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Scheduling of Multiple Autonomous Guided Vehicles for an Assembly Line using Minimum Cost Network Flow

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Abstract

This paper proposed a parallel automated assembly line system to produce multiple products having multiple autonomous guided vehicles (AGVs). Several assembly lines are configured to produce multiple products in which the technologies of machines are shared among the assembly lines when required. The transportation between the stations in an assembly line (intra-assembly line) and that among stations in different assembly lines (inter assembly line) are performed using AGVs. Scheduling of AGVs to service the assembly lines and the corresponding stations are proposed. In the proposed problem, the assignment of multiple AGVs to different assembly lines and stations is performed using minimum-cost network flow (MCF). It optimizes weighted completion time of tasks for each short-term window by formulating the task and resource assignment problem as MCF problem during each short-term scheduling window. The novelties of the paper are as follows: to configure an autonomous assembly line, to model a minimum cost network flow, and to develop a heuristic solution approach. The results and comparisons show the effectiveness and efficiency of the model and solution algorithm.

Keywords: Parallel assembly line, Autonomous guided vehicle (AGV), Scheduling, Minimum cost network flow.

1. Introduction

An automatic guided vehicle (AGV) is an unmanned, computer-controlled mobile transport unit used for material handling and transportation in a wide range of industries. In addition, known as a self-guided vehicle or self-propelled vehicle, an AGV is a vehicle that is powered by a battery or an electric motor and is able to perform tasks without human supervision or operation. AGV manufacturers program AGVs to drive to specific points and perform designated functions such as load transferring, small components assembling, pallet loading and transportation, towing or lifting products and tooling change out, without the aid of a human driver. Autonomous guided vehicles are becoming increasingly popular worldwide in applications that call for repetitive actions over a distance or for transporting extremely heavy loads and are commonly used as alternative for fork lifts, conventional conveyor systems, and manually powered push-pull carts. AGV systems provide great benefits in terms of increasing efficiency and reducing human error, and varieties of AGVs, such as material handling robots, automatic guided carts, and transfer cars, are used in the place of manual labor for a number of applications. Automated guided vehicles are also commonly used as automatic guided military vehicles and armored vehicles in defense industries or for clean room applications in which human presence may be undesirable. Industries, such as aerospace, automotive assembly, general manufacturing, mail and newspaper, food and beverage processing, and components assembly, all use types of guided vehicles to help improve work flow.

Fixed sequences of operations with manual and automated tasks being repeated, within each cycle, have become the industrial assembly practice for a long time. In the automotive assembly, typically, different vehicles are assembled with the use of the same assembly line. Such assembly systems are characterized by their ability to assemble different models of a given product without holding large inventories (Kim and Jeong, 2007; Makris et al., 2012; Michalos et al., 2014). This paradigm is very efficient when its production is set to the maximum throughput, but cannot cope well with technical problems and malfunctions. Specifically, in industries with increased complexity (e.g., the automotive, the whitegoods, the electronic assembly, the aerospace, etc.), a holistic perspective of the main manufacturing attributes is required to be considered in manufacturing decisions concerning cost, time, quality, and flexibility. Flexibility is the key to adapting to the changes taking place in the market and in global economic environment (Chryssolouris, 2006). To manage these dynamics, several paradigms, such as holonic (Zhao et al., 2010), flexible (Chryssolouris, 2006), lean

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(Houshmand and Jamshidnezhad, 2006), reconfigurable (Koren and Shpitalni, 2010), evolvable, self-organizing (Ueda et al., 2010), and autonomous assembly systems (Scholz-Reiter and Freitag, 2007), have been partly realized in the last decades. The flexibility and adaptability is realized by clustering the assembly system into subsystems and modules, which get a certain degree of autonomy and control themselves in a decentralized way (Valente and Carpanzano, 2011; Duffie and Piper, 1987). Angerer et al. (2010) presented applications of mobile manipulators that are mainly used for machine tending and logistics tasks. However, the flexibility provided through the mobility of resources is only partially investigated into performing assembly operations in contrast to the extensive research on their use in logistics operations. The main reasons for that are the technical constraints such as navigation robustness, arm weight, accuracy, and gripping technologies. By integrating such units with line level, intelligent control algorithms are capable of undertaking any task along the line if the task requirements are met in terms of hardware.

Robots are capable of undertaking a variety of tasks (processing and handling), and therefore, infinite alternatives can be realized when multiple aspects in the decision making, such as robot type selection, sequencing, motion planning, etc., are being considered. This, for example, goes beyond the application of agent-based control in Computer Numerical Controller (CNC) machines that are usually part of Flexible Manufacturing Systems (FMS). In this case, the machines have several programs stored and the agents decide which one to be executed on the basis of the pending operations (Michalos et al., 2016). The dynamic nature of the tasks (pick and place from unknown positions, navigation in the shop floor, etc.), discussed in this paradigm, requires a much more complex coordination between the resources themselves (horizontal integration) as well as the higher level of coordination services (vertical integration) that has not been investigated for these types of resources (Michalos et al., 2016). Agent-based approaches, flexible in pursuing a smooth operation though, are not generic enough to support a dynamic operation by multiple, yet dissimilar, resources. The affluence of robotic equipment available and the respective capabilities offered call for technologies such as standardized interfaces for integration and configuration of different hardware and software components, thorough hardware and software abstraction capabilities and decoupling of parameters request, storage and acquisition with the use of open frameworks.

In the existing assembly systems, the capability of offering more variants per model and introducing new models faster is constrained by the current technologies and equipment of mass production operations, incapable of supporting product variability (Daaboul et al., 2011; Hu et al., 2011). Achieving flexibility and adaptability that can be defined as the production system's sensitivity to internal and external changes is regarded as one of the most promising solutions (Bi et al., 2010; Short and Burn, 2011) over the last years. To this direction, different production system types have emerged. The reconfigurable assembly system (RAS), for instance, is an integrated, computer-controlled system of assembly robots, automated guided vehicles, and buffers that can be used for assembling a variety of similar product types. This system is characterized by its ability to add or remove assembly devices by the "Plug and Produce" architecture, while, at the control level, it shows its capability of intelligence and autonomy. An assembly system is called "autonomous" if it is able to cope with all uncertainties in the real-world execution (control and sensing) of an assembly task planned offline and with the (re) planning itself (Sudo et al., 2012). These definitions can efficiently convert the assembly system types focusing on this work. The main building blocks that enable such functionalities are presented hereafter.

Automated guided vehicles (AGVs) are used as a material handling device in flexible manufacturing systems. Traditionally, AGVs were mostly used in manufacturing systems, but currently other applications of AGVs are extensively developed in other areas, such as warehouses, container terminals, and transportation systems. Fazlollahtabar and Saidi-Mehrabad (2015a) discussed literature related to different methodologies to optimize AGV systems for the two significant problems of scheduling and routing at manufacturing, distribution, transshipment, and transportation systems. They categorized the methodologies into mathematical methods (exact and heuristics), simulation studies, metaheuristic techniques, and artificial intelligent-based approaches.

Fazlollahtabar et al. (2015a) considered a scheduling problem for multiple automated guided vehicles (AGVs) in a manufacturing system. Considering that the due date of AGVs is required for material handling among shops in a job-shop layout, their earliness and tardiness are significant in satisfying the expected cycle time from an economic viewpoint. Earliness results in AGVs waiting and tardiness cause temporary part storages in the shop floor. They proposed a mathematical program to minimize the penalized earliness and tardiness. Since the mathematical program was difficult to solve with a conventional method, an optimization method in two stages, i.e., searching the solution space and finding the optimal solutions, was proposed. The performance of the proposed mathematical model was tested in a numerical example and compared with several methods in the current literature.

Fazlollahtabar et al. (2015b) proposed a complicated routing/scheduling problem for multiple automated guided vehicles (AGVs) in a manufacturing system. The model considered a new concept of turning point for deadlock resolution. A case study in real industrial environment was conducted. The findings lead the decision-makers to develop a user interface decision support as a simulator to plan the AGVs' movement through the manufacturing network and help AGVs to prevent deadlock trap or conflicts. The proposed decision support program can easily be commercialized. The benefits of such commercialization

are: increasing the quality of material handling, improving the delivery time and preventing delays, decreasing the cost of traditional handling, enabling computerized planning and control, tracking intelligent robots and validatation in simulation environment. For more reviews and analysis, readers are referred to (Fazlollahtabar and Saidi-Mehrabad, 2015b).

Nowadays, mixed-model assembly lines are applied in a wide range of industries to mass-produce customized products to order, e.g., in automobile industry. An important decision problem in this context receiving a lot of attention from researchers and practitioners is the sequencing problem, which decides on the succession of workpieces launched down the line. However, if multiple departments with diverging sequencing objectives are to be passed or unforeseen disturbances like machine breakdowns or material shortages occur, a resequencing of a given production sequence often becomes equally essential (Boysen et al., 2012). An important planning task in just-in-time mixed-model assembly systems is to find a production sequence which levels demand rates for all required materials and production processes. This sequencing problem is referred to as level scheduling and has received widespread attention in research and practice alike and has been still vividly discussed up until now (e.g., Corominas et al., 2007; Boysen et al., 2009a). Boysen et al. (2009b) provide a recent survey on this and other mixed-model sequencing approaches. The generation of leveled production schedules is of high significance for mixed-model assembly lines, in which parts and materials are supplied just-in-time by multi-level production processes. The output rate variation problem is the standard mathematical representation of this complex level scheduling problem and has been extensively studied by research thus far (Fliedner et al., 2010).

In this paper, a scheduling problem to make coupled decisions about AGV/station scheduling and assembly line/station assignments for an autonomous guided vehicle assembly line manufacturing system is proposed. Specifically, a two-fold framework is proposed in this research that: (1) allows for assembly line level of hierarchical decision making for resource and task assignment; (2) formulates the assignment decision as a minimum-cost flow (MCF) problem during each short-term window and solves it by an efficient network optimization algorithm.

The remainder of the paper follows here. Section 2 proposes the problem as well as its formulations and describes a network flow-based model for the assignment of tasks and resources during each short-term scheduling window. Section 3 presents the decision making process and a heuristic for solution. Numerical example is given in Section 4. We conclude in Section 5.

2. The Proposed Pproblem and Modelling

We proposed parallel automated assembly lines to produce multiple products in a flexible manufacturing system. For each product, an automated assembly line is configured including several stations. Although parallel assembly lines are configured gradually and considering the promotion in technology, rise in the customers demand, and new product development process, some stations or machines may be used commonly among the assembly lines due to high expenditures incurred in buying a separate one for each line. The products are dispatched to the corresponding assembly line by autonomous guided vehicles (AGVs), and then carried to the next station. The cycle time is computed for all processing activities to fulfill production plan and satisfy demands of various products produced in different assembly lines. In this proposed problem, the assignment of multiple AGVs to different assembly lines and the stations is an aim. To conceptualize the proposed system, dispatching rules decompose the product/station assignment into station routing and product dispatching. Resources and tasks are assigned sequentially while interaction is made between AGVs and stations. An overview of the AGV handling system is shown in Figure 1.

Fig. 1. An overview of an AGV handling system

This research proposes a framework of an AGV-based parallel assembly line control system, which consists of a manufacturing system for decisions of AGV dispatching/next station selection and a station control scheme. AGVs and station scheduling decisions are usually made at the assembly line level. The proposed scheduling optimizes weighted completion time of tasks for each short-term window by formulating the task and resource assignment problem as a minimum-cost network flow (MCF) problem during each short-term scheduling window. AGVs are dispatched immediately after arriving at the manufacturing system. The products arrive at the system according to the customer orders following a specific distribution. The due date of products is assigned by the

well-known Total Work Content Rule. The scheduling determines the AGV-station schedule during each short-term scheduling window as described in previous section. At the assembly line, once an AGV is dispatched into the station, it will become active for the AGV/station scheduling decision process. During each short-term scheduling window, a set of candidate AGVs and a set of candidate stations are selected to formulate a minimum-cost network flow problem. Only those AGVs, whose current operation routes (station) are not committed or are about to complete their current operations within the scheduling window while next operation route is not yet decided, are selected for the decision process. The start time and finish time of estimated AGV operation will be calculated based on the current status of each candidate AGV and current schedule of each candidate station. The model will be solved by using the network simplex algorithm, and the solution will be converted into temporary routes for candidate AGVs. If start time of an AGV temporary operation is within the current scheduling window, then that route will be committed and the AGV will be added to the corresponding station schedule. The available time of that station will be updated accordingly. It is assumed that during each operation, an AGV may require more than one station for a process. Each process step of an AGV with a different type of station is called an operation sequence.

2.1. MCF model formulation

In this section, the network flow-based models for task-resource assignments are presented. The scheduling procedure for the assembly line level is then illustrated in sections 4.1. Let's consider a network configuration to simplify modelling and optimization. During each short-term scheduling window, a set of candidate tasks and resources is selected at each level from the proposed manufacturing system to be formulated as a Minimum Cost Flow (MCF) problem. The task's ready time and resource (station or machine) available time are considered as if they are static. The task/resource assignment is further formulated as a minimum network flow problem illustrated in Figure 2.

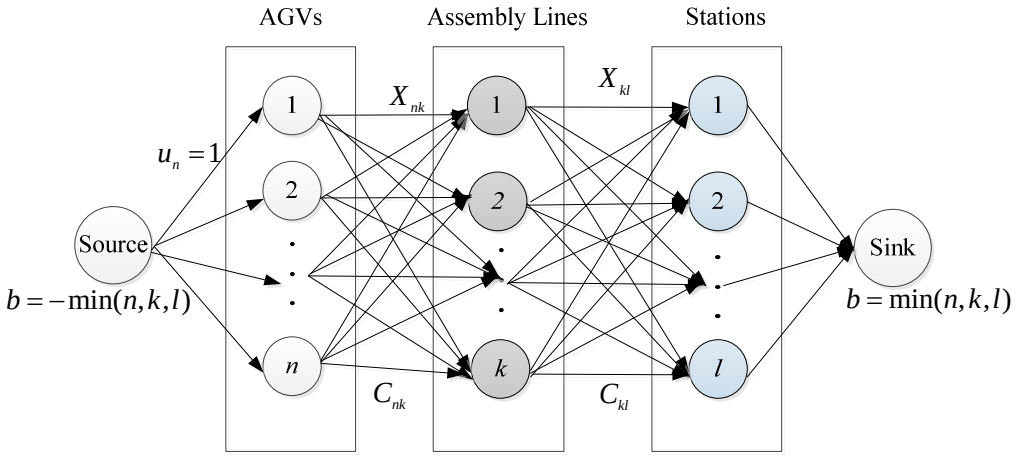

Fig. 2. The proposed three-layer network flow model of task and resource assignment

Nodes in *n* are candidate tasks (e.g., AGVs at the assembly line). Nodes in *k* correspond to the required resources (e.g., assembly line, stations) by those candidate tasks. Node "source" and node "sink" are dummy nodes, which serve as start node and end node.

The arcs between candidate tasks and resources represent alternative assignment of the resources to tasks. All arcs are unit capacity. The net flow at the start node is minimum value of the number of candidate tasks and the number of candidate resources. The net flow at end node is the negative value of net flow at start node. The net flow values for all the remaining nodes are zero. The cost coefficients for arcs between the start node and candidate task nodes are set to zero. The cost coefficients (*Cnk*) for arcs between candidate resource nodes and end node are all zero as well. The cost coefficients corresponding to alternative assignment of resource to task are determined to optimize weighted completion time of tasks. The detailed derivations of these cost coefficients are explained in the following sections. The formulated minimum network flow problem can be summarized as follows:

Indices:

k index for assembly lines
l index for stations
n index for AGVs

Variables:

X_{nk}, X_{kl} Flow of arc from node *n* (or *k*) to node *k* (or *l*)

Parameters:

U_{nk}	Capacity of the arc from node *n* to node *k*
C_{nk} , C_{kl}	Cost associated with assigning task *n* (or *k*) to resource *k* (or *l*)
V	Set of nodes in the networks
bn	Net flow at node *n*
A	Set of directed arcs connecting nodes in the networks
Ain(n)	Set of arcs that is immediate predecessors to node *n*
Aout(n)	Set of arcs that is immediate successors to node *n*.

and the MCF mathematical program is,

$$Min \sum_{(n,k)\in A} C_{nk}X_{nk} + \sum_{(k,l)\in A} C_{kl}X_{kl}, \quad (1)$$

s.t.

$$\sum_{k\in A_{in}(n)} X_{kn} - \sum_{k'\in A_{out}(n)} X_{nk'} = b_n, \quad \forall n \in V, \quad (2)$$

$$\sum_{l\in A_{in}(k)} X_{kl} - \sum_{l'\in A_{out}(k)} X_{kl'} = b_k, \quad \forall k \in V, \quad (3)$$

$$0 \le X_{nk} \le U_{nk}, \quad \forall (n,k) \in A, \quad (4)$$

$$0 \le X_{kl} \le U_{kl}, \quad \forall (k,l) \in A. \quad (5)$$

The above-formulated model can be solved efficiently by the network simplex algorithm.

Data required for MCF model:

tw	the current system time
td_l	the due time of station *l*
td_n	the due time of AGV *n*
trp_l	the remaining processing time of station *l*
trp_n	the remaining processing time of AGV *n*
tp_l	the processing time of station *l*
tp_n	the processing time of AGV *n*
tr_l	the ready time at which the last product in station *l* is completed
tr_n	the ready time at which the last AGV *n* is dispatched
tm_l	the available time at which the last scheduled station *l* is completed
tm_n	the available time at which the last scheduled AGV *n* is dispatched
d_{nl}	the expected travel time delay of AGV *n* from its current location to station *l*
ts_n	the estimated start time of AGV *n*
tf_n	the estimated finish time of AGV *n*
ts_l	the estimated start time of station *l*
tf_l	the estimated finish time of station *l*

The expected travel time delay is the time to transfer an AGV from its previous operation station to its subsequent operation station at the assembly line level scheduling. When *trn* is less than *tw*, it means that AGV *n* is ready before the current time. If the time AGV *n* becomes ready plus the expected travel time delay *dnl* is greater than the available time of AGV *tmn*, then the AGV *n* will be idle waiting for the station. Otherwise, AGV *n* will arrive at station *l* early and wait for products to become available. Therefore, the AGV start time can be estimated by the following expression.

$$ts_n = \max\left\{\left(\max\left\{tr_n, tw\right\} + d_{nl}\right), tm_n\right\}, \quad (6)$$

The finish time of an AGV will be the start time plus the expected processing time of the AGV, i.e.,

$$tf_n = ts_n + E\left(tp_n\right), \quad (7)$$

Also, when *trl* is less than *tw*, it means that station *l* is ready before the current time. If time station *l* becomes ready plus the expected travel time delay *dnl* is greater than the available time of station *tml*, then station *l* will be idle waiting for the AGV. Otherwise, AGV *n* will arrive at station *l* early and wait for product to become available. Therefore, the station start time can be estimated by the following expression

$$ts_l = \max\left\{\left(\max\left\{tr_l, tw\right\} + d_{nl}\right), tm_l\right\}, \quad (8)$$

The finish time of a station will be the start time plus the expected processing time of the station, i.e.,

$$tf_l = ts_l + E\left(tp_l\right). \quad (9)$$

3. Decision and Solution Processes

At the assembly line level, the information about both of the line urgency and station workload should be included into the AGV and station assignment decision process. Two types of decisions made in static sub problems at the assembly line level are:

1) When *l*, the number of candidate stations, and *n*, the number candidate AGVs, are not equal, select *l* AGVs from *n* candidates if *n*>*l* (AGVs with lower weight (w_n), smaller slack time or larger process time will be preferred). Select *n* stations from *l* candidates if *l*>*n*.
2) After *p* candidate AGVs and *p* candidate stations being selected, where *p* = min (*l*, *n*), assign selected *p* AGVs to *p* stations.

Consequently, the total weighted completion time $w_n tf_n$ is used as the cost coefficient, where w_n is the ratio of AGV slackness to the remaining processing time.

$$w_n = \begin{cases} \dfrac{d'_n - trp_n}{trp_n}, & d'_n > trp_n \\ \dfrac{1}{trp_n}, & otherwise \end{cases} \quad (10)$$

where $d'_n = d_n - tw$ and trp_n is the remaining process time of AGV *n*. Furthermore, stations are subject to breakdowns during an operation. Hence, high variation in station availability will result in significant deviation of the finish time estimation from the actual time. To reduce this uncertainty, the AGV start time ts_n is used instead of tf_n, since the objective of total weighted completion time can be approximated by the total weighted task start time. Then, the cost coefficient of AGV/station assignment becomes:

$$C_{nl} = \left(\frac{\max\{1, td_n - tw - trp_n\}}{trp_n} \right) \times ts_n, \quad (11)$$

In order to balance the station workload and prioritize the urgent lines, the stations with earlier start time, which means a lower workload, should be chosen in the dynamic decision process. The first term in the bracket is the line urgency defined by AGV slackness over remaining processing time. If the AGV is already late, i.e., behind the due date, the urgency of AGV for line will be 1 over remaining processing time. The second term, AGV operation start time, serves the purpose of balancing the workload of stations, since the operation start time is determined by the available time of the candidate station and the possible travel time delay of the AGV. Therefore, the station with an earlier start time, which means a lower workload, will be more desirable in the dynamic decision process. At the assembly line level, tasks that need to be scheduled are operations of AGVs. The required stations are major binding resources to be assigned to each AGV. Only those AGVs, whose current operation stations are not committed or their current operations are about to complete within the scheduling window while their next operation route (station) is undecided, are selected as candidate AGVs.

When the number of candidate stations and the number of candidate AGVs become equal after *p* candidate AGVs and *p* candidate stations being selected, where *p*=min (*l*, *n*), MCF models (1)-(3) can be formulated to minimize the total adjusted start time, using cost coefficient C'_{nl} defined in equation (12). The candidate operations will be assigned to the stations with earlier adjusted task start times, which correspond to high percentage of machines available at the stations.

$$C'_{nl} = \left(ts_n + \sum_{p=1}^{N_m} \delta_{nlp} \times W_p \right), \quad (12)$$

where N_m is the number of AGVs required by station *l* of a product and δ_{nlp} is defined as follows:

$$\delta_{nlp} = \begin{cases} 1, \text{ if AGV } p \text{ is not at station } l \text{ before time } ts_n + \sum_{o=1}^{p-1} \left(P_{nlo} + \delta_{nlo} . W_o \right) \\ 0, \ otherwise \end{cases}, \quad (13)$$

Wp is the expected AGV waiting time for *p*th required machine type for a product's operation. It is estimated by using a constant multiplier (lead time constant) multiplied by processing time as a waiting time estimate. When *p*th required machine is not available by the estimated start time ($ts_n + \sum_{o=1}^{p-1} \left(P_{nlo} + \delta_{nlo} . W_o \right)$) of *p*th sequence with processing time of P_{nlo}, a waiting time of W_p will be incurred. *THL* is the scheduling horizon length, and *tw(p)* is the time epoch at the beginning of *pth* scheduling horizon.

3.1. Heuristic algorithm

Step 1. Select the candidate tasks whose unscheduled operation sequences become ready during *p*th scheduling window between times *tnow(p)* and *tnow(p) + THL*. If no candidate task is selected, stop. Otherwise, continue.

Step 2. Select the candidate AGVs (required by candidate station) and formulate the MCF model P1 (1)-(5) using coefficient (11).

Step 3. Solve model P1 formed in step 2. Reformulate another MFC model P2 (1)-(5) using all selected AGVs and stations in the solution of model P1 using the coefficients based on equation (12).

Step 4. Solve the model P2 formed in step 3,

Loop: If the estimated start time of selected operation *i* is less than

time *tnow(p)*+ Δ_t, implement operation *i*, otherwise continue;

Until: all of *p* selected operations are checked.

Step 5. Wait until time *tnow(p)*+ Δ_t, then *p*=*p*+1, go to step 1.

As stated before, since AGV urgencies and station availabilities have larger impact on the overall system performance at the assembly line level, they are considered with higher priorities in selecting AGVs and stations when the number of AGVs and stations is not equal in step 2.

4. Numerical Study

The purpose of this section is to test the effectiveness of the proposed method by an implementation study and comparison with other scheduling approaches. AGV routing problem has been conceived to represent the system, which maps the proposed heuristic algorithm. Consider an industrial system with 14 parallel assembly lines. An FMS consisting of 13 workstations is under study, using the production data abstracted from the industrial FMS. There are five identical vertical turning centres (VTL), four identical vertical machining centres (VMC), two identical gear shaper stations, one wash and deburr station, and one coordinate measuring machine (CMM). In the load/unload (L/UL) area, there are four identical L/UL stations and 13 bi-level storage buffers, including four active buffer stands, which are the only passages allowing AGVs to go to workstations from L/UL area or return from workstations to L/UL stations. Let the length of an AGV that protects it from collision be 1.5 ft. Consider a situation, where the AGV is coming from and going to the stations shown in the following set:

J={(1,8),(2,11),(5,12),(6,9),(4,1),(12,6),(8,5),(9,2),(7,3),(10, 4)}.

The problem is to route AGVs along the bi-directional path layout, so that the completion time will be minimum. There are a total of nine products with their inter-arrival times exponentially distributed with a mean of 25 minutes. Due dates are set to be uniformly distributed to 2 to 3 times of a product's process time. Three identical AGVs provide product-handling services between 13 workstations and four active buffer stands at the L/UL area. Table 1 shows the basic implementation data used in this example.

Table 1.
Basic implementation data

Parameters	Input data
Number of stations	13
Machine buffer capacity	5
Number of jobs	124
Number of AGVs	3
AGV velocity	1 m/s
Number of products	9
Average station processing time	123–188 minutes
Product inter-arrival time distribution	Exponential (35) minutes
Due date setting rule	Uniform 2–3 times of total processing time
AGV processing time	Exponentially distributed with mean of 2 minutes

The AGVs and stations scheduling decisions are passed back to the real-time scheduler module after the CPLEX network solver solves the model. The maximum time used for each real-time decision process is about 2.25 seconds, including time for selecting candidate tasks and resources and formulating and solving the MPL model through CPLEX. Ten replications with 20000 minutes of production time for each replication were simulated to compare the performance of the proposed real-time scheduler. The details of processing sequence of different products by AGVs along with the obtained completion time of AGVs, finish time of station, and delay time are shown in Table 2.

Table 2
The outputs of the proposed model

Product number	Processing sequence: Station number (processing time in minutes)	Completion time for AGV	Finish time for station	Delay time of AGV
1	6(1)-7(1)-8(1)-10(2)	17	150	1.00
2	2(1)-6(1)-8(2)-9(2)-10(4)-12(2)	17	200	1.00
3	8(1)-11(3)-13(4)	14	800	1.00
4	9(4)	26	700	2.00
5	4(5)-5(3)-112(4)	11	150	1.00
6	6(5)-12(1)	16	700	1.00
7	3(5)-6(3)-13(5)	26	250	2.00
8	5(4)-6(5)-8(1)	26	850	2.00
9	4(1)-5(5)-8(1)-11(1)	1	100	0.00

According to the sequence shown in Table 2, the products are processed to find out the makespan as well as delay time of AGVs. Start time is the time for the start of a particular part in a station. Finish time is the time when the product completes its operation in a particular station. The third column shows the completion time of each of the products.

The product with the largest completion time shows the makespan of the schedule considered in this example. Time is shown in minutes form for better computation. In this example, products are arranged in a sequence generated by the working algorithm. Whenever an AGV is engaged in an operation, the waiting time of the product to be operated by that AGV is added to the total processing time of a product. The designed assignment and scheduling heuristic algorithm was coded in Matlab 7.1. After many trials, it was found that the procedure is able to achieve the objective criteria well before the termination of the heuristic algorithm. From the last generation of trial schedule with minimum cost, an optimal schedule was selected. A comparison among various scheduling rules' details are as follows:

1. According to Earliest Due Date (EDD) scheduling rule,
Completion time=262;
Delay=26;
Schedule: 4, 7, 8, 13, 10, 12, 1, 2, 6, 3, 5, 9, 11.

2. According to Largest Processing Time (LPT) scheduling,
Completion time=187;
Delay=27;
Schedule: 8, 12, 13, 3, 6, 7, 4, 2, 5, 11, 10, 9, 1.

3. According to Shortest Processing Time (SPT) scheduling,
Completion time=227;
Delay=31;
Schedule: 7, 9, 10, 11, 5, 2, 4, 1, 6, 3, 13, 12, 8.

- The most optimum schedule according to the proposed MCF-heuristic algorithm came out to be as: 12, 7, 5, 1, 2, 9, 4, 3, 11, 10, 6, 13, 8, with completion time of 154 and delay time of 11.

5. Concluding Remarks and Future Research Directions

The present work is focused on scheduling of AGVs in an FMS environment using MCF heuristic algorithm as shown in Figure 2. The scheduling of AGVs using MCF algorithm aims at minimizing the completion time considering delay time as well as makespan (processing) time. A comparison based on this algorithm has been carried out with some scheduling rules. The algorithm has been encoded in CPLEX and Matlab 7.1 edition, as shown in Table 2. The algorithm has proved to be efficient in many of the bench mark problems addressed in the literature. The computational time has been reasonable and the solutions obtained are optimal. Although the obtained results are useful, further research is needed to achieve the demanded level of reliability imposed by the complexity of the transportation task itself. For further research, detailed analytical models of failure occurrence are used when the equipment breakdown could develop in updating the AGV and station schedule to improve the performance further. The proposed model may be regarded as a framework suitable for extension and application to other industrial system such as container terminals, warehouse system, etc.

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