ICAS 2021 SHANGHAI
International Council of the Aeronautical Sciences
32^{nd} Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

ENABLING THE SMART SHOP FLOOR THROUGH THE INTEGRATION OF IoT AND AUTONOMOUS INTELLIGENCE

XU Aiming
Chengdu Aircraft Industrial (Group) Co., Ltd.
Huangtianba Weiyi Road, Chengdu, Sichuan, 610073,
China

Abstract

The smart shop floor relies on the integration of IoT and autonomous intelligence that batter decision-make of manufacturing processes by dynamic perception of the factory status and real-time analyzation of the vast amounts of data produced by manufacturing systems. Over the IoT, the manufacture resources including: manufacturing cells, AGVs, materials, fixtures, software systems, etc. can communicate and cooperate with each other in real time. Then a centralized decision-making system can be made to rescheduling the resources to get a better recover from the disruptions of the manufacturing system. In this paper, the autonomous intelligent agent system is researched in the context of a smart workshop for aircraft structural parts.

Keywords: Smart shop floor, IoT, Autonomous intelligence, Agent

1. Introduction

Manufacturing system of the smart shop floor has the characteristics of self-adaptive, flexible, reconfigurable and self-organizing, which can efficiently support the mixed production of multi variety, variable batches of products [1]. The complexity of workshop manufacturing process makes it easily be affected by various disturbances inside and outside the workshop, which makes the high dynamic and timely control requirement of production processes [2,3].

In smart shop floor need higher requirements for the adaptive control of workshop production process [4,5]. On the basis of real-time perception of the manufacturing system, the methods of prediction of the manufacturing processes, real-time automatic adaptive scheduling, dynamic control of the logistics process, etc., can be used to improve the workshop production efficiency [6-8].

Lots of researches has been done to improve the ability of workshop manufacturing process to deal with complex disturbance factors. At present, the related research is mainly focused on the field of rescheduling method of workshop manufacturing resources, including rescheduling algorithm, scheduling mechanism and scheduling evaluation method [9-12].

However, the practical application effect of relevant achievements is still limited, because of the difficult to obtain real-time status of manufacturing state and the complexity of disturbance factors and their influences. In order to solve the problem of self-adaptive management and control of workshop, inspire by the theory in the field of distributed artificial intelligence, many researches have researched the workshop control system based on multi agent theory [13,14]. In recent years, with the digital and intelligent improvement of workshop, real time state perception of the manufacturing system becomes a reality. And, with advantages of the flexibility, anti-interference and adaptive, many researchers have paid more attention to multi-agent system, and received lots of achievements [15,16].

This paper mainly researches the dynamic control enabling method of the smart shop floor through the integration of IoT and autonomous intelligence. First, the smart workshop and system architecture of aircraft structural parts will be introduced. Second, the event perception system by IoT edge computing terminal will proposed to deal with the discrete and amount of event massages timely. Third, the smart agent model with a perceptual structure which can react autonomously according to the state of itself and event of other agents of the system will be introduced. Finally, the smart workshop of aircraft structural parts will be discussed to illustrate the autonomous intelligent agent system described above.

2. System architecture of the smart workshop

A smart workshop and system architecture of aircraft structural parts is used as an example in this paper, which is constituted in cyber-physical space by virtual digital workshop and physical workshop [17,18]. By smart agent, the CPS (Cyber-physical systems) model of manufacturing resources can be build up. Over the IoT, smart workshop architecture (Figure 1) is built upon physical layer, communication layer, mapping layer, logical process layer and decision layer. Functions of different layers will be detail described in the following.

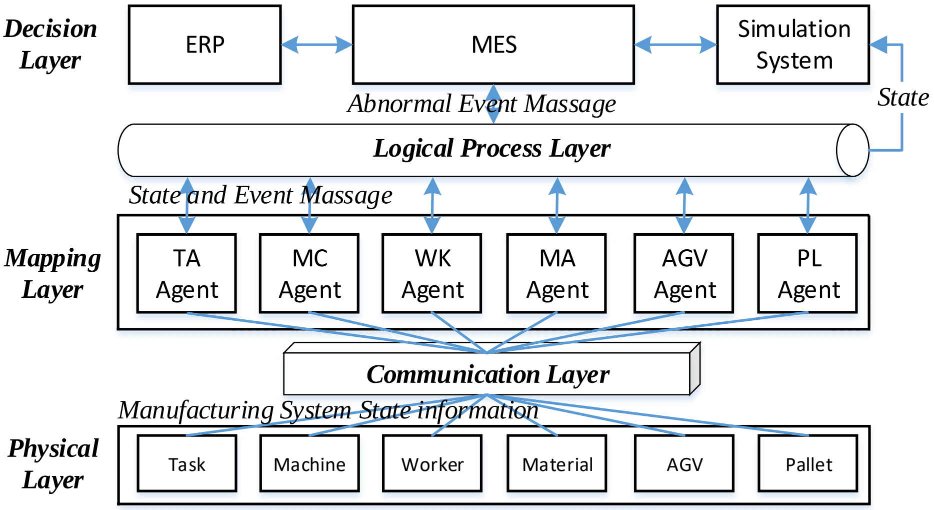

Figure 1 – Smart workshop architecture.

Physical layer is composed by manufacturing task (TA), manufacturing center (MC), workers (WK), Material (MA), automated guided vehicles (AGV) and pallet (PL), etc. The different physical objects are communicate with each other by communication layer. Physical layer is the OT (Operation technology) layer which processing and implement the operating instructions sent by the corresponding agents through communication layer .

Communication layer establishes communication between mapping layer and physical layer. By IoT technologies the manufacturing system state information can be real-time perceived and fused by IoT terminals, then transmitted by 5G wireless network form physical to the virtual world. It also receive massage from mapping layer and transform them into control information and transmit them to physical objects.

Mapping layer is composed by autonomous intelligent agents of entities in physical layer. By smart agent the CPS (Cyber-physical systems) model of manufacturing resources can be build up, which can autonomy make operating instructions with received sate information of manufacturing system.

With communication protocol and negotiation mechanisms, the logical process layer connects different agents of mapping layer with each other to deal with normal and abnormal events. And it will also send the event massage to the decision layer to deal with the abnormal events.

According to the type of the event received, the decision layer will evaluate its impact on the production process, and make a resource scheduling decision according to the impact of the disturbance event.

3. Event perception system by IoT edge computing terminal

The large of uncertainty abnormal events makes the complexity of smart workshop. The dynamic control of the workshop depend on timely event perception of manufacturing system. This paper proposes an IoT and agent based system to deal with the discrete and amount of event massages. Through IoT，it can quickly collect manufacturing system state information and feed back to the upper corresponding smart agents in real time, so as to improve the rapid perception and response ability of the smart shopfloor, as shown in Figure 2.

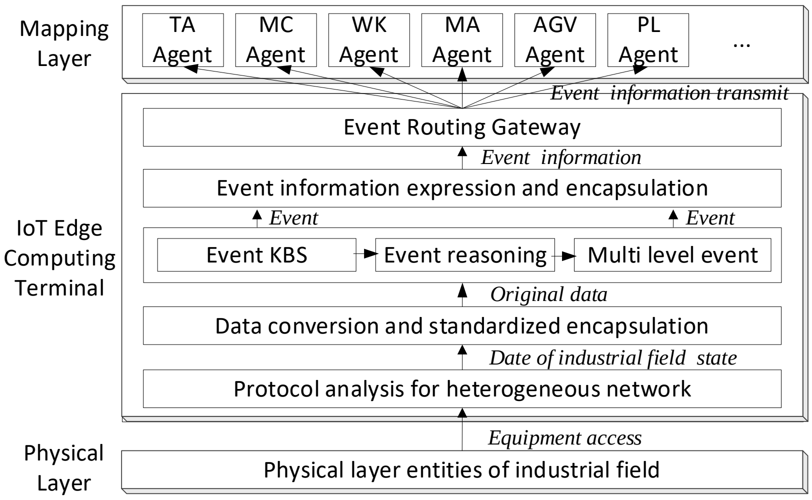

Figure 2 – IoT edge computing terminal architecture.

In the architecture, the connecting between physical entities and smart agent is built up by 8 steps, the event perception processes are described as follows:

Step(1): Each physical layer entity sends their status messages to the access module, which provide a variety of heterogeneous network access IO for main types of communication protocols.

Step(2): Through protocol analysis for heterogeneous networks, the RFID, Zigbee, OPC-UA, CAN, Serial port, etc. can all be connected and transformed into TCP/IP.

Step(3): By Data conversion and standardized encapsulation, the data of the status messages can be converted and encapsulated into JSON standardized data package and sent by MQTT.

Step(4): The original data send to the event process module, with event knowledge base the original data can be changed into event massages by types of data characteristics, through event reasoning engine the related events can be find.

Step(5): By event information expression and encapsulation module, the event can be expressed by the model (1), id is the event identifier, name is the type of the event; location is the place where the event happened; timestamp is the event time property; then the events information of the terminal is encapsulated into JSON.

$$Event=(id, name, location, timestamp) \qquad (1)$$

Step(6): Through event routing gateway, the interested event information can be pushed to subscribed agents.

4. Smart multi-agent of manufacturing shop floor

4.1 Event processing based on agent perception structure

This paper adopts an event processing framework based on agent perceptron structure, as shown in Figure 3, which is divided into three main modules: event acquisition, event filtering and event processing.

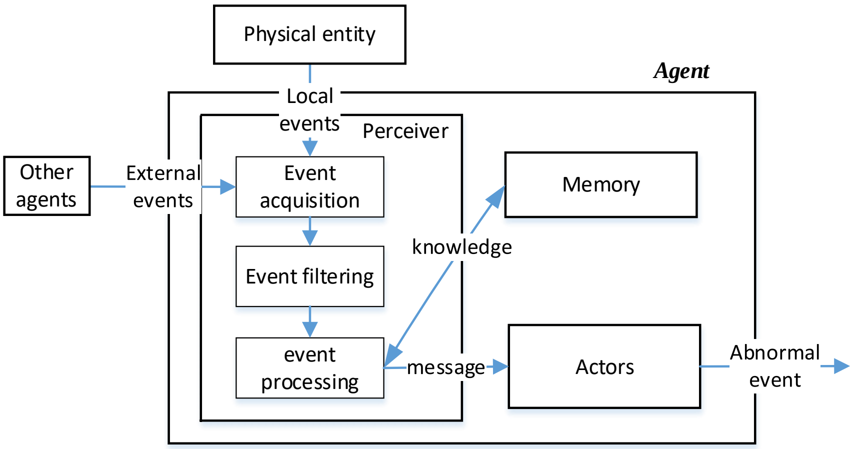

Figure 3 – Smart agent architecture.

The main function of event acquisition module is to receive local events information sent by corresponding physical entity and monitor the external events sent by other agents in time, through pre-defined and real-time monitoring of concerned events.

The event filtering module is to filter the events that are not concerned or cannot be handled. This module contains an event list, which stores the information of all events concerned by the agent in advance. If current received event is an event in the list, it will be directly processed as a legal event; Otherwise, it will be sent to the user to handle it artificial. If the event is received, it will be expanded into the event list. When next time, this event is appeared, it will be treated as a legal event for processing.

Event processing can produce a variety of abnormal events in the manufacturing process of discrete workshop. Event processing can help to find and respond to problems in time.

The event-condition-action rule is used to process the events. A complex event processing rule can be expressed as:

Event [pattern]: If [condition part]; then [action part 1]; otherwise [action part 1];

Event [pattern] represents the complex event pattern to be matched, such as whether need to cycle processing, priority, etc.; If [condition part] indicates the condition to be satisfied, if satisfied, then [action part 1] is executed; if not, then [action part 2] is executed.

When events message sent from event processing to actors module, the actors will evaluate whether the event will result in a bad effect to the manufacturing system. If so, this event will be defined as an abnormal event and sent to decision layer to rescheduling the manufacturing system.

4.2 Events monitored by smart agents

The types of agents in the shop floor mainly including: task agent and resource agent. They are monitoring the event happened in manufacturing field real time, as shown in table 1. Task agent mainly monitors task status, including: random arrival of tasks, priority changing, and whether there is emergency insert etc.. Resource agent class (AGV, materials, equipment, tooling, pallet, personnel, etc.) is responsible for the status of various manufacturing resources involved in the production processes.

Table1 Main agent classes and monitoring events

Agent	Main monitoring events
Task Agent	Task delay, new task, inspection completion, priority adjustment, task cancellation, etc.
Material Agent	Material detention, material in and out, material inspection, Material application, etc.
Machine Agent	Equipment failure monitoring, maintenance progress, equipment recovery and availability, etc.
Worker Agent	Departure, out of work, etc.
AGV Agent	AGV failure, AGV application, AGV back to warehouse, etc.
Pallet Agent	Pallet loading status, pallet in and out, etc.

5. Work shop rescheduling based on IPSO

5.1 Rescheduling performance evaluation

This paper is to monitor the abnormal events, and drive a rescheduling immediately after the abnormal events be monitored. the abnormal events information is the rescheduling signal of the manufacturing system.

In rescheduling decision-making, the selection of rescheduling plan is determined by the rescheduling performance evaluation. According to the idea of JIT, the workpiece should be completed in the scheduled time, so when the production is completed early or delayed, the corresponding delivery cost will be generated. The delivery cost formula is as follows:

$$M_i = \begin{cases} a(t_{ei} - t_i) & t_i \le t_{ei} \\ bw_i(t_i - t_{ei}) & t_{ei} \le t_i \le t_{di} \\ bw_i(t_{di} - t_{ei}) + w_i(t_i - t_{di}) & t_{di} \le t_i \end{cases} \tag{2}$$

M_i stand for the delivery cost of manufacturing task mission i;

t_{ei} stand for the estimated completion time of mission i;

t_i stand for the actual completion time of mission *i* in the rescheduling plan;
t_{di} stand for the deadline time of mission *i*;
a is the penalty coefficient when $t_i \le t_{ei}$;
b is the penalty coefficient when $t_{ei} \le t_i \le t_{di}$;
c is penalty coefficient when $t_{di} \le t_i$;
w_i stand for the coefficient of the emergency importance of mission *i*;
The delivery cost evaluation of the rescheduling plan *SC* can be calculated by formula (3):

$$SC = \sum_{i=1}^{n} M_i \tag{3}$$

5.2 Rescheduling based on IPSO

5.2.1 Problem description

The workshop is composed of m sets of equipment, and the number of workpieces to be completed in the current task is n. $M=\{ m_1 , m_2 ,\dots, m_m \}$ stand for the equipment; Tasks stander by $J=\{ j_1 , j_2 ,\dots, j_n \}$; processes can be marked by $O=\{ O_{i1} , O_{i2},\dots, O_{ij} \}$; P_i stand for the priority of task *i*; $S_{i,j}$stand for the process *j* starting time of task *i*; $C_{i,j}$stand for the process *j* manufacturing time of task *i*; $E_{i,j}$ stand for the process *j* finish time of task *i*. c, the scheduling model can be described as:

$$\begin{aligned} &F = \min(SC) \\ &s.t.\ S_{i,j} \le E_{i,j} \\ &P_{i,j} = P_{i-1,j} \\ &S_{i,j} \le S_{i+1,j} \end{aligned} \tag{4}$$

5.2.2 Improved particle swarm optimization algorithm

The traditional particle swarm optimization (PSO) algorithm was proposed by Kennedy in 1995 after investigating the cooperative foraging behavior of birds [19-21]. The iterative formulas of velocity and displacement are summarized as follows:

$$\begin{gathered} v_{i,j}(t+1) = v_{i,j}(t) + c_1 r_1 \left(pbest_{i,j}(t) - x_{i,j}(t)\right) + c_2 r_2 \left(gbest_{i,j}(t) - x_{i,j}(t)\right) \\ x_{i,j}(t+1) = x_{i,j}(t) + v_{i,j}(t+1) \end{gathered} \tag{5}$$

i stand for the particle *i*; *j* stand for the *j* dimension; $v_{i,j}(t)$ stand for the *j*-dimensional velocity vector of particle *i* at time *t*; $x_{i,j}(t)$ represents the position component of the *j*-dimension of particle *I* at time *t*; $pbest_{i,j}(t)$ represents the population's optimal position at time *t*; $gbest_{i,j}(t)$ represents the component of the *j*-dimension of particle *i* at time *t*; $c_1, c_2 \in [0,1]$.

In order to solve the problem of premature convergence, roulette selection operator is introduced to improve PSO. Suppose the size of the algorithm is n, the fitness transformation function of individual *i* can be described as : $F_i = e^{-(f(p_i)-f(p_g))/t}$, the particle selection process of the roulette is as follows:

Step(1): Calculate the probability that each individual *i* is selected to iterate: $P_i = F_i / \sum_{i=1}^{n} F_i$;

Step(2): Construct a roulette: $\sum_{j=1}^{i} P_j \quad j \in \{1,2,\dots,n\}$;

Step(3): By simulating roulette bet particle selection operation, the system provides a random number *r*, $r \in [0,1]$, if $\sum_{j=1}^{i-1} P_j \le r \le \sum_{j=1}^{i} P_j$, individual *i* can be selected to the offspring population;

Step(4): Repeat step 3 to get enough new individuals to construct a new species group.

6. Case study

A smart workshop for aircraft structural parts and production processes is proposed in this paper as an example, as shown in Figure 4. Through the integration of CNC and automatic production line state of the manufacturing sate and machine status can be available. Through UWB and RFID methods the state of the logistics system can be received. And, task agents, load agents, AS/RS agents, MC agents, AGV agents, etc. of the smart workshop are constructed by smart multi-agent methods. By these agents and management system of the workshop, normal events perception and processing can be deal with by the agents, as shown by Figure 5. The abnormal events will be sent to the management systems of the decision layer to rescheduling the manufacturing processes, as shown in Figure 6.

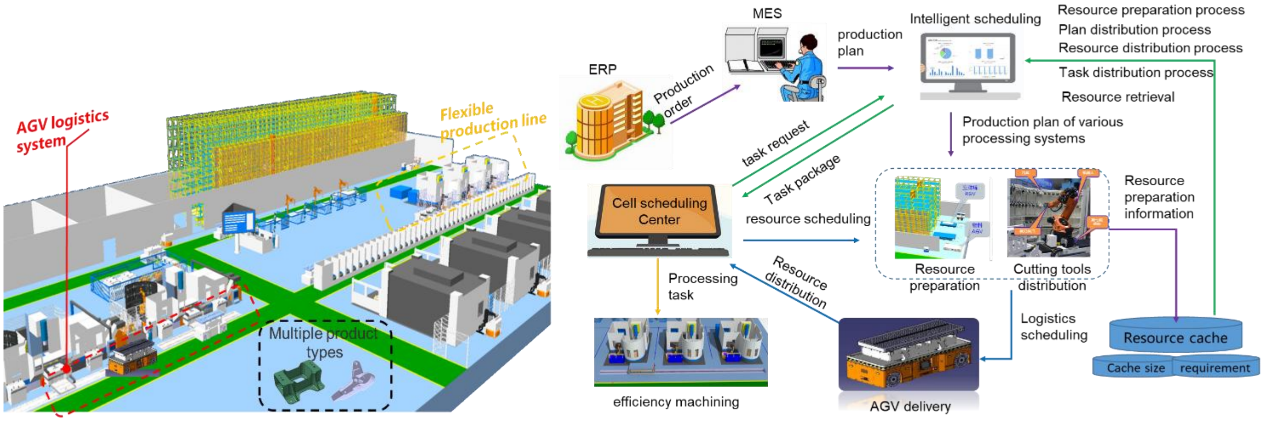

Figure4 – The smart workshop of aircraft structural parts.

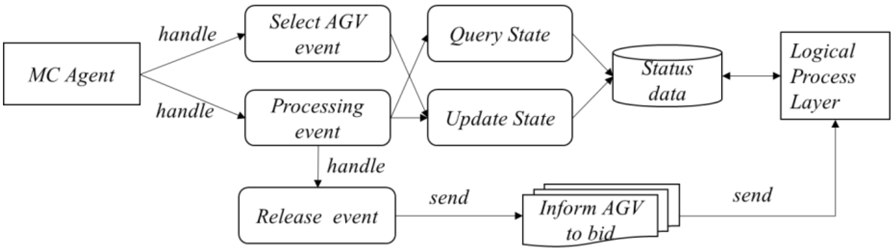

Figure5 – Normal event processing of the MC agent.

In figure 6, when the machine MC2 breakdown after finishing the process 2 of task 5, the abnormal event message will be send to MES system of the shopfloor, and through the logical process layer the MES can got other state messages it concerned sent by other agents. With these messages the rescheduling decision of the manufacturing system will be made. Then by scheduling module of the MES system, using IPSO method the manufacturing plan will be rescheduled.

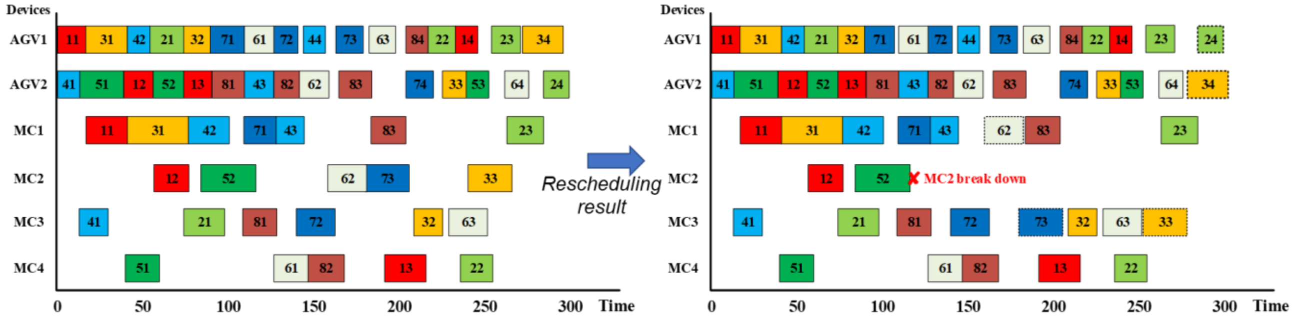

Figure6 – Rescheduling result when MC2 breakdown.

7. Conclusions

In this paper, the autonomous intelligent agent system is researched in the context of a smart workshop for aircraft structural parts. Over the IoT and autonomous intelligence, the smart workshop architecture is constructed by physical layer, communication layer, mapping layer, logical process layer and decision layer. The event perception system by IoT edge computing terminal is described, and the abnormal event will be reasoned and send form logical process layer to decision layer. Then, a rescheduling method based on IPSO is instructed to make a better decision of the manufacturing system. Therefore, dynamic decision of smart shopfloor can be realized.

Acknowledgements

This research was sponsored by the National Key Research and Development Program of China under Grant No.2020YFB1712500.

References

[1] Wang X, Yew A W W, Ong S K, et al. Enhancing smart shop floor management with ubiquitous augmented reality. *International Journal of Production Research*, Vol.58, pp 2352-2367, 2020.

[2] Leitao P. A holonic disturbance management architecture for flexible manufacturing systems. *International Journal of Production Research,* Vol.49, pp 1269-1284, 2011.

[3] Hou D, Li T. Analysis of random disturbances on shop floor in modern steel production dynamic environment. *Procedia Engineering*, Vol.29, pp 663-667, 2012.

[4] Valente A, Carpanzano E. Development of multi-level adaptive control and scheduling solutions for shop-floor automation in reconfigurable manufacturing systems. *CIRP annals*, Vol.60, pp 449-452, 2011.

[5] Shirazi B, Mahdavi I, Solimanpur M. Intelligent decision support system for the adaptive control of a flexible manufacturing system with machine and tool flexibility. *International Journal of Production Research*, Vol.50, pp 3288-3314, 2012.

[6] Zhao C. A quality-relevant sequential phase partition approach for regression modeling and quality prediction analysis in manufacturing processes. *IEEE Transactions on Automation Science and Engineering*, Vol.11, pp 983-991, 2013.

[7] Lee K K. Fuzzy rule generation for adaptive scheduling in a dynamic manufacturing environment. *Applied Soft Computing*, Vol.8, pp 1295-1304, 2008.

[8] Chow H K H, Choy K L, Lee W B. A dynamic logistics process knowledge-based system-An RFID multi-agent approach. *Knowledge-Based Systems*, Vol.20, pp 357-372, 2007.

[9] SALIDO M A, ESCAMILLA J, BARBER F, et al. Rescheduling in job-shop problems for sustainable manufacturing systems. *Journal of Cleaner Production*, Vol.162, 2016.

[10]ZAKARIA Z, PETROVIC S. Genetic algorithms for match-up rescheduling of the flexible manufacturing systems. *Computers & Industrial Engineering*, Vol.62, pp 670-686, 2012.

[11]Nouiri M, Bekrar A, Trentesaux D. An energy-efficient scheduling and rescheduling method for production and logistics systems. *International Journal of Production Research*, Vol.58, pp 3263-3283, 2020.

[12]Weixi J, Youyong C, Chaoyang Z, et al. Abnormal Event Driven Rescheduling Decision Making in Discrete Manufacturing Workshop. *Journal of System Simulation*, Vol.30, pp 40-43, 2018.

[13]Shpilevoy V, Shishov A, Skobelev P, et al. Multi-agent system “Smart Factory” for real-time workshop management in aircraft jet engines production. *IFAC Proceedings Volumes*, Vol.46, 204-209, 2013.

[14]Leitão P, Barbosa J, Trentesaux D. Bio-inspired multi-agent systems for reconfigurable manufacturing systems. *Engineering Applications of Artificial Intelligence*, Vol.25, pp 934-944, 2012.

[15]Shi L, Guo G, Song X. Multi-agent based dynamic scheduling optimisation of the sustainable hybrid flow shop in a ubiquitous environment. *International Journal of Production Research*, Vol.59, pp 576-597, 2021.

[16]Mezgebe T T, El Haouzi H B, Demesure G, et al. Multi-agent systems negotiation to deal with dynamic scheduling in disturbed industrial context. *Journal of Intelligent Manufacturing*, Vol.31, pp 1367-1382, 2020.

[17]Tang D, Zheng K, Zhang H, et al. Using autonomous intelligence to build a smart shop floor. *Procedia Cirp*, Vol.56, pp 354-359, 2016.

[18]Zhang H, Zhang G, Yan Q. Digital twin-driven cyber-physical production system towards smart shop-floor. *Journal of Ambient Intelligence and Humanized Computing*, Vol.10, pp 4439-4453, 2019.

[19]Garcia-Gonzalo E, Fernandez-Martinez J L. A brief historical review of particle swarm optimization (PSO). *Journal of Bioinformatics and Intelligent Control*, Vol.1, pp 3-16, 2012.

[20]Rini D P, Shamsuddin S M, Yuhaniz S S. Particle swarm optimization: technique, system and challenges. *International journal of computer applications*, Vol.14, pp 19-26, 2011.

[21]Zhu H, Wang Y, Wang K, et al. Particle Swarm Optimization (PSO) for the constrained portfolio optimization problem. *Expert Systems with Applications*, Vol.38, pp 10161-10169, 2011.

Copyright Statement