Manufacturing systems, Industrial automation, Task scheduling, Service diagram**

I. Introduction

In pursuit of a sustainable future, an increasing number of factories are adopting Automated Guided Vehicles (AGVs) to reduce energy consumption. By automating repetitive tasks such as material transportation in manufacturing plants and warehouses, AGVs significantly enhance operational efficiency and reduce production costs [1]. As AGVs become more prevalent, especially in large-scale manufacturing systems with lots of vehicles, the scheduling and distribution have become critical concerns [2].

The AGV scheduling problem in manufacturing has been studied in recent literature. In manufacturing shopfloor, AGVs either follow predetermined tracks guided by pre-laid wires, makers or lasers, or navigate freely without any restrictions [3]. Numerous studies have proposed models that consider task allocation [4] [5] and conflict-free routes [6] [7] [8] based on fixed pathways. However, these studies neglect the sequence between AGVs. Under fixed tracks systems, overtaking is not allowed, as it would require additional hardware and increase computational complexity. Assigning tasks to AGVs positioned back in the queue may reduce overall operational efficiency.

With the increasing emphasis on green manufacturing, energy consumption has become a crucial consideration in AGV dispatching and routing. In addition to meeting operational demands and time constraints, dispatching strategies also account for the limited battery capacity of AGVs. Several researchers have proposed mathematical models that consider battery constraints, including full charging [9] [10] and partial charging strategies [11] [12]. De Ryck et al. [13] proposed methods that can effectively improve the resource management efficiency of industrial AGV systems. AGVs can independently decide when to visit a charging station and how long to charge.Singh et al. [14] investigated an AGV scheduling problem with partially recharged AGV batteries under the consideration of a critical battery threshold. However, these models neglect the sequence of charging operation, especially with limited charging stations.

In this paper, we proposed a highly integrated mixed integer linear programming (MILP) model for AGV scheduling problems involves the loading sequence, collision avoidance and flexible charging strategy. Our model introduces a directed acyclic graph (DAG) to model task assignment, with each task request modelled as vertices and edges, overcoming the limitations of the First Come First Serve (FCFS) constraint.

The remaining structure of this paper is arranged as follows. Section II introduces the notations and problem description.

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Section III introduces the directed acyclic graph (DAG) and presents the MILP formulation; Section IV provides an illustrative example and a performance comparison of the proposed model. Section V concludes this paper and outlines future directions.

II. Problem Description

This section lists the notation used and describes the scheduling and routing problem in a real shopfloor environment.

A. Notation

The notations used throughout this paper are summarized in the following tables. These include the problem configuration parameters, decision variables, and abbreviations that are essential for problem formulation and subsequent analysis.

TABLE I
Subscript Indices and Parameters

Set and indices	
G_s	The service graph.
G_r	The route graph.
V_s	The set of vertices in the service graph G_s.
V_r	The set of vertices in the route graph G_r.
N	The set of charging station nodes (station 0 means no charging).
C	Battery capacity.
L	Lowest battery level.
P_n	Battery charging rate (power) for charging station $n \in N$.
E_u	Energy consumption for task $u \in V_s$.
r	Region of the route network. Region 0 ($r = 0$): from loading stations area to unloading station area; Region 1 ($r = 1$): from unloading station to charging station area; Region 2 ($r = 2$): from charging stations to loading stations.
Parameters	
T_u^{EPT}	The earliest pickup time for task $u \in V_s$.
T_u^{LDT}	The latest delivery time for task $u \in V_s$.
T_u	The minimum operation time needed for completing task $u \in V_s$.
T_{uv}	The minimum backhaul trip time from task $u \in V_s$ to its successive task $v \in V_s$

TABLE II
Decision Variables

Variables	Description
x_{uv}	=1, task $v \in V_s$ is the next task of task $u \in V_s$. =0, otherwise.
y_{uvr}	y_{uvr}=1, the operation of task $u \in V_s$ is earlier than the operation of task $v \in V_s$ in region r, otherwise y_{uvr}=0.
x_{un}	$x_{un} = 1$, charging at charging station $n \in N$ after completing task $u \in V_s$. otherwise, $x_{un} = 1$.
t_u^s	The start time of task $u \in V_s$ in the service graph G_s.
t_u^e	The end time of the task $u \in V_s$ in the service graph G_s.
t_{uv}	The backhaul trip time from task $u \in V_s$ to $v \in V_s$.
tc_u^s	The start time of the charge operation for the task $u \in V_s$ in the service graph G_s.
tc_u^e	The end time of the charge operation for the task $u \in V_s$ in the service graph G_s.
a_u^i	The arrival time for node $i \in V_r$ in task $u \in V_s$ in the route graph G_r.
d_u^i	The departure time for node $i \in V_r$ in task $u \in V_s$ in the route graph G_r.
b_u	Battery level at the beginning of task $u \in V_s$.
t_{un}	Charging time for task $u \in V_s$ at the charging station $n \in N$.

as the bridge between the ERP and the physical operations on the factory floor.

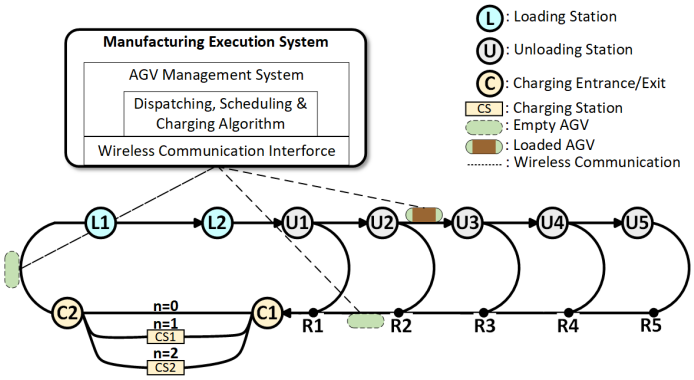


Fig. 1. Real Shopfloor

B. AGVs System

AGVs move along predefined paths in the workshop with a network of routes designed to facilitate the efficient transport of materials. This network consists of various waypoints, including loading and unloading stations, charging stations, and intermediate stops. Figure 1 shows an example route network layout of a shopfloor. The shop floor has two loading stations L1 and L2, five unloading stations, U1, U2, ..., U5, and two charging stations CS1 and CS2. It also includes waypoints that serve as intermediate nodes connecting different paths within the system. N AGVS are available to transport materials from one of the loading stations to an unloading station. Each material transport activity is referred to as a "transport service". M transport service requests are submitted to the AGV operation management system via the manufacturing management system, e.g., the enterprise planning systems (ERP). The AGV dispatching and scheduling algorithm works

A Transport Service Request (TSR) is a formal specification of a transport task that needs to be performed by an AGV. TSR is used by the dispatching or fleet management system to assign tasks to AGVs. A typical TSR includes the following information: (1) Origin and destination (OD), where the item or load needs to be picked up and delivered. (2) Earliest pickup time (EPT) T_u^{EPT}, The earliest time the load is available for pickup. For TSRs with the same loading station, the First Come First Service (FCFS) rule applies, which means a load available earlier must leave the loading station before an later load. (3) Latest Delivery Time (LDT, T_u^{LDT}) is the latest acceptable time by which the delivery must be completed. The TSR serves as an input to the dispatching algorithm, which assigns the request to an AGV based on availability, proximity, current load, and operational constraints.

In AGV dispatching, a full completion of a transport service consists of two tasks: Pick and Delivery (P&D), and Backhaul.

The P&D task involves the loaded AGV moves from its origin to the destination. Once delivery is completed, the Backhaul task repositions the AGV, often traveling empty, to the origin of the next assigned transport service. The P&D task completes the core transport request, and the backhaul task prepares the AGV for its next assignment. As shown in Figure 1, the P&D tasks take place in the forward region $r = 0$ from loading stations to unloading stations, and the Backhaul tasks take place in the backward region $r = 1$.

There are two charging stations located between waypoints C1 and C2. The AGV can be charged by selecting a charging station, or it can bypass the charging stations. The decision to charge or bypass depends on factors such as battery level, time constraints, and the overall efficiency of the route.

III. Directed Acyclic Graph Formulation

This section presents a formal mathematical formulation of the AGV operation management problem. A directed acyclic graph (DAG) is developed to capture task precedence, route connectivity, and charging opportunities. We then translate this graph representation into a mixed-integer linear programming (MILP) formulation, defining decision variables for task assignment, timing and charging.

A. Route graph model of workshop floor layout

A route network on a workshop floor refers to the system of paths and connections that facilitate the movement of AGVs within the workspace. This network is composed of various waypoints and the path connecting two neighbouring waypoints. These waypoints are key locations or stations, such as loading or unloading stations, charging stations, and the junctions or intersection of two paths. A route is the predefined path taken by an AGV from an origin to a destination, passing through one or more waypoints along the way. A route typically involves multiple connected paths, where each path represents a segment of the journey connecting two neighboring waypoints. The route is designed to ensure efficient, safe, and timely movement of the AGV, taking into consideration factors like traffic flow, obstacles, and operational constraints.

The paths may be either one-way or two-way, depending on the design, ensuring smooth traffic flow and minimizing the risk of congestion or collisions. Unidirectional paths, commonly arranged as dual one-way tracks for opposing directions, are widely used in workshop floors to simplify AGV movements and improve operational efficiency [15]. By having AGVs move in the same direction, the unidirectional traffic minimizes the risk of collisions between AGVs, particularly preventing deadlock situations.

In this paper, we consider a route network of unidirectional paths on a workshop floor. Such a route network can be modelled as a directed graph $G_r = (V_r, A_r)$ with a set of vertices V_r representing the key waypoints in the route network and a set of arcs $A_r \subseteq V_r \times V_r$ representing the unidirectional paths. The operation of P&D task and the backhaul task are as follows;

a) Pickup-and-delivery (P&D) Tasks: The material transport demand is modeled as a set of pickup-and-delivery (P&D) tasks on the workshop layout graph $G_r = (V_r, A_r)$. Each scheduled task for an AGV is defined as a 5-tuple (u, i, j, T_u, E_u), where $i, j \in V_r$, represents the loading and unloading station nodes, respectively, in the real-world workshop layout graph G_r. The operation time T_u includes the loading time at the origin node i, the travel time from i to the destination node j, and the unloading time at node j. The energy consumption E_u accounts for the energy used during loading, traveling, and unloading.

b) Backhaul operation: In addition to the P&D task, another type of trip is the backhaul operation, where the AGV travels from its current unloading station to the next loading station to handle the subsequent assigned transport request. During the backhaul operation, AGV must choose one and only one charging station from $N = \{0, 1, 2, \ldots, n\}$ to partial or full charging. Charging station 0 indicates that no charging is performed.

B. Service assignment graph model

To address the constraints and reduce the computational complexity of the AGV scheduling and flexible charging problem, we introduce a Directed Acyclic Graph model, referred to as service graph G_s. As illustrate in Figure 2, this loop-free graph captures both precedence relationships and charging constraints involved in assigning AGVs to material transport tasks. The service graph shown in Figure 2 repsents the task assignment of 6 TSR tasks to 2 AGVs, where i_0 and i_1 represent the two AGVs, and i_2 to i_7 represent the tasks. The numbers on each arc indicate the travel time required. The diagram includes all feasible sequences, such as from task 5 to task 2; however, transitions such as from task 5 to task 6 are not possible.

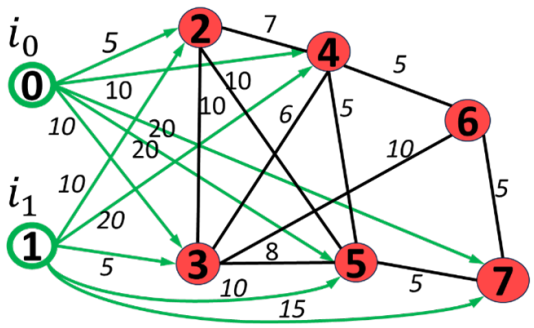


Fig. 2. Service graph in the illustrative example

The proposed service graph $G_s = (V_s, A_s)$ consists of a set of vertices V_s and a set of arcs $A_s \subseteq V_s \times V_s$. There are three types of vertices: Task vertices and AGV vertices.

- Task vertices $s \in V_s$: each operation vertex v_s represent a single P&D task (u, i, j, T_u, E_u) in workshop graph G_r.
- AGV vertices $i \in V_s$: vertex i represent the i-th AGV at its initial location where I is the set of AGVs.

Let an arc $(u, v) \in A_s$ represents the connection between two vertices $u \in V_s$ and $v \in V_s$ in service graph G_s. The arc (u, v) represents the backhaul movement from the destination of a P&D service task u to the origin of its successive service task v. The variable x_{un} indicates the selected charging station. When $x_{un} = 1$, it denotes that charging station n is chosen. If $n = 0$, it means no charging station is visited. Assumptions in AGV scheduling problem are given.

- Each AGV operates normally without shutdown, collisions, or other failures.
- Each task is assigned to a single AGV. No merging of multiple tasks onto one AGV or splitting of a single task among multiple AGVs is allowed.
- The travel time and energy consumption between the stations are fixed for each AGV.
- A charging station can charge only one AGV at a time.
- The workflow follows a fixed sequence: Pick and Delivery task, backhaul task.
- Partial charging is allowed; each AGV is permitted to leave the charging station once the battery level exceeds the critical threshold and the energy required for the next task.

C. Objective function

$$\min \left(C_{\max} + \sum t_u^e \right) \tag{1}$$

The objective function aims to minimize a combination of two key performance metrics: makespan and the total completion time of all tasks. By minimizing the weighted sum of these two terms, the objective function balances between reducing the overall project duration and improving the efficiency of task-level scheduling.

D. Constraints

a) Constraints to represent objectives:

$$t_u^e \le C_{\max}, \quad \forall u \in V_s \tag{2}$$

Constraint (2) indicates that makespan is the maximum completion time among all tasks.

b) Constraints in task allocation:

$$t_u^s + T_u \le t_u^e, \quad \forall u \in V_s \tag{3}$$

$$T_u^{\mathrm{EPT}} \le t_u^s, \quad \forall u \in V_s \tag{4}$$

$$T_u^{\mathrm{LDT}} \ge t_u^e, \quad \forall u \in V_s \tag{5}$$

$$\sum_v x_{uv} \le 1, \quad \forall u, v \in V_s,\ u \ne v \tag{6}$$

$$\sum_u x_{uv} \le 1, \quad \forall v, u \in V_s,\ u \ne v \tag{7}$$

$$t_u^e + t_{uv} + \sum_{n \in N} t_{un} \cdot x_{un} \le t_v^s + M(1 - x_{uv}), \quad \forall u, v \in V_s,\ u \ne v \tag{8}$$

Constraint (3) ensures the completion time of each task. Constraint (4) ensures each task start time cannot before the Earliest Pickup Time. Constraint (5) ensures each task end time cannot after Latest Delivery Time. Constraint (6) limits each service has only one successor, except for the last service of each AGV. Constraint (7) limits each service has only one predecessor, except for the first service of each AGV. Constraint (8) ensures that if task v is scheduled immediately after task u, its start time follows the end time of task u, including the travel and charging durations.

c) Charging operation and constraints:

$$\sum_{n \in N} x_{un} = 1, \quad \forall u \in V_s \tag{9}$$

$$tc_u^s \ge t_u^e, \quad \forall u \in V_s \tag{10}$$

$$tc_u^e \ge \sum_{n \in N} t_{un} \cdot x_{un} + tc_u^s, \quad \forall u \in V_s \tag{11}$$

$$tc_v^s \ge tc_u^e - M\left(3 - y_{uvr} - x_{un} - x_{vn}\right), \quad \text{for } r = 1 \tag{12}$$

$$b_v \ge b_u - E_u + \sum_{n \in N} P_n \cdot x_{un} \cdot t_{un} + M(1 - x_{uv}) \tag{13}$$

$$b_v \le b_u - E_u + \sum_{n \in N} P_n \cdot x_{un} \cdot t_{un} - M(1 - x_{uv}) \tag{14}$$

$$b_v \le C \tag{15}$$

$$b_u \ge L + E_u \tag{16}$$

Constraint (9) ensures that one and only one charging station is selected after task u (charging station 0 means no charging). Constraint (10) ensures that the charging operation of task u starts after its end time. Constraint (11) limits the end time of the charging operation. Constraint (12) restricts each charging station to serve only one vehicle at a time, where $r = 1$ denotes the charging station region. Constraint (13)(14) represents the level of the battery at the beginning of each task, expresses equality using greater than or equal to ($\ge$) and less than or equal to ($\le$) in Gurobi. Constraint (15) restricts the battery level to be below the battery capacity. Constraint (16) ensures that the battery level at the start of each task is greater than the minimum battery level and the task's energy consumption.

IV. Simulation and Result Discussion

In this section, numerical experiments are conducted to evaluate the performance of the proposed mathematical model. The model is solved with Gurobi educational software. The time limit for the Gurobi solver is configured to be 3600 seconds. Encoded are in Python 3.11 and run on a Intel(R) Core(TM) i7-10510U CPU @ 1.80GHz processor with 16GB RAM, the model is evaluated through numerical examples.

A. *Illustrative Example*

The illustrative example involves 3 AGVs and 10 task requests, as summarized in the Table III. The loading and unloading stations for each task request are randomly generated based on a Poisson distribution. The processing time and energy consumption associated with each task are determined by the specific locations of the corresponding loading and unloading stations. The real shopfloor layout, as shown in Figure 1.

The illustrative example is computed in 0.34 seconds, resulting in a makespan of 1111 seconds, with a total charging of 56 seconds. The AGV plan is illustrated in Figure 3.

Each colored trajectory represents a transport job assigned to a specific AGV. The horizontal axis indicates the timeline in seconds, while the vertical axis corresponds to the spatial location, including pickup stations (L1–L2), charging stations (C1–C2), unloading stations (U1–U5), and return stations (R1–R5). As shown, the jobs are distributed among three AGVs (AGV0, AGV1, and AGV2), and each AGV performs multiple jobs in sequence.

For AGV routing, each vehicle is assigned a single transport service at a time, which consists of a P&D task and a backhaul task. The loading stations, unloading stations and travel time are accurate based on TSR. The diagram shows that there are no two or more vehicles occupy the same station at the same time clearly. Additionally, all vehicles travel at the same constant speed, so overtaking does not happen along the route. However, vehicles may choose to charge from C1 (entrance of charging) to C2 (exit of charging).

For task allocation, the diagram shows that no tasks are overtaken at the same station. Additionally, no task is assigned to a vehicle that is trailing behind others in the queue, which ensures compliance with the FCFS rules.

TABLE III
TRANSPORT SERVICE REQUEST (TSR)

Task ID	Loading	Unloading	Processing Time (s)	Earliest Pick Time (s)	Latest Delivery Time (s)	Energy Consumption (kWh)
0	L1	U3	170	0	1800	0.85
1	L2	U3	160	36	1836	0.80
2	L2	U1	120	72	1872	0.60
3	L1	U1	130	108	1908	0.65
4	L1	U1	130	144	1944	0.65
5	L2	U4	180	180	1980	0.90
6	L1	U1	130	216	2016	0.65
7	L2	U3	160	252	2052	0.80
8	L2	U2	140	288	2088	0.70
9	L2	U5	200	324	2124	1.00

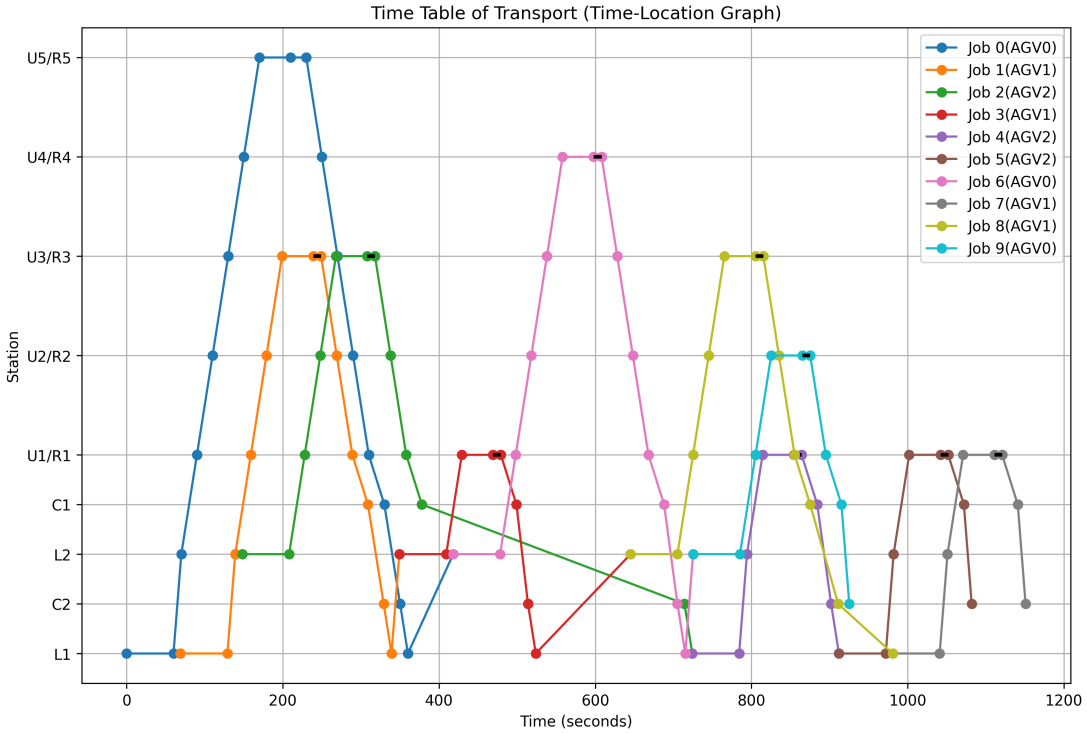


Fig. 3. Time Table of Transport

TABLE IV
COMPARISON OF MAKESPAN AND COMPUTATION TIME

Number of Tasks	Makespan (s)	Computation Time (s)		
		Proposed Model	Guo et al. [6]	Yao et al. [4]
10	1111	0.35	0.86	41.03
15	1774	16.17	24.82	77.42
20	2231	121.37	63.68	1088.31

B. Model Analysis

To evaluate the performance of the proposed model, experiments with different task volumes were conducted. As illustrated in Table V, the makespan is optimized for task sets of 10,15 and 20 tasks, respectively. The results indicates that the average time of per task remains approximately 110 seconds, which demonstrates the stability of the proposed model in handling different task scales.

In the manufacturing environments, computation time is an important factor, particularly for real-time system where scheduling decisions need be made as soon as possible in response to newly generated tasks or unexpected operational interruptions [16]. The performance of the proposed model is compared with the MILP models developed by Guo et al. and Yao et al., all of which consider constraint including conflict-free, task allocation and charging. The experimental results shows that the proposed model is more computationally efficient, particularly under 15 tasks. Although the computation time increases for 20 tasks, the proposed model still maintains a stable and acceptable level of optimization performance. The result shows the applicability of the proposed MILP model in manufacturing and reflects the effectiveness of the DAG model in reducing the number of decision variables.

V. CONCLUSION

This paper presents a highly integrated MILP model for the AGVs dispatching, scheduling and charging problem based on a DAG model. A material transport service is formulated as a two-step process comprising a P&D task and a backhaul task. The DAG model represents P&D tasks as vertices and the backhaul tasks as edges. Numerous illustrative examples are used to evaluate the effectiveness and efficiency of the model. Simulation results show that proposed model can obtain an optimal solution with FCFS, collision avoidance and flexible charging constraints. The model proves efficient in solving small and medium scale instances within a short computational time. In future research, we aim to enhance the computational efficiency of the MILP model by improving the solution algorithms. This includes refining the objective functions, incorporating advanced cutting plane techniques, and exploring decomposition methods to reduce model complexity. Additionally, we will research parallel computing algorithms to accelerate the solution process for large-scale instances.

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