フレキシブル生産システムにおける動的工程設計のための自律型エージェント*

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Autonomous Agents for Dynamic Process Planning in the Flexible Manufacturing System*

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Rapid changes of market demands and pressures of competition require manufacturers to maintain highly flexible manufacturing systems to cope with a complex manufacturing environment. This paper deals with development of an agent-based architecture of dynamic systems for incremental process planning in the manufacturing systems. In consideration of alternative manufacturing processes and machine tools, the process plans and the schedules of the manufacturing resources are generated incrementally and dynamically. A negotiation protocol is discussed, in this paper, to generate suitable process plans for the target products real-timely and dynamically, based on the alternative manufacturing processes. The alternative manufacturing processes are presented by the process plan networks discussed in the previous paper, and the suitable process plans are searched and generated to cope with both the dynamic changes of the product specifications and the disturbances of the manufacturing resources. We initiatively combine the heuristic search algorithms of the process plan networks with the negotiation protocols, in order to generate suitable process plans in the dynamic manufacturing environment.

1. Introduction

In the last decade, changes in market requirements toward a larger variety and diversity of products in smaller batch sizes has led to many concepts of next generation of reconfigurable and agile manufacturing systems. The newly proposed manufacturing systems contain collaborative intelligent entities that can dynamically adjust themselves to dynamic status of market requirements and early response to customers' demands. Some automobile manufactures are gradually adopting their production ways to support diversity of customer needs and to decrease the lead time for developing new products[1].

The process planning tasks traditionally transform the product information into the manufacturing process information including the machining process sequences and the sequences of the machining equipment[2]. The process planning tasks are very complicated and time consuming, if it is applied to the

dynamically changing FMSs (Flexible Manufacturing Systems). To facilitate the dynamic and adaptable manufacturing activities in the FMS, a new methodology with appropriate architecture is needed to handle the process planning tasks, in order to cope with dynamic changes of the products and the manufacturing processes in the FMSs.

The multi-agent approaches are becoming increasingly important for the FMSs to increase the productivity and the profitability through the greater shop floor agility and flexibility[3]. The multi agent systems provide us a systematic way to deal with the dynamic changes of the products and the manufacturing processes in the FMSs. This research applies a multi-agent architecture to a real time process planning system in the FMSs, which generate suitable process plans based on the status of the FMSs. The objective of the paper is to develop a multi-agent architecture for the process planning of one kind of product that rapidly adopt the process plans to cope with the product changes and the unexpected disturbances in the FMSs. A process plan network and a heuristic search algorithm are proposed to generate suitable process plans real-timely. The approach does not need any time for generating the process plans, and the process plans of the product are generated incrementally

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through the manufacturing. The calculation time of the case studies show that this approach is suitable for real time application.

2. Literature Review

Previous research papers on the process planning include object oriented approaches[4,5], GA based approaches[6,7], neural network-based approaches[8,9], feature-driven approaches[10,11], Petri net-based approach[12], and knowledge based approaches[13,14]. In addition to the centralized approaches above mentioned, much attention has been given to agent based systems, which are one of the distributed Artificial Intelligence (AI) approaches. Cooperative intelligent agents have recently been applied to the distributed process planning systems, instead of large expert systems. Agent based approach is also being recognized as one of the effective ways to realize a dynamic process planning systems in the FMS.

Shih and Srihari[15] proposed a distributed AI-based framework for process planning. Their approaches decompose the entire production control task into several subtasks implemented by some intelligent agents. Sluga et al.[16] proposed similar agents called Virtual Work Systems (VWSs) as the building blocks for the decision-making in a distributed manufacturing environment. The VWSs represent manufacturing work systems in the information space, and are structured as the autonomous agents. Zhang et al.[5] proposed an agent based adaptive process planning system on top of an object oriented manufacturing resources modeling framework. Cooperative Computer-Aided Process Planning (CoCAPP) attempts to distribute whole complex process planning activities into multiple specialized problem solvers and to coordinate them to solve the complex problems[17]. The CoCAPP attempted to satisfy five major requirements: autonomy, flexibility, interoperability, modularity, and scalability. Tue et al.[18] introduced a method called Incremental Process Planning (IPP) for one-kind-of-a production in such environment. The IPP is used to extent and to modify a primitive plan (a skeleton process plan) incrementally, according to new features that are identified from a product design until no more new features can be found. Wang and Shen[19] developed a generic methodology of Distributed Process Planning (DPP) for intelligent and dynamic decision-making in the process planning. The central focus is given to design to control concept that utilizes machining features, intelligent agents and function block standards.

Sugimura et al.[20] describe a conceptual architecture based on the autonomous elements called holons to integrate the process planning and the scheduling. The holonic architecture enables distributed decision-making of the job holons and the scheduling holon which cooperate with each other. A systematic approach was proposed to select suitable combination of the process plans generated by the job holons and

to generate suitable production schedules by applying the genetic algorithm and the dispatching rules. Nassehi et al.[21] examine the application of the collaborative multi-agent systems in designing an object-oriented process planning system for prismatic components in a STEP-NC compliant environment. They proposed specification and design of a prototype system entitled the multi-agent system for computer aided process planning.

The multi-agent architecture has been widely applied to the process planning systems, as shown in the literature. The methods proposed in the literature deal mainly with the process planning tasks in the static environment in which the product specifications and the manufacturing system status are stable. However, it is now required to develop a process planning system applicable to the dynamic environment in which some unforeseen disturbances may occur. The objective of the paper is to propose a multi-agent based system for the process planning in the dynamic environment, in order to cope with the product changes and the unforeseen disruptions, such as the malfunction of the machine tools. The processing time for generating the process plans and handling the unforeseen disruptions is short, and makes it suitable for real time process planning and manufacturing. The following issues are discussed in the paper.

- (1) Target flexible manufacturing systems.
- (2) Multi-agent system for dynamic process planning.
- (3) Flexibility and robustness of the proposed architecture.
- (4) Simulation software and experimental results.

3. Target Flexible Manufacturing System

The basic configuration of the target FMSs are shown in Fig. 1. The manufacturing systems consist of a set of machine tools, preparation stations, input and output buffers, AGVs (Automated Guided Vehicles), fixtures and cutting tools. The input jobs are transformed by a process plan to the finished products through the manufacturing processes including machining, transportation, and fixturing processes. The inputted jobs are firstly fixed on the fixtures at the preparation stations and transmitted to the input buffers by the AGVs. The jobs are then transported

Fig. 1 Configuration of the target manufacturing system

to the machine tools in order to carry out the machining processes required. If the re-fixturing is required to change the positions and orientations of the jobs against the fixtures, the jobs are transported to the preparation stations and the re-fixturing process is carried out at the preparation stations. When all the required machining processes of the jobs are finished, the finished jobs are transported to the preparation stations to separate the jobs from the fixtures, and the jobs are transmitted to the output buffers.

4. Multi Agent Architecture

A multi-agent architecture is proposed to carry out the dynamic process planning. The agent system incrementally generates suitable process plans of the one kind of product, which include the machining sequences of the machining features and the sequences of the machine tools, based on the dynamic status of the FMSs. In the following sections, the system architectures proposed here are discussed in the context of the agent definitions and the negotiation protocols among the agents.

4.1 Agents Definition

Two types of agents are considered in this research to develop the process planning systems. They are, physical agents and information agents. The physical agents represent jobs, the manufacturing resources and the machining processes in the FMSs. The manufacturing resources considered here are the machine tools, the preparation stations, the AGVs (Automated Guided Vehicles), the fixtures and the cutting tools. The information agents are virtual agents which are responsible for governing the negotiation protocol and decision-making.

4.1.1 Physical agents

Job agents

The job agents represent the jobs to be manufactured in the FMSs. The role of the job agents in the process planning is to certify the correct machining processes of the jobs. The job agents include the following information to describe the orders and the machining features.

(1) Job information

The job information section describes the order information, the locations and the progresses of the machining processes of the jobs.

(2) Machining features

The machining feature section gives the machining features of the jobs and their technical data such as the types, the tolerances and the roughness. These technical data are required to select appropriate machining processes.

(3) Process plan networks

The process plan networks capture the generated process plans in hierarchical ways, and provide for alternative process plans[4]. It includes all the alternative process plans that satisfy the technological requirements of the jobs.

Fig. 2 UML class diagram of physical agents and their relations

(4) Job Status

We consider the following status for the job agents.

- Idle: The job agent is idle and waiting for the next machining operations.
- Machining operation: The job agent is under machining processes on the machine tools.
- Transportation and re-fixturing: The job agent is transported and/or re-fixtured for its next machining operations.

Machine tool agents

The machine tool agents represent the machine tools. The agents representing such resources as the preparation stations and the AGV are not considered, at present, since only the machining processes are discussed in the present research. We have multi machine tool agents in this research, and for each existing machine tool in the manufacturing system, we consider a machine tool agent in the multi agent system. The machine tool agents are responsible for generating proposals to the machining processes required from the job agents. The proposals include the machining time, the transportation time and the re-fixturing time needed to carry out the required machining processes of the job agents. The machine tool agents include the following information to represent the machine tools in the FMSs.

(1) Machine tool information

The machine tool section specifies the shape generation functions, which are represented by the cutting motions, the spindle directions, the feed motions and the maximum product size.

(2) Machine tool status

We consider the following status for the machine tool agents in the simulation.

- Idle: The machine tool is idle and negotiating with job order agents for next machining operation
- Machining operation: The machine tool is machining the job agent
- Breakdown: The machine tool has been

broken and is under recovery process

(3) Cutting tool

The characteristics of the cutting tools are described in the cutting tool section, which includes the information about the cutting tool types, the tool sizes and the cutting edge types.

(4) Fixture

The fixture section describes the fixture types, and the positions of the fixtures against the spindle axis.

Machining process agents

The machining process agents represent the machining processes of machining features of the jobs, which are carried out by the machine tools. Only one machining process agent is considered here which represents all the machining process. The agents include the following information.

- (1) Machining process ID which is the combination of the ID of the machine tools, the ID of the fixtures and the ID of the cutting tools.
- (2) Machining process types and machining features types, which can be generated by the machining processes.
- (3) Surface roughness, tolerances and material removal rate of the machining processes.
- (4) Machining process status

The status represents the dynamic status of the machining processes in the FMSs. The machining process agents have the following status.

- inactive: if one of the machine tool, the cutting tool and the fixture related to the machining process are broken-down.
- active: otherwise.

4.1.2 Information agents

The information agents are virtual agents for governing the negotiation protocol and decision-making.

Production engineering agent

The production engineering agent generates the job agents, the machine tool agents, and the machining process agents to specify the geometric and technological information of the jobs, the machine tools and the machining processes of the FMSs. Only one production engineering agent is considered here. The agent plays a key role for initializing the information of the physical agents.

Job order agents

The job order agents represent the manufacturing tasks. They are information agents, which carry out the negotiation processes between the job agents and the machine tool agents to generate suitable process plans. The job order agents have crucial influence on the system performance by deploying efficient decision-making mechanism to select the appropriate machine tools for the individual machining features of the jobs.

4.2 Negotiation Protocol

A negotiation protocol among the agents is required to coordinate the distributed decisions of the

individual agents for solving the complex problems in the process planning of the FMSs. It also supports the job specification changes and breakdown of the machine tools during the manufacturing processes of the jobs. In the present paper, only one job is considered in the process planning and scheduling for the first development phase. Therefore, the agents related to the job are single, they are the job agent and the job order agent. The problems to be solved here are as follows.

- (1) Selection of candidate machining processes for individual machining features.
- (2) Selection of suitable combinations of the machine tools, the cutting tools and the fixtures.
- (3) Selection of suitable machining sequences of the machining features.

We apply the contract net protocols[22] which are widely used in the agent based scheduling problems. In the protocol proposed here, the individual agents have three types of boards named “request boards”, “proposal boards” and “status boards” for the communication among the agents. Fig. 3 shows the roles of the boards. The requests from the other agents are firstly sent to the request boards, and the agents scan and receive the requests from the boards, every fixed time intervals named RTIP (Reading Time Interval Period). The individual agents secondly generate the proposals to the requests, and store them in the proposal boards. The status of the agents are changed and stored in the status board, if necessary.

Fig. 3 Communication with other agents

The communications between the boards and the other agents are controlled by a communication system, which is common to all the agents. The agents communicate with each other through the messages. We have two types of messages shown in the followings;

- Messages for handling the changes of the job specification and the manufacturing processes.
- Messages for handling the process planning and scheduling tasks.

We have the priority for analyzing the messages by the agents. The first priority is given to the messages related to the changes of the job agents or the manufacturing processes.

The general format of the messages related to process planning and scheduling and their attributes is

Table 1 General format for messages

Attribute	Size (Character)	Description
Z x	1	Message Status
V x x x x x	5	Valid time window for message
N x x x x x	5	Message unique ID
T x x	2	Message type
C x x	2	Current position of requester
S x x	2	Sender ID
R x x	2	Receiver ID
P x x	2	Machining process ID
F x x	2	Machining feature IDs
X x x x x x	5	Manufacturing time of next operation
E x x x x x	5	Estimation of completion time

summarized in the Table 1. The symbol “x” in the table means the characters representing the contents of the messages.

Fig. 4 summarizes the negotiation protocol proposed here to generate suitable process plans and schedules by the distributed decision-makings of the individual agents and the negotiations among the agents. The negotiation processes are carried out through the following steps.

Step 1: Initialization

The production engineering agent firstly generates the job agent, the machine tool agents and the machining process agent to initialize the status of the target FMSs. It also defines the machining features, which can be generated simultaneously by the same combinations of the machine tools, the cutting tools and the fixtures, and assigns them to the job agent.

Step 2: Requests for available machining processes

The job agent reads all the requests from its request board every RTIP (Reading Time Interval Period) and analyses the messages according to their priority. If there are some messages related to the job specifications changes, these messages are analyzed first and the machining features and their specifications are updated. These messages are generated and sent from the production engineering agent.

For the process planning and scheduling tasks, the job agent selects a set of the machining features, which can be machined in the next machining process, based on the precedence constraints among the machining features. For example, let us consider a case shown in Fig.5. This part consists of three machining features (see Fig.5 (b)). They are, one slot MF1, and two holes MF2 and MF3. The precedence constraints for this example is shown in Fig. 5(c).

The machining process agent proposes a set of available machining processes for the individual machining features. The machining process agent reads all the requests from its request board every RTIP and analyses the messages according to their priority. If there are some messages related to the machining process changes including breakdown of manufacturing resources, such as machine tools, cutting tools or

Fig. 4 Negotiation protocol among agents for process planning and scheduling

Fig. 5 An example of parts

Table 2 Alternative machining processes for machining features MF1 and MF3

Machining Features	Machining Process ID	Machine Tool ID	Fixture ID	Cutting Tool ID
MF1	mp_1	mt_1	fi_1	ct_1
MF1	mp_4	mt_2	fi_2	ct_1
MF3	mp_3	mt_1	fi_2	ct_2
MF3	mp_6	mt_2	fi_1	ct_2

mt_1 :Vertical machining center

mt_2 :Horizontal machining center

ct_1 :End Milling, ct_2 :Drill

adding new manufacturing resources, these messages are analyzed first and the list of available machining processes are updated. The machining process agent then analyses the messages related to process planning and scheduling tasks.

In the first step, the machining features MF1 and MF3 are sent to the machining process agent, and it selects a set of available alternative machining processes for the individual machining features, based on the specifications of the machining features, such as the geometries, the sizes, the surface roughness, and the tolerances as shown in the Table 2.

Fig. 6 Process plan network

The selected machining processes include the information about the machine tools, the cutting tools and the fixtures. The selected machining processes for the individual machining features are sent back to the job agent.

The job agent generates a set of groups of the machining features, which can be machined by the same combinations of the machine tools, the cutting tools and the fixtures. This means that the grouped machining features are machined by one machining process concurrently, and the job agent generates the nodes representing all the grouped machining features in the process plan networks as shown in the first level nodes N_1, N_2, N_3, N_4 in Fig.6.

The contents of the process plan networks are described in the previous paper[23]. The individual nodes in the process plan networks represent a set of the machining features which could be machined by one machining process. An algorithm also generates nodes representing the machining sequences of the machining features based on the precedence constraints. The information of the generated nodes is sent to the job order agent for the negotiations.

Step 3: Requests generation by job order agent

The job order agent reads all the generated nodes from its request board and creates requests for the machining process execution for the individual nodes of the process plan networks, which are the groups of the machining features that can be generated by same

Table 3 Generated requests by job order agent

Process plan network nodes	Generated requests by job order agents
N_1	Z1V01000N00001T01 C00S01R01P01F01
N_2	Z1V01000N00002T01 C00S01R01P04F03
N_3	Z1V01000N00003T01 C00S01R02P05F01
N_4	Z1V01000N00004T01 C00S01R02P07F03

machine tools. The generated requests are sent to the request boards of the corresponding machine tool agents. The content of request includes the machining features and selected machine tool, cutting tool and fixture. As you can see in Fig. 6, there are four nodes N_1, N_2, N_3, N_4 in the first level of the process plan network. For each of them, the requests shown in the Table 3 are generated according to the message format in Table 1, and sent to the related machine tools mt_1 and mt_2 .

Step 4: Proposal preparation by machine tool agents

The machine tool agents read all the requests from their request boards every RTIP (Reading Time Interval Period). The machine tool agents analyze the request messages, and generate appropriate propos-

als to all the requests. In this paper, we consider two different ways for generating appropriate proposal for each request by the machine tool agents, as shown in the followings.

- Minimum manufacturing time

The machine tool agents calculate the manufacturing time for the next machining processes of the job agent and generate proposals. The manufacturing time considered here includes the machining time, the transportation time, the re-fixturing time, and the tool changing time.

- Minimum completion time

The machine tool agents estimate the completion time of the remaining machining features of the job agent. A procedure is developed and given to the job agent to estimate the minimal completion time of the remaining machining features, as shown in Fig. 6. It is not necessary to generate the entire process plan network and just some parts of the process plan network are generated to estimate the completion time of the remaining machining features. The job agent starts the procedures from the start node which is specified by the machine tool agent, and repeat to generate and to select suitable successive nodes with the minimum machining time. When all the machining features are included in the process plan networks, the job agent finds both the machining sequences of the machining features and the estimated minimal completion time. Consider a case where we are at node N_i of the process plan network and we are going to estimate the manufacturing time from the node N_i to the end node. The algorithm for calculating the estimated minimum completion time from node N_i to the end node is summarized in the followings.

Initialization :

- Set *RMF* and *AMF*. The *RMF* is the set of the remaining machining features. The *AMF* is the set of the available machining features that do not have any preceding machining features and could be done firstly considering the precedence constraints among the nodes of the process plan networks ($AMF \subseteq RMF$).
 - Put the node N_i in *ECTS* set. The *ECTS* is the set of the nodes in the path from node the N_i to the end of the process plan network, which has the minimum manufacturing time.
 - Set a initial node N_i . In the N_i , $RMF = \{\text{set remaining machining features}\}$, $AMF = \{\text{set of machining features without any successors}\}$.
- (1) Generate a set of successor nodes $SN = \{N_j | j = 1, 2, \dots\}$ of the node N_i for all feasible machining processes $mp_r = (mt_i, fx_f, ct_t)$, $r = 1, \dots, R$, (R total number of available machining processes) by applying the following algorithm.
- Cluster all features of the *AMF* set of the

node N_i that could be machined with the machining process mp_r .

- Generate a new node N_j representing a set of machining features which can be machined by the machining process mp_r and put it in the *SN* set. The links to the nodes N_j , which are successor nodes, are stored in the node N_i for further processing.
 - Estimate the manufacturing time for node N_j that includes the time of the machining, the transportation and the re-fixturing processes.
 - Update the *RMF* and *AMF* sets for the node N_j .
- (2) Select a successor node N_k form the *SN* set which has the minimum machining time for the next step of extension, and move it to the *ECTS* set.
- (3) If *RMF* set of N_k is not empty consider node N_k as node N_i and go to (1).
- (4) If *RMF* set of N_k is empty, it means that we are in the end of the process plan network. The sum of the manufacturing time for the nodes in *ECTS* set is the estimation of the minimum completion time from node N_i to the end.

Let us consider a case where we are going to calculate the estimation of minimum completion time for node N_1 at the process plan network shown in Fig. 6. We start with node N_1 , and there are four successor nodes N_5, N_6, N_7, N_8 from the node N_1 as shown in Fig.6. We select the node N_5 which has the minimum manufacturing time, and we put it in the *ECTS* set. We expand the node N_5 at the next stage of the algorithm and there are two successor nodes N_9, N_{10} . The node N_9 is selected and which has the minimum manufacturing time, we put it in the *ECTS* set. As you can see in Fig.6, for the node N_9 the *RMF* set is empty and the algorithm stops. It is because that there are no remaining machining features in the node N_9 . The sum of the manufacturing time for the nodes in *ECTS* set is the estimation of the completion time from node until end.

Following this, the job agent returns the estimated completion time to the machine tool agents. As you can see in the Fig.6, the estimation of completion time for all nodes N_1, N_2, N_3, N_4 are calculated and these values are returned to the machine tool agents. This procedure can estimate the completion time of all the remaining machining features, however it requires the additional communications between the machine tool agents and the job agent.

The machine tool agents generate proposals for each request as shown in Table 4, and send them back to the job order agent which include the manufacturing time of the next operation or the estimated minimum completion time.

Step 5: Selection of appropriate proposal by job order agent

The job order agent scans all the received proposals from the machine tool agents every RTIP, and se-

Table 4 Generated proposals by machine tool agents

Received requests	Generated proposals by machine tool agents
Z1V01000N00001T01 C00S01R01P01F01	Z1V01080N00005T02C00 S01R01P01F01X738E2070
Z1V01000N00002T01 C00S01R01P04F03	Z1V01080N00006T02C00 S01R01P04F03X1397E2227
Z1V01000N00003T01 C00S01R02P05F01	Z1V01080N00007T02C00 S02R01P05F01X685E2525
Z1V01000N00004T01 C00S01R02P07F03	Z1V01080N00008T02C00 S02R01P07F03X1312E2440

lects an appropriate proposal based on the either the minimum manufacturing time or the estimated minimum completion time. The job order agent selects the node N_3 according to the minimum manufacturing time, or the node N_1 according to the estimated minimum completion time. The job order agent informs both the job agent and the machine tool agent that the machining features sent from the job agent shall be machined by the machine tool of the selected node. This means that the job order agent dynamically generates the process plans and the production schedules of the job agent and the machine tool agents.

The job agent and the machine tool agent selected here carry out the requested machining processes in the next step. Therefore, the status of these agents are changed, and the status data are stored in the status boards. All the agents monitor the status data if necessary.

Step 6: Preparation for next operation

When the machine tool agent completes the machining operations of the job agent, the job agent modifies its process plan networks. That is, the job agent deletes the corresponding nodes representing the group of the machining features which have been completed by the machine tool agent. New nodes of the process plan networks are generated to specify the groups of the machining features to be machined in the next step. The procedures presented in Steps 2 to 6 are repeated until the job agent does not have any remaining machining features.

4.3 Flexibility and Robustness of the Negotiation Protocol

One of the advantages of the multi agent architectures is that they are robust and dynamic. They can quickly react to unexpected events, and adapt themselves when conditions change. Compared to the centralized systems, agent architectures are easy to maintain, modify and extend as the requirements of the system change and grow according to the market and through the time. The flexibility and the robustness of the proposed method are discussed in the context of the response to the unforeseen changes of the job and the machining processes. The job agent utilizes the process plan networks representing all candidate machining process routes of the job, and generates

suitable process plans incrementally, referring to the status of the machine tools. It is not necessary to generate the entire process plan network for selecting suitable the process plan of the job at the start of manufacturing. Therefore, pre-defined and fixed process plans are not required, and the process plans are dynamically generated from the candidate machining process routes specified in the process plan networks. The proposed architecture increases the flexibility and the robustness of the FMSs.

The negotiation protocol as shown in the Fig. 7 has been extended to support the unforeseen changes. The agents communicate and generate messages as shown in the Fig. 7 to handle the changes of the job and the machining processes.

Fig. 7 Negotiation protocol among agents for supporting unforeseen changes

As you can see in Fig. 7, the production engineering agent may modify the geometric and the technological specifications of the job to be machined. In this case, the contents of the job agent are modified, in particular, the contents of the machining features are modified to represent the new specifications including the following examples;

- Add a new machining feature and its constraint precedence.
- Change in specifications of the machining features such as size, tolerance and roughness.
- Combining two machining features to make one machining feature.
- Splitting one machining feature to two different machining features.

In some cases, it is possible to realize the job specification changes during the manufacturing processes of the job. As we discussed in the previous section, the job agent, after its RTIP, firstly analyzes the messages related to the changes of the job specifications and then expand the process plan network according to the updated information of the machining features. So, we make sure that any changes in the job specifications will be implemented in the system real timely.

For the cases where some machine tools or cutting tools are added and/or removed, the contents of the machine tool agents and the machining process agent are added and/or removed from the agent systems. If some machine tools are broken down, the

Fig. 8 Synchronizing the agents for generating requests and proposals

corresponding machining processes become inactive, and the contents of the machining process agent are modified. Same as the job agent, the machining process agent firstly analyzes the messages related to the changes of the manufacturing changes after its RTIP. We are able to pursue any changes in the manufacturing processes real timely.

4.4 Synchronization

The Petri nets[24] are used, in the research, for synchronizing the messages and the negotiation protocols between the different agents. This Petri nets control both the sequence and the timing of the interaction and the messages between the agents. Each Petri net represents one agent or interacting agents. Fig. 8 shows an example of the interaction between the agents for generating and sending the requests to the request board of the machine tool agents and generating the proposals by the machine tool agents. These Petri nets are linked with each other with global transitions (See transitions, t_2 , t_4 , t_8 , t_{14} , t_{17} in Fig. 8).

5. Simulation Software and Experimental Results

A prototype of the agent based dynamic process planning and scheduling system have been developed for the case studies, as shown in Fig. 9. The system developed here is able to simulate the distributed decision-makings of the agents, the negotiation among the agents, and generate a suitable process plan and a schedule for an inputted job.

Fig. 9 Simulation system

Some case studies have been carried out to verify the applicability of the proposed system to the integrated process planning and scheduling problems in the FMSs. The FMS considered here includes 7 machine tools and 50 different machining processes. Figure 10 shows the shapes of the job agent for the case studies. The detailed information of the machining features and the machining resources of the case studies are brought in the previous paper[23]. The RTIP in the simulation is set to be 2 sec. for the machine tool agents, 1.5 sec. for the machining process agent, 4 sec. for the job order agent and 2.4 sec. for the job agent. We compare the effectiveness of the proposed architecture with the centralized method which can generate the optimum solution. We also assess the

Table 5 Generated process plans for different case studies

Case	Problem Size		Centralized approach	Agent based approach	
				Minimum manufacturing time	Minimum completion time
	Number of machining features	Number of machining processes	Optimal completion time	Completion time /increasing percentage	Completion time /increasing percentage
(a)	32	14	8211.1	11277.3 / +37.34%	8233.3/ +0.27%
(b)	20	8	20057	21376.1 / + 6.58%	20074.1/ +0.09%
(c)	24	13	7662.4	13722.1 / +79.08%	7680.1/ +0.23%

architecture when some unforeseen disturbances occur during the manufacturing.

5.1 Performance Analysis

We apply A* algorithm[4] as the centralized static approach to search the process plan networks and to find the optimal solution for the cases (a), (b) and (c) of Fig. 10. We use the proposed architecture for the dynamic process planning for the all cases. The following two cases are considered.

Fig. 10 Jobs considered in case studies

- Case 1: Minimum manufacturing time

In the first case, the job order agent selects its proposal based on the index of the minimum manufacturing time of the required machining features. The machine tool agents can generate their proposals without the communication with the job agent.

- Case 2: Minimal completion time

In the second case, the job order agent selects its proposal based on the index of the minimal completion time of the remaining machining features. The results are summarized for three cases in Table 5. The results of the proposed method are almost same as the ones generated by the centralized approach in the context of the completion time.

5.2 Robustness against Malfunction of Machine Tools

Additional experiments are carried out for the job as shown in Fig. 11 to assess the robustness of the proposed architecture against the malfunction of the machine tools and job specification changes. The original process plan for the job is shown in Table 6. In the experiment 1, the machine tool “MT12” is broken down after finishing the machining features MF4, MF5, MF6, MF12, MF13, MF15 and the recovery time is set to be 300 sec. In the experiment 2, the cutting tool number “CT111” is broken down after finishing the machining feature MF22. As you can see in Table 6, the proposed architecture can dynamically generate alternative process plans to cope with the malfunctions of the machine tools and the cutting tools. The job agent can be dynamically allocated to another manufacturing route in the process plan networks.

Fig. 11 Job considered in robustness analysis

In the other experiments, the following unforeseen changes have been considered in the job specifications.

- Change the roughness of the machining feature.
 - MF9 at simulation time 700. The machining processes and the machining time of the machining feature will be changed.
- Add a new machining feature to the job.
 - MF24 at simulation time 2500. The job has 23 machining features at the start of manufacturing and we add a new machining feature with new precedence constraint for it.

As shown in Table 6, the proposed architecture can dynamically generate updated process plans to

Table 6 Generated process plans and for jobs for case studies

Conditions	Process Plans	Flow Time
Without unforeseen changes	[(MT12,FI8,CT115) (MF14),1011.7] [(MT12,FI1,CT111) (MF4,MF5,MF6,MF12,MF13,MF15),1615.8] [(MT12,FI2,CT111) (MF8,MF9,MF18),754.4] [(MT12,FI8,CT111) (MF22),251] [(MT12,FI3,CT117) (MF3),129.3] [(MT12,FI9,CT111) (MF7),263.6] [(MT12,FI1,CT111) (MF10),251] [(MT12,FI4,CT111) (MF11),136.8] [(MT14,FI5,CT133) (MF1,MF2),1092.3] [(MT14,FI9,CT133) (MF16,MF17),126.9] [(MT17,FI1,CT163) (MF19,MF20,MF21,MF23),1604.1]	7272.9
Malfunction of machine tool "MT12 "	[(MT12,FI8,CT115) (MF14),1011.7] [(MT12,FI1,CT111) (MF4,MF5,MF6,MF12,MF13,MF15),1615.8] [(MT6,FI1,CT55) (MF18),1009.8] [(MT12,FI8,CT111) (MF22),1151.2] [(MT12,FI3,CT117) (MF3),129.3] [(MT12,FI9,CT111) (MF7),263.6] [(MT12,FI1,CT111) (MF10),251] [(MT12,FI2,CT111) (MF8,MF9),747] [(MT12,FI4,CT111) (MF11),136.8] [(MT14,FI5,CT133) (MF1,MF2),1092.3] [(MT14,FI9,CT133) (MF16,MF17),126.9] [(MT17,FI1,CT163) (MF19,MF20,MF21,MF23),1640.1]	9175.5
Breakdown of cutting tool " CT111 "	[(MT12,FI8,CT115) (MF14),1011.7] [(MT12,FI1,CT111) (MF4,MF5,MF6,MF12,MF13,MF15),1615.8] [(MT12,FI2,CT111) (MF8,MF9,MF18),754.4] [(MT12,FI8,CT111) (MF22),251] [(MT12,FI3,CT117) (MF3),129.3] [(MT12,FI4,CT113) (MF11),137.1] [(MT14,FI5,CT133) (MF1,MF2),1092.3] [(MT14,FI9,CT133) (MF16,MF17),126.9] [(MT14,FI6,CT133) (MF7),263.6] [(MT12,FI1,CT113) (MF10),1146.5] [(MT17,FI1,CT163) (MF19,MF20,MF21,MF23),1640.1]	8168.7
Job specification changes	[(MT12,FI8,CT115) (MF14),1011.7] [(MT12,FI3,CT117) (MF3),129.3] [(MT14,FI3,CT133) (MF12),1007.3] [(MT14,FI5,CT133) (MF1,MF2),196.9] [(MT14,FI9,CT133) (MF16,MF17),126.9] [(MT14,FI6,CT133) (MF7),263.6] [(MT14,FI1,CT133) (MF4,MF8),830] [(MT14,FI4,CT133) (MF10,MF13,MF15),869.6] [(MT14,FI4,CT135) (MF18),25.3] [(MT6,FI1,CT51) (MF11),1028.3] [(MT6,FI4,CT51) (MF6),163.8] [(MT6,FI1,CT51) (MF22),214] [(MT6,FI3,CT51) (MF5),408.4] [(MT6,FI2,CT51) (MF9),515.9] [(MT6,FI2,CT51) (MF24),214] [(MT17,FI1,CT165) (MF20),1297.4] [(MT17,FI1,CT163) (MF19,MF21,MF23),352]	8654.4

Note: The highlighted sections show the differences updated process plan compared to original process plan.]

Note: [(MT ×, FI ×, CT ×)|(MF ×,...), × × ×] indicate [(Machine tool number, Fixture number, Cutting tool number)|(Machining feature number,...), Manufacturing time]

Manufacturing time = machining time + transportation time + refixturing time + negotiation time

cope with the changes of job specifications. The differences of the updated process plans compared with the preliminary process plan are highlighted in the Table 6. The sequence of all the updated process plan have been changed and the new machining resources are selected for machining feature with different machining time as shown in Table 6. As you can see in Table 6, new machining resources have been selected for machining feature MF9 as its roughness changed through the manufacturing.

6. Conclusion

An agent based process planning and scheduling system was discussed, aimed at realizing flexible and robust FMSs. The following remarks are concluded.

- (1) A multi-agent system consisting of five basic agents and a negotiation protocol was proposed to carry out the various tasks in the process planning. The individual agents have the capability for the distributed decision-making and the communications with the other agents.

- (2) A systematic procedure was proposed to generate suitable process plans of the job and suitable schedules of the machine tools. The proposed method is able to solve the process planning problem concurrently and dynamically, with use of the search algorithms of the process plan networks.
- (3) Some case studies have been carried out to verify the effectiveness and the robustness of the proposed method to the dynamic process planning problems in the FMSs. It was shown that the proposed distributed methods are effective to incremental generation of the process plans, and that the near optimal solutions can be generated. It was also shown that the proposed architecture generates alternative process plans dynamically, to cope with the malfunctions of the machine tools.

The future work will focus on expansion of the agent architecture for the integrated process planning and scheduling for the multi job problems, which is more complex and require advanced negotiation protocol and agent decision-making models.

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