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An Integrated Timetable Optimization and Automatic Guided Vehicle Dispatching Method in Smart Manufacturing

Jiarong Yao*, Rong Su, Chaopeng Tan

Abstract — **Automatic guided vehicle (AGV) fleet management always plays a significant role in smart manufacturing, which is widely studied as a representative nondeterministic polynomial-hard combinatorial optimization problem. With more smart factories featuring specialization in production line and human-robot interaction, AGVs are commonly bound with specific tracks, loading and unloading stations, which makes the current routing algorithms fail to play their path searching ability in complicated network topology. Thus, an integrated timetable optimization and AGV dispatching (TOAD) model is proposed aimed at such case, shifting the emphasis of routing to station selection and route selection from the perspective of timetable designing, while still considering the mixed directivity of layout, conflict avoidance, AGV availability and charging requirements. Targeted at makespan minimization, an improved genetic algorithm (GA) is used for solution with a heuristic operator to seek a better solution within shorter time. The proposed method is evaluated using an empirical factory case study with field data as input, with a comparison with the exact algorithm and standard GA. Results show that a smaller makespan and a shorter computation time can be obtained by the proposed TOAD model in large-scale scenarios, demonstrating a promising application prospect.**

I. Introduction

The development of Industry 4.0 puts intelligent manufacturing under the spotlight with an aim to transform and upgrade the manufacturing industry. Automated guided vehicles (AGVs), as a representative product of smart manufacturing, have been extensively employed in many manufacturing industries and widely studied as a research object in fleet management and material handling [1]. As a transportation tool, AGV bridges supply and demand both spatially and temporally. Considering the capacity and kinetics property of AGV itself, how to find an optimal match between the spatial-temporal allocation of AGVs and the time-dependent transportation demand within a transportation network of a smart factory is significant to production efficiency, which prompts the development of substantial AGV scheduling methodologies [2]. Most current studies mainly model AGV scheduling as a nondeterministic polynomial (NP)-hard combinatorial optimization problem, consisting of two sub-problems, namely AGV dispatching and AGV routing [3]. Dispatching is in essence a task allocation problem at the tactical level [3][4], while routing is to select the specific paths that each AGV will execute to accomplish its transportation tasks at the operation level, meanwhile ensuring collision-free travel [5]. Classified as a vehicle routing problem (VRP), the optimal path between two points is usually found using graph-theoretic algorithms, like Dijkstra, A*, and so on [6]-[7]. Early studies of AGV scheduling solve these two sub-problems using a sequential optimization strategy which is simple and timesaving [8], but independently solving these two sub-problems in order may cause infeasible schemes in real-world case due to specific assumptions like conflict ignorance. Integrated modeling of two sub-problems realizes the interaction between the task allocation and path searching considering the simultaneous moving of multiple AGVs [9]. Modelled as a nonlinear mixed integer programming (MIP) problem in most existing studies, the complexity grows significantly especially under large-scale cases, which spawns lots of efforts in finding economic and effective solutions like metaheuristic algorithms, deep reinforcement learning algorithms, etc. [10]-[12]. However, a considerable amount of research in the above integrated AGV scheduling methods and solution algorithms are oriented at the complexity caused by a large-scale grid network for routing [13]. Such elaborated routing algorithms may appear overbuilt when applied in simple or specific network topologies, which is not cost-effective to obtain a barely satisfactory solution with considerable computation cost in path searching. In such case, the space for scheduling optimization lies in the travel time saved by sensible arrangement of task lists at the level of AGV fleet from a global perspective rather than the travel time shortened in routing at the level of single AGV.

Therefore, in this study, the AGV scheduling problem is transformed into an integrated timetable optimization and AGV dispatching (TOAD) problem aimed at layouts composed of disconnected tracks for AGV transportation. Route design is applied on the dedicated track layout for AGVs of different operations so that the AGV scheduling is not choosing the path between the origin and destination (O and D) of a task, but the task is chosen when a AGV chooses a route to stop at the task's O and D. In this way, AGV scheduling is realized through the timetable optimization to reduce travel time between the OD pair of each task at the tactical level, and vehicle dispatching to coordinate the arrival as well as departure time of AGVs to facilitate seamless movement at the operation level. A nonlinear mixed integer programming model is established based on this modeling idea, considering the layout topology characteristics, conflict avoidance and charging requirements. The contributions of this paper are

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twofold. First, it offers a new integrated optimization model that combines a AGV fleet scheduling model and a timetable coordination model considering AGV conflict avoidance among multiple tracks. Second, strategies like vehicle holding and stop-skipping for bus transit route optimization at the control level are transferred to AGV scheduling in manufacturing and embedded in the GA algorithm to improve the optimum searching efficiency and solution quality. To the best of our knowledge, this is the first time that such an integrated timetable optimization and AGV dispatching model is proposed for AGV scheduling in smart manufacturing.

II. Problem Statement

A. Research Problem

With an increasing trend of process specialization and human-robot collaboration in smart manufacturing, heterogeneous AGVs are adopted to serve different production operations, correspondingly equipped with dedicated tracks or rails configurated in the factory layout, such as the scenario in Fig.1. The AGVs only move on their specific tracks to complete material handling tasks of a certain operation, while different tracks don't share their AGVs. For material handling of each operation area, AGVs mainly transport the materials between loading and unloading stations whose correspondence relationship are given, consisting of three types, one-to-one, one-to-many, and many-to-one. Transportation tasks assigned to AGVs are generally given in the form of the origin station to load materials and the destination station to unload materials. AGVs are expected to complete all such tasks using as little time as possible.

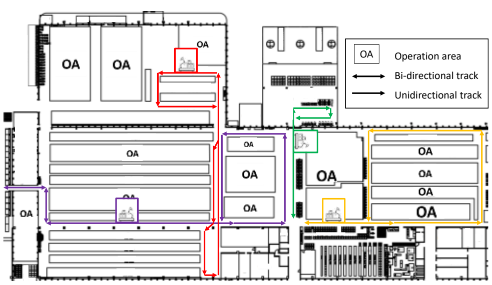


Figure 1. A sketch of research scenario

Aimed at such research scenario, the following assumptions are made:

1) AGVs move along a prescribed guide paths in the factory layout, whether in the form of surficial track or track embedded in the ground. No overtaking is allowed for following AGVs with an AGV moving ahead.
2) AGVs get charged on the track, thus when an AGV is getting charged at the charging station, the following AGVs cannot overtake it. Charging can be interrupted to give way to the other AGVs as long as the battery level is sufficient after recharging.
3) AGVs stand by at the start point before scheduling and return to the start point after all tasks completed.
4) Waiting to avoid conflicts is assumed as standing by at waypoints instead of waiting at the middle of edges.
5) A safety headway should be kept between consecutive moving AGVs.
6) Enough buffer space for materials is assumed at loading and unloading station.

B. Motivations of Proposing TOAD Model

Given the AGV fleet, track layout and material handling stations on the track, the problem of AGV scheduling is analogous to the timetable optimization and vehicle dispatching steps in bus transit planning with the network route design step completed. Although rarely seen in current AGV scheduling studies, timetable optimization is an important topic in public transit or planning, which is to determine the arrival and departure times of transit buses or shuttle buses at stops/stations along a fixed or changeable route, in order to improve the level of service from the perspective of passengers [14]. It is noted that Hu et al. once proposed the concept of "AGV reservation timetable" in solving the conflict-free scheduling of multi-load AGVs in manufacturing logistics between production lines and external truck delivery, however the reservation timetable actually refers to the occupation time window of node and edge availability, which is different from the temporal-spatial trip plan of public transit [15]. Usually taking the form of an IP or MIP model, the integrated modelling of timetable optimization and transit vehicle scheduling, or even involving route design has been developed regarding the bus transit system characteristics, optimization objective and solution methods [16]-[17].

Thus, the existing bus service management methodologies become useful source of reference, which is exactly the motivation of proposing the TOAD model for the research scenario in Subsection A. The research objective to determine the optimal schemes of when and which AGV should take on the task generated at which station, and how it moves along the track for its trip, can thus be transformed to determining a set of AGV routes with corresponding frequencies, timetables, and headways, regarding the AGV as the transit bus to serve the transportation of materials. The difference between these two problems lies in that the timetables of the intersecting transit lines should be coordinated to enable passenger transfer, while the timetables of the intersecting tracks of different AGVs should be coordinated to avoid the conflicts between AGVs moving along different tracks, which preserves the interaction between the two subproblems, timetable optimization and vehicle dispatching, in the integrated modelling, while endowed with new meaning in the domain of AGV scheduling.

III. Methodology

This section develops an integrated timetable optimization and AGV dispatching model for scheduling of heterogeneous AGV fleet in a multi-track layout with mixed edge directivity. The following passages focus on detailing each part of the model, including notations, objective function, constraints and the optimization algorithm.

A. Notations

To facilitate the illustration of the TOAD model, notations used in the model are listed in Table I.

TABLE I. Notation Declaration

Indices	
i	the index of AGV, $i \in \{1,2,\cdots,I\}$
k	the index of trip in the trip chain of an AGV, $k \in \{1,2,\ldots,K\}$.
s_l	the index of loading stations, $s_l \in \{1,2,\ldots,S_l\}$
s_u	the index of unloading stations, $s_u \in \{1,2,\ldots,S_u\}$

n_{s_l}	the index of transportation tasks at loading stations, $n_{s_l} \in \{1,2,\ldots,N_{s_l}\}$
c	the index of charging stations, $c \in \{1,2,\cdots,C\}$
w	the index of waypoints, $w \in \{1,2,\cdots,W\}$
y	the index of all nodes on the track, $y \in \{w\} \cup \{s_l\} \cup \{s_u\} \cup \{c\}$
m	the index of matched pair of loading and unloading stations for material flow, $m \in \{1,2,\cdots,M\}$
r	the index of routes, $r \in \{1,2,\cdots,R\}$
TC	AGV trip chain plan, $TC = \{tc_i \mid i = 1,2,\cdots,I\}$, $tc_i = \{r_k \mid k = 1,2,\cdots,K\}$
Parameters	
h_{min}	the minimal headway between consecutive AGVs
$L_{w,w'}$	the length of the edge linking waypoint w and w'
L_r	the length of route r
v	the moving speed of AGVs
$T_{n_{s_l}}$	the generation time of transportation task n_s at loading station s_l
δ_m	the energy consumption rate of AGVs at moving state
δ_d	the energy consumption rate of AGVs at dwelling/stand-by state
δ_c	the charging rate of AGVs at charging station
E^{min}	the threshold battery level for AGVs to get charged
t_l,t_u	the loading/unloading time of AGVs
Δ_c	the unit time interval of charging
E_i^{ini}	the initial battery level of AGV i, measured by percent
Decision variables	
$x_{s,i,k}$	binary variable, equals to 1 if AGV i serve the material handling task at station s in its k^{th} trip; 0, otherwise
$x_{c,i,k}$	binary variable, equals to 1 if AGV i get charged at charging station c in its k^{th} trip; 0, otherwise
$p_{y,i,k}$	binary variable, equals to 1 if the route of the k^{th} trip of AGV i passes node y; 0, otherwise
$A_{i,y,k}$	the arrival time at waypoint w of AGV i in its k^{th} trip
$D_{i,y,k}$	the departure time at waypoint w of AGV i in its k^{th} trip
Intermediate variables	
N_c	the charging time of AGV in units of Δ_c, $N_C \in \mathbb{Z}$
$E_{i,y,k}^{est}$	the battery level when AGV i leaves node y at its k^{th} trip
$\Delta E_{i,k}^{yy'}$	the energy consumption of AGV i when it pass the edge linking nodes y and y' at its k^{th} trip

B. Objective Function

The ultimate purpose of AGV scheduling is to increase the production efficiency given the incoming product orders, while ensuring the safety standard. Here makespan is used as the optimization objective of AGV scheduling, referring to the completion time of all transportation tasks, as shown in Eq. (1).

$$Z = \min_i \{A_{i,w^e,K}\} \tag{1}$$

Where, w^e refers to the last waypoint of the trip, which is the start point according to assumption (3). The latest arrival time when the AGV fleet return to the start point after finishing the last transportation task is used to denote the makespan, and is to be minimized through timetable design and dispatching arrangement.

C. Constraints

- Route constraint

According to assumption (3), Eq. (2) ensures that the first waypoint and the last waypoint of each trip of AGVs are the same, that is the start point, which is analogous to the terminal station of public transit. Here the superscript s, e are used to denote the first and last waypoint of a trip, while they are actually the same waypoint.

$$p_{w^s,i,k} = p_{w^e,i,k} = 1, \forall i,k \tag{2}$$

To ensure that each trip should serve at least one material handling task, which can be represented by the AGV's visit of the corresponding OD pair of loading and unloading stations, the route of each service trip should meet the constraint in Eq. (3) ~ (8).

$$\forall i,k, \sum_m \sum_{s_l} x^m{}_{s_l,i,k} + \sum_m \sum_{s_u} x^m{}_{s_u,i,k} = 2N \tag{3}$$

$$\forall i,k,m, \sum_m \sum_{s_l} x^m{}_{s_l,i,k} = \sum_m \sum_{s_u} x^m{}_{s_u,i,k} \tag{4}$$

$$\forall i,k,m, \sum_{s_l} x^m{}_{s_l,i,k} = \sum_{s_u} x^m{}_{s_u,i,k} \tag{5}$$

$$\forall i,k,m \sum_m \sum_{s_l} x^m{}_{s_l,i,k} \geq 1 \tag{6}$$

$$\forall i,k,m \sum_m \sum_{s_u} x^m{}_{s_u,i,k} \geq 1, \tag{7}$$

$$\forall i,k,s \in \{s_l\} \cup \{s_u\}, p_{s,i,k} \geq x_{s,i,k} \tag{8}$$

$N \in \mathbb{N}$ is a natural number, $N > 0$.

Unlike loading/unloading stations and charging stations, waypoints can be regarded as non-functional stations, thus the arrival and departure time of waypoints should satisfy Eq. (9).

$$\forall i,k,w,\ p_{w,i,l}(D_{i,w,k} - A_{i,w,k}) = 0 \tag{9}$$

The travel time of any edges on the track is determined by edge lengths and AGVs' moving speed, as shown in Eq. (10).

$$\forall i,k,y, p_{y,i,k} p_{y',i,k} (A_{i,y,k} - D_{i,y',k} - \frac{L_{y,y'}}{v}) = 0 \tag{10}$$

- AGV dispatching constraint

According to assumption (5), a safety headway should be kept for the inter-arrival time of any station or waypoint for two consecutive AGVs moving on the track, as given by Eq. (11) ~ (13). Here the AGVs are assumed to depart sequentially from the index of 1, i.e., $A_{i+1,w^s,k} > A_{i,w^s,k}$.

$$\begin{gathered} p_{w,i,k} p_{w,i+1,k} (A_{i+1,w,k} - A_{i,w,k} - h_s) \geq 0, \forall k,w,i > 1 \\ p_{w,1,k} p_{w,i+1,k-1} (A_{1,w,k} - A_{I,w,k-1} - h_s) \geq 0, \forall k > 1, w, i = 1 \end{gathered} \tag{11}$$

$$\forall i,k = \left\lfloor \frac{\sum_1^{i-1} \sum_1^k p_{w^s,i-1,k}}{I} \right\rfloor + 1 \tag{12}$$

$$\begin{gathered} \forall i,k,y \in \{s_l\} \cup \{s_u\} \cup \{c\}, \\ p_{y,i,k} p_{y,i+1,k} (A_{i+1,y,k} - D_{i,y,k} - h_s) \geq 0 \end{gathered} \tag{13}$$

In a smart factory featuring mass production, the number of transportation tasks is far larger than the number of AGV fleet. AGVs are thus scheduled to move along the track in cycles, forming a trip chain where the routes in each trip may be different. Therefore, the departure time of the next trip of the first AGV in the fleet is constrained by the departure time of the current trip of the last AGV of the fleet, while the departure time of the first trip can be set as the start of the scheduling period, that is $A_{1,w^s,1} = 0$.

- Material handling constraint

For each material handling task, the arrival and departure time of AGVs at the corresponding loading and unloading stations should meet the constraints in Eq. (14) ~ (15).

$$\forall i,k,s_l, D_{i,s_l,k} - A_{i,s_l,k} = x_{s_l,i,k} * t_l \tag{14}$$

$$\forall i,k,s_u,\ D_{i,s_u,k} - A_{i,s_u k} = x_{s_u,i,k} * t_u \tag{15}$$

The number of visits to the matched OD pairs of all the trip chains of the AGV fleet should be sufficient to complete the given task list, as given by Eq. (16).

$$\forall i,k,s_l, \sum_i \sum_k x_{s_l,i,k} \geq N_{s_l} \tag{16}$$

Only when a transportation task is generated will an AGV be scheduled to stop at the corresponding loading station, which is given by Eq. (17).

$$\forall i,k,s_l, x_{s_l,i,k} (A_{i,s_l,k} - \min \{ T_{n_{s_l}} \mid n_{s_l} > \textstyle\sum_i \sum_k x_{s_l,i-1,k} \}) \geq 0 \tag{17}$$

For a trip serving a certain material handling task, the dwelling of AGVs at the unloading station is bound to be placed after the dwelling at the loading station, as given by Eq. (18).

$$\forall i,k,m,x^{m}{}_{s_l,i,k}x^{m}{}_{s_u,i,k}(D_{i,s_l^m,k}-A_{i,s_u^m,k})<0 \tag{18}$$

- Resource constraint

All available AGVs are assumed to be used, as given by Eq. (19).

$$\sum_{i} p_{w^s,i,1}=I \tag{19}$$

- Conflict avoidance constraint

According to assumption (1), for AGVs moving on the same track, two types of conflicts should be avoided, rear-end collision for AGVs moving in the same direction which is held by Eq. (11) ~ (13), and head-on collision for AGVs moving in the opposite direction on a bidirectional edge, which is given by Eq. (20). It is noted that Eq. (20) is also applicable for a segment or in other words, a loop, consisting of several bidirectional edges, where the right-of-way is limited to only one AGV. For loops detected in the layout of mixed edge directivity, the timetable optimization should schedule the departure frequency of AGV fleet in a way that following AGV enters the loop area right after the leading AGV leaves the loop area without waiting if the routes of their trips all involve the loop area.

$$\begin{gathered}\forall y,y',k,k',\\ p_{y,i,k}p_{y',i,k}p_{y',i+1,k'}p_{y',i+1,k'}(D_{i,y',k}-A_{i+1,,y',k'})\le 0\end{gathered} \tag{20}$$

According to assumption (4), for AGVs moving on different tracks intersecting with each other, orthogonal conflicts should be avoided at the intersection of two tracks, which is called conflict points and denoted as y^{CP} in this study. In such case, the conflict point is regarded as an extra station for which the safety headway holds for AGVs of the involved tracks, as given by Eq. (21).

$$\begin{aligned}\forall i,i',y_1,y_1',y_2,y_2',y^{CP},k,k',\ |p_{y_1,i,k}p_{y_1',i,k}(D_{i,y_1,k}+\frac{L_{y_1,y^{CP}}}{v})\\ -p_{y_2,i',k'}p_{y_2',i',k'}\left(D_{i',y_2,k'}+\frac{L_{y_2,y^{CP}}}{v}+h_s\right)|\ge 0\end{aligned} \tag{21}$$

Where, the subscript 1,2 are used to distinguish the two tracks intersecting with each other, and conflict point y^{CP} is exactly the intersection of the edge linking y_1 and y_1' of track 1 and the edge linking y_2 and y_2' of track 2.

- Charging constraint

AGVs are assumed to be fully charged before the scheduling, as given by Eq. (22).

$$\forall i,\ E_i^{ini}=100\% \tag{22}$$

The battery level of AGVs is dependent on the power consumption of both the moving and dwelling processes, as given in Eq. (23). As shown in Eq. (24), once the battery level is lower than E^{min}, AGVs should move to the charging station to get charged. The upper and lower boundaries of the charging time is given by Eq. (25) ~ (26), while the charging time can be scheduled based on the remaining tasks and the status of other AGVs. After charging, the battery level is updated by Eq. (27). When AGVs are dwelling at the charging station to get charged, the departure time is given by Eq. (28) ~ (29).

$$\begin{aligned}\forall i,k,y,y',\Delta E_{i,k}^{yy'}=E_{i,y-1,k}^{est}-E_{i,y,k}^{est}\\ =p_{y,i,k}[\delta_m*\frac{L_{y-1,y}}{v}-\delta_d*(D_{i,y,k}-A_{i,y,k})]\end{aligned} \tag{23}$$

$$x_{c,i,k}=\begin{cases}1, E_{i,c,k+1}^{est}\le E^{min}\\ 0, otherwise\end{cases} \tag{24}$$

$$N_c^{min}=\left\lfloor\frac{1}{\delta_c*\Delta_c}(E_{i,c,k}^{est}-E_{i,c,k+1}^{est})\right\rfloor \tag{25}$$

$$N_c^{max}=\left\lceil\frac{1}{\delta_c*\Delta_c}(100-E_{i,c,k}^{est})\right\rceil \tag{26}$$

$$\forall i,k,c,E_{i,y_c+1,k}^{est}=p_{y_c,i,k}*(E_{i,y_c,k}^{est}+x_{c,i,k}*N_C*\delta_c*\Delta_c-\Delta E_{i,k}^{y_c y_c+1}) \tag{27}$$

$$\forall i,k,c,\ D_{i,c,k}-A_{i,c,k}=x_{c,i,k}*\Delta_c*N_C,N_C\in[N_c^{min},N_c^{max}] \tag{28}$$

$$\forall i,k,c,p_{c,i,k}\ge x_{c,i,k} \tag{29}$$

Where y_c denote the index of charging station c in the node list of the route chosen by AGV i in it k^{th} trip.

D. Optimization Model

Considering all the above constraints, an integrated timetable optimization and AGV dispatching (TOAD) model is established as a mixed integer programming model, as shown in Eq. (30).

$$\begin{gathered}\min Z\\ s.t.\ \text{Eqs. (2) ~ (29)}\\ x_{s,i,k}\in\{0,1\},x_{c,i,k}\in\{0,1\},p_{y,i,k}\in\{0,1\},A_{i,y,k}>0,D_{i,y,k}>0\end{gathered} \tag{30}$$

E. Solution Algorithm

As a NP-hard combinatorial optimization problem in essence, the integrated timetable optimization and AGV dispatching problem features high complexity especially when its scale increases. Exact solvers may perform poorly in such case, thus a metaheuristic algorithm, an improved genetic algorithm (IGA) is used here to solve the TOAD model. Based on the makespan calculated using Eq. (1), the reciprocal of the makespan is used as the fitness function given in Eq. (31). The smaller the makespan, the higher the fitness of the individual.

$$f(pn)=\frac{1}{Z_{pn}} \tag{31}$$

As shown in the flowchart in Fig. 2, a heuristic operator for trip chain adjustment is added in the crossover and mutation process to improve the optimum searching ability, which works in the following three aspects.

a) Transportation task combination: For the two tasks expected to be completed in consecutive trips in the AGV trip chain, two tasks can be completed in one trip if there exists a route stopping at the loading and unloading stations required by both tasks, which can reduce the makespan of the task list assigned to the AGV.

b) Short-turn routes: It can be regarded as the derivative of the task combination treatment, as it further compares the improvement of different task combination cases for three consecutive trips. The original route choice is expected to be replaced by a short-turn route, which can explore a better solution within a broader scale.

c) Fleet coordination: If all the AGVs in the AGV fleet serve the tasks generated at the same loading station in the same trip, then the route choice of all the AGVs can be replaced by the shortest route serving this specific loading station, which will simplify the AGV fleet timetables to make them move with the highest departure frequency (or in other words, the smallest departure interval), which can increase the transportation capacity, thus reducing the makespan.

By solving the model of Eq. (30) through IGA, the scheduling scheme can be obtained regarding: (i) the selection of route for a AGV transportation trip; (ii) which AGV runs on the transportation trip to serve which material handling task; and (iii) the arrival and departure times at each station in the whole trip chains assigned to each AGV.

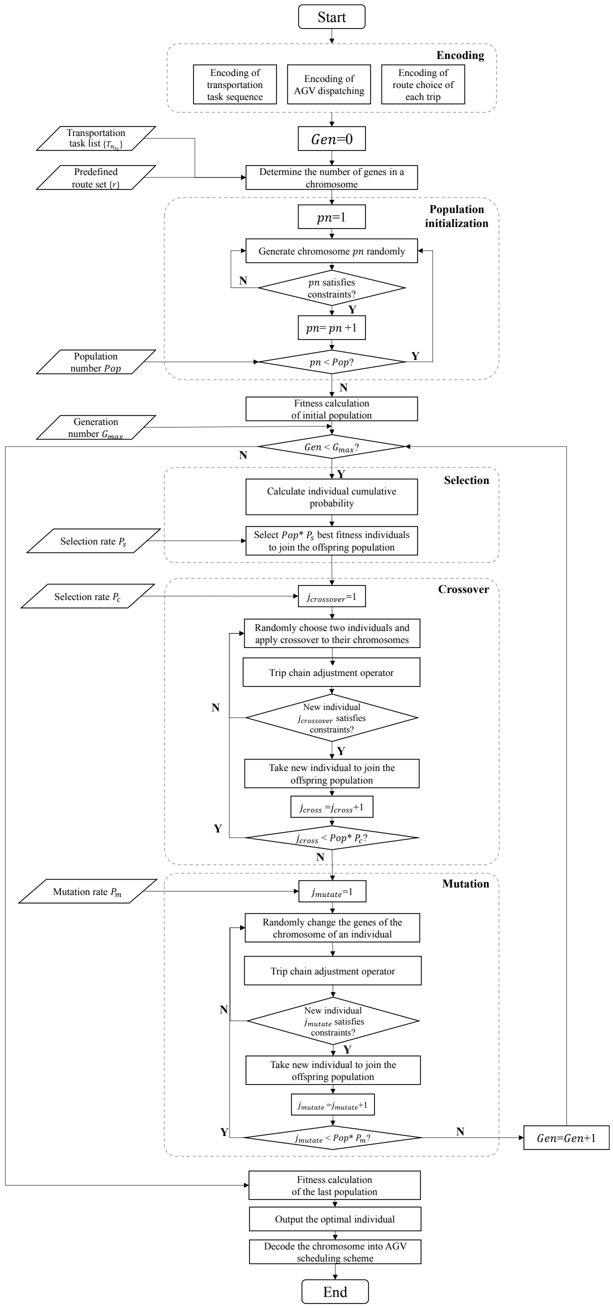


Figure 2. Flowchart of IGA

IV. Evaluation

A case study was conducted for evaluation of the TOAD model, with horizontal comparison with exact algorithm and the classic genetic algorithm (CGA) without the trip chain adjustment operator. The solution algorithms are encoded in Python and run using a desktop with a 2.50 GHz 8-core i7-11700 CPU and 16 GB RAM.

A. Case Information

Based on the empirical information of an actual manufacturing workshop shown in Fig. 1, the layout of the tracks is extracted and shown in Fig. 3, including the directivity of edges, distribution of functional stations, charging requirement, as well as the available AGVs for scheduling. The edge length data and AGV properties like moving speed and energy consumption are given from survey data. The matched OD pair of transportation tasks are assumed given, as shown in Table II, including one-to-one, one-to-many and many-to-one patterns.

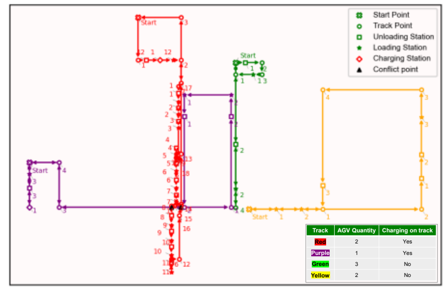


Figure 3. Track layout of the case study

TABLE II. Matched OD Pairs of Transportation Task and Task Input of the Large-Scale Case

Track	Origin - Destination	Loading /Unloading time (s)	Task number	Total
Green	LoadingStation1 - UnloadingStation2	16	44	100
	LoadingStation2 - UnloadingStation1	16	56	
Yellow	LoadingStation1 – UnloadingStation1,2	16	33	100
	LoadingStation2 – UnloadingStation1,2	16	33	
	LoadingStation3 – UnloadingStation3	16	34	
Purple	LoadingStation1,2 – UnloadingStation3	16	26	50
	LoadingStation3 – UnloadingStation1,2	16	24	
Red	LoadingStation12 – UnloadingStation1~11	14	14	50
	LoadingStation1~11 – UnloadingStation12	14	36	

For comparison, the exact algorithm (EA) of solving the mixed integer programming model for integrated job shop scheduling and conflict-free routing problem (JSSP-CFRP) proposed in [18] is selected and evaluated in the yellow track scenario, although the modelling idea is different from the TOAD model. With a maximum run time limit of 600s for GUROBI, the exact solver fails to output a solution when the input scale increases to 10 tasks, thus a 5-task case is conducted. The arrival time of input tasks are all set as 0, i.e., the start of the scheduling period.

For the parameters of IGA, the population number and generation number are set 10. Results show that the IGA obtains a makespan of 1145s with a computation cost of 0.579s while the EA obtains a makespan of 1183s with a computation cost of 9.170s. Though the makespan of IGA is only slightly better than EA by 3.2%, the computation efficiency of IGA is obviously superior to EA by nearly an order of magnitude. In this yellow track case, TOAD model is solving the departure headway of a AGV fleet with the same route, while JSSP-CFRP model mainly deals with simple path searching and conflict avoidance for each individual AGV, which leads to the gap in computation costs of two methods. Through this small-scale case, the effectiveness of TOAD model and the advantage of IGA over EA is justified.

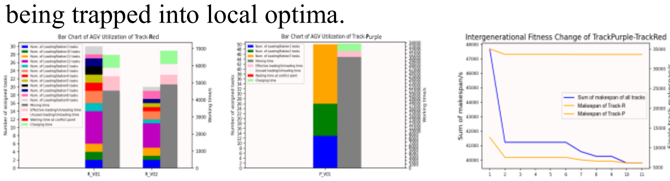
With the increase in the scale of task list and the decision variables considering conflicts of intersecting tracks, comparison between CGA and IGA is further conducted to test the efficiency of IGA regarding the heuristic trip chain adjustment operator. As shown in the task list distribution in the last two columns in Table II, a large-scale case of 300 tasks is evaluated. For CGA, the population number and generation number are set 10, the same as IGA. The scheduling of AGVs of four tracks can be divided into two types of scenarios, AGV scheduling for single tracks (green track and yellow track), and AGV scheduling for intersecting tracks (red track and purple track).

As shown in Table III, IGA is better than CGA regarding both scheduling performance and computation cost in all tracks, except for a slight increase in the computation cost in the case of green track. It is noted that the two values of makespan of the red and purple track denote the makespan of the red track and purple track respectively. The improvement of makespan ranges from 9.24% to 23.21%, while the decrease of computation cost can reach an order of magnitude in the case of intersecting tracks. Such significant gain in computation efficiency in the intersection track scenario may be due to the conflict avoidance of AGVs by adopting available short-turn routes on the red track, which justifies the effectiveness of the trip chain adjustment operator in IGA.

TABLE III. COMPARISON BETWEEN CGA AND IGA

Algorithm	**Scenario** / **Indicators**	**Green track (100 tasks)**	**Yellow track (100 tasks)**	**Red & Purple track (100 tasks)**
CGA	Makespan (s)	8765	26907	7108, 37081
	Computation cost (s)	0.91	1.44	46.88
IGA	Makespan (s)	7757	20661	6147, 33655
	Computation cost (s)	1.01	1.15	7.63

The task distribution and the convergence curve of fitness function of the intersection track scenario are further visualized in Fig. 4. It can be seen that the utilization of AGVs is relatively well balanced, and IGA is shown to have the capacity of fast convergence and optimum searching to avoid being trapped into local optima.



(a) Red track (b) Purple track (c) Convergence curve

Figure 4. Visualization of scheduling scheme and algorithm performance

V. CONCLUSION

An integrated timetable optimization and AGV dispatching (TOAD) model is proposed aimed at the AGV scheduling of heterogeneous AGV fleets within a transportation network with mixed edge directivity under smart manufacturing environment in this study. Different from the exiting integrated AGV dispatching and routing models focusing on temporal-spatial sequencing of the occupation of nodes and edges among different AGVs, the proposed TOAD model deals with the matching between transport capacity supply and transportation demand from the perspective of trip-level time arrangement regarding the AGV fleet trip chains. An improved genetic algorithm is used for solution by adding three heuristic operators for solution fine tuning. The effectiveness of TOAD in scheduling and the efficiency of IGA is evaluated and justified through a case study based on an actual manufacturing factory with horizontal comparison using two benchmarks, showing promising prospect in large-scale application in reality.

For future research, evaluation under different scenarios is expected for the TOAD model to explore its applicability. Besides, the comparison of different metaheuristic algorithms should be conducted to seek a most suitable solution algorithm in terms of solution quality as well as computation cost.

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