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통합 제조 시스템 설계 : 공정 계획과 AGV 경로 설계의 통합 접근

Integrated Manufacturing Systems Design : Integrated Approach to Process Plan Selection and AGV Guidepath Design

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Abstract

The manufacturing environment on which this research is focused is an FMS in which AGVs are used for material handling and each part type has one or more process plans. The research aims at developing a methodology whereby, given a part and volume mix for production during any production session, the best set of process plans including one plan per part type is selected and the best unidirectional AGV guidepath is designed. The methodology is built on the premise that the AGV guidepath can be dynamically reconfigured in response to changes in parts and lot sizes combination. For the integrated PPS/FGD problem in which two functions of process plan selection (PPS) and flexible AGV guidepath design (FGD) are integrated, a zero-one integer programming model is developed. The integrated problem is decomposed into two subproblems, process plan selection given a directed AGV layout and AGV guidepath design with a fixed process plan per part type. A heuristic algorithm that alternately and iteratively solves these two subproblems is developed. The effectiveness of the heuristic algorithm is tested by solving various randomly generated sample problems and comparing the heuristic solutions with those obtained by an exact procedure. From the test results, the following conclusions are drawn: 1) For a reasonable size problem, the heuristic is very effective. 2) By integrating the two functions of PPS and FGD, a remarkable benefit in total production time for a given part and volume mix is gained.

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1. Introduction

To survive in a highly competitive and dynamic environment driven by market demands for diversification and ephemeralization of products and technology, a modern manufacturing system is forced to change. It is required to not only simultaneously handle a number of small batches but optimally plan and control their production coping with unexpected situations such as machine and tool breakdowns and urgent orders. In other words, a part is required to be flexibly and optimally manufactured in response to the prevailing shop conditions. These requirements for flexible manufacture cannot be satisfied by adopting a traditional process plan for a part type. It is because the traditional process plan specifies the only way to transform a workpiece from its raw material state to the final product state without considering the dynamic characteristics of shop floor (i.e., system bottleneck by traffic congestion or overloaded machines) or abnormal situations such as machine breakdowns and bottleneck [9, 10]. Usually, a process plan specifies the required machine tools, machine operation sequence, machining conditions (i.e., speed, feed rate, depth of cut, etc.), requirements for tools and auxiliary devices, tool path and NC part program, etc. [3, 8].

To overcome disadvantages caused from traditional process plans, it is recommended to select a process plan for each part type whenever part and volume mix are determined [23]. Process plan selection is a production strategy that makes possible the use of static multiple process plans in dynamic batch production environment. A set of process plans including one plan for each part type is selected in order to accomplish the minimum time production for all the parts in production order, not for individual part type. In this paper [23], a fixed distance between a pair of workstations is implicitly assumed due to a fixed traffic layout for in-process part tranportation. However, for a manufacturing system with automated guided vehicle system (AGVS) in which many part families can be processed simultaneously, it is not necessary to assume the distances between workstations are fixed. If either an easily reconfigurable guidepath layout with optical (or chemical) paths painted or taped on the floor or virtual unidirectional guidepaths as employed for free ranging AGV systems is used, it may increase the productivity of the overall system to correspondingly redesign AGVS guidepath layout whenever the material flow volume and pattern in the shop change [22].

This paper addresses the process plan selection on a dynamically reconfigured AGV guidepath layout in response to production order variations. As identified in [21], both functions, *process plan selection (PPS) and flexible guidepath design (FGD)*, are affected by product and volume mix change and designed with the same objective of minimizing production time. Furthermore, between these two functions, decision in one area affects system performance in the other area. Because of such strong relationships, sequential or individual optimization of these functions cannot guarantee the global optimum design and operation of a target manufacturing system. For example, it is assumed that the sum of processing and transportation time is used as a criterion to evaluate a process plan. While the processing time is obtained by simply summing the estimated processing times on each machine in the route, the transportation time can be calculated only with the distances between workstations. Therefore, a process plan can be evaluated based on an AGV guidepath layout designed. On the other hand, AGV guidepath layout is designed with the material flow volumes among workstations, which are calculated with the machine tool routing and lot size specification for each part type in part mix. Thus, before process plan selection, AGV guidepath layout cannot be optimally designed.

Integration of primary functions in manufacturing including product design, process planning, production planning and control, and AGV guidepath layout design will improve the overall performance of a manufacturing system if conducted in such a way that the subtasks related to individual functions are well coordinated and harmonized. However, in spite of the benefits that can be obtained by simultaneously dealing with process plan selection and AGV guidepath design in response to production order, to our knowledge, no research was reported in the open literature for integrating these two functions.

But, issues on integration of process planning with production planning are discussed in [4, 11, 12, 16, 20], and with group technology cell formation in [15, 19, 24]. Effectiveness of multiple process plans is justified in [1, 9, 10, 25, 26]. Process plan selection is presented in [2, 14, 23]. AGV guidepath layout design problem which aims at determining traffic flow directions of AGVS guidepath layout segments or aisles has been dealt in [5, 6, 7, 13]. The guidepath design is also known in the literature as the "flow path design".

The main focus of this paper is on the integration of *process plan selection (PPS) and flexible AGV guidepath design (FGD)*. For every production order, since the integrated approach deals with PPS and FGD simultaneously, better production plans would be obtained, compared with those which would be obtained with traditional sequential optimization (i.e., FGD first and then PPS or *vice versa*). The solutions for the integrated PPS/FGD problem will include a specification of the unidirectional guidepath layout for the AGV system and a set of process plans composed of one process plan per part type. The proposed integrated problem is referred to as the integrated PPS/FGD problem in this paper. The research goal is to formulate the integrated

PPS/FGD problem that dynamically responds to changes in part mix and volume mix, and to develop a mathematical model using an integer programming technique as well as its solution methodology to obtain a good solution.

The remainder of this paper is organized into five sections. The problem is defined by specifying the objective function and input and output requirements in Section 2. Mathematical model development for the integrated PPS/FGD problem is followed. Section 4 presents a solution method by decomposing the integrated problem. Section 5 presents some results to test and assess the efficiency and feasibility of the developed solution technique. This is accomplished through the use of illustrative problems. Finally, identification of the research contributions and future research directions concludes the paper.

2. Problem Formulation

In this paper, the integrated PPS/FGD problem is defined as follows: *Given a part mix and their lot sizes, a set of process plans for each part type, and an undirected AGVS guidepath layout, simultaneously select a set of process plans containing one process plan for each part type and design a unidirectional AGVS guidepath layout such that the total production time due to the production order is minimized, subject to balancing both the workloads on machines and the volumes of traffic flow on the network aisles or arcs.*

2.1. Objective Function

In a production environment in which several part types are simultaneously produced in batches, the shop time of each part is composed of processing time, transportation time, waiting times in input and output queues. The four sources of shop time are well explained through a simple production scenario in which parts are sequentially processed through two workstations #1 and #2, and transported by a fleet of automated guided vehicles. A Gantt chart representation of these sources of shop time for a unit part is illustrated in Figure 1.

Since the waiting times in input and/or output queues are dynamically minimized through scheduling of parts and vehicles during production time, for the integrated PPS/FGD approach whose solution must be obtained before production commencement, only two categories of shop time, processing and transportation time are influential to its optimization. For the integrated PPS/FGD problem formulation, let an *ideal production time for production order* be defined as the total time in which all parts in production order are produced under the assumption of an ideal situation in which both waiting times for being processed at input queue and delivered at output queue are zero. Then, the integrated PPS/FGD problem can be optimally solved by minimizing the *ideal production time for*

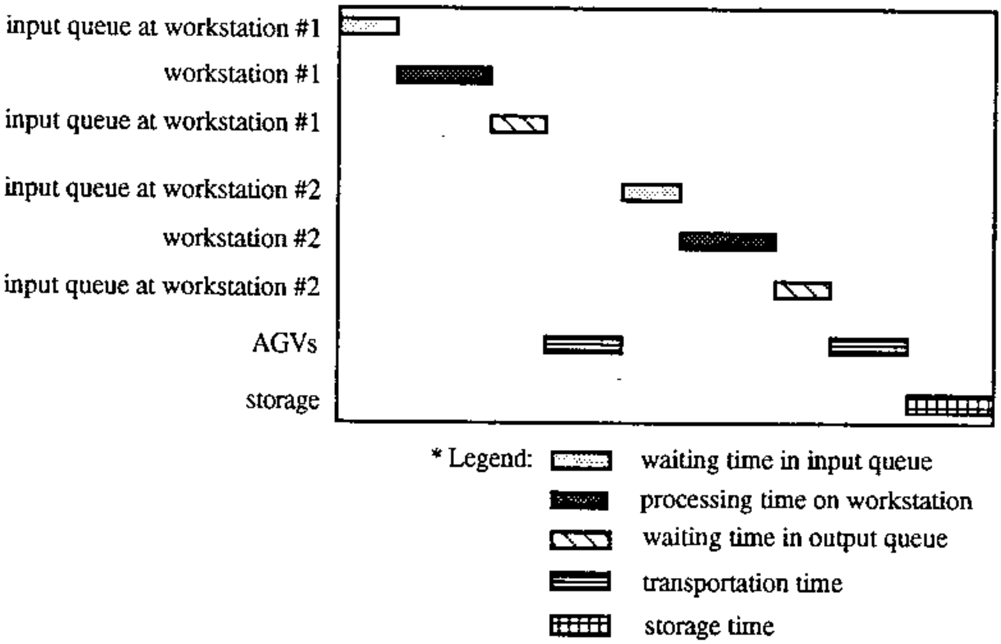


Figure 1. Gantt Chart Representing Shop Time

production order.

Even though the minimum ideal production time is obtained before production, if the workloads and traffic loads are not evenly distributed, then the actual production cannot be optimized. Process plan selection without considering machine tool workload balancing may result in system bottleneck, and consequently longer processing time. Traffic load balancing on the network segments is as important as workload balancing among machine tools. Layout design with unbalanced traffic loads can cause traffic congestion, blocking, and the need of dynamic rerouting during production time. Consequently these can lead to longer actual production time and high production cost. In this paper, the workloads and traffic loads balancing is considered as constraints.

2.2. Overall Structure

Since guidepath layout design has influence on the travel time of both empty and loaded vehicles, the optimum layout should be designed in consideration of both loaded and empty vehicle trips. However, since empty vehicle flows are influenced by part and vehicle dispatching decisions and other stochastic events (e.g., machine breakdowns, vehicle failures, etc.), it is difficult to exactly determine the empty vehicle flow pattern prior to the completion of production. This is because a two-step layout design procedure was employed to insure the completeness of the AGV guidepath layout in [22]. The AGV guidepath layout is *complete* if and only if there exist paths for loaded vehicles to move materials from the load sources to their destinations and paths through which the empty vehicles at drop-off stations can access any pick-up stations where transportation loads originate.

Figure 2 illustrates that the integrated PPS/FGD model simultaneously solves PPS and FGD in response to production order. The module outputs both a unidirectional AGV layout and a set of process plans that contains only one process plan for each part type.

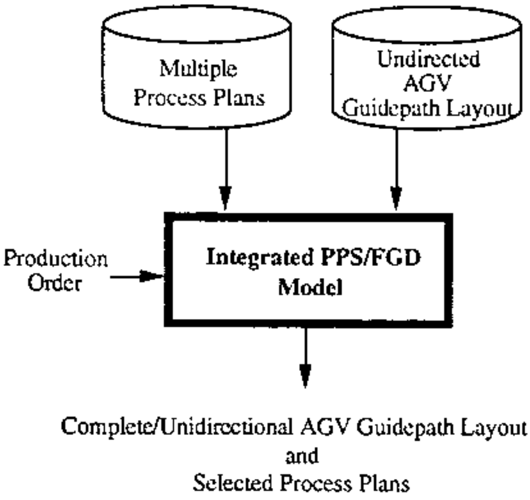


Figure 2. Overall Problem Structure

2.3. Input/Output Requirements and Representations

The integrated PPS/FGD model takes as input, production order, multiple process plans for each part type contained in the order, and an undirected guidepath layout. From the undirected guidepath layout, the following data are automatically generated by the system: multiple flow paths between every two workstations, travel distance for each flow path generated, and path conflict factor between every two flow paths, which indicates whether the two paths are in directional conflict.

Let L_{kl} be a material flow link from workstation k to l. Material flow link is defined a pair of workstations, source and destination on which workpieces are transported. Given K workstations, let $\boldsymbol{L}$ be a set of all flow links whose maximum number is $K(K-1)$.

A flow path (or simply a path) is defined as a physical route from one workstation to another through which workpieces are transported, while a flow link is a logical connection between two workstations. In an undirected layout, multiple and distinctive flow paths for each flow link can be defined. Let R_{klp} and τ_{klp} be respectively the pth path for flow link L_{kl} and its travel time (or distance), where $p = 1, \cdots, v_{kl}$ and v_{kl} is the number of all flow paths for the flow link. Let $\boldsymbol{A}$ be a set of all arcs in an AGV layout. Given flow paths in the layout, an indicator that defines the relationship between a path and an arc is as defined below:

$$\omega_{klpab} = \begin{cases} 1, & \text{if flow path } R_{klp} \text{ uses arc } A_{ab}, \\ 0, & \text{otherwise,} \end{cases}$$

where $A_{ab} \in \boldsymbol{A}$.

A production order contains part mix (or set of part types) $\boldsymbol{M} = \{1, 2, \cdots, i, \cdots, M\}$ and their lot sizes $\boldsymbol{q} = \{q_1, q_2, \cdots, q_i, \cdots, q_M\}$, where q_i is the lot size for part type i. Multiple process plans for part type i is expressed by the notation, $\boldsymbol{P}_i = \{P_{i1}, P_{i2}, \cdots, P_{ij}, \cdots, P_{i}n_i\}$, where P_{ij} is the jth process plan for part type i, and $n_i = |\boldsymbol{P}_i|$.

A process plan consists of a process routing and estimated processing time on each workstation in the route. A process route can be expressed by a set of consecutive pairs of workstations visited. Let ϕ_{ijkl} be a coefficient that relates process plan P_{ij} and flow link L_{kl}. Then it is defined as follows:

$$\phi_{ijkl} = \begin{cases} 1, & \text{if process plan } P_{ij} \text{ visits workstation } l \\ & \text{immediately after workstation } k, \\ 0, & \text{otherwise.} \end{cases}$$

Using the binary coefficient introduced, a process plan P_{ij} can be expressed as follows: $P_{ij} = \{[\cdots, \phi_{ijrs}, \cdots, \phi_{ijkl}, \cdots, \phi_{ijKL}] : [t_{ijs}, \cdots, t_{ijk}, \cdots, t_{ijK}]\}$, where r, s, k, l, K, and $L \in \boldsymbol{K}$, and t_{ijk} is processing time on workstation $k \in \boldsymbol{K}$.

The *path conflict factor* between two paths indicates whether both paths are conflict in direction or not. The path conflict factor is one if there are arcs shared by both paths in reverse direction. If the conflict factor between two paths is zero, it means that the paths do not contain any conflict arcs and consequently, can design a unidirectional guidepath layout. Let $\beta_{(klp)(rsq)}$ be the path conflict factor between two paths, R_{klp} and R_{rsq} · $\beta_{(klp)(rsq)}$ is defined as follows:

$$\beta_{(klp)(rsq)} = \begin{cases} 1, & \text{if } \sum_{A_{ab} \in A} \boldsymbol{AND}(\omega_{klpab}, \omega_{rsqba}) > 0. \\ 0, & \text{otherwise,} \end{cases}$$

where **AND**(A, B) means a logic AND of boolean variables A and B. **AND**(A, B) is one only when both boolean variables are one (A = B = 1).

3. Model Development

Since the integrated PPS/FGD problem simultaneously deals with process plan selection and AGV guidepath design, two decision variables as well as two parameters to constrain the maximum loads on workstations and arc segments are defined below.

$$x_{ij} = \begin{cases} 1, & \text{if process plan } P_{ij} \text{ is selected,} \\ 0, & \text{otherwise.} \end{cases}$$

$$y_{klp} = \begin{cases} 1, & \text{if flow path } R_{klp} \text{ is selected for flow link } L_{kl}, \\ 0, & \text{otherwise.} \end{cases}$$

W_k maximum available machining time on workstation k.

W'_{ab} maximum allowable number of AGV trips through arc A_{ab}.

Let t_{mij} and t_{tij} be respectively machining and transportation time for q_i parts associated with process plan P_{ij}. Then the ideal production time z, total time span in which all the parts in production order are processed and transported, is defined as in Eq. (1).

$$z = \sum_{i=1}^{M} \sum_{j=1}^{n_i} (t_{mij} + t_{tij}) x_{ij} \qquad (1)$$

And, the processing time t_{mij} for q_i parts related to process plan P_{ij} is defined as follows:

$$t_{mij} = q_i \sum_{k=1}^{K} t_{ijk} \qquad (2)$$

The time span to transport q_i parts using process plan P_{ij} is determined by the quantity of the parts to be transported, the number of trips, and distances between adjacent workstations visited by the process plan. With the assumption that an AGV delivers only one unit load at a time, the number of AGV's trips from workstation k to l is the same as the number of unit loads for that part type. When a process plan P_{ij} is used, the number of AGV's trips to deliver q_i parts from workstation k to l is given in the following Eq. (3). The $[x]^+$ means the smallest integer greater than or equal to x.

$$N_{ijkl} + \phi_{ijkl} \left[\frac{q_i}{u_{ij}} \right]^+ \qquad (3)$$

where u_{ij} is unit load size of part type i when using process plan P_{ij}.

Since a unique path for a flow link cannot be defined until the unidirectional guidepath layout is specified, the transportation time t_{tij} for q_i parts associated with process plan P_{ij} is expressed as a function of guidepath layout.

$$t_{tij} = \sum_{L_{kl} \in \boldsymbol{L}} \sum_{p=1}^{v_{kl}} N_{ijkl} \, \tau_{klp} \, y_{klp} \qquad (4)$$

If the objective function is used alone, the following problems will occur: 1) bottleneck can occur on preferred workstations, and 2) traffic congestion on a segment of AGV network. To prevent these circumstances, two constraints are formulated. Also, to design a unidirectional guidepath layout, all the selected flow paths should be consistent in directions. The third constraint is formulated to ensure the unidirectionality of the guidepath layout.

From the definitions of variables and the derivations above, the integrated PPS/FGD problem can be modeled as a zero-one integer program as shown below:

$$\mathit{Minimize}\ z = \sum_{i=1}^{M} \sum_{j=1}^{n_i} \left(t_{mij} + \sum_{L_{kl} \in \boldsymbol{L}} \sum_{p=1}^{v_{kl}} N_{ijkl} \, \tau_{klp} \, y_{klp} \right) x_{ij} \qquad (5)$$

subject to

$$\sum_{j=1}^{n_i} x_{ij} = 1, \quad \forall_i \qquad (6)$$

$$\sum_{p=1}^{v_{kl}} y_{klp} = 1, \quad \forall_{L_{kl}} \qquad (7)$$

$$\sum_{i=1}^{M} \sum_{j=1}^{n_i} q_i t_{ijk} x_{ij} \le W_k, \quad \forall_K \qquad (8)$$

$$\sum_{L_{kl} \in \boldsymbol{L}} \sum_{p=1}^{v_{kl}} \omega_{klpab} \left(\sum_{i=1}^{M} \sum_{j=1}^{n_i} N_{ijkl} x_{ij} \right) y_{klp} \le W_{ab}, \quad \forall A_{ab} \qquad (9)$$

$$\sum_{L_{kl} \in \boldsymbol{L}} \sum_{p=1}^{v_{kl}} \sum_{\substack{L_{rs} \in \boldsymbol{L} \\ L_{rs} \neq L_{kl}}} \sum_{p=1}^{v_{rs}} \beta_{(klp)(rsq)} y_{klp} y_{rsq} = 0 \qquad (10)$$

$$x_{ij} \in \{0, 1\}, \quad \forall P_{ij} \qquad (11)$$

$$y_{klp} \in \{0, 1\}, \quad \forall R_{klp} \qquad (12)$$

Constraints (6) and (7) ensure that only one process plan per part type and only one path for each flow link are selected respectively. Constraint (8) ensures that the processing time on workstation k is less than or equal to the maximum available time W_k on workstation k. Constraint (9) ensures that the total number of AGV trips through an arc A_{ab} is less than or equal to the maximum allowable number of AGV trips A_{ab} on the arc. Constraint (10) ensures that any two selected paths have no arc conflict. Thus, a unidirectional guidepath layout connecting input and output nodes is designed by the set of consistent paths selected. Constraints (11) and (12) ensure the integrality of the decision variables.

In the above non-linear integer programming model formulated, the numbers of $\boldsymbol{x}$ and $\boldsymbol{y}$ variables are the same as those of all the process plans and all the flow paths defined in the problem respectively. Besides the $\boldsymbol{x}$ and $\boldsymbol{y}$ variables, the non-linear terms, $\boldsymbol{xy}$ and $\boldsymbol{yy}$ in Constraints (9) and (10), make the model more complicated. For example, consider a problem with five process plans for each of five part types, and four flow paths for each of six material flow links. For such a simple problem, the number of $\boldsymbol{x}$, $\boldsymbol{y}$ variables, and $\boldsymbol{xy}$ and $\boldsymbol{yy}$ terms are 25(=5×5), 24(=6×4), 600(=25×24), and 576 (=24×24) respectively.

4. Solution Method Development

To develop a heuristic algorithm the integrated PPS/FGD model is broken down into two small subproblems. If a fixed unidirectional guidepath layout is given instead of the undirected one as input, the integrated PPS/FGD problem turns into the problem of selecting a set of process plans only. The reduced problem is referred to as a *process plan selection on a fixed guidepath layout (PPS/FL)*. The *PPS/FL* outputs a set of process plans containing one process plan for each part type in part mix on a fixed unidirectional guidepath layout. On the contrary, with the assumption that only one process plan for each part type is given, the integrated problem reduced to AGV guidepath layout design problem. The reduced problem generated by fixing the process plan and focusing on the assignment of direction to the undirected network is referred to in this paper as *flexible guidepath design with fixed set of process plans (FGD/FP)* problem.

Figure 3 depicts the relationship between decomposed two subproblems. By exploiting the interrelationship between them, an iterative heuristic algorithm is developed. A proposed algorithm seeks a good solution by iteratively or alternately solving the PPS/FL and FGD/FP problems until the objective function value does not decrease any further. No optimal solution is guaranteed from the algorithm.

The subproblem PPS/FL is described in [21,

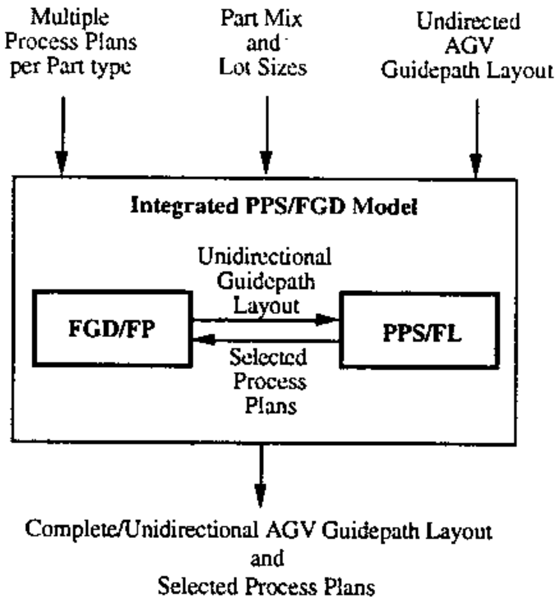


Figure 3. Decomposition of Integrated PPS/FGD Problem

23], and its solution method is used for a solution of the integrated PPS/FGD problem. The selected process plans, the results of PPS/FL, are in turn used as input to the other subproblem FGD/FP. Given fixed process plans, a set of material flow links $\boldsymbol{L}$ is defined as pairs of workstations through which materials are transported. For each flow link L_{kl} in $\boldsymbol{L}$, let Q_{kl} be the vehicle flow quantity to be transported on the flow link. The set of the flow quantities $\boldsymbol{Q}$, usually represented as a from-to matrix of material flow in the papers [5, 6, 7, 13, 16, 18], is a major input to FGD/FP problem. The material flow quantities Q_{kl} is obtained as the total number of AGV's trips on the material flow link L_{kl}:

$$Q_{kl} = \sum_{i=1}^{M} \sum_{j=1}^{n_i} X_{ijkl} x_{ij} \qquad (13)$$

AGV guidepath design problems with material flow quantities are dealt in several papers [5, 6, 7, 13, 22]. One of the solution methods can be used for a solution of FGD/FP subproblem. The following abbreviations are used in describing the heuristic algorithm:

SP	solution set of process plans obtained from PPS/FL.
SL	solution layout obtained from FGD/FP.
FP	given fixed set of process plans, $FP = \{P_{i\bullet} \mid \forall_i\}$, where $P_{i\bullet}$ is a selected process plan for part type i.
FL	given unidirectional layout.

A complete heuristic algorithm for the integrated PPS/FGD problem is described below:

1. <u>Initialization</u>
   Obtain an initial unidirectional layout IFL and an initial set of process plans IFP. Set $FL = IFL; FP = IFP; z_2$, $= \infty$.
2. Solve ***PPS/FL*** with FL to obtain SP and its objective function value z_1.
   If $z_1 < z_2$, then set $FP = SP$ and go to Step 3.
   Otherwise, go to Step 4.
3. Calculate T_m and $\boldsymbol{Q}$ with FP.
   $T_m = \sum_{i=1}^{M} t_{mi\bullet}$, where $t_{mi\bullet}$ is machining time for q_i parts using $P_{i\bullet}$ in FP.

   Solve ***FGD/FP*** with $\boldsymbol{Q}$ as input to obtain SL and transportation time T_t for $\boldsymbol{Q}$.

Set $z_2 = T_m + T_t$.

If $z_1 > z_2$, then set $FL = SL$ and go to Step 2.

Otherwise, go to Step 4.

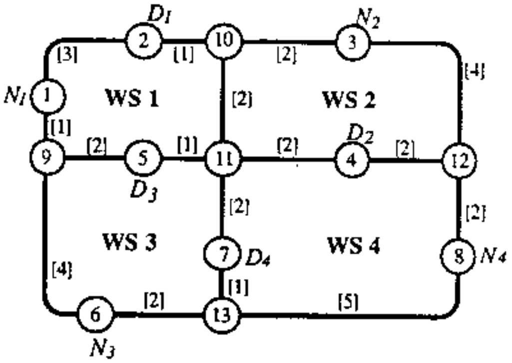
4. Termination: the solution $\{FP, FL\}$ is obtained.

5. Prototype Example and Experimental Results

Based on the solution methods in [21] and [22] for PPS/FL and FGD/FP respectively, the proposed heuristic algorithm was coded in C programming language. Given a production order of product mix and their lot sizes, multiple process plans per part type, and an AGV guidepath layout, the program is activated. The output of the system is a set of selected process plans composed of one plan for each part type and a unidirectional guidepath layout. Simple prototype example is solved to illustrate its solution procedure. Input formats for multiple process plans and multiple flow paths are also provided. To study the feasibility and effectiveness of the heuristic algorithm, a set of computational experiments are conducted using a set of sample problems.

5.1. Prototype Example

Consider a manufacturing system (e.g., FMS) with four workstations, in which automated guided vehicles are the major material handling system to connect the workstations. Figure 4 depicts the departmental layout of the FMS used as example. A production order of three part types $\boldsymbol{M} = \{1, 2, 3\}$ and their lot sizes $\boldsymbol{q} = \{150, 100, 50\}$ is made. For each part type, multiple process plans are given as listed in Figure 5. For illustrative purposes for this prototype example, a unidirectional guidepath layout as shown in Figure 6 is arbitrarily chosen and used as the initial layout (IFL) for the proposed algorithm.



*Legend 1) D_k = drop-off station of workstation k.
2) N_k = pickup station of workstation k.
3) numbers in bracket are travel times of AGVs on the aisles.
4) WS = workstation

Figure 4. Undirected AGV Guidepath Layout of Prototype Example

Part 1
- Process Plan 1: WS1(8) → WS2(7)
- Process Plan 2: WS1(2) → WS3(3) → WS2(3)
- Process Plan 3: WS1(4) → WS3(2) → WS4(4)

Part 2
- Process Plan 1: WS3(16) → WS4(6)
- Process Plan 2: WS2(3) → WS1(7) → WS4(3)
- Process Plan 3: WS3(5) → WS1(5) → WS4(3)

Part 3
- Process Plan 1: WS2(10) → WS4(2) → WS1(5)
- Process Plan 2: WS4(8) → WS2(4) → WS3(3)
- Process Plan 3: WS1(7) → WS4(4) → WS3(5)
- Process Plan 4: WS4(10) → WS2(15)

*Legend: numbers in parenthesis denote processing times on the workstations

Figure 5. Multiple Process Plans of Prototype Example

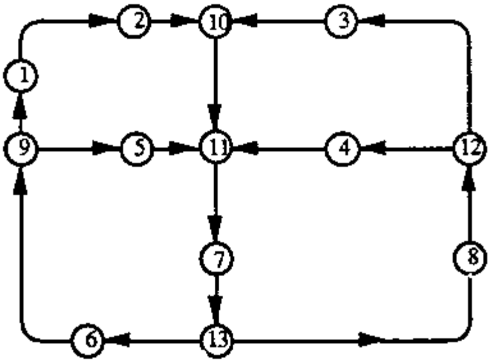


Figure 6. Initial Feasible Unidirectional Layout

By applying the proposed heuristic algorithm, the example problem is solved. A final solution is obtained in three iterations. All intermediate solutions obtained by solving the two subproblems PPS/FL and FGD/FP at each iteration of the algorithm application are listed in Table 1.

5.2. Computational Experiments and Results

A computational experiment of the heuristic algorithm is made for problems with various production environments. Sixteen test problems are generated by changing the number of workstations from 3 to 6 and the number of part types from 4 to 7. For all part types, the number of process plans for each part type is randomly generated from the uniform distribution in the range from 2 to 5. Each process plan with part routing and processing times on workstations is randomly generated from the uniform and triangular distributions. Four different AGVS guidepath layouts with 4, 5, 6, and 7 workstations are chosen and used.

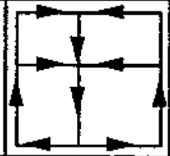
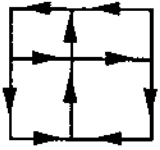
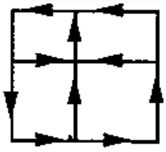
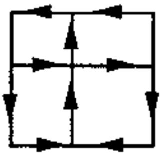
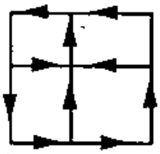
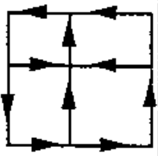
For each problem, two solution methods are applied: exhaustive search and heuristic method. First, an exhaustive search method finds a solution by solving the FGD/FP problems for all the possible combinations of process plans. For example, for a problem with 5 part types, 3 process plans for each part type and 5 workstations, the AGV guidepath design problem (i.e., FGD/FP) is solved 243($=3^5$) times consecutively. The set of process plans and the unidirectional guidepath layout with the minimum objective function value are selected as a solution.

The computational experimentations for the 16 problems with random number of process plans and preprocessed flow paths are executed on the VAX 8550 cluster. The results showing the ideal production time and the CPU times taken are reported in Table 2. For nine problems out of sixteen, the objective function values from the heuristic algorithm are the same as those from the exhaustive search procedure. For the 16 test cases whose results are reported in Table 2, the statistics are collected on various measures and reported in Table 3.

6. Conclusions

For a manufacturing system in which an automated guided vehicle system is operated on a flexible AGV guidepath layout, process plan selection has close interrelationships with

Table 1. Heuristic Solution Procedure for Prototype Example

	iteration 1		*iteration 2*		*iteration 3*	
	PPS/FL	**FGD/FP**	**PPS/FL**	**FGD/FP**	**PPS/FL**	**FGD/FP**
INPUT		$\{P_{11}, P_{23}, P_{34}\}$		$\{P_{13}, P_{22}, P_{32}\}$		$\{P_{13}, P_{22}, P_{32}\}$
OUTPUT	$\{P_{11}, P_{23}, P_{34}\}$		$\{P_{13}, P_{22}, P_{32}\}$		$\{P_{13}, P_{22}, P_{32}\}$	
T_t	4500	3000	2950	2650	2650	2650
T_m	4800	4800	3550	3550	3550	3550
z	9300	7800	6500	6200	6200	6200
CPU*	1 secs	3 secs	1 secs	6 secs	1 secs	6 secs

*CPU=CPU time on Macintosh SE

AGV guidepath design. Each set of process plans containing one process plan for each part type may require a different AGV guidepath layout. In other words, there is a mapping between process plan selection and AGV guidepath layout requirements. Hence, the use and execution of multiple process plans without concurrently considering the design of AGV guidepath layout cannot guarantee optimal production.

The integration of the two functions, process plan selection and AGV guidepath layout design, is the main focus in this research. The integration aims to globally find a solution that selects a set of process plans and designs an appropriate unidirectional AGV layout for a manufacturing mission. By simultaneously addressing these two functions, the operational flexibility is increased for an automated manufacturing system equipped with CNC machine tools and AGVS.

Process plan selection and AGV guidepath design problem fall into a flexible design and planning task that responds to the part and volume mix variations. The current research can be extended by considering the short term (or dynamic) planning and control tasks (i.e., job scheduling and dispatching, vehicle scheduling, empty vehicle dispatching, etc.). The other area is to integrate the automatic generation of process plans (i.e., computer-aided process planning) and flexible AGV guidepath design.

Table 2. Results of Computational Experiments

M		K = 4	K = 5	K = 6	K = 7
3	I	26200 [00:00:09]	45400 [00:02:09]	35900 [00:01:42]	52950 [00:01:51]
	II	26200 [00:00:01]	45550 [00:00:06]	35900 [00:00:04]	52950 [00:00:07]
4	I	25910 [00:01:05]	32780 [00:05:08]	36950 [00:07:29]	53210 [00:32:49]
	II	26470 [00:00:03]	32780 [00:00:03]	36950 [00:00:05]	53210 [00:00:16]
5	I	26520 [00:10:40]	34850 [00:15:53]	35400 [00:17:27]	46370 [01:23:09]
	II	26570 [00:00:08]	38530 [00:00:12]	35400 [00:00:08]	47490 [00:00:44]
6	I	26150 [00:07:00]	42510 [00:28:18]	38800 [01:28:29]	51010 [05:28:54]
	II	26150 [00:00:03]	42510 [00:00:09]	40730 [00:00:17]	55050 [00:01:17]

*Legend : 1) M=number of Part Types.
2) K=number of Workstations.
3) I denotes results from Exhaustive Search Method.
4) II denotes results from Heuristic Algorithm.
5) CPU times in bracket represent [hr:min:sec].

Table 3. Statistics for Various Measures

Ratio for which optimum solutions were found by heuristic	Average deviation from optimum based on all samples	Average deviation based on samples in which non-optimums were found	Time ratio to solve all samples by heuristic *vs.* exhaustive method
56 %	*1.78 %* *(10.56%)**	*4.08 %* *(10.56%)**	*0.59 %*

* worst case deviation

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