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Implementation of agent based holonic control in discrete manufacturing

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A B S T R A C T

The present paper is aimed at implementation of agent based holonic manufacturing control, a Distributed Problem Solving (DPS) approach that relies on the principle of dynamic team formation through negotiation and cooperation by a group of intelligent system entities. A holonic system comprising product holon, resource holon, and integrated process planning and scheduling holon is developed to execute a customer order where negotiation based task allocation and scheduling is accomplished by Contract Net Protocol (CNP). The bids submitted by the resources are evaluated by Simple Additive Weight (SAW) technique under Fuzzy Multi Criteria Decision Making (FMCDM) environment. The priority of the products is established by the critical ratios (CR) to form the basis of scheduling rule. The necessary message based communication is accomplished using eXtensible Markup Language (XML) having specific Document Type Definition (DTD). The control is implemented by Linux operating system with Java.

A R T I C L E I N F O

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1. Introduction

Ever increasing market demands to meet stringent customer requirements together with socio-economic changes have compelled the business houses to practice new and innovative approaches that would be commensurable with the business trends and help sustain in the highly tumultuous global market. The present day's manufacturing business fraternity is characterized by increasingly complex customized product, constant product innovation, different volume mix, smaller batch sizes, improved quality and shorter lead time [1]. The manufacturing enterprises therefore ought to thrive for new control strategies that can provide reasonably good solution to tackle the situation. This eventually calls for a new system approach and methodology that would be reconfigurable, can offer adequate robustness and high degree of flexibility, remain fault tolerant, yet economical [2, 3].

Holonic control is a trade-off between hierarchical and heterarchical approach that successfully blends their merits to combat the challenges by offering high degrees of flexibility and preserving robustness in view of disturbances [4, 5]. The system utilizes a number of intelligent modules to undertake negotiation and cooperation based work by virtue of which these modules are capable of intelligent decision making as and when required to realize flexible manufacturing.

The paper presents a Multi Agent System (MAS) based holonic manufacturing control for task allocations through negotiation and to prepare local schedules for execution of customer orders.

The well known Contract Net Protocol (CNP) is followed for the purpose of negotiation and bidding. The merit of various resources is evaluated in the light of several criteria having varying degree of importance. The evaluation and ranking of the resources is carried out by Simple Additive Weight (SAW) method under FMCDM paradigm and the priority of the products are established by critical ratios. The necessary communications among the agents are established by XML following specific ontology. The execution is implemented considering Linux as operating system and Java as a tool.

2. Holonic manufacturing and multi agent system

Holonic Manufacturing System (HMS) was developed in the framework of Intelligent Manufacturing System (IMS) that is promised to offer very high degrees of flexibility by undertaking negotiation and cooperation based work. It is a hybrid control structure to derive the benefits of the hierarchical and heterarchical control simultaneously in the sense that it retains the stability and guaranteed performance of the former and ensures flexibility and adaptability of the later [4, 5]. This system relies on the principle of Distributed Problem Solving (DPS) [6] where a set of modules called holons negotiate and cooperate dynamically amongst themselves to carry out a specific task.

The concept of holon is credited to the Arthur Koestler [7] who had proposed the word "holon". It is a combination of the Greek word holos means whole, with the suffix–on, which, as in proton or neutron suggests a particle or part. He developed a set of principles that can explain the self-organizing nature of biological and social systems. The concept is extended to the manufacturing environments where basic entities called holons can reconfigure and combine with others to become more powerful to execute specific task(s) dynamically to cope with the challenging and unpredictable environments. The holons exhibit the dual properties of autonomy and cooperation [8] that enable them to form dynamic working groups in view of intended objectives (task execution). A holon has a physical processing part as well as information processing part. Successful implementation of the holonic concept results in the following potential advantages: (a) efficient use of available resources, (b) robustness to disturbances; (c) adaptability to rapid changes, and (d) possibility of implicit optimization of the global objective(s). The holonic approach is superior over traditional hierarchical control like that of CIM in many respects. (i) It offers more flexibility and agility, (ii) the system entities can respond quickly and dynamically to the environmental changes by undertaking negotiation and cooperation based work, (iii) a complex and bigger problem is distributed among nodes and therefore reliability is high, and (iv) the approach is compatible to the complex manufacturing environment.

The Multi-Agent System (MAS) on the other hand is a general software technology that deals with the information processing in a control system. In essence, holonic concept is realized by agent based system. An agent is envisaged as an autonomous component that represents physical or logical objects in the system, capable to act in order to achieve its goals, and being able to interact with other agents, when it does not possess knowledge and skills to reach alone its objectives [9].

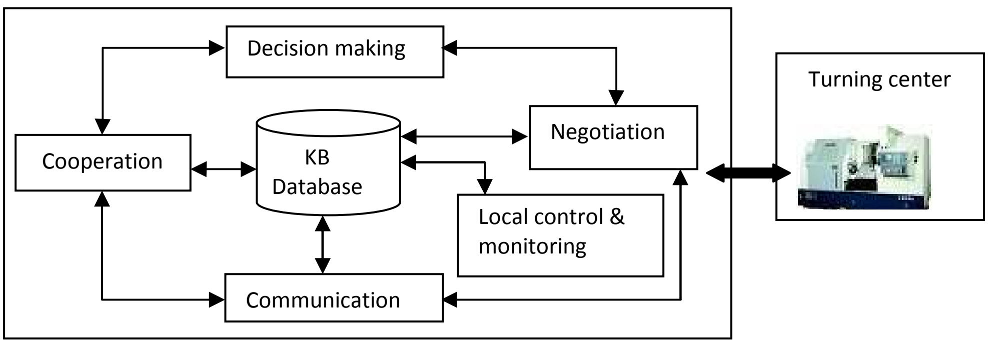

Fig. 1 A generic agent architecture

A multi agent system is conglomeration of several intelligent agents engaged in cooperation based work to fulfill a common goal. An agent possess behavioral attributes like autonomy (ability to take one's own decision by virtue of proactiveness), social ability (interacts with other agents by mutual message-based communication) and reactivity (agents can sense and respond to changes in the environment) [10]. A generic agent architecture is shown in Fig. 1. The detailed study of holonic and multi agent based system is reported in various literatures [11-14]. Both HMS and MAS having strong commonalities like autonomy, cooperation, team formation etc. it is prudent to combine both the paradigms to accrue the benefits of the two. Agent based holonic control is an approach that helps to realize integration of process planning and scheduling in addition to several other potential advantages [15-19].

3. Earlier work

Brussel et al. [11] developed PROSA architecture using the object oriented concepts of aggregation and specialization. The basic structure can be augmented with staff holon that provides expert knowledge. The resulting architecture has a high degree of self-similarity, which reduces the complexity to integrate new components and enables easy reconfiguration of the system. Cao et al. [13] developed a hybrid multilayer agent structure to realize an agile manufacturing network of agents having autonomous and cooperative properties. Two different algorithms, namely the routing wasp algorithm and the scheduling wasp algorithm, are combined to solve the job shop dynamic scheduling problem. The results from simulation experiments exhibit that the principle of the algorithms is simple involving less computations and can be applied to multi-batch dynamic scheduling in an unpredictable situation.

Cardin and Castagna [20] outlined the advantages of using discrete-event simulation as an online forecasting tool for HMS. The simulation was carried out considering the PROSA model and finally an application on an industrial sized HMS is described to demonstrate the validity of the approach. Lai [21] developed a holonic manufacturing system that is poised to satisfy the agility, distribution, and robustness requirements. Sudo et al. [22] developed a communication technique for production plan generation in an autonomous production system comprising product agents, part agents, and assembly machine agents. The proposed system utilized an event driven architecture. The dynamic scheduling is accomplished by negotiation among the agents. Simulation experiments were conducted to prove the merit of the system. Adam et al. [23] proposed a holonic multi-agent system (HoloMAS) to provide an adaptive control mechanism for manufacturing systems, where the local objective of a holonic agent is accomplished by interactions with others following CNP. The performance is validated using simulations and through a real implementation on a flexible assembly cell and the results exhibit that the notion of role helps to adapt and manage perturbations.

Renna [24] followed a multi-agent based dynamic scheduling in manufacturing cells where a part agent negotiates with the machine agent for task allocation using the criteria of improving the resource efficiency according to the manufacturing cell objectives. As a benchmark the proposed approach is compared to a methodology based on the evaluation of the workload of the manufacturing cells. The performance is evaluated by a simulation environment in several dynamic conditions: internal (manufacturing cells characteristics) and external (demand changes) and the results manifest the potential ability of the approach to operate in a very dynamic environment. Nejad et al. [25] developed a multi-agent architecture of an integrated and dynamic system for process planning and scheduling for multiple jobs. A negotiation protocol is utilized to generate the process plans and the schedules of the manufacturing resources and the individual jobs dynamically and incrementally, based on the alternative manufacturing processes and also to handle unforeseen disturbances. The results obtained from few case studies shows that the proposed multi-agent architecture is capable of generating appropriate process plans and schedules. Leitao [26] addressed the manufacturing challenges arises out of chaotic situations by introducing a holonic disturbance management architecture based on the ADACOR foundations. The disturbance handling functions are performed in a distributed manner, introducing a predictive dimension to the re-scheduling problem and considering the major types of shop floor disturbances. Experimental results exhibit the applicability of the proposed approach.

Lim and Zhang [27] developed a currency-based iterative agent bidding mechanism to effectively and cost-efficiently integrate the activities associated with production planning and control to optimize process planning and schedule following genetic algorithm so as to enhance the agility of manufacturing systems to accommodate dynamic changes in the market and production. Leitao et al. [28] proposed a bio-inspired MAS to solve complex manufacturing problems. The author opined that main biological insight is to use the simple and effective mechanisms of biological systems to deal with complex problems by adaptation to the new situations. A solution, based on potential fields, for controlling a flexible manufacturing system was used to illustrate the applicability of the concept in manufacturing that yields encouraging results.

4. Proposed holonic manufacturing system

The proposed HMS is depicted in Fig. 2. The manufacturing system holarchy comprises Resource holon, Product holon and Integrated Process Planning & Scheduling holon along with the system manager as human element.

Resource holon includes three turning centers (R_1, R_2, R_3) of varying capacity and specifications. The machine tool acts as physical part and the agent that controls it, acts as information processing part. The activities of the resource agent includes assessment of its ability in response to a job, submission of bid, getting the operation plan, preparation of the local schedule and monitoring the progress of execution. In view of alteration/modification in facilities, the same is communicated to the process planning holon for preparation of alternative plan. Further, a resource communicates with other resources for cooperation based work.

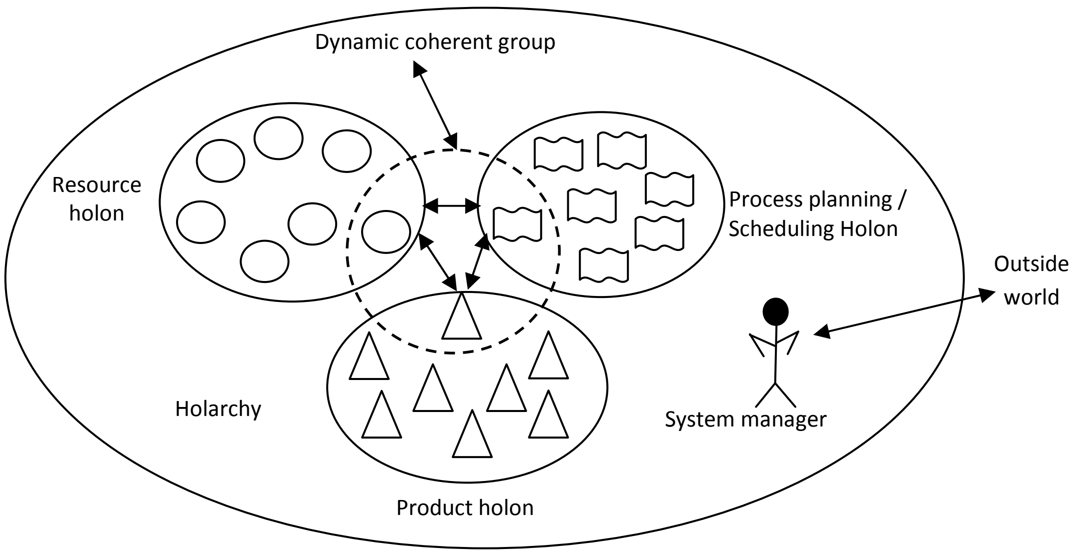

Fig. 2 Proposed holonic system

Product holon keeps a track of information's about quality of the raw materials, quantities to be manufactured, operations to be carried out, total processing time etc. which are compatible to its requirements. Product holon comprises four different products (P_1, P_2, P_3, P_4) of varying sizes and attributes. Additionally, the product agent is responsible for evaluation of bid submitted by the resources for the purpose of negotiation and task finalization.

Integrated Process planning and scheduling holon maintains database of the products and the resources and accordingly generates the operation plan. On demand, the operation plan is issued for the purpose of negotiation based task allocations. Modified operation plan can also be generated depending on the addition/alteration of resources and facilities. Further, once local schedules are finalized, the scheduling holon prepares the global schedule. In view of any disturbances, the earlier schedule is modified accordingly. The integration of process planning and scheduling helps to optimize both simultaneously as a single problem considering the constraints of both domains [15, 16, 19].

The system manager is envisaged as the nucleus of the system. The system manager is the interface between the system and the outside world (customer) and establishes congruence among the different modules of the system.

The system architecture for the proposed system, a client-server model, is shown in Fig. 3. It utilizes a number of programmable controllers for resources and these are connected to machine PC's (resource agent) through hubs. All machines PC's are connected to each other via Ethernet topology. This Ethernet topology is also connected to a server. The system also considers several PC's that represent product (product agent) and all of these are connected to each other by the same Ethernet which in turn connected to the same server. The server is connected to the integrated process planning and scheduling agent (database) so that the products as well as the resources can communicate with it. There is a user interface which the system manager can access and also communicate with the system entities. The system utilizes Linux platform (Linux OS) and JAVA for implementation. JAVA environment (JRE: JAVA runtime environment) provides tools for developing applications.

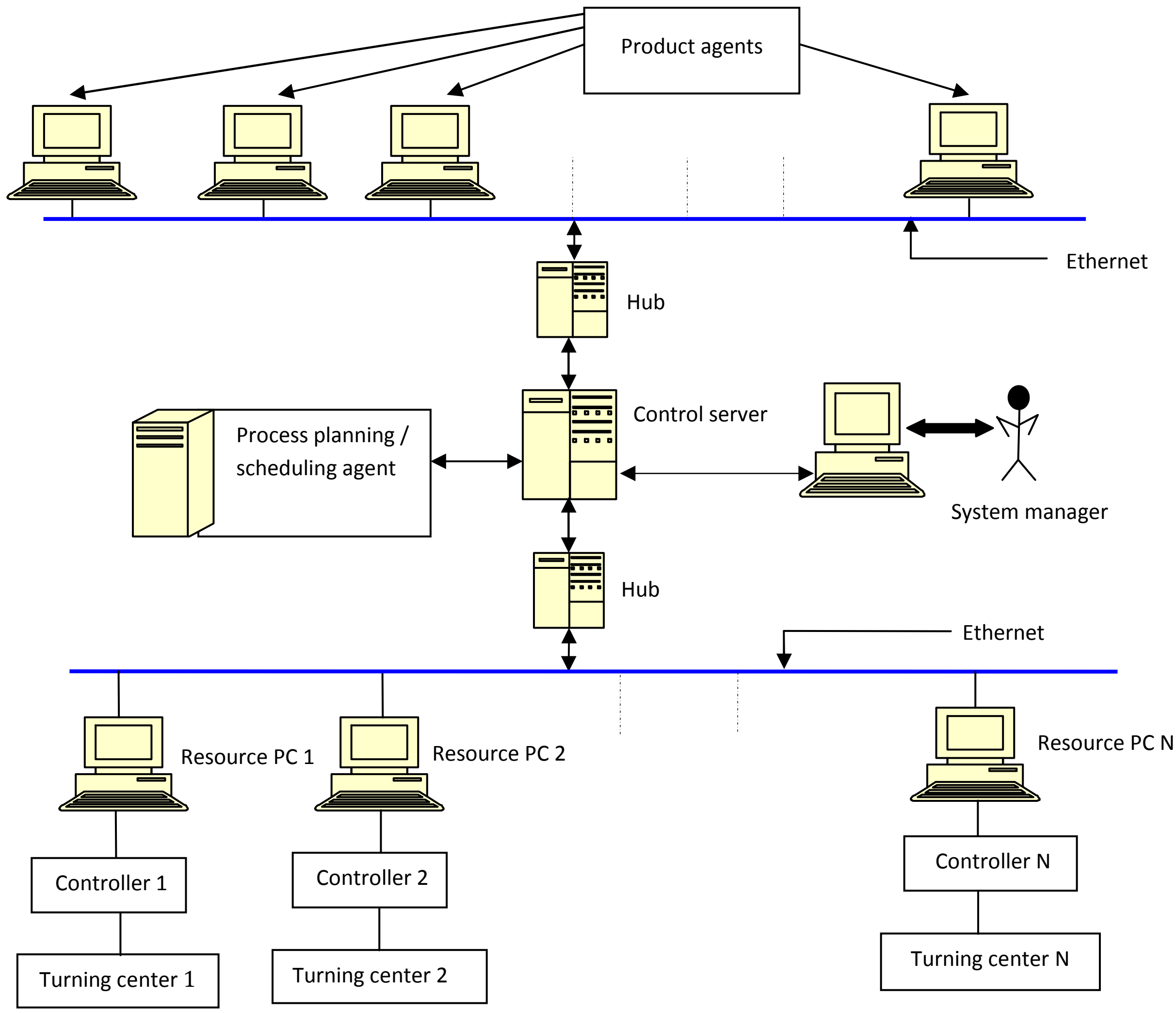

Fig. 3 System architecture

5. Execution methodology

This section presents sequential procedures of execution of customer order in the proposed system.

5.1 Negotiation based task allocation mechanism

The negotiation based task allocation is accomplished following well-known Contract Net Protocol (CNP) [6]. It is widely used methodology to specify problem-solving communication and control for nodes in a distributed problem solver. Task distribution is effected by a negotiation process, a discussion carried on between nodes with tasks to be executed and nodes that may be able to execute those tasks. This is essentially a 3 tier process that considers phase by phase negotiation activities – starting from the initial task announcement to the final task allocation by a bidding mechanism. The procedure is depicted by sequence diagram in Fig. 4.

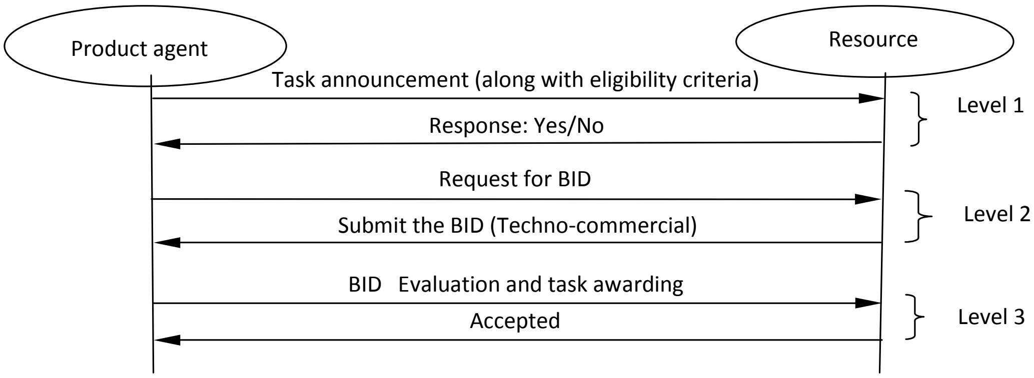

Fig. 4 Sequence diagram showing message transfer during negotiation

5.2 Communication

Communication among different agents is accomplished using XML following a specific ontology. Ontology refers to common structure so that holonic agents can use same semantics of terms in the message for communication and exchange data. A Document Type Definition (DTD) schema defines its elements and attributes and the associated rules that the subsequent XML would apply. A sample DTD schema for task announcement by the product(s) is presented below.

```
<?xml version="1.0"?>
<!DOCTYPE task_announcement [
<!ELEMENT task_announcement (to,from,Task_Specification,Material_Quality,Lot_size,Eligibility_Specification)>
<!ELEMENT to (#PCDATA)>
<!ELEMENT from (#PCDATA)>
<!ELEMENT Task_Specification (TS1,TS2,TS3,TS4)>
<!ELEMENT TS1 (#PCDATA)>
<!ELEMENT TS2 (#PCDATA)>
<!ELEMENT TS3 (#PCDATA)>
<!ELEMENT TS4 (#PCDATA)>
<!ELEMENT Material_Quality (#PCDATA)>
<!ELEMENT Lot_size (#PCDATA)>
<!ELEMENT Eligibility_Specification (ES1,ES2)>
<!ELEMENT ES1 (#PCDATA)>
<!ELEMENT ES2 (#PCDATA)>
]>
```

The corresponding XML message (sniplets) based on the above DTD considering product P_3 and resource R_2 reads like:

```xml
<?xml version="1.0"?>
  <task_announcement>
        <to>R2</to>
        <from>P3</from>
        <Task_specification>
              <TS1>Turning</TS1>
              <TS2>Facing</TS2>
              <TS3>Profiling</TS3>
              <TS4>Threading</TS4>
        </Task_specification>
        <Material_Quality>Medium Alloy Steel</Material_Quality>
        <Lot_size>1</Lot_size>
        <Eligibility_specification>
              <ES1>Minimum bed length 1180mm</ES1>
              <ES2>Grooving depth of 4 mm</ES2>
        </Eligibility_specification>
  </task_announcement>
```


The capability of a resource in the light of maximum bed length (1500 mm) and maximum grooving depth (5 mm) are verified by the following program.

```c
#include<stdio.h>
#include<conio.h>
void main()
{
        float length=1500, depth=5.0;
        float l,d;
        clrscr();
        printf("\n\nEnter length of the product:");
        scanf("%f",&l);
        if(length>l)
        {
                printf("Enter depth of the groove:");
                scanf("%f",&d);
                if(depth>d)
                {
                        printf("\n Resource  can accommodate product");
                }
                else
                {
                        printf("\n Resource  cannot  accommodate product");
                }
        }
        else
        {
            printf("\n Resource cannot accommodate product");
        }
        getch();
}
```

The message corresponds to the initial response and the subsequent bid from a capable resource R_2 appears like this:

(i) Initial response


```xml
<?xml version="1.0"?>
<Response>
        <to>P3</to>
        <from>R2</from>
        <Response>Yes</Response>
</Response>
```

(ii) Bid


```
<?xml version="1.0"?>
  <Bid_Submission>
          <to>P3</to>
          <from>R2</from>
          <BS1>Power 20kW</BS1>
          <BS2>Accuracy 0.006 mm</BS2>
          <BS3>No. of Tools 12</BS3>
          <BS4>Cost/unit time 2.38 INR (#)</BS4>
          <BS5> Machining time 38.75 minutes</BS5>
  </Bid_Submission>
```


(#) means Indian Rupee

5.3 Bid evaluation by MCDM technique

Multi-criteria or multi-attribute decision making (MCDM/MADM) techniques traditionally rank and select the alternatives by their composite values or scores in a ratio scale. A problem with at least two alternatives and at least two conflicting criteria is considered as a MCDM problem. When Fuzzy set theory is applied to MCDM then the procedure is termed as FMCDM. SAW is one of the most promising tools for solving FMCDM problem and is used for ranking the resources. Five techno-commercial criteria namely power (C_1), accuracy (C_2), number of tool holding capacity in turret (C_3), cost/unit time (C_4) and machining time (C_5) with their respective weights are considered for the purpose of ranking the resources.

All the criteria of the resources except C_5 remain unaltered for different products. Although machining time changes for different products and also varies from resource to resource; its relative ranking for different products however, remains same. We therefore adopt triangular fuzzy numbers (TFN) to express machining time (as per Table 1) so that only one set of commutation can be applied equally well for all the products. The performance ratings of other criteria are defined in crisp variables. As a decision maker the weights of criteria are expressed in fuzzy numbers (refer Table 2). All the criteria are classified into two categories: benefit (for which higher values are desirable) and non benefit (for which lower values are desirable). Lower machining time although desirable, it is converted to benefit criteria as per Table 1.

The stepwise Procedure of SAW technique is presented below:

Step 1: Formation of decision matrix with performance scores. Performance score or performance rating is the value of alternative on each criterion provided by the decision maker.

$$D = \begin{matrix} & \\ A_1 \\ \cdots \\ A_i \\ \cdots \\ A_m \end{matrix} \begin{matrix} C_1 & \cdots & C_j & \cdots & C_n \\ \end{matrix} \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

x_{ij} is the performance rating of alternative A_i with respect to criterion C_j, m is the number of alternatives and n is the number of criteria. Here the performance rating x_{ij} is either crisp or fuzzy expressed as $x_{ij} = (a_{ij}, b_{ij}, c_{ij})$.

Step 2: Formation of weight matrix

$$|W = \widetilde{w_1} \quad \ldots \quad \widetilde{w_i} \quad \ldots \quad \widetilde{w_n}| \tag{2}$$

where, $\widetilde{w}_j = {}^1/_3 \left(\alpha_j, \beta_j, \gamma_j\right)$ is weight of criterion *j*.

Step 3: Defuzzification of performance score by the equation

$$x_{ij} = {}^{1}/_{3}\left(a_{ij} + b_{ij} + c_{ij}\right) \tag{3}$$

Step 4: Defuzzification of weight

$$\overline{w}_j = {}^{1}/_{3}\left(\alpha_j + \beta_j + \gamma_j\right) \tag{4}$$

Step 5: Normalization of score of alternative is obtained using following equations

$$\overline{x}_{ij} = \frac{x_{ij}}{\max_i(x_{ij})}, \text{ for benefit criteria } j \tag{5}$$

$$\overline{x}_{ij} = \frac{\min_i(x_{ij})}{\mathrm{x_{ij}}}, \text{ for non-benefit criteria } j \tag{6}$$

Step 6: Normalization of importance weights of criteria is carried out using following equation

$$w_j^N = \frac{\overline{W}_j}{\sum_{j=1}^{n} \overline{W}_j}, \text{ where } \sum_{j=1}^{n} w_j^N = 1 \tag{7}$$

Step 7: Computation of Composite Score (CS_i) for alternative *i*

$$CS_i = \sum_{j=1}^{n}\left(w_j^N * \overline{x}_{ij}\right) \tag{8}$$

Step 8: Ranking the resources in descending order of composite scores (CS_i). Higher CS_i of the alternatives is better and desirable and the alternative having the highest CS_i is selected as the best one that corresponds to the best performance.

Table 3 shows the basic decision matrix and the weight matrix in terms of crisp and linguistic variables. Performance ratings of the alternatives and weights after defuzzification and normalization along with final composite scores (CS_i) and ranks of the resources are presented in Table 4.

Table 1 Degree of performance rating of resources

Linguistic variable	Abbreviation	TFN
Very Poor	VP	(0, 1, 3)
Poor	P	(1, 3, 5)
Medium	M	(3, 5, 7)
Good	G	(5, 7, 9)
Very Good	VG	(7,9,10)

Table 2 Degree of weights of criteria

Linguistic variable	Abbreviation	TFN
Very Low	VL	(0, 0.1, 0.3)
Low	L	(0.1, 0.3, 0.5)
Moderate	M	(0.3, 0.5, 0.7)
High	H	(0.5, 0.7, 0.9)
Very High	VH	(0.7, 0.9, 1.0)

Table 3 Weight matrix and decision matrix in terms of crisp and linguistic variables

Resource	Criteria ⟶	C_1 (kW) (+)	C_2 (mm) (-)	C_3 (+)	C_4 (INR/min) (-)	C_5 (min) (+)
	Weight ⟶	M	H	M	VH	H
R_1		7.5	0.012	8	0.892	M
R_2		20	0.006	12	2.38	VG
R_3		15	0.008	12	1.31	G

Note: Benefit criteria are shown (+) and non-benefit criteria are shown (-)

Table 4 Defuzzified and normalized weights and scores, (CS_i) and ranking of alternatives

Resource	Criteria →	C_1	C_2	C_3	C_4	C_5	(CS_i)	Ranking
	Weight →	0.1531	0.2142	0.1531	0.2654	0.2142	...	...
R_1		0.375	0.5	0.67	1	0.576	0.656	3
R_2		1	1	1	0.375	1	0.834	1
R_3		0.75	0.75	1	0.681	0.81	0.782	2

5.4 Scheduling

Scheduling is the allocation of resources to job over time and considered as NP-hard type of problem. It is a type of optimizing problem involving one or more criteria, predominantly the time. However, the complexity of this problem increased by many times in dynamic environment.

In the context of present work, each product negotiates with the resources, selects the best one (as evaluated through MCDM), finalizes the agreement and fits into the time window. Since all the products are generated at a time, it gives rise to a conflicting situation – leading to an in-decision problem. This conflict is resolved by assigning a priority index (PI) to each product on the basis of the critical ratio (CR). The products are prioritized according to the ascending order of CR and one having the lowest CR is given the first opportunity for negotiation. The critical ratio (CR) is computed as: due date / total processing time.

Table 5 shows the CR of the products along with PI. Since there are three resources and four products, the product having the highest CR (P_2 in this case) needs to wait. The resource that becomes free at the earliest (R_1 in this case) deals with P_2. Machining time for various product-resource combinations are shown in Table 6.

Table 5 CR and PI's of products

Product	CR	PI
Mandrel (P_1)	0.56	3
Sleeve (P_2)	1.57	4
Shaft (P_3)	0.27	1
Flange (P_4)	0.40	2

Table 6 Machining time (min)

Product	Resource product		
	R_1	R_2	R_3
P_1	**3.62**	2.39	2.52
P_2	**2.24**	0.98	1.48
P_3	57.53	**38.75**	45.52
P_4	29.05	21.01	**23.14**

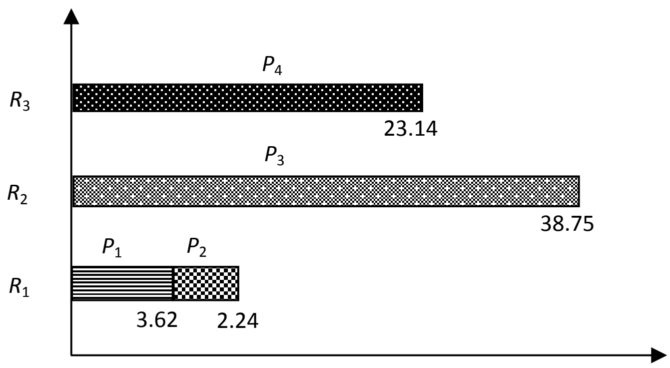

Fig. 5 Resource scheduling

In the 1st phase of negotiation, P_3 having the minimum CR, gets the first opportunity for negotiation. The bid evaluation shows that R_2 is the best resource and therefore it is the automatic choice. Thus the local schedule of R_2 is framed. Since R_2 remains engaged up to 38.75 min it cannot participate in any further bidding within this time frame. The next product P_4 therefore selects R_3 (2nd rank holder) for processing. P_1 having the 3rd position has no other choice but to go with R_1. Since R_1 becomes free at the earliest (after 3.62 min), the last product P_2, waiting in the queue, is allocated to it. The complete local and global schedule is shown by Gantt chart in Fig. 5.

6. Discussion and conclusion

The paper clearly identifies the present day's market requirements and advocates for agent based holonic manufacturing system as a possible solution. The key characteristics of the agent based holonic approach are autonomy and cooperation based work that enables the functional entities to realize distributed control. Holons being intelligent and self-reliant, consider several issues for negotiation based task allocation. In the proposed system, product agents negotiate with the resource agents and bargain on several techno-commercial criteria for ranking and allocation of work. The CNP is a well-known bidding mechanism adopted in the present work for negotiation based task allocation. The bids are evaluated by SAW technique which is simple yet powerful to judge the relative merit (ranking) of the resources. Conflict arises out of simultaneous creation of products is avoided by determining the critical ratio of the products; although one could have followed other criterion. In negotiation based task allocation, each agent tries to optimize its own work and hence global optimization is implicit. In view of changes in the resources, the ranking (as per algorithm) can be updated quickly, justifying the technique amenable under changing circumstances. In view of disturbances, the system entities can collaborate with others dynamically to find out any possible solution by virtue of cooperation. The proposed system although is a simpler one, it tries to replicate the real-life environment; thereby augmenting its credibility in practical situations. Future work is directed towards implementation of the philosophy in a larger and complex environment to accrue its benefit in full perspective.

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