A New Agents-Based Model for Dynamic Job Allocation in Manufacturing Shopfloors

M. Owliya, Mozafar Saadat, Rachid Anane, and M. Goharian

***Abstract*—Market-based mechanisms such as the contract net protocol (CNP) are very popular for dynamic job allocation in distributed manufacturing control and scheduling. The CNP can be deployed with different configurations of the system elements. Every configuration corresponds to a basic or a hybrid topology. The subject of topology is generally discussed in the field of "distributed systems." Inspired from the notion of topology in the distributed systems, this paper proposes a ring-like model as a competitor for the web-like CNP-based job allocation within the concept of holonic manufacturing systems. Details of the algorithm for scheduling and assignment of jobs to resources in the ring structure is presented and its performance is compared with both CNP-based distributed model, and the centralized conventional scheduling of a real manufacturing case study involving a major turbine production plant. Comparison of performance indicators such as time and cost of operations shows that the distributed models clearly outperform the conventional practice with meaningful impact on the production economy. As a possible implementation strategy, a hybrid switching model, composed of both competing models, is proposed.**

***Index Terms*—Agent, holon, job allocation, manufacturing, topology.**

I. Introduction

UNCERTAINTIES in modern markets have pushed manufacturing systems to be more efficient and flexible, causing emergence of new scheduling and control philosophies. Information technology has assisted this transformation with providing powerful enabling tools. Holonic and agent-based systems in manufacturing are among the most promising solutions suggested by researchers. They have many characteristics in common, although the former stems from a philosophical control approach, while the latter is rather a distributed artificial intelligence tool [1]. Agent-based manufacturing can cover the holonic manufacturing philosophy and provide a technology platform for its implementation [2]. Both concepts oppose conventional centralized decision making, and increase adaptability and responsiveness to changes and disturbances.

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Manufacturing job/resource allocation using holon or agent concepts has been widely researched and presented in the relevant literature. Market-based algorithms such as the contract net protocol (CNP) in many variations are extensively used; but methods other than the CNP have been rarely presented. This research proposes a new insight into this issue, inspired by the notion of topology in the "distributed systems." The model developed in this way becomes applicable where types of jobs and capabilities of resources vary. A typical example is a manufacturing shopfloor where different types and sizes of CNC machine tools and assembly stations produce various parts from different raw materials. Considering the above-mentioned relationship between multiagent system (MAS) and holonic manufacturing system (HMS), the model uses agent-based methods and tools for development purposes, but takes the advantage of HMS philosophy in presentation. This is because the holonic notion has a distinct capability to map and present the real manufacturing environment.

This paper is structured as follows. Section II delivers a review on the basic concepts of holonic and multiagent systems. Manufacturing scheduling, and more specifically, dynamic job allocation in HMS is reviewed including its correlation to system's topology. Section II presents the concept and details of the models introduced in this paper for job allocation in holonic manufacturing. The models are then evaluated in Section IV, where their agent-based simulation and an industrial case study are presented for models' evaluation through a number of experimentations. Having analyzed the capability of both models, they were integrated such that they complement each other in a hybrid system.

II. Job Allocation in Holonic Manufacturing System

A manufacturing system consists of a variety of interrelated entities, including machines, work centers, parts, products, transport equipment, and labor. In holonic manufacturing systems, these entities can be considered as holons provided that they have characteristics such as autonomy and cooperation [3]–[5].

A holon has a self-similar fractal structure of its subholons, interacting with other holons in a holonic organization referred to as holarchy. A holarchy combines order and stability of hierarchical systems with flexibility of fully distributed flat structures (heterarchies). In such a structure holons are independent, and can make decisions with minimum interference and control by their higher levels [6].

The manufacturing system entities could also be represented by agents. An agent is a software program that, like a holon, operates autonomously in an environment and has its own objectives. An agent has control over its actions and internal state [7]. An organization of interacting agents is referred to as MAS. The agents within a MAS normally need to cooperate with one another to solve the intended problem. The cooperation requires interaction between them. This will lead to the formation of a network [8].

The network may be formed in different applications and contexts. For instance, a multiagent system for distributed manufacturing supply chain has been developed [9], while an agent-based distributed control system for workshop machines has been suggested to help cope with dynamic environments [10]. Agent networks are also very common for resources allocation using market mechanisms [11], [12].

One important difference between agents and holons is that a holon can be composed of a set of holons again, while an agent cannot be divided into some other agents [6]. However, in solving many problems they can be used interchangeably [2], [13].

In general, the scheduling problem in manufacturing consists of planning shopfloor activities over time while considering availability and capacity constraints of resources. In practice, manufacturing scheduling is a short-term allocation of tasks to resources to determine which task is to be performed when, and on which resource [14]. In reality in a manufacturing environment many disturbances occur during the running schedule such as, for example, rush orders, machines breakdown, quality problems, and raw material shortage. This therefore calls for the allocation plan to be *dynamic*.

Further, manufacturing scheduling can be seen as a distributed problem from physical as well as logical points of view [15]. It can benefit from *distributed* methods that improve its reaction to disturbance and allow parallel computing [14]. In distributed methods, scheduling algorithm is distributed over a number of system elements, and their collective knowledge and scheduling power contribute to the overall performance of the system. Distribution is linked to the system and decision making aspect, while decentralization is the term normally used for physical elements and operational units [16]. In manufacturing, decentralized entities can naturally help distribution of scheduling and job allocation.

The holonic and agent-based paradigms support both the required attributes, i.e., dynamism and distribution. These methods combine central rules with distributed strategies to improve responsiveness, instead of using only central optimized and complex scheduling algorithms [17]. In a recent survey on dynamic scheduling techniques, multiagent-based scheduling has been identified as holding a prominent position by researchers [18]. One of the earliest attempts to use distributed dynamic approach in manufacturing by deploying agent-based concept was the work by Parunak [19]. That research used the CNP for assignment of jobs to machines. Later, a market-like agent model for resource allocation was suggested, which allowed multistep negotiation between parts and resources [20].

In the 1990s, HMS emerged from a joint international initiative on intelligent manufacturing systems [21]–[23]. It was based on the concept of holonic systems as an organization of holons that collaborate with one another toward the overall system goal. HMS has been extended in various aspects of manufacturing activity from shop floor to enterprise integration, virtual enterprises and supply chain, with a particular focus on scheduling and control issues [24].

Job allocation techniques proposed in the context of HMS are similar to those of agent-based manufacturing. They are mostly based on market mechanism and fall into two categories: order driven (job allocation) and resource driven (resource allocation) [1]. Market-based algorithms for planning/scheduling applications normally form star-like or web-like contract net [25]. This is naturally due to interaction among the net entities. One-buyer, multiple-sellers spontaneously lead to a star-like topology; while multiple-buyers, multiple-sellers form a web of interacting entities.

Despite the popularity and advantages that market mechanism has, it has some drawbacks such as difficulty to guarantee avoidance of extreme situations [1]. In the contract net protocol, the number of interactions and messages remarkably increase when there are a large number of agents. This requires more processing time for the messages when compared with the time needed to perform the actual work [26]. There are also concerns about the system to lock due to flood of messages. Limited tender instead of unlimited broadcast of jobs, having the resources' typical bids in advance, group formation in resource holons, and task prioritization are amongst the strategies suggested to overcome such concerns [26]. However, the concerns are not critical when dealing with real manufacturing applications, where a limited and sensible number of resources exist.

Taking into consideration various topologies in a distributed system, it would be possible to define alternative job allocation models. For example, Minar's work [27], which included a series of basic and hybrid topologies, would be of relevance here. In this paper, the topology is presented as a basic element in the system function, whether it is physical or logical. Here a classification of the topologies for distributed systems is presented, in which ring-based basic or hybrid topologies are prominent. The ring has the advantages of fault tolerance and simple scalability when compared with the star topology, although the combination of both offers both power and simplicity [27]. In other words, the ring can fairly enhance the popular star architecture. More recently, Zhang *et al.* [28], [29] have classified agent network topologies into three general categories: centralized, decentralized, and hybrid, to complete the work by Minar. They generally believed that the topology issue is of high importance in agent communication and cooperation. Switching interaction topology of multiagent systems has already been considered in previous works [30], [31]. However, they did not address the standard network structures and interaction protocols for the job allocation investigated in this research.

III. Models for Holonic Job Allocation

Given the two different types of arrangement and interaction of resource holons, this section discusses two models for job allocation. The first model is a web-like topology based on the established CNP. The second model, however, is a proposed ring topology with peer-to-peer interaction capability. This is a new model for job allocation whose performance will be evaluated in a subjective comparison with both the CNP-based model, and the conventional scheduling practice. The two models are elaborated in the following subsections.

Irrespective of the models used, the holonic terms based on PROSA reference architecture [4] imply that once an order is launched by the order holon, product holon provides the necessary information of the relevant product. These are, for instance, bill of material and product tree information, process plans, geometrical data, and standard operation times (including setup and transport). Here a set of different parts to be produced (order subholons or tasks) is formed, which contains the part specifications. The tasks that may have some dependence on one another according to the process plans shall be allocated to the available resource holons for execution in specified time limits. Penalty charges are due for violating the time limits. Therefore, the tasks are prioritized prior to starting the allocation process. The priority is determined by the critical path, chain of prerequisites, and margin to the due time. More specifically, the following rules are implemented in building the models:

1) in a series of tasks to be allocated, those in the critical path have the highest priority, with the next priority given to the tasks with fewer margins left to due time;
2) task dependence is to be observed—i.e., all prerequisite tasks are carried out prior to the main task;
3) each resource cannot simultaneously operate on more than one task.

Another fact to be considered in the models is that some of the parts may not be able to start at time zero due to unavailability of their required raw material or any other reason. Resource holons (representing the machines) each have their own technical capabilities, constraints, and associated costs (operational and idleness, which carry different rates for each machine). They have autonomy in decision making, with specified criteria, and are capable of cooperating toward the overall system goal. The system goal plans and performs all jobs with minimum total time and cost.

A. CNP-Based Model

As discussed in Section II, allocation of jobs to the resource holons is usually done through bidding mechanisms. The CNP is very common for such purposes, although its implementation details may vary in different applications [32]. In an efficient CNP-based model for dynamic job allocation, the resource holons are normally interconnected as a web-like network of autonomous cooperating peers, where each can act as a manager and/or a contractor resource for job execution. This makes the model highly robust due to redundancy of autonomous resource/manager (R/M) holons [25].

Job allocation based on CNP can be properly performed with each peer taking the role of manager (R/M) in this autonomous architecture. The only problem, however, is the lack of a global view, which is necessary for coordination and optimization of the schedules. To tackle this problem, a mediator or higher level supervisor is added in order to coordinate the behavior of local holons for a global dynamic scheduling [18]. The mediator is able to advise or overrule the decisions taken by the resource holons for achieving the whole system goals or resolving any conflict. The peer-to-peer autonomous architecture of the local resource holons provides resilience against unexpected events, while at the same time the mediator improves the global performance. Cooperation among resource holons can be appropriately realized through combination of this mediation mechanism with the CNP [18].

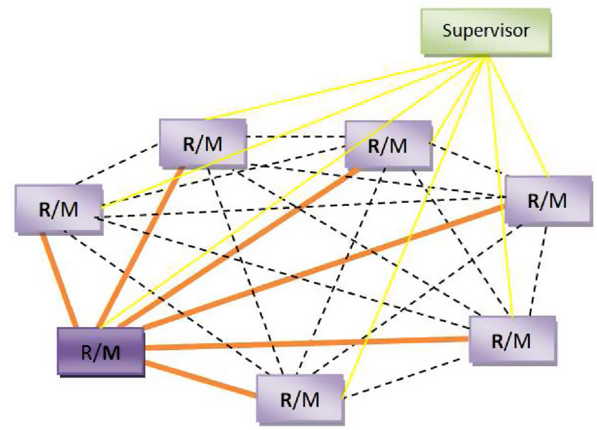

Fig. 1. CNP-based model.

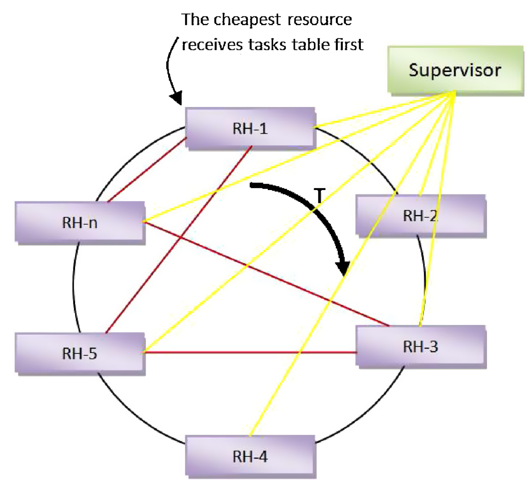

Fig. 2. Ring arrangement of the resource holons.

The resource holons consist of two parts: a decision making and scheduling part, and a physical component (e.g., machines). The nonphysical part could be a class object in an object oriented software or an agent in a multiagent system. The two portions can act in parallel, allowing the holon to execute tasks at the same time as it is engaged with scheduling and allocation process. The mediator, however, has a control function only, without a physical part. This is a rule holon or "software-only holon" [24], or "explicit control entity" [33]. It also has a global knowledge of tasks and available resources.

In the model, at the first step, the mediator or supervisor holon distributes the incoming set of tasks among all peers so that the condition of sequential processes for production

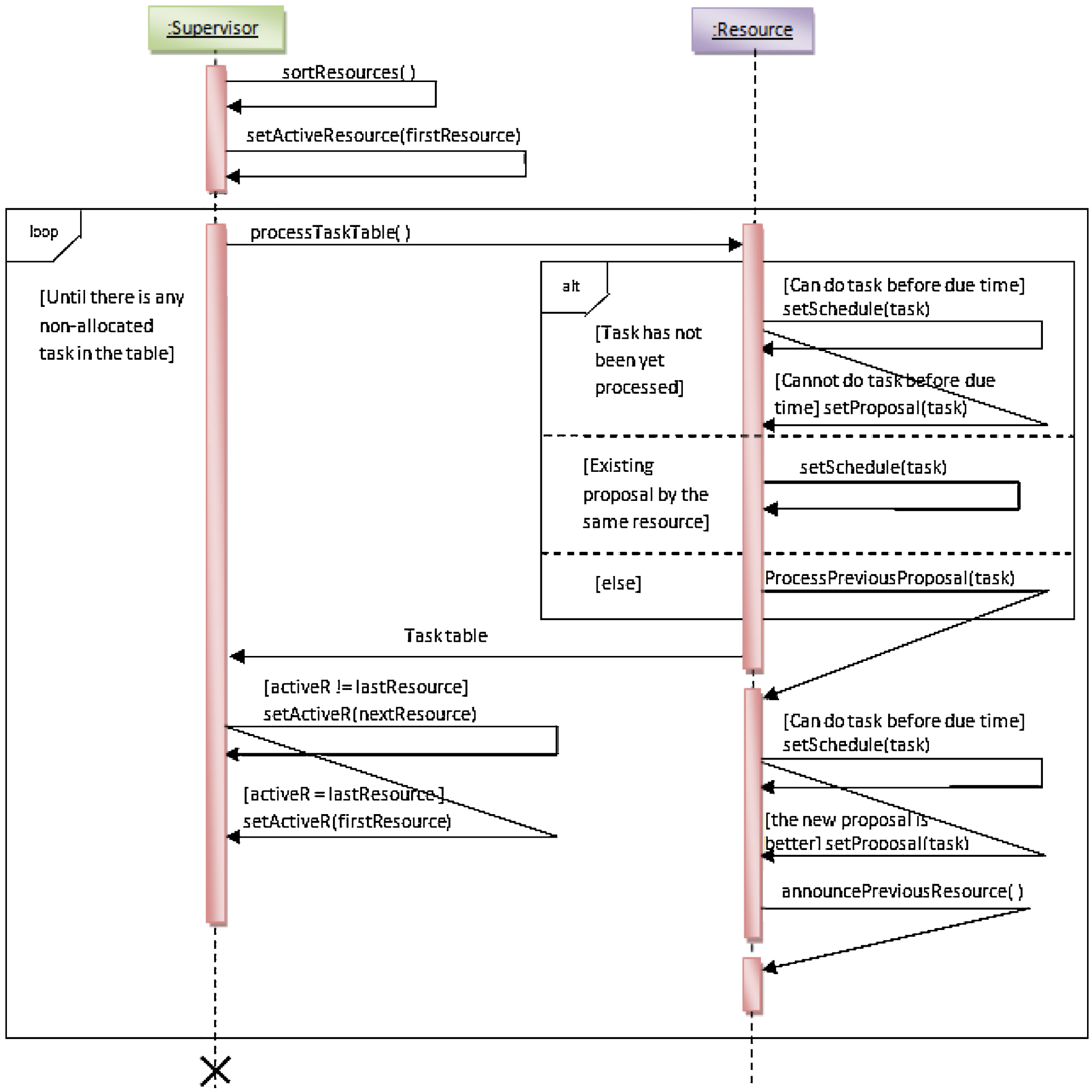

Fig. 3. UML sequence diagram for the proposed model.

of a part (dependence of the tasks) is duly considered. This initial distribution is not of course the intended task allocation. In the next step, each holon having a task list in hand after the initial distribution acts as a manager and uses CNP for negotiation and task allocation to achieve the final schedule. As depicted in Fig. 1, every holon has a connection to all others for interactions required by CNP. When a holon plays a manager role, it asks all available resources to bid for a task. Then, the processes of bidding, bid evaluation, decision making, awarding contract, and informing will follow as per the CNP.

B. Proposed Model Based on Ring-Like Topology

The proposed model in this research is based on a ring-like topology with an algorithm different to the CNP. This means that resource holons are basically arranged to form a ring as illustrated in Fig. 2. In this model, through the information from order and product holons, a table of tasks to be carried out is created for a manufacturing order. The table includes details and specifications of the tasks, which are prioritized as per the rules specified above. Here, a supervisor holon similar to the previous model exists. The supervisor circulates the prioritized task table in the ring among the resource holons (RHs) successively (like a ring token) and monitors it. Resource holons are sorted in the ring by the rates of their operating cost, which is a known factor for each machine based on its depreciation of investment together with the running costs. The RH with the lowest operating cost receives the token first (for instance, RH-1 as the cheapest resource in Fig. 2).

Each resource that holds the token at a given time reviews the tasks remained in the table, and finds the ones that match its technical capabilities. The matching is done in this stage by using if-then inference, which checks for the manufacturing process (turning, milling, assembly, and so on) required by the part and its geometry. Capability of the resource must be higher than, or equal to, what is needed by the part. A resource larger than what is required causes a cost increase. However, the time factor is of highest importance and overrules the increased cost if necessary. The resource then takes out all the tasks that can be performed within their due times with a selfish and greedy behavior, adds them to its local schedule, and starts performing the one with the highest priority. Each resource cannot be working on more than one task (operation) at a given time. If necessary, selfishness of the resource holons may be moderated toward the overall goal of the system by the supervisor holon. This will depend on the quantity and nature of the tasks set.

Furthermore, the RH leaves a proposal for other tasks that have been unable to be completed prior to their due times. Therefore, the next RH that receives the table, and that is unable to satisfy the due times, compares the remaining proposal with that of its own, and decides which to be kept in the task table for further circulation (the worse proposal will be omitted). In this model, the resource holons can interact with all their peers in the ring structure whenever needed (this is shown by the diagonal lines between RHs in Fig. 2). For instance, when a holon has replaced its own proposal for a task, it will notify the holon that had set the previous proposal, to update its local schedule. Each resource has its local schedule, in which tasks' IDs are saved together with all other attributes of the tasks undertaken, or those for which a proposal is offered. The table will be passed on to the next RH until all tasks are assigned. The logical behavior of the allocation process mentioned above is shown in the UML sequence diagram of Fig. 3.

The solution described above is a new approach to distributed task allocation using a ring structure with advantage of peer to peer interactions. It is completely different to the CNP, although it still uses a bidding mechanism to a limited extent. In the next section, this model is compared with CNP-based model using a number of performance indicators. Both models are then compared against the conventional scheduling practice of a real manufacturing shopfloor in an industrial case study.

IV. Evaluation of the Model

This section evaluates the ring-like model of dynamic job allocation, by comparing its results against the CNP-based model, and the scenario of a conventional manufacturing practice. The comparison has been made possible through a series of agent-based simulation experiments, and data from an industrial case study as explained below.

A. Experimentation Platform

The system used for simulation of the models and respective experiments is a Java-based software constructed using Repast agent simulation toolkit [34]. Repast is a well-known open source platform developed at the University of Chicago, Chicago, IL. The agents in the simulation system of this research represent their counterpart holons of a holonic manufacturing system as shown in Fig. 4. Here, the resource agents in the system have two components: one for scheduling and decision making, and the other for operation (task execution).

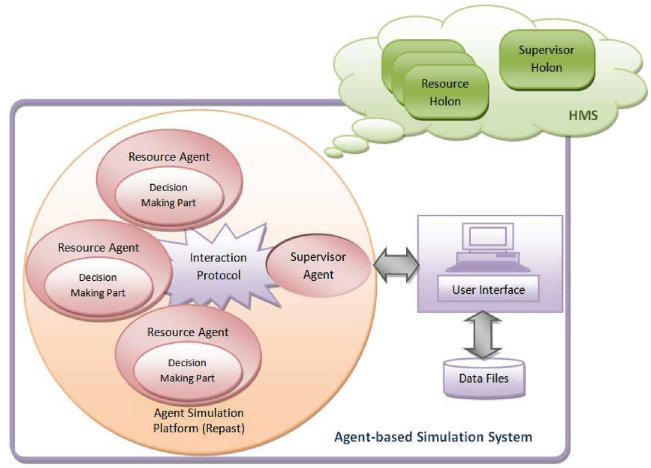

Fig. 4. Overall architecture of simulation system.

B. Description of the Case Study

To perform experiments and evaluate the models, the research utilizes data of a case study involving a manufacturing shopfloor of heavy-duty turbines for power generation industry. Operations in the shopfloor consist of various machining (turning, milling, and boring), as well as preassembly processes on the parts of the product. Incoming material to the shopfloor is cast, forged, or welded parts, requiring to be machined with CNC machine tools. Many operations are dependent on prerequisite operations specified by the process plans. Table I gives a data set of the tasks from the case study, which are processed on the required workstations (resources) of different sizes, costs, and capabilities.

Performance of an allocation plan in such a manufacturing environment is normally judged through a number of performance indicators, such as time, cost, and utilization of the machinery. Time is usually the most important indicator in the majority of occasions. It specifies the maximum time of completing a manufacturing order (a set of parts composing a product or one of its subassemblies). A manufacturing process for making each part is referred to as a task to be assigned to the available resources. For every single task, the standard operation time, the due time, and the penalty charge in case it exceeds due time are known.

C. Results and Discussion

A set of 30 experiments have been carried out and organized in the simulation system. A diverse range of scenarios for manufacturing orders have been implemented in the experiments in order to obtain various results. All test results have been averaged to produce a cumulative comparison between the models. In addition to comparing the ring-like model with the CNP-based, it is important to see how it performs against the usual scheduling practice of the manufacturing shopfloor. Therefore, a simulation of the real-world manufacturing planning has also been performed using the industrial case study data.

Table II illustrates the results of the 30 experiments for each model, as well as conventional practice of the case study. The output data are averaged to give an overall estimation about the models, and then normalized to a percentage scale (average/max average*100), for a comparison in the chart of Fig. 5. The three right-hand-side columns of Table II, however,

TABLE I
DATA FROM THE INDUSTRIAL CASE STUDY

Task ID	Start Time	Operation Hours	Due Time	Manufacturing Process
1	0	65	250	Turning
2	0	93	300	Turning
3	0	73	280	Turning
4	0	181	370	Turning
5	0	98	190	Turning
6	0	98	210	Turning
7	0	137	300	Turning
8	0	9	440	Turning
9	0	9	300	Turning
10	0	10	300	Turning
11	30	221	300	Turning
12	0	160	520	Turning
13	0	146	400	Turning
14	0	39	180	Turning
15	20	19	300	Turning
16	0	203	330	Turning
17	0	229	330	Turning
18	0	82	400	Turning
19	0	39	500	Turning
20	0	71	530	Turning
21	0	76	280	Milling
22	0	132	420	Milling
23	0	73	230	Milling
24	0	146	150	Milling
25	0	151	200	Milling
26	0	180	200	Milling
27	0	183	190	Milling
28	0	83	90	Milling
29	0	99	110	Milling
30	0	130	150	Milling
31	0	320	350	Milling
32	0	238	250	Milling

TABLE II
EXPERIMENTAL RESULTS (TIME IN HOURS)

No. of Experiments	CNP-Based Model	Ring-Like Model	Conven. Practice	CNP-Based Model	Ring-Like Model	Conven. Practice
1	753	745	801			
2	732	841	905			
3	654	512	750	713	699	819
4	753	745	755			
5	681	727	758			
6	578	558	581	692	688	758
7	853	745	855			
8	853	811	876			
9	853	801	884	746	721	796
10	947	898	961			
11	853	834	859			
12	853	848	854	780	755	820
13	853	846	855			
14	753	846	841			
15	1009	920	1015	799	778	837
16	792	745	904			
17	625	633	653			
18	625	586	611	779	758	818
19	625	589	628			
20	625	590	592			
21	625	633	640	757	736	789
22	625	589	631			
23	625	589	631			
24	587	606	618	739	718	769
25	580	606	671			
26	580	606	611			
27	580	512	585	721	702	753
28	580	613	619			
29	580	621	650			
30	580	621	650	707	694	741
Average:	707	694	741			
Ave. (%):	95	94	100			

contain step-by-step averaging of the results. The uniform trend of the averages gives sufficient confidence in the number of experiments performed.

In general, the agent-based models exhibit their dominance with respect to the conventional practice. Both models outperform conventional practice at least by 5%, as shown in Fig. 5, for the average total time elapsed to complete the manufacturing order. The better performance over conventional practice can also be seen in almost every individual experiment given in Table II. Although results of the ring-like model exhibit a slight advantage over the CNP-based model, no significant difference could be concluded in terms of mean or variance of the two sets of results. Depending to the condition of the task allocation case, one of the models may lead to a better performance, but with no one showing an absolute dominance over the other. Utilization of the relative advantage of one model in each single case is therefore important. The platform presented in Section VI is presented to realize this idea.

Cost of manufacture is another key factor that is compared in Fig. 6. The results show that the agent-based job allocation models are very close to one another, and no meaningful difference in their performance could be recognized. However, both are 3% better than the cost resulted from the conventional workshop scheduling. It should be mentioned that the cost

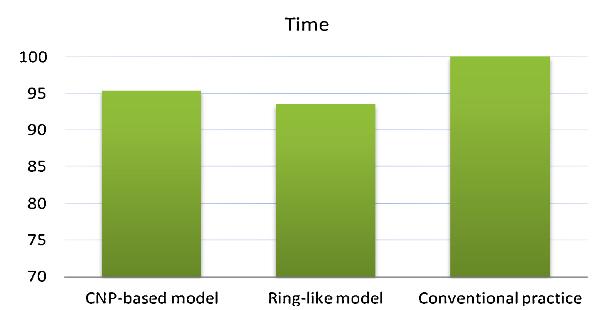

Fig. 5. Comparison of models for the total time of accomplishing the order.

parameter is not independent of the time spent on the execution of an order. However, the slight difference between the "time" and "cost" results is due to the fact that cost is not only associated with the operation of the machines, but also with their idleness, as well as the penalty charge to the resources when they pass due times. The small percentage differences in either time or cost will have significant impact on operational costs of the factory. This will be visualized through examples in Section V.

Fig. 7 shows the comparative results of resource utilization in percentage. Again, the results for both agent-based models considered are close to each other, although the CNP-based

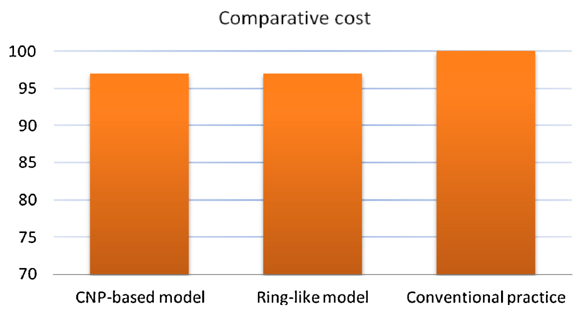

Fig. 6. Total operational cost (normalized).

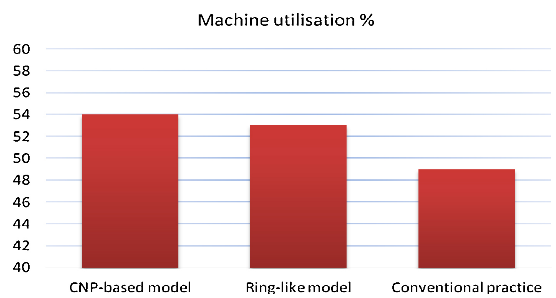

Fig. 7. Utilization (busyness) of the machines.

model offers a slight advantage. However, both have utilized the machines more by at least 4% on average, when compared with the outcome of the conventional scheduling for the same orders in the case study.

In summary, the proposed ring-like model, together with the CNP-based, offers higher performance compared to the conventional practice in the case study. The next section will put the results in context, and discusses the significant impact that such efficiency gains will have on the production economy of the manufacturing plant considered in the case study.

V. Further Clarifications on the Real-World Impact

Better scheduling and allocation of machines in each method leads to more performance of the machines, and subsequently, to a higher overall equipment effectiveness, which is a major key performance indicator of the manufacturing plant. To appreciate the order of difference that the small percentage figures can make in operation of a real practical case, some typical indications are presented in Table III.

Annual production rate of the shopfloor used in the case study of this research is 20 large scale turbines. This rate demands around 200 000 operation hours per year in the casings and stationary parts workshops used for the purpose of this paper. Therefore, a 5–6% time saving (Fig. 5) equals 10 000–12 000 h, which means around 1.5 times annual capacity of one CNC workstation in the plant. Considering the cost of adding one machine of similar type, this results in the saving of at least £2M investment costs. An additional benefit includes decreasing the product delivery lead time. Further, Fig. 6 illustrates that the two agent-based models are more cost effective than the conventional practice by 3%. This suggests that the workshop operational cost that is almost £10M a year will have a £300k annual saving.

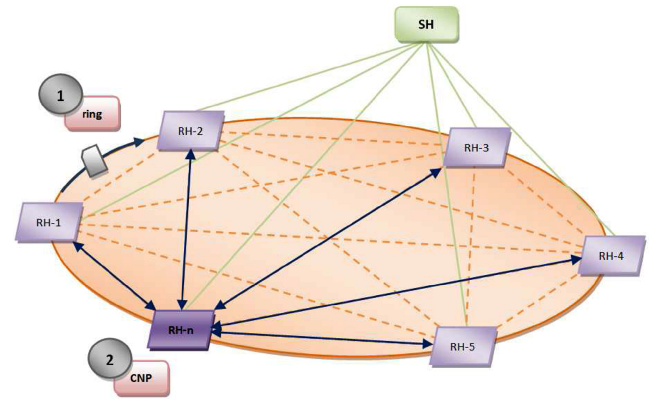

Fig. 8. Hybrid switching model.

TABLE III
Typical Savings Compared With the Conventional Practice

	CNP-Based Model	Ring-Like Model
Time	10 000 machining hours per year	12 000 machining hours per year
Operational cost	£300k per year	£300k per year

VI. Overview of a Possible Implementation Strategy

The ring-like model seriously contends with the established CNP-based model, as shown in Section IV-C. This section attempts to utilize advantages of both the job allocation models in holonic manufacturing. This is achieved by pairing them in a hybrid switching model, allowing them to compete for the best performance on a case-by-case manufacturing scenario against the associated key performance indicators. The solution will offer the best fit model expected to reduce both time and cost of manufacturing operations. This is shown in Fig. 8.

The RHs are arranged around the ring, and every RH is connected to others for possible peer-to-peer interactions. A supervisor holon at the top maintains its connection with all RHs for the relevant coordination as defined in each model (given in Section III). It does not have a direct decision making role in the task allocation process. Two scenarios exist in Fig. 8: scenario 1 with circumferential movement of the token using all rules and algorithm of the ring-like model, while scenario 2 runs the contract net protocol over the web of interacting holons as described earlier. For every specific case and manufacturing data provided, both scenarios can be run in agent-based simulation, their results compared, and the more appropriate one is selected for manufacturing operation. The model can simply switch between the ring-like and CNP-based solutions depending on their performance for each specific situation. By choosing the most important and desired manufacturing performance indicator (time, cost, and so on) in a given situation, the best solution will be offered by the system.

VII. Conclusion

This paper presented a new model for dynamic job allocation among resource holons within the concept of holonic manufacturing system. The model is based on a ring topology of the resource holons, monitored by a supervisor holon. Based on the ring structure, a new algorithm was developed for scheduling and the assignment of tasks to resources. This was proved to be comparable when compared with a job allocation model based on the established CNP. Both models competed closely in terms of manufacturing performance indicators, including time and cost, when simulated and tested using the data from a real turbine manufacturing plant. Both models exhibited advantages over the plant's conventional scheduling practice in terms of time, cost and resource utilization, and resulted in significant production efficiency gains. This paper suggested a hybrid model whereby the two individual models will compete for specific performance indicators in any particular manufacturing scenario.

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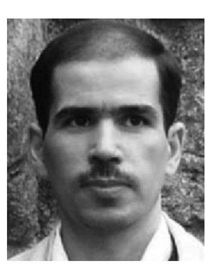

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