Agent-Based Distributed Manufacturing Process Planning and Scheduling: A State-of-the-Art Survey

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***Abstract*—Manufacturing process planning is the process of selecting and sequencing manufacturing processes such that they achieve one or more goals and satisfy a set of domain constraints. Manufacturing scheduling is the process of selecting a process plan and assigning manufacturing resources for specific time periods to the set of manufacturing processes in the plan. It is, in fact, an optimization process by which limited manufacturing resources are allocated over time among parallel and sequential activities. Manufacturing process planning and scheduling are usually considered to be two separate and distinct phases. Traditional optimization approaches to these problems do not consider the constraints of both domains simultaneously and result in suboptimal solutions. Without considering real-time machine workloads and shop floor dynamics, process plans may become suboptimal or even invalid at the time of execution. Therefore, there is a need for the integration of manufacturing process-planning and scheduling systems for generating more realistic and effective plans. After describing the complexity of the manufacturing process-planning and scheduling problems, this paper reviews the research literature on manufacturing process planning, scheduling as well as their integration, particularly on agent-based approaches to these difficult problems. Major issues in these research areas are discussed, and research opportunities and challenges are identified.**

***Index Terms*—Agents, distributed manufacturing systems, manufacturing scheduling, multiagent systems, process planning.**

I. INTRODUCTION

MANUFACTURING process planning and scheduling are usually considered to be two separate activities in manufacturing. Manufacturing process planning determines how a product will be manufactured. It is the process of selecting and sequencing manufacturing processes and parameters so that they achieve one or more goals (e.g., lower cost, shorter processing time, etc.) and satisfy a set of domain constraints. Manufacturing scheduling, on the other hand, is the process of assigning manufacturing resources over time to the set of manufacturing processes in the process plan. It determines the most appropriate time to execute each operation, taking into account the temporal relationships between manufacturing processes and the capacity limitations of the shared manufacturing resources. The assignments also affect the optimality of a schedule with respect to criteria such as cost, tardiness, or throughput. In summary, scheduling is an optimization process where limited resources are allocated over time among both parallel and sequential activities [136]. Such an optimization process is becoming increasingly important for manufacturing enterprises to increase their productivity and profitability through greater shop floor agility to survive in a globally competitive market [98].

This paper describes the complexity of manufacturing process-planning and scheduling problems (Section II), and reviews the research literature in manufacturing process planning (Section III), manufacturing scheduling (Section IV), and the integration of process planning and scheduling (Section V), particularly focusing on agent-based approaches in these areas. Major issues in these research areas are discussed (Section VI), research opportunities and challenges addressed (Section VII), and a brief conclusion stated (Section VIII).

The objective of this paper is not to provide an extensive survey of general manufacturing process-planning and scheduling systems, but to focus on the agent-based approaches and their applications in manufacturing process planning and scheduling. An earlier survey of multiagent systems for intelligent manufacturing systems, including agent-based manufacturing process planning, scheduling, and control, can be found in [92]. More discussions on the applications of agent technology to collaborative design and manufacturing can be found in [94].

II. PROBLEM COMPLEXITY

The problem of manufacturing process planning and scheduling has been introduced in Section I. This section discusses the complexity of the problem and the difficulty in solving it.

The scheduling problem exists not only in manufacturing enterprises, but also in organizations like publishing houses, universities, hospitals, airports, and transportation companies. It is typically NP-hard, i.e., it is impossible to find an optimal solution without the use of an essentially enumerative algorithm, with computation time increasing exponentially with problem size. However, the manufacturing scheduling problem is one of the most difficult of all scheduling problems. More detailed discussions and analyses of scheduling problems can be found in [5], [29].

A well-known manufacturing scheduling problem is the classical job shop scheduling where a set of jobs and a set of machines are given. Each machine can handle at most one job at a time. Each job consists of a chain of operations, each of which needs to be processed during an uninterrupted time period of given length on a given machine. The purpose is to find the best schedule, i.e., an allocation of the operations to time intervals on the machines, that has the minimum total duration required to complete all jobs. The total number of possible solutions for a classical job shop scheduling problem with n jobs and m

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The problem becomes even more complex in the following situations.

1) When other manufacturing resources, such as operators and tools, are also considered during the scheduling process. For a classical job shop scheduling problem with n jobs, m machines, and k operators, the total number of possible solutions could be $((n!)^m)^k$.
2) When both process planning and manufacturing scheduling are to be done at the same time. Traditional approaches that treat process planning and manufacturing scheduling separately can result in suboptimal solutions for the two phases. Integrating the two phases into one optimization problem, by considering the constraints of both domains simultaneously, can theoretically result in a global optimal solution, but it increases the solution space significantly.
3) When unforeseen dynamic situations are considered. In a job shop manufacturing environment, rarely do things go as expected. The system may be asked to include additional tasks that are not anticipated, or to adapt to changes to several tasks, or to neglect certain tasks. The resources available for performing tasks are subject to changes. Certain resources can become unavailable, and additional resources can be introduced. The beginning time and the processing time of a task are also subject to variations. A task can take more or less time than anticipated, and tasks can arrive early or late. Other uncertainties include power system failures, machine failures, operator absence, and unavailability of tools and materials. An optimal schedule, generated after considerable effort, may rapidly become unacceptable because of unforeseen dynamic situations on the shop floor and a new schedule may have to be generated. This kind of rescheduling problem is also called dynamic scheduling or real-time scheduling.

III. APPROACHES TO MANUFACTURING PROCESS PLANNING

A. Traditional Approaches

Traditionally, manufacturing process planning is a task that transforms design information into manufacturing processes and determines the sequence of operations [15]. Maintaining the consistency of process plans and keeps them optimized is a difficult task. Since 1965, when Nieble [74] reported the first computer-aided process planning (CAPP) system, numerous research efforts have been reported in this area.

Generally, CAPP approaches can be classified into two categories: variant and generative. The success of the variant approach depends on group technology and computerized database retrieval. When a new part enters a factory, a previous similar process plan is retrieved from the database and modified to suit the new part. This method is especially suitable for companies with few, and relatively fixed, product families and a large number of parts per family. Most of the earlier CAPP systems can be categorized under the variant approach [2]. The generative approach, on the other hand, can be used to automatically generate an optimal process plan according to the part's features and manufacturing requirements. Most of the generative artificial intelligence techniques. They are oriented toward the needs of large companies, especially those producing products with large variety and small batch sizes. However, a truly generative process-planning system that can meet industrial needs and provide an appropriate generic framework, knowledge representation methods, and inference mechanisms has not been developed so far [134].

Various approaches to CAPP have been proposed in the literature [2], [25]. Research studies on process planning include object-oriented approaches [105], [132], GA-based approaches [70], [131], neural-network-based approaches [21], [69], Petri net-based approaches [53], feature recognition or feature-driven approaches [114], [119], and knowledge-based approaches [108], [118]. These approaches and their combinations have been applied to some specific problem domains, such as tool selection [24], [56], tool path planning [7], [45], machining parameters selection [3], [37], process sequencing [129], and setup planning [75], [125].

Recently, the research focus on process planning has shifted toward solving problems in distributed manufacturing environments. Tu *et al.* [115] introduced a method called incremental process planning (IPP) for one-of-a-kind production (OKP) in such environments. The IPP is used to extend or modify a primitive plan (a skeletal process plan) incrementally according to new features that are identified from a product design until no more new features can be found. A complete process plan generated by the IPP may include alternative processes.

B. Agent-Based Approaches

Apart from centralized AI approaches [e.g., genetic algorithms (GAs), neural networks, fuzzy logic, and expert systems], agent technology is emerging as a solution for distributed AI that has attracted a wide attention. Instead of being one large expert system, cooperative intelligent agents are being used in developing distributed CAPP systems. The agent-based approach is also being recognized as an effective way to realize adaptiveness and dynamism of process planning. The following are some examples of agent-based process-planning systems.

1) Shih and Srihari [99] proposed a distributed AI-based framework for process planning. Their approach decomposes the entire production control task into several subtasks, each of which is implemented by an intelligent agent. By working collaboratively, the agents can reach a solution for the problem.
2) CoCAPP [133], [134] was proposed to distribute complex process-planning activities to multiple specialized problem solvers and to coordinate them to solve complex problems. The CoCAPP attempts to satisfy five major requirements: autonomy, flexibility, interoperability, modularity, and scalability. It builds cooperation and coordination mechanisms into distributed agents using knowledge-based techniques. Each agent in the system deals with a relatively independent functional domain in process planning.
3) Zhang *et al.* [132] proposed an agent-based adap-

object-oriented manufacturing resources modeling (OOMRM) framework. The OOMRM describes manufacturing resources' capability and capacity in an object-oriented manner, while the AAPP is implemented as an integrated process-planning platform. Instead of automating process-planning tasks completely, the AAPP system provides an interactive mode to enable experienced manufacturing engineers to make decisions at crucial points. Five agents are used in the AAPP to carry out part information classification, manufacturing resources mapping, process planning, human planning, and machining parameter retrieval. A contract net-based scheme is utilized as the coordination protocol between agents.

4) Sluga *et al.* [102] introduced a virtual work system (VWS) as the essential building block for in a distributed manufacturing environment. The VWS represents a manufacturing work system in the information space, and is structured as an autonomous agent. It is a constituent entity of an agent network in which dynamic clusters of cooperating agents are solving manufacturing tasks. The decision-making in process planning is based on a market mechanism consisting of bidding–negotiation–contracting phases. The VWS approach aims at enabling dynamic decision-making based on the actual state of the manufacturing environment.
5) CyberCut [103] is a research project that aims at developing a networked manufacturing service for rapid part design and fabrication on the Internet. A critical part of this service is an automated process-planning module that is capable of generating process plans to satisfy the desired geometries and specified requirements. Three types of agents are designed to facilitate CyberCut: primary process-planning agent, environmental planning agent, and burr minimization tool path planning agent [22]. The multiagent planning module incorporates conventional and specialized planning agents for environmental consideration and burr minimization. However, the interactions between agents are based on human decisions.
6) IDCPPS [14] was reported to be an integrated, distributed, and cooperative process-planning system. The process-planning tasks are broken into three levels, namely, initial planning, decision-making, and detail planning. The initial planning deals with the manufacturability evaluation of a design and the generation of alternative processing routes based on feature reasoning. The decision-making level takes place when the orders have been released for production on the shop floor. The result of this step is a ranked list of near-optimal alternative plans that considers the availability of shop floor resources. The detail planning is executed just before manufacturing begins. This step finishes the final selection of machines, tools, cutting parameters, and the calculation of machining cost and time. Different functional modules are grouped into different agents, including the three process-planning agents dealing with the above three-level planning, plus the task agents, resource agents, and coordination agents (CAD/Process coordination). However, the whole framework seems to have been designed at a high level. No practical systems were reported.
7) Similarly, Lim and Zhang [55] introduced an APPSS system, which is made up of a number of agents and functional modules. This system is mainly used for the dynamic reconfiguration and optimization of resource utilization in manufacturing shop floors by considering the real-time process-planning and scheduling issues.
8) Kornienko *et al.* [50] considered process planning as a typical constraint satisfaction problem to generate an optimized plan in a distributed way satisfying all restrictions in the presence of different disturbances. An agent plays different "roles" and has a *primary algorithm* (determined by interactive pattern) and a set of *emergency states* to handle local emergencies or global emergencies. In case an agent is in emergency state recognized by the activity guard agent, it could either resolve the emergency by itself or request a rescue agent to handle it.

In addition to the above systems, there are also other similar research efforts toward agent-based process planning [78], [110]. All these systems tend to solve the process-planning problem by cooperation and negotiation among intelligent agents. The agents making up the systems usually use the function decomposition approach as described in Section VI.

IV. APPROACHES TO MANUFACTURING SCHEDULING

A. *Traditional Approaches*

Because of its highly combinatorial aspects (NP-complete), dynamic nature, and practical usefulness for industrial applications, the scheduling problem has been widely studied in the literature by various methods: heuristics, constraint propagation techniques, constraint satisfaction problem formalisms, Tabu search, simulated annealing, GAs, neural networks, fuzzy logic, etc. [136].

As direct methods are not available for complex scheduling problems, search methods are usually adopted to solve these problems. However, the simplest generate-and-test search strategy is not a reasonable approach for large complex problems. Many local search algorithms are more appropriate. These algorithms require a cost function, a neighborhood function, and an efficient method for exploring the neighborhood.

A variety of neighborhood search methods have been created including climbing, simulated annealing, etc. These methods offer heuristic refinements to the generate-and-test. Heuristic approaches try to replace the exhaustive search strategies with some sophisticated experience. With the aid of heuristics in searching strategies, good solutions (though possibly non-optimal) to hard problems can be found within greatly reduced computation time.

The Petri Net approach and its variants, due to its graphical representation and mathematical analysis of the control logic of a manufacturing system, provide a powerful approach to model, control, and schedule an automated system, in both its information flows and its material flows. Colored timed structured, reusable, and easily maintainable control/decision knowledge that can be used in scheduling/dispatching.

Constraint satisfaction is another search procedure that operates in the space of constraint sets rather than in the solution set space [59], [60], [68].

The objective of multisite scheduling [86] is to support the scheduling activities of a global scheduler or schedulers in distributed production plants in a cooperative way. A schedule generated on a global level must be translated into detailed schedules as part of the local scheduling process. In the case of a disturbance, feedback between the local and global levels is essential. Global-level data are derived from aggregated local data, and are normally imprecise or estimated.

Several approaches take advantages of search strategies in which even cost-deteriorating neighbors are accepted. Simulated annealing uses an analogy with the physical process of annealing, in which a pure lattice structure of a solid is made by heating up the solid in a heat bath until it melts, then cooling it down slowly until it solidifies into a low-energy state. As designed, simulated annealing is a randomized neighborhood search algorithm and it has been successfully applied to solve many single-objective scheduling problems. Tabu search combines deterministic iterative improvements with the possibility of accepting cost-increasing solutions occasionally—to direct the search away from local minimum [32]. In GAs, learning occurs through a solution selection process. GAs discover superior solutions to global optimization problems adaptively (akin to the evolution of organisms in the natural world) by searching for small, local improvements rather than big jumps in a solution space. Fuzzy logic-based scheduling is used to support the scheduling activities in a multisite scheduling scenario [86]. In this system, a global scheduler or schedulers in distributed production plants work in a cooperative way, based on adequate modeling and processing of imprecise data. A robust prescription is created for the local scheduling systems.

All the traditional scheduling methods, whether analytical, heuristic, or metaheuristic (including GAs, Tabu search, simulated annealing, artificial neural networks, fuzzy logics), encounter great difficulties when they are applied to real-world situations. This is because they use simplified theoretical models and are essentially centralized in the sense that all computations are carried out in a central computing unit. The intelligent agent technologies, on the other hand, suggest an innovative, lightweight approach to scheduling problems. This essentially distributed approach is more flexible, efficient, and adaptable to real-world dynamic manufacturing environments.

B. *Agent-Based Approaches*

Within the past decade, a number of researchers have applied agent technology in attempts to resolve scheduling problems. Applications include manufacturing flow shop scheduling [18], [113] and job shop scheduling [49], [59], [60], transportation scheduling [27], power distribution scheduling [44], computing resource scheduling [31], meeting scheduling [100], medical extensive bibliography on multiagent scheduling in manufacturing systems is compiled by Schiegg [88].

Agent-based approaches have several potential advantages for distributed manufacturing scheduling [95].

a) These approaches use parallel computation through a large number of processors, which may provide scheduling systems with high efficiency and robustness.
b) They can facilitate the integration of manufacturing process planning and scheduling.
c) They make it possible for individual resources to trade off local performance to improve global performance, leading to cooperative scheduling.
d) Resource agents may be connected directly to physical devices they represented for so as to realize real-time dynamic rescheduling (of course, not immediate rescheduling after any change in the working environment for the sake of system stability). It may therefore provide the manufacturing system with higher reliability and device fault tolerance.
e) Schedules are achieved by using mechanisms similar to those being used in manufacturing supply chains (i.e., negotiation rather than search). In this way, the manufacturing capabilities of manufacturers can be directly connected to each other and optimization is possible at the supply chain level, in addition to the shop floor level and the enterprise level.
f) Other techniques may be adopted at certain levels for decision-making, e.g., simulated annealing [48] and GAs [33], [96].

C. *Research Literature on Agent-Based Manufacturing Scheduling*

Research in agent-based manufacturing scheduling has been more active and has a richer literature base than that in agent-based manufacturing process planning. This section provides a detailed review in a structured way.

1) Earlier Attempts: Shaw may be the first person who proposed using agents in manufacturing scheduling and factory control. He suggested that a manufacturing cell could subcontract work to other cells through a bidding mechanism [89], [90]. Yet Another Manufacturing System (YAMS) [80] is another example of an early agent-based manufacturing system, wherein each factory and factory component is represented as an agent. Each individual agent has a collection of plans as well as knowledge about its own capabilities. The Contact Net protocol [104] is used for interagent negotiation.

2) Methodologies and Techniques: Different methodologies and techniques have been proposed, developed, and used in the literature for agent-based manufacturing scheduling.

a) CORTES [84], [111] uses micro-opportunistic techniques for solving the scheduling problem through a two-agent system, where each agent is responsible for scheduling a set of jobs and for monitoring a set of resources.
b) Baker [6] proposed a market-driven contract net for heterarchical agent-based scheduling. This agent architecture

c) Logistics Management System (LMS) [28] applies integration decision technologies to dispatch-scheduling in semiconductor manufacturing. It uses functional agents, one for each production constraint, and a judge agent to combine the votes of all the perspectives. Each agent partially models those aspects of the environment that are needed to satisfy its objective. Its uniqueness is a voting protocol for communication among agents.

d) Liu and Sycara [59] proposed a coordination mechanism called Constraint Partition and Coordinated Reaction (CP&CR) for job shop constraint satisfaction. This system assigns each resource to a resource agent responsible for enforcing capacity constraints on the resource, and each job to a job agent responsible for enforcing temporal precedence and release-date constraints within each job. Moreover, a coordination mechanism called Anchor&Ascend is proposed for distributed constraint optimization. Anchor&Ascend employs an anchor agent to conduct local optimization of its subsolution and interacts with other agents that perform constraint satisfaction through CP&CR to achieve global optimization [60].

e) In AARIA [79], the manufacturing capabilities (e.g., people, machines, and parts) are encapsulated as autonomous agents. Each agent seamlessly interoperates with other agents in and outside the factory boundary. AARIA used a mixture of heuristic scheduling techniques: forward/backward scheduling, simulation scheduling, and intelligent scheduling. Scheduling is performed by job, resource, and operation.

f) Miyashita [68] proposed an integrated architecture for distributed planning and scheduling using the repair-based methodology together with the constraint-based mechanism of dynamic coalition formation among agents. A prototype system called CAMPS is implemented, in which a set of intelligent agents try to coordinate their actions for satisfying planning/scheduling results by handling several intra- and interagent constraints.

g) Usher [116] presented an experimental approach for performance analysis of a multiagent system for job routing in job-shop settings: i) under various information levels for constructing and evaluating bids, and ii) under actual real-time process data for the negotiation process. Some simple but practical mechanisms are proposed and implemented.

h) Lu and Yih [61] proposed a framework that utilizes autonomous agents and weighted functions for distributed decision-making in elevator manufacturing and assembly. This system dynamically adjusts the priorities of subassemblies in the queue buffer of a cell by considering the real-time status of all subassemblies in the same order.

i) In [4], an agent-based scheduling system, incorporating game theoretic based agent cooperation, is presented to solve the n-job three-stage flexible flow shop scheduling problem. With scheduling task represented by a series of digraphs, MIP (mixed integer programming, minimizing makespan) is used by individual agents to schedule their jobs, and the final solution is reached by agent cooperation

3) Approaches and Architectures: To satisfy the requirements for next-generation manufacturing systems, researchers have proposed and developed a number of approaches and architectures for agent-based manufacturing scheduling and control.

a) Burke and Prosser [10] described a distributed asynchronous scheduling (DAS) system. The DAS architecture consists of three types of entities: knowledge resources, agents, and a constraint maintenance system. The agents were originally developed as a multiagent heterarchy to represent only resources (O-agents). The final development includes agents for aggregations of resources (T-agents) and an agent for overseeing the whole scheduling process (S-agent). This final scheduling system organizes agents into a hierarchical architecture, in which the S-agent assigns operations to the T-agents and the T-agents assign these operations further to O-agents, respectively. While DAS is able to make a correct schedule, however, it has no method for optimizing that schedule.

b) Scheduling in architecture for distributed dynamic manufacturing scheduling (ADDYMS) is decomposed into two levels [12]: the first level involves the assignment of a manufacturing work cell to a task, and the second consists of the determination of a local resource as well as other aspects, such as workers and tools, which may possibly be shared among a number of work cells. Corresponding to these two levels, there are two kinds of agents: site agents and resource agents. The system is composed of several connected site agents, each of which is in turn connected with its subsite agents and some local resource agents.

c) Lin and Solberg [58] showed how a market-like control model could be used for adaptive resource allocation and distributed scheduling. They modeled the manufacturing shop floor exactly like a market place, where each task agent enters the market carrying certain "currency" and bargains with each resource agent on which it can be proposed. At the same time, each resource agent competes with other agents to get a more "valuable" job. The market mechanism, using multiple-way and multiple-step negotiation, is incorporated to coordinate different agents, including part agents, resource agents, database agents, and communication agents.

d) Interrante and Rochowiak [43] proposed using active scheduling in the development of a multiagent architecture for dynamic manufacturing scheduling.

e) Murthy *et al.* [72] described an agent-based scheduling system based on the A-team architecture, in which functional agents generate, evaluate, improve, and prune a pool of candidate solutions. This system can be considered to be a blackboard system.

f) Kouiss *et al.* [49] proposed a multiagent architecture for dynamic job shop scheduling. Each agent represents a work center and performs a local dynamic scheduling by applying an adaptive dispatching rule. Depending on local and global considerations, a new selection of dispatching rule is carried out when a predefined event occurs. The selection method is improved through the optimization of

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