*Dynamic Resource Allocation Optimization for Digital Twin-driven Smart Shopfloor**

Haijun Zhang
School of Mechatronics Engineering
Zhengzhou University of Aeronautics
Zhengzhou, P. R. China
zhanghj@zua.edu.cn

Guohui Zhang, Qiong Yan
School of Management Engineering
Zhengzhou University of Aeronautics
Zhengzhou, P. R. China
joan2055@163.com

***Abstract*—Smart manufacturing is the core in the 4th industrial revolution. It is very important that how to realize the intelligent interaction between hardware and software in smart manufacturing. The paper proposes the architecture of Digital Twin-driven Smart ShopFloor (DTSF), as a contribution to the research of the research discussion about Digital Twin concept. Then the scheme for dynamic resource allocation optimization (DRAO) is designed for DTSF, as an application of the proposed architecture. Furthermore, a case study is given to illustrate the detailed method of DRAO. The experimental result shows that the proposed scheme is effective.**

Keywords—smart manufacturing; resource allocation; digital twin; dynamic optimization; shopfloor

I. INTRODUCTION

Smart manufacturing has become the trend of global manufacturing development, which is the core in the 4th industrial revolution. Technological convergence is the main feature of smart manufacturing, e.g., cloud computing, artificial intelligence (AI), Internet of things (IoT), Radio Frequency Identification (RFID) etc. In recent years, most manufacturing power countries have made some strategical responses of the manufacturing industry to the 4th industrial revolution. For example, the United States proposes "Industrial Internet", which can realize the intelligent interaction between hardware and software in manufacturing based on the Internet technology. Germany carries out "Industrie 4.0", where the architecture of intelligent manufacturing is based on the Cyper Physical System (CPS). Japan sets up an organize named as "Industrial Value Chain Initiative" (IVI), where is participated by various manufacturing enterprises, equipment manufacturers, system integrators etc, and proposes Industrial Value Chain Reference Architecture (IVRA) for smart plant. China puts forward "Made in China 2025", where the deep integration of informatization and industrialization is the main clue, and the industrial ecological system and the new manufacturing mode are constructed under the information condition.

Most manufacturing activities take place in the shopfloor, which is one of importance carrier on smart manufacturing and smart plant. Smart shopfloor includes intelligent production systems, networked distributed production facilities etc, in order to achieve the goal of intelligent manufacturing process. The focus of smart manufacturing, smart plant and smart shopfloor is at different levels. Smart manufacturing focuses on improving the national competitiveness, and the place of manufacturing industry in the global industry and areas. Meanwhile, smart manufacturing can also improve the management level of the agricultural industry, service industry etc. Smart plant focuses on the product lifecycle and the level of whole plant management. In smart plant, the lean management of supply chain (customer-plant-suppliers) is realized through automatization and informatization, which isn't to satisfy but to mine customer requirement. Smart shopfloor focuses on the level of production, which includes production management, product quality, On-time delivery, production facility, safety production, logistics, energy management etc.

In smart shopfloor, the interconnection and interoperability among automation equipments are realized by using the Machine-to-Machine (M2M) technology and the IoT network. The production awareness (including customer requirement, raw material, workers, process, devices, and safety) and real-time data analysis are executed for automatic decision and accurate execution. One key of smart shopfloor is how to realize the interconnection and interoperability of production elements between the physical shopfloor and the cyber one. Then according to the information of cyber shopfloor, the production mode can be adjusted intelligently and the production resource would be replaced timely in the physical shopfloor, namely the dynamic resource allocation for smart shopfloor. Through dynamic resource allocation, the product design, bill of material, order, plan, process, logistics can be different for each customer or each product to cut out the waste in the product chain. In the product mode of dynamic resource allocation, the initial production plan can be changed at any time before production or during production. Therefore, this paper focuses on the Dynamic Resource Allocation Optimization (DRAO) for Digital Twin-driven Smart Shopfloor (DTSF).

II. DIGITAL TWIN

According to the research motivations outlined in the Introduction, the section answers the following research questions: "What is the definition of Digital Twin in related literature?" and "What is the application of Digital Twin?"

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The concept Twin can date back to NASA's Apollo program, where two identical space vehicles were built[1]. One vehicle stayed on earth to simulate the conditions of the other vehicle in the space. Then the former vehicle was seen as the twin of the latter. The twin was used extensively for training during flight preparation. During the flight mission it was used to mirror the flight conditions as precise as possible [2]. It's noted that the twin of space vehicle remains hardware not digital form. Due to the development of simulation technologies, the idea of twin extended the design phase of product, which leaded to a complete digital model to mirror the physical device along all the phases of the lifecycle. The term Digital Twin was brought to the general public for the first time in NASA's integrated technology roadmap under the technology area 11: Modeling, Simulation, Information Technology & Processing [3]. A Digital Twin is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc. [4]. As the emergence of new technologies, Schluse and Rossmann defined the digital twin as virtual substitutes of real world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the internet of things and services [5].

The similar concept of Digital Twin was presented by Grieves at one of his presentation about PLM in 2003 at University of Michigan [6]. The characteristics of Digital Twin are as follows [7]: (1) To integrate various types of data from physical entity and to map the physical entity faithfully; (2) To exist along the lifecycle of physical entity and evolve with the physical one, and to accumulate knowledge from the physical one; (3) Not only to describe the physical entity, but also to optimize the physical one based on the cyber model.

Owing to know the past and present states of product, the applications of the Digital Twin focused on the maintenance, diagnostics and prognostics of products or equipments, which are as core characteristics of the Digital Twin concept. For example, Reifsnider and Majumdar discussed multiphysics stimulated simulation digital twin methods for fleet management[8]. Tuegel proposed the Airframe Digital Twin for designing and maintaining airframes[9]. Rios et al. reviewed the different topic of aircraft digital twin, i.e. product identification, product lifecycle, product information, product configuration, product models, and software applications[10].

In fact, research on the Digital Twin in the manufacturing is an evolution of the already ongoing research stream. The Digital Twin is used to simulate a CPS system[25,30] or smart product[11]. For example, in 2013 the first works reporting research on Digital Twin in manufacturing sector appeared. In particular, Lee and colleagues considered it to be the virtual counterpart of production resources, and not only of the product, setting the basis for a debate about the role of the Digital Twin in advanced manufacturing environments, such as the envisioned Industry 4.0 with its core technologies, big data analytics and cloud platforms [12].Schroeder et al. proposed the use of AutomationML to exchange data between the digital twin and other systems in the future manufacturing [13]. In 2015, based on digital twin, the General Electric Company plan to monitor, diagnose and prognosticate the aircraft engine on the cloud platform (Predix) [14]. In China, Hair employs Digital Twin in the "Internet Factory" [15]. Tao etc. discussed the theory and implementation of the communication and interaction between physical and cyber shopfloor based on digital twin data [16]. Zhuang etc. investigated the implementation approach of product digital twin in the stage of product design, manufacturing and service [17]. Tao etc. suggested a novel concept of digital twin shop-floor (DTS) based on digital twin[18].

III. DIGITAL TWIN-DRIVEN SMART SHOPFLOOR (DTSF)

The section answers the following Research Questions: "What is the architecture of digital twin-driven smart shopfloors?" and "What is the role of the Digital Twin in smart shopfloors?"As an industrial reference of implementing DT, this paper proposes the architecture of digital twin-driven smart shopfloor, which is consisted of five layers as follows (Fig.1):

(1)Physical shopfloor layer: it refers to the integration of physical entities, which response to accept instructions and perform tasks, e.g., machine tool, Automated Guided Vehicle (AGV), robot, worker, part, sensor, Radio Frequency Identification (RFID) etc. In addition to the functions of the traditional shopfloor, the layer needs to have ability of heterogeneous, multi-source, real-time perception based on IoT.

(2)Shopfloor network layer: it refers to the network infrastructure, which is the bridge between the physical space and cyber space. These technologies include industrial internet, internet, industrial wireless network, mobile internet etc. The network employed in the layer focuses on reliability, real time and convenience.

(3)Shopfloor data layer: this layer includes production data, tooling data, equipment data, material data, quality data, cost data, human data, environmental data etc, which are the base of digital twin-driven smart shopfloor;

(4)Cyber shopfloor layer: this layer is most characteristic layer, which is consisted of various models, e.g., geometric model, manufacturing attribute model, behavior rule model, data fusion model;

(5)Shopfloor application layer: it refers to the integration of shopfloor application systems, which are response for decision support, e.g., job scheduling optimization, real-time monitoring of manufacturing resources, quality monitoring, material delivery optimization etc.

IV. DYNAMIC RESOURCE ALLOCATION OPTIMIZATION (DRAO) FOR DIGITAL TWIN-DRIVEN SMART SHOPFLOOR(DTSF)

A. The scheme of DRAO for DTSF

This scheme of dynamic resource allocation optimization (DRAO) is based on the digital twin smart shopfloor (DTSF), Because the digital twin technology can provide the real-time data acquisition and dynamic simulation, which would provide the related production data and a simulation tool. Therefore, this scheme would include as follows (Fig.2):

Step 1: In the physical shopfloor layer, the data related to production would be acquired based on the IoT network, which also called as digital twin data. These huge amounts of data would be managed and stored in the shopfloor data layer;

Step 2: According to the real-time data in the shopfloor data layer, the models can reflect the physical shopfloor truly in real time, that constructs a mapping between physical shopfloor and cyber one;

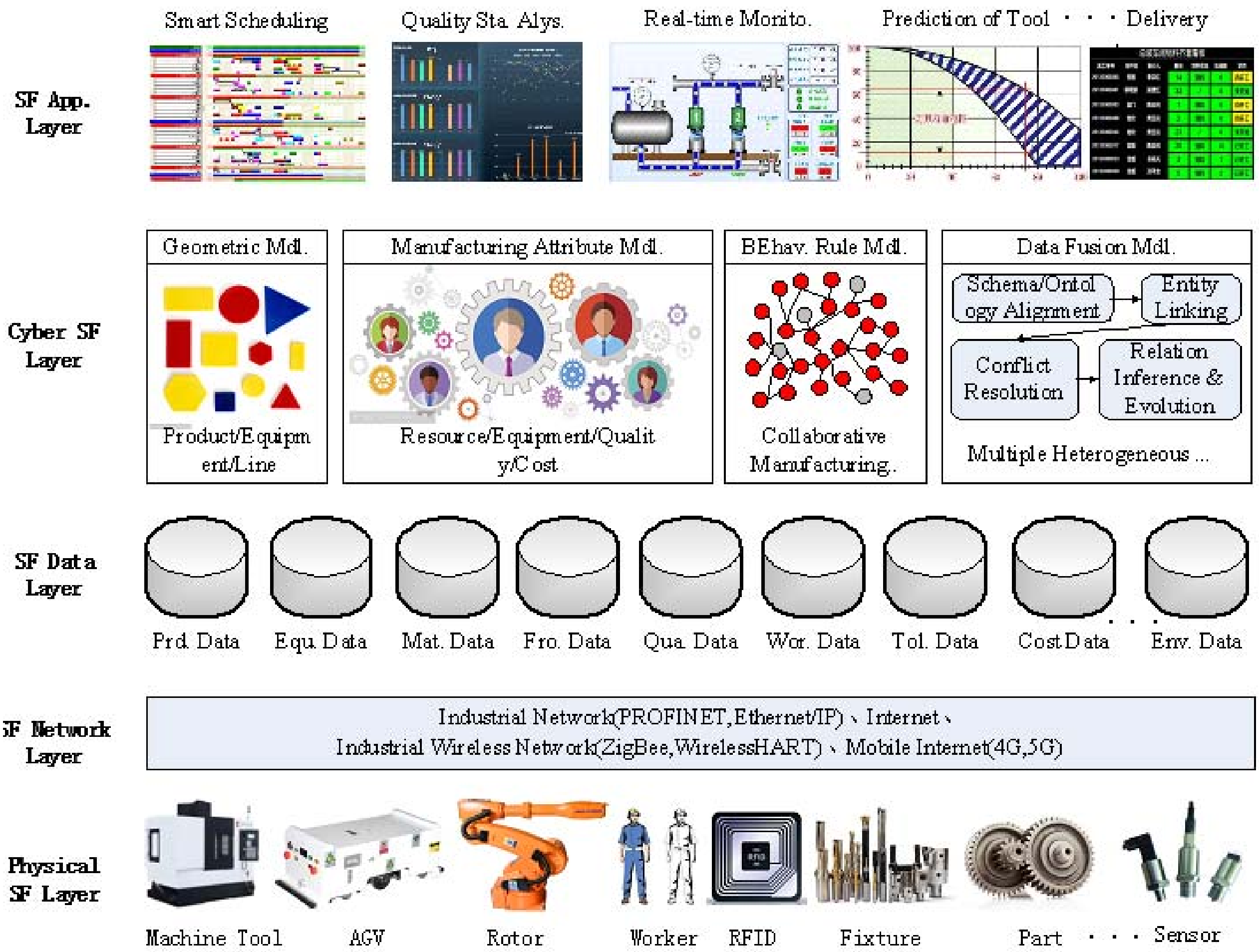


Fig. 1 The architecture of DTSF

Step 3: In the shopfloor application layer, intelligent algorithms can be employed to optimize the models in the cyber shopfloor layer. The optimization results would be provided to the shopfloor manager graphically and digitally. It's noted that the shopfloor manager should choose an optimization result for the final order, which are received in the physical shopfloor layer through network;

Step 4: When there was failure in the physical shopfloor, e.g., equipment breakdown, material shortage, urgent orders, the shopfloor data layer would pick up these kinds of abnormal information, and then the cyber shopfloor layer would map the real-time status;

Step 5: In the shopfloor application layer, intelligent algorithms can be employed to optimize the models again. The optimization results would be provided to the shopfloor manager to decide reallocation or not. If yes, the new order would be transferred to the physical shopfloor through network.

As above mentioned, the more accurate, more real-time information can be provide to the shopfloor managers based on the digital twin technology. Therefore, the shopfloor manager can reduce the workload and get the optimal resource allocation.

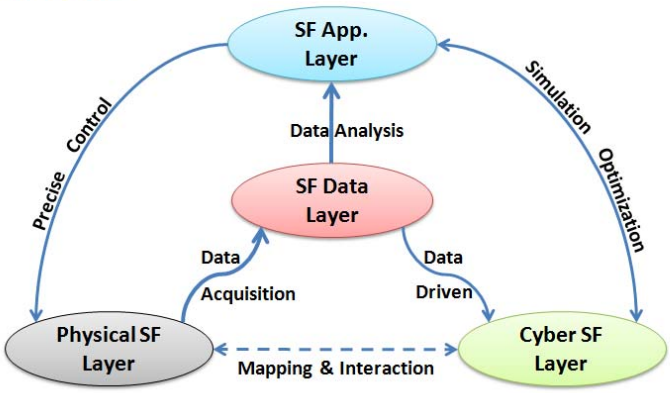


Fig. 2 The scheme of DRAO for DTSF

B. *Case study*

In a machining shopfloor, there are 6 machines and 4 workpieces to be machined. Each workpiece has different behavior rule model (namely process routing). The process time of each operation is different to each machine, which is listed as in Table 1. The 1st column refers to the index of workpieces to be machined; the 2nd column refers to the index of operations; the process time corresponding to every machine locates in the 3rd to 8th column. The symbol refers that the operation could not be machined at the corresponding machine. To simulate the failure in the physical shopfloor, this paper provides 3 scenes, as shown in Table 2. The 1st column refers to the index of failure; the 2nd column refers to the index of fault machine; the 3rd column refers to the point of failure; the 4th column refers to the maintenance time of machine.

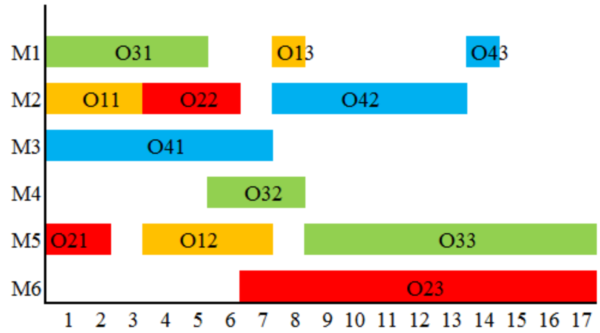
According to Step3 in Section B, two allocative schemes are got in the shopfloor application layer, as shown in Fig.3. Take Scene 3 for example, at point of 5, these machines M1, M4 and M5 break down. In the allocative scheme a, if it employed the Right Shift (RS) strategy, the operation O32 and O33 would be delayed. As a result, the final completion time should be 23 time unit. However, if it employed the proposed DRAO for DTSF, the final completion time would be 18 time unit. For Scheme b shown in Fig.4, the final completion time would be 23 time unit using the RS strategy. However, the completion time should be 18 time unit, as shown in Fig.5. The comparative result is shown in Table 3, where employs two performance functions: one (f1) is to minimize the maximum completion time, and the other (f2) is to minimize the difference between before and after allocation optimization. As seen in Table 5, the proposed DRAO is superior to the RS. The completion time f1 would not extend or the extended time by DRAO is shorter than that by RS. Meanwhile, as a whole, Scheme a is superior to Scheme b. Because in Scene 2, f1 is equal to zero for Scheme a using DRAO, while f1 is equal to 1 for Scheme b using DRAO.

Table 1 A Case for DRAO

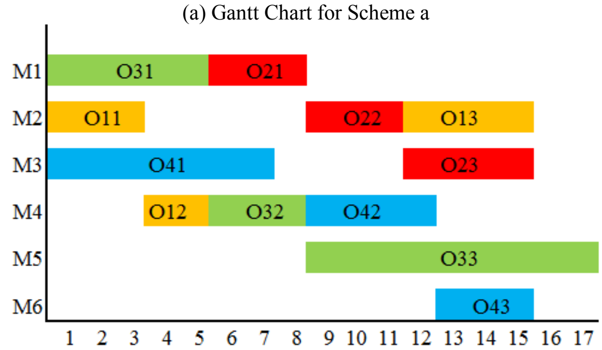
Job	Oper.	Canditated Machines and process time					
		M1	M2	M3	M4	M5	M6
J1	O11	2	3	4	—	—	—
	O12	—	3	—	2	4	—
	O13	1	4	5	—	—	—
J2	O21	3	—	5	—	2	—
	O22	4	3	—	—	6	—
	O23	—	—	4	—	7	11
J3	O31	5	6	—	—	—	—
	O32	—	4	—	3	5	—
	O33	—	—	13	—	9	12
J4	O41	9	—	7	9	—	—
	O42	—	6	—	4	—	5
	O43	1	—	3	—	—	3

Table 2 Cases for Equipment Fault

Scene	Fault mach.	Fault Mom.	Maint. Time
1	M6	5	4
2	M2	11	5
	M3	11	3
3	M1	5	2
	M4	5	6
	M5	5	1



(a) Gantt Chart for Scheme a



(b) Gantt Chart for Scheme b

Fig.3 Gantt Chart for Two Initial Schemes

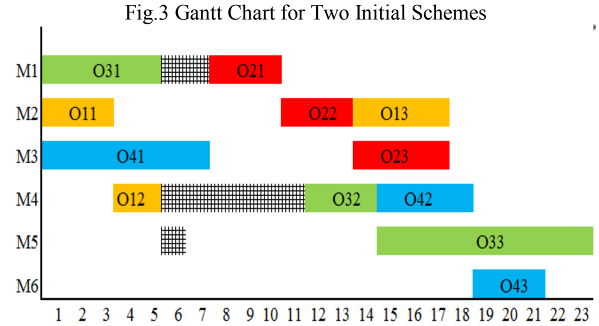


Fig.4 Gantt Chart for Scheme b (Scene 3) by RS

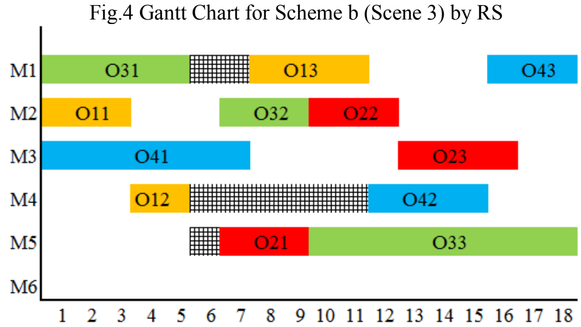


Fig.5 Gantt Chart for Scheme b (Scene 3) by DRAO

Table 3 Comparative Result of DRAO and RS

Scene	Scheme	DRAO		RS	
		f1	*f2*	*f1*	*f2*
1	a	17	0	20	3
	b	17	0	17	0
2	a	17	0	18	1
	b	18	1	20	3
3	a	18	1	23	6
	b	18	1	23	6

V. CONCLUSION

The Digital Twin (DT) is one of the main technologies associated to the Cyper Physical System (CPS). It has just begun to study on DT in manufacturing. This paper proposed an architecture of digital twin-driven smart shopfloor (DTSF) for manufacturing industry. The architecture includes five layers: shopfloor application layer, cyber shopfloor layer, shopfloor data layer, shopfloor network layer, physical shopfloor layer. Based on the architecture of DTSF, the scheme for dynamic resource allocation optimization (DRAO) is designed for DTSF. Finally, a case study is given to illustrate the DRAO for DTSF. Our next works are summarized, such as real-time data collection, digital twin driven shop-floor modeling, further application of digital twin in resource allocation optimization except the failure prediction.

Acknowledgment

This paper is partially supported by National Natural Science Foundation of China (No. 51705472), Aeronautical Science Foundation of China (No. 2015ZG55018), and Key Scientific Research Projects of Henan Higher Education (No. 18A460033, 18A460034).

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