AASPMP: Design and Implementation of Production Management Platform Based on AAS

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***Abstract*—Intelligent transformation for traditional factories is a widely discussed topic. The key to this transformation is ensuring the integration between information technology and operational technology. However, it is a challenging task in industry owing to the communication heterogeneity of the underlying production equipment (horizontal communication), and inefficient interactions between the equipment and information decision center (vertical communication). In this paper, we explore asset administration shell (AAS), an asset virtualization technology, shielding heterogeneous physical communication protocol of production equipment. Besides, to promote inefficient communication between the equipment and information decision center, we adapt OPC UA protocol as the communication protocol of AAS for vertical communication. In addition, time-sensitive networking (TSN) is applied to ensure communication between the AAS and the corresponding physical device. Above operations ensure devices interconnection and interoperability. On this basis, we propose an AAS-based production management platform (AASPMP), which aims at the coverage from the demand side to the production side. Such an intelligent system characterizes three layers to decompose complicated system functionalities, and a visible client is provided for the convenience of remote operation and maintenance. We deploy our system on the actual production system and demonstrate the effectiveness of our design.**

***Index Terms*—Intelligent transformation, AAS, OPC UA, TSN, production management platform**

I. INTRODUCTION

Traditional manufacturing is tailored for the large-scale production of a certain product. This mode is difficult to cope with current changing product demands. With the development of information technology and operation technology, the conception of the smart factory is proposed in Industry 4.0 [1] to solve this problem. Smart factory aims at deep integration of information technology and operational technology to realize flexible and customized manufacturing.

To integrate these two technologies, there exist two challenges in traditional industrial. First, in real industrial scenario, horizontal communication (e.g., communication between PLC and the robot arm) is heterogeneous because production equipment from diverse manufacturers provides different and confidential communication protocols. In this case, massive data is hard to collect for intelligent applications, such as anomaly detection. Second, the production strategy must be timely to response changing production requirements in smart factory. Unfortunately, vertical communication (e.g., dynamic task scheduling to a robotic arm) is inefficient as data transmission latency from physical production devices to digital information center is unacceptable.

Physical device virtualization, proposed by Industry 4.0, is a promising approach to alleviate these problems. AAS, as an important virtualization technology recommended in Industry 4.0, treats one entity, whether it is a physical entity (e.g., an actual production device) or a virtual object (e.g., a production process), as an asset. Asset metamodels in AAS abstract these assets with their attributes, and provide unique digital counterparts in the digital world.

In this paper, we leverage AAS to solve the two above mentioned challenges, heterogeneous horizontal communication and inefficient vertical communication. For heterogeneous horizontal communication, we firstly treat underlying production equipment as assets, and design asset metamodels to digitize physical equipment. In the digital world, digital counterparts of these heterogeneous devices can communicate more flexibly, shielding heterogeneous physical communication protocols of production equipment. As for inefficient vertical communication, information decision center is more accessible to the production information without accessing physical devices, benefiting from the above device virtualization. To further promote the efficiency of vertical communication, we unify the communication interface of AAS via OPC UA protocol that industry 4.0 recommends. Besides, time-sensitive networking (TSN) [2] is also applied to ensure communication between the AAS and the corresponding physical device.

After these, interconnection and interoperability can be guaranteed. On this basis, we propose the AAS-based production management platform (AASPMP). Unlike previous efforts that focused on the industrial site, AASPMP can assign tasks from the demand site and perform the corresponding production on the industrial site, completing the coverage from the demand site to the production site. In AASPMP, the entire production system is divided into three layers to decompose system functionalities.

The device layer contains all asset metamodels for this system, and acts as a bridge connecting the device equipment and its corresponding digital counterparts. The resource layer is responsible to integrate unorganized information from

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the device layer via resource-specific AAS, called R_{AAS}. The management layer decomposes system functionalities and owns four modules, namely monitoring, control, scheduling, and anomaly detection module, respectively. More concretely, the monitoring module derives the concerning device status information and production process information from asset metamodels. The control module can adjust the production process and device status via the interoperability between asset metamodels and physical devices. By OPC UA protocol, we can obtain the customer's remote demands, and assign tasks according to currently available production capacities. The assignment result will be performed through the control module. For safety, the anomaly detection module exploits the stored history device data to detect production anomalies via rule-based and learning-based methods. Finally, deployment on the real production system demonstrates the validity of our design. Our contributions are summarized as follows:

- To solve the heterogeneous horizontal communication, we design AAS to virtualize the complicated production equipment. Besides, we attach OPC UA protocol to AAS for promoting vertical communication.
- We propose an AAS-based production management platform (AASPMP) that covers from the demand side to the production side. And a visual client is designed for the remote operation and maintenance.
- The extensive experiment is conducted to verify the validity of AASPMP in the actual production system.

The rest of this paper is organized as described below. In Section II, we briefly reviewed the recent work. Next, in Section III, framework and components of AASPMP are presented in detail. In Section IV, a practical case is introduced to clarify its application. Finally, we make a conclusion in Section V.

II. RELATED WORK

With the proposition of Industry 4.0, smart manufacturing has attracted much attention. Recent work can be branched into three categories from the technical prospective.

A. DT Based Methods

DT is an advanced technology for smart manufacturing. DT builds digital counterparts for physical devices, and simulates their functionalities and mechanisms [3]. The core features behind DT are real-time connection, bidirectional mapping and dynamic interaction. Guo *et al.* leveraged the flexibility of software based DT to quickly model the fast-changing factory design and easily find some design flaws [3]. In addition, DT based on several devices (e.g., devices on a hierarchy) could help managers efficiently get concerned information [4]. Furthermore, VREDI [5] combined the technology of AAS and DT. It inherited AAS advantages for efficient asset management and interoperability, and supported DT-based technical functionalities. However, building digital counterparts for the physical entities is difficult as the industrial device mechanisms are too complex to be modeled in digital world. Instead of virtualizing devices completely, we try to abstract devices via their key features that we are interested in. This not only helps operators filter redundant information, but reduces time consumption for unnecessary delicate designs.

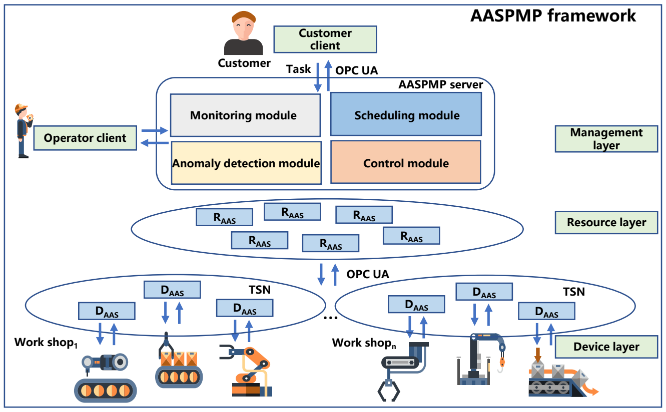


Fig. 1: The overview of AASPMP framework.

B. OPC UA Based Methods

OPC UA provides the unified communication protocol in application layer, and information model in OPC UA has been extensively applied to represent physical entity in information world. Considering the heterogeneous communication protocol of distributed edge devices, Lee *et al.* [6] exploited OPC UA for M2M interaction in distributed smart factory platform. Park *et al.* [7] designed the information model for legacy equipment in the universal edge gateway. And the edge gateway provided the OPC UA protocol in convenience of equipment configuration and communication. Muniraj *et al.* [8] utilized OPC UA protocol for communication with higher-level machines and same-level machines to improve the decision-making ability of the whole system. Kim *et al.* [9] built a Cyber Physical Product System based on 5G network by central OPC UA server. And they studied that how OPC UA modeled the logic and data generated in product process. As there exists some inspiring work based on OPC UA, AAS has advantages over OPC UA in asset management.

C. AAS Based Methods

AAS proposed by Industry 4.0 targets at virtualizing physical assets to better manage them. Leveraging AAS to achieve interoperability among devices with different communication protocols, Cavalieri *et al.* [10] designed a generic model for predictive maintenance. Lv *et al.* [11] proposed an asset management method to perform some basic tasks in the edge and relieve the computation load in the cloud. Lu *et al.* [12] encapsulated AAS into modules, improving the scalability of AAS. They could compose different production lines for various scenarios by dragging and dropping AAS of needed devices. These aforementioned work focuses on the production side, while our AASPMP is more systematic, considering the production side as well as the customer side.

Algorithm 1 Time priority algorithm

```
Input: The order set, $O$; The production unit set, $P$;
Output: The needed time, $Time$; The energy cost, $Energy$;
for each $O_i$ do
    $P_a = P \cap Type(O_i)$;
    if $P_a = \varnothing$ then
        return Error;
    end if
    for each $p_i \in P_a$ do
        $t.append(get\_time(p_i, O_i))$;
        $e.append(get\_cost(p_i, O_i))$;
    end for
    while $P_a[idx(min(t)].t + min(t) \geq O_i.t$ do
        $t.delete(min(t))$
    end while
    $P_a[idx(min(t)].t += min(t)$;
    $P_a[idx(min(t)].e += e[idx(min(t)]$;
end for
return $Time = max(P.t), Energy = sum(P.e)$;
```

Algorithm 2 Energy priority algorithm

```
Input: The order set, $O$; The production unit set, $P$;
Output: The needed time, $Time$; The energy cost, $Energy$;
for each $O_i$ do
    $P_a = P \cap Type(O_i)$;
    if $P_a = \varnothing$ then
        return Error;
    end if
    for each $p_i \in P_a$ do
        $t.append(get\_time(p_i, O_i))$;
        $e.append(get\_energy(p_i, O_i))$;
    end for
    while $P_a[idx(min(e)].t + t(idx(min(e))) \geq O_i.t$ do
        $e.delete(min(e))$
    end while
    $P_a[idx(min(e)].t += t[idx(min(e)]$;
    $P_a[idx(min(e)].e += min(e)$;
end for
return $Time = max(P.t), Energy = sum(P.e)$;
```

III. SMART FRAMEWORK

AASPMP is characterized by three layers, namely the device layer, resource layer, and management layer. Device layer aims to virtualize production equipment into digital world via the technology of AAS. For better clarification, we notate the AAS that is special for physical devices as D_{AAS}. To digitize the equipment, we design D_{AAS} for each device by featuring their key attributes. According to industry 4.0 recommendation, one visualized device is necessarily represented by the globally unique Asset information attributes, asset administration shell information attributes, and some other specific descriptive information. The details will be discussed later in Section III-A. In the resource layer, R_{AAS} targets to integrate device resources (i.e., device usages). More specifically, R_{AAS} collects the device layer information, and categorizes these resources for upper application. The top layer, management layer, mainly focuses on the service-oriented functions about platform production. According to different requirements, we design four modules, namely monitoring, scheduling, control and anomaly detection module. Finally, we integrate these modules into the server, and authorized people can access their concerned information via a visual client in a server-client manner.

A. *Asset Metamodule*

Following the Industry 4.0 instruction, we design asset metamodels for physical equipment. The asset information consists of Asset ID, Asset kind and Submodel. Asset ID indicates the globally unique identification of the asset in the virtual world. And Asset kind reflects whether the asset is a virtual type or a physical instance. For a simple device, these may be sufficient, while complicated devices need additional more fine-grained Submodel to describe. Submodel model comprises of four attributes, including Capability, Concept description, Data element, and Reference. Capability attributes indicate the potential of an asset to achieve certain task (e.g., robotic arm rated load and rated power) in the physical or virtual world. And Concept description attributes provide the illustration about the certain device specific functionality. (e.g., the robotic arm is responsible to assemble products). Data element attributes define basic variables of the corresponding physical devices, including static information and dynamic information. Reference attributes show mutual relationships among AAS or between AAS and external entities.

B. *Communication Architecture*

Devices of different producers often are with diverse protocols and interfaces. For the purpose of real-time access to data, the D_{AAS} exchanges information with its corresponding physical device via the proprietary protocol, where TSN is applied to guarantee the communication. All D_{AAS} of each workshop will be embedded into intelligent gateways, where the D_{AAS} completes the inter communication by OPC UA protocol. In such cases, we can achieve regional autonomy when it is unnecessary to request the schedule from management layer. In higher layer, the resource layer, the R_{AAS} categories unorganized information from D_{AAS} by OPC UA interfaces. This facilitates AASMPM server to get access to the concerned information. For efficient human-computer interaction, the management layer provides API to call aforementioned four modules so that operators and customers can connect the server by the client.

C. *Monitoring Module*

It is important for the smart manufacturing system to get access to devices and production process information, which are mainly exploited by operators for operation and maintenance. AASPMP can also get static asset information of each device, such as the device model, device capability, and device reference. In addition, dynamic data generated by the production process can also be captured and displayed in real time. Furthermore, we store the monitored history information for the upper application like condition diagnosis and prognosis. For each device in the smart manufacturing system, AASPMP provides GUI to monitor static assets and dynamic production information for authorized operators.

D. *Scheduling Module*

We consider to allocate tasks to different workshops. The procedure is that when the customer sends tasks through the customer client, scheduling module firstly requests current available resources from R_{ASS}, and checks whether the whole production system is competent to the coming tasks. If the system is able to perform these tasks, we will take into account what way to product them. In this paper, we consider the time priority (Algorithm 1) and energy priority (Algorithm 2) production scheduling. Depending on the resource usage, scheduling module performs the two production schedules to obtain the respective time consumption. T_t means time consumption of the time priority, and T_e means time consumption of energy priority. In general, the time priority is more energy consuming compared to the energy priority, while T_t is smaller than T_e. For our setting, when task deadline is loose than T_e, the energy priority production schedule is the default scheduling approach for saving energy.

E. Control Module

The most prominent advantage for AASPMP is that it can make timely reactions according to different remote requirements. When the production scheduling is planned, the control module will automatically send commands to intelligent gateways, and these commands further arrive the terminal equipment by the aforementioned communication architecture in Section III-B. Besides scheduling, authorized operators can proactively adjust production strategies and change device statuses. The control flow from clients to the server of AASPMP is as follows:

- Clients send the requests to the server.
- The server needs to parse requests and transform them to legal commands that corresponding devices can understand.
- The server sends translated commands to physical devices through the communication architecture.
- The server receives feedback signals from physical devices.
- The clients receive the reaction from the server.

F. Anomaly Detection Module

Detecting event anomalies and product defects is important to the production system. Device history data is stored to serve as the database. According to features of different devices, we use rule-based and learning-based methods to capture normal data patterns. Anomalies will be output when the running data deviates the normal patterns.

IV. CASE STUDY

In order to verify the validity of AASPMP, we deploy it on a discrete intelligent manufacturing system. The main production process is to manufacture customized waterproof boxes. As shown in Fig. 2, this production system is mainly composed of several typical production equipment, as illustrated in Table I. For the purpose of device virtualization, we design the AAS for aforementioned equipment in the manufacturing system. Next, as described above in Section III, we design monitoring module, scheduling module, control module and anomaly detection module. In addition, Fig. 3 depicts a visible client for more efficient human-computer interaction.

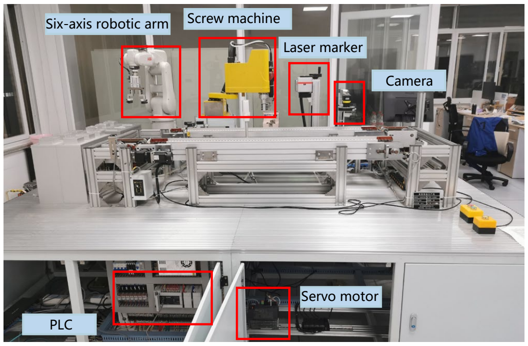


Fig. 2: Discrete intelligent manufacturing system.

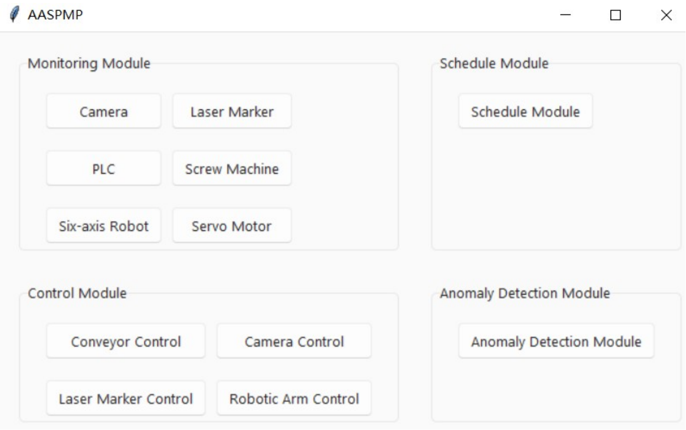


Fig. 3: AASPMP GUI client.

A. AAS Construction

According to Section III-A, asset metamodels have three main components including Asset ID, Asset kind and Submodel. First, we design the corresponding contents in XML files, and further transform them to asset metamodels. Combining the OPC UA protocol, the AAS can communication with other AAS via OPC UA protocol. As shown in Table II, we portray production equipment with different Asset ID (e.g., equipment mode) to provide unique indexs in the production system. Since these devices are physical entities, their Asset ID attributes are instance. Capacity, Concept description, Data element and Reference are also presented in Submodel. For explaining the reason for such design, we take the six-axis robotic arm as an example. `WR 580mm` represents that the moving range of the robotic arm is 580mm, and `LC 3kg` reflects the payload of the robot arm is 3kg. Concept Description is `assemble` as the robot arm is responsible to assemble the workpiece in the production system. Regarding the Data element attributes, the six values represent the angle information of six freedom degrees. Finally, based on the fact that the previous process affects the next one, Reference considers the workflow in the production system.

B. Monitoring Module Implementation

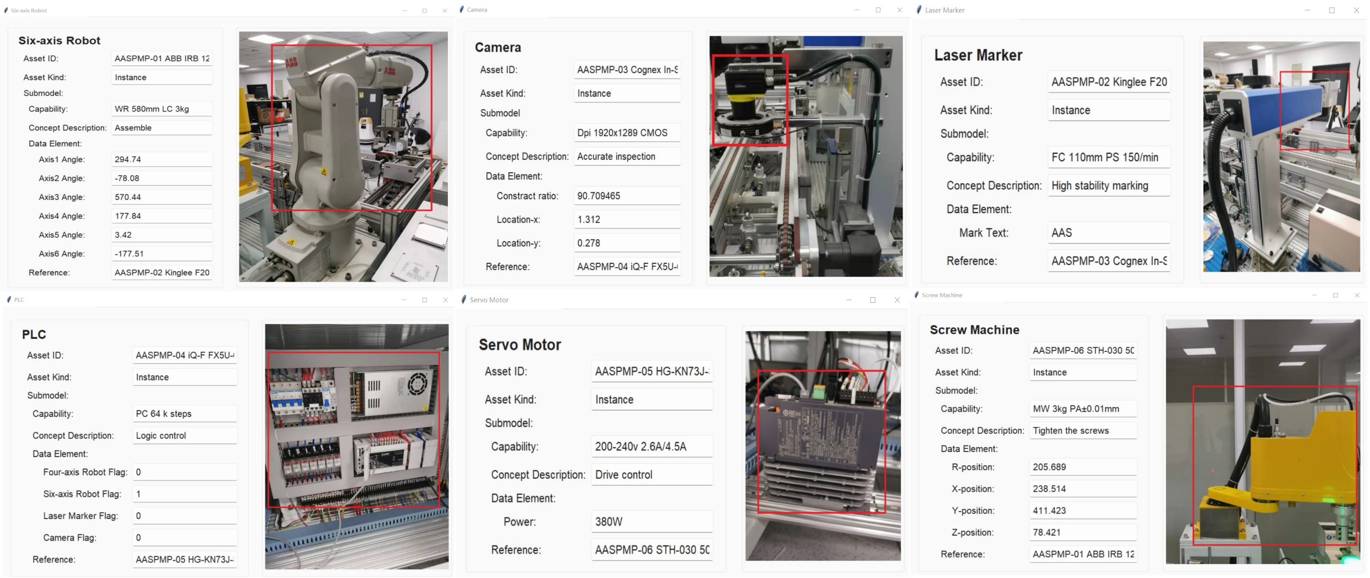
To monitor production information in real time, we show concerned AAS contents in a visual client. As illustrated

TABLE I: Components of the production system.

Component	Device	Model	Function
Assembly unit	Six-axis robotic arm	ABB IRB 120 Robot	Cover the waterproof case
Laser marking unit	Laser marker	Kinglee F2000	Print the logo onto the workpiece
Quality inspection unit	Industrial camera	Cognex In-Sight 7010C	Complete the visual inspection of the object
Logic control unit	Programmable Logic Controller	MELSEC iQ-F FX5U-64MT	Control the whole production process
Screw machine unit	Four-axis robotic arm	STH-030 500	Tighten screws
Drive unit	Servo motor	HG-KN73J-S100	Drive the conveyor belt

TABLE II: AAS designs of the production system.

metamodel	Six-axis robotic arm	Laser marker	Industrial camera	PLC	Servo motor	Screw machine
Asset ID	AASPMP-01 ABB IRB 120	AASPMP-02 Kinglee F2000	AASPMP-03 Cognex In-Sight 7010C	AASPMP-04 iQ-F FX5U-64MT	AASPMP-05 HG-KN73J-S100	AASPMP-06 STH-030 500
Asset kind	Instance	Instance	Instance	Instance	Instance	Instance
Submodel/Capability	WR 580mm LC 3kg	FC 110mm PS 150m/min	Dpi 1920x1289 CMOS	PC 64 k steps	200-240v 2.6A/4.5A	MW 3kg PA±0.01mm
Submodel/Concept description	Assemble	High stability marking	Accurate inspection	Logic control	Drive control	Tighten screws
Submodel/Data element	Arm position	Mark text	Inspection location	Production flag	Output power	Arm angle
Submodel/Reference	AASPMP-02 Kinglee F2000	AASPMP-03 Cognex In-Sight 7010C	AASPMP-04 iQ-F FX5U-64MT	AASPMP-05 HG-KN73J-S100	AASPMP-06 STH-030 500	AASPMP-01 ABB IRB 120



Six-axis Robot
Asset ID: AASPMP-01 ABB IRB 12
Asset Kind: Instance
Submodel:
Capability: WR 580mm LC 3kg
Concept Description: Assemble
Data Element:
Axis1 Angle: 294.74
Axis2 Angle: -78.08
Axis3 Angle: 570.44
Axis4 Angle: 177.84
Axis5 Angle: 3.42
Axis6 Angle: -177.51
Reference: AASPMP-02 Kinglee F20

Camera
Asset ID: AASPMP-03 Cognex In-S
Asset Kind: Instance
Submodel
Capability: Dpi 1920x1289 CMOS
Concept Description: Accurate inspection
Data Element:
Constract ratio: 90.709465
Location-x: 1.312
Location-y: 0.278
Reference: AASPMP-04 iQ-F FX5U-

Laser Marker
Asset ID: AASPMP-02 Kinglee F20
Asset Kind: Instance
Submodel:
Capability: FC 110mm PS 150/min
Concept Description: High stability marking
Data Element:
Mark Text: AAS
Reference: AASPMP-03 Cognex In-S

PLC
Asset ID: AASPMP-04 iQ-F FX5U-
Asset Kind: Instance
Submodel:
Capability: PC 64 k steps
Concept Description: Logic control
Data Element:
Four-axis Robot Flag: 0
Six-axis Robot Flag: 1
Laser Marker Flag: 0
Camera Flag: 0
Reference: AASPMP-05 HG-KN73J-

Servo Motor
Asset ID: AASPMP-05 HG-KN73J-
Asset Kind: Instance
Submodel:
Capability: 200-240v 2.6A/4.5A
Concept Description: Drive control
Data Element:
Power: 380W
Reference: AASPMP-06 STH-030 5C

Screw Machine
Asset ID: AASPMP-06 STH-030 5C
Asset Kind: Instance
Submodel:
Capability: MW 3kg PA±0.01mm
Concept Description: Tighten the screws
Data Element:
R-position: 205.689
X-position: 238.514
Y-position: 411.423
Z-position: 78.421
Reference: AASPMP-01 ABB IRB 12

Fig. 4: Monitoring interfaces of each equipment in AASPMP.

in Fig. 4, we show important information of six production equipment. Static information mainly depicts the device attributes, such as device ID and device capacity. Real time device statuses, e.g., the robot position and conveyor speed, are described as dynamic information. Observing the information, we can grasp the production information of the whole system.

C. Scheduling Module Implementation

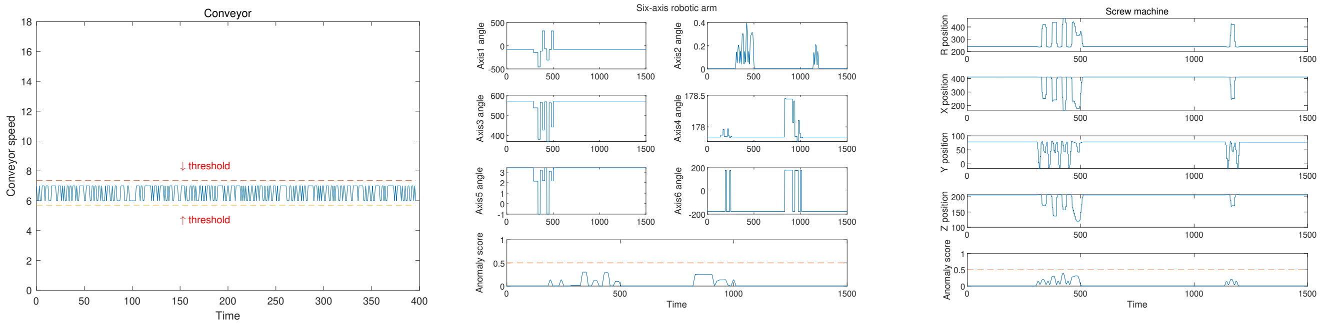
Since there is only one production system, we cannot valid our scheduling algorithms in the actual scene. In this case, we simulate the situation where there exist multiple workshops and different types of tasks. To present intuitive results, we study time and energy consumption of two aforementioned algorithms with the number of tasks increasing in Fig. 6.

D. Control Module Implementation

New scheduling plan or production strategy adjustment of authorized operators requires the interoperability of the production system. In our setting, controlled variables mainly contain conveyor speed, robot arm position, laser mark text, and camera localization. Conveyor speed can change the production speed. Besides the production speed, robot arm is controlled to perform different tasks. For laser mark text and camera localization, they need to apply different settings for various customization products.

E. Anomaly Detection Module Implementation

To ensure the safety of production systems, the task of anomaly detection is important. In the production system,



(a) (b) (c)

Fig. 5: Anomaly detection for production equipment in AASPMP. (a) Rule-based detection for conveyor. (b) and (c) Learning-based detection for the six-axis robotic arm and screw machine.

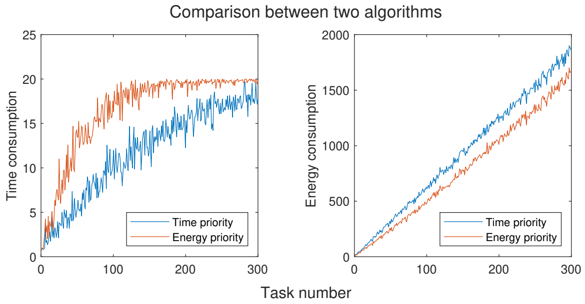


Fig. 6: Comparison between two algorithms when there are five types of tasks and fifteen work shops.

we try to detect device faults, including the conveyor, six-axis robotic arm, and screw machine. For the conveyor, small speed fluctuation is acceptable, so we empirically declare the anomaly when the speed exceeds the setting value by 5%. As for the six-axis robotic arm and screw machine, their working mechanisms are more complex, and they generate multidimensional time series. Consequently, the anomaly detection module may fail to accurately output faults only via rule-based ways, i.e., larger than a threshold. Therefore, we record their history data to capture normal patterns of the multidimensional features by learning-based methods (e.g., autoencoder), and declare anomalies once the data deviates learned normal patterns. Fig. 5 presents the running data of each device and corresponding detection results, where the red dotted line represents the set threshold.

V. CONCLUSION

In this paper, we propose AAS based production management platform AASPMP, covering from the customer side to the industrial side. AASPMP virtualizes production equipment, integrates industrial resources, and further contains four modules to decouple complex production functionalities. In addition, for better human-computer interaction, visible clients are designed. In the future, we will deploy our scheduling algorithms to multiple discrete manufacturing systems.

REFERENCES

[1] M. Hankel and B. Rexroth, “The reference architectural model industrie 4.0 (rami 4.0),” *ZVEI*, vol. 2, no. 2, pp. 4–9, 2015.

[2] L. L. Bello and W. Steiner, “A perspective on ieee time-sensitive networking for industrial communication and automation systems,” *Proceedings of the IEEE*, vol. 107, no. 6, pp. 1094–1120, 2019.

[3] J. Guo, N. Zhao, L. Sun, and S. Zhang, “Modular based flexible digital twin for factory design,” *Journal of Ambient Intelligence and Humanized Computing*, vol. 10, no. 3, pp. 1189–1200, 2019.

[4] K. T. Park, Y. W. Nam, H. S. Lee, S. J. Im, S. D. Noh, J. Y. Son, and H. Kim, “Design and implementation of a digital twin application for a connected micro smart factory,” *International Journal of Computer Integrated Manufacturing*, vol. 32, no. 6, pp. 596–614, 2019. [Online]. Available: https://doi.org/10.1080/0951192X.2019.1599439

[5] K. T. Park, J. Yang, and S. D. Noh, “Vredi: virtual representation for a digital twin application in a work-center-level asset administration shell,” *Journal of Intelligent Manufacturing*, vol. 32, no. 2, pp. 501–544, 2021.

[6] Y. K. Lee, S.-J. Lee, H. Lee, and D. Yoon, “Implementation of distributed smart factory platform based on edge computing and opc ua,” in *IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society*, vol. 1, 2019, pp. 4235–4239.

[7] H. M. Park and J. Wook Jeon, “Opc ua based universal edge gateway for legacy equipment,” in *2019 IEEE 17th International Conference on Industrial Informatics (INDIN)*, vol. 1, July 2019, pp. 1002–1007.

[8] S. P. Muniraj and X. Xu, “An implementation of opc ua for machine-to-machine communications in a smart factory,” *Procedia Manufacturing*, vol. 53, pp. 52–58, 2021, 49th SME North American Manufacturing Research Conference (NAMRC 49, 2021). [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2351978921000093

[9] J. Kim, G. Jo, and J. Jeong, “A novel cpps architecture integrated with centralized opc ua server for 5g-based smart manufacturing,” *Procedia Computer Science*, vol. 155, pp. 113–120, 2019, the 16th International Conference on Mobile Systems and Pervasive Computing (MobiSPC 2019),The 14th International Conference on Future Networks and Communications (FNC-2019),The 9th International Conference on Sustainable Energy Information Technology. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1877050919309330

[10] S. Cavalieri and M. G. Salafia, “A model for predictive maintenance based on asset administration shell,” *Sensors*, vol. 20, no. 21, p. 6028, 2020.

[11] B. Lv, Y. Zhang, F. Yang, and J. He, “Edge asset management based on administration shell in industrial cyber-physical systems,” in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, 2020, pp. 3817–3822.

[12] Q. Lu, X. Li, G. Li, M. Li, J. Zhou, J. Liu, X. Shen, and F. Zhu, “A general asset administration shell platform for production line design,” in *2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI)*, 2021, pp. 192–195.