Digital Twin Framework of Manufacturing System Integrated with Renewables Based on Event-triggered Hybrid Scheduling

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Abstract

The increasing adoption of renewable energy sources (RESs) in manufacturing plants has led to growing interest in efficiently integrating these variable energy sources into production processes. The Event-Triggered Hybrid Scheduling (ETHS) approach was developed to generate both off-line and on-line schedules for varied components by engaging components of diverse flexibilities at various scheduling stages. However, ETHS primarily focuses on the virtual system, leaving a gap in effectively channelling critical data from the physical to the virtual system. In this study, we introduce a comprehensive framework for creating a digital twin of manufacturing systems integrated with RESs. This framework categorises the flexibilities of different components, outlines strategies for transferring data from the physical to the virtual environment and explains how the results from the virtual model inform decision-making in the physical system. A case study was undertaken to validate our proposed digital twin model, revealing its capability to balance system performance, robustness, and computational efficiency.

Keywords
Digital twin, renewable energy, production scheduling and event-triggered hybrid scheduling.

1. Introduction
The global landscape of manufacturing has been dominated by fossil fuels for decades. However, with the growing awareness of sustainability and relevant planning like net zero emissions, renewable energy sources (RESs) are being adopted by the manufacturing factories aiming at reducing carbon footprints. Relevant investigation shows great potential that on-site RESs generation in manufacturing factories will contribute to the carbon neutrality (Shi et al. 2022). Meanwhile, the integration of on-site RESs poses challenges in the coordination of energy management and production scheduling due to the uncertain nature of RESs (Impram et al. 2020).

In recent years there have been numerous research targeting at coordinating the energy management and production scheduling for factories, which can be classified into two major categories. One category focuses on the modelling and scheduling of the virtual system, providing multiple scheduling methods, among which event-triggered hybrid scheduling (ETHS) was recently proposed as a promising method to balance the system performance, robustness and computational efficiency (Zhean et al. 2023). The other category targets at designing the digital twin, which includes both the virtual system modelling and the information flow between the physical and virtual system. The digital twin design acts as a further development of the scheduling method in the virtual system, which could progressively improve the applicability of the method in factories. Nevertheless, there still lacks a digital twin design of the manufacturing system based on ETHS, which could guide the user to handle the massive information between physical and virtual system.

Therefore, this paper is targeted to building the digital twin of a RESs integrated manufacturing system based on ETHS. Two main research questions can be concluded: 1) How to design the virtual system according to the physical system configuration? 2) How to build the channel for data flow between the virtual system and the physical system? In this paper, the authors will propose a comprehensive framework for creating the required digital twin. The framework categorises the flexibilities of different components, outlines strategies for transferring data from the physical to the virtual environment and explains how the results from the virtual model inform decision-making in the physical system. This paper is organised as follows. Section 2 provides a literature review of relevant research. Section 3 introduces the proposed method of digital twin design. Section 4 provides experiments to validate the framework. Section 5 analyses the experimental results and discusses further improvements. Section 6 concludes the paper.

2. Literature Review

This section reviews relevant research. Scheduling methods in the virtual system will first be reviewed, including their pros and cons. The digital twin design will then be reviewed, leading to the gap in the existing research. All the reviewed papers are summarised in Table 1 about their main properties.

Table 1. Main properties of the research in the literature review

	Physical System	Virtual System	RESs Consideration	Approach of Scheduling	Scope of Scheduling
Pei et al. (2023)		√	√	Optimisation	Off-line scheduling
Zhai et al. (2017)		√	√	Optimisation	On-line scheduling
Cai et al. (2023)		√	√	Heuristic	On-line scheduling
Wang et al. (2021)		√	√	Optimisation + Optimisation	Off-line scheduling + On-line scheduling
Nouiri et al. (2020)		√	√	Optimisation + Heuristic	Off-line scheduling + On-line scheduling
Zhean et al. (2023)		√	√	Optimisation + Heuristic	Off-line scheduling + On-line scheduling + Heuristic evaluation
You et al. (2022)	√	√	√	Optimisation	Off-line scheduling
Yan et al. (2022)	√	√		Optimisation	On-line scheduling
Eunike et al. (2022)	√	√		Optimisation	On-line scheduling
Liu et al. (2019)	√	√		Optimisation	On-line scheduling
This work	√	√	√	Optimisation + Heuristic	Off-line scheduling + On-line scheduling + Heuristic evaluation

The approaches in scheduling methods can be mainly divided into optimisation and heuristics. An optimisation problem including objective function, control variables and constraints will be formulated to calculate the schedules for system components. For example, Pei et al. (2023) formulated an optimisation problem to minimise energy consumption for a two-machine system, Zhai et al. (2017) minimised makespan for a flow shop system integrated with wind turbines. Optimisation approach usually has better performance at the same time of increasing the complexity of computation. In contrast, heuristic approach sacrifices the long-term performance for a faster calculation, which designs specific heuristic rules in real-time to decide the states of components. For example, Cai et al. (2023) designed the production logistics for each processing unit and automated guided vehicles to pick jobs. Optimisation and heuristics can be applied together. For example, Nouiri et al. (2020) not only scheduled production beforehand, but also designed several heuristic criteria to assign tasks in real time. Zhean et al. proposed ETHS, which used several optimisation problems to calculate schedules and a heuristic evaluation in real-time to decide which optimisation problem to apply.

The scope of scheduling includes off-line scheduling, on-line scheduling and heuristic evaluation. Off-line scheduling calculates schedules without real-time information. In the off-line scheduling of two machines in Pei et al. (2023), even though the energy consumption was modelled carefully, the real-time disturbances could influence the real consumption significantly. On-line scheduling requires real-time information, which requires efficient computation. Zhai et al. (2017) and Cai et al. (2023) scheduled production in real-time, which requires real-time machine status, order status, etc. to calculate schedules for machines. The combination of off-line scheduling and on-line scheduling could initialise the schedule at first while adjusting the schedules without recalculating the complex off-line scheduling problem, thus reducing the real-time computation stress. Both Wang et al. (2021) and Nouiri et al. (2020) provides initial schedules before production, and applied their optimisation problem or heuristics to adjust schedules in real-time, largely improving the system robustness. Furthermore, ETHS proposed by Zhean et al. (2023) introduced a real-time heuristic evaluation, which evaluated the system performance and decide whether to adjust highly-flexible states or reschedule all states, further balancing the system performance, robustness and computational efficiency. Nevertheless, ETHS requires significant real-time information from the physical system, lacking a digital twin design to improve the information flow.

The development of digital twin could compensate the lack of interaction between physical and virtual system based on the above scheduling methods. For off-line scheduling, You et al. (2022) designed the virtual energy system to forecast and schedule the energy components in day-ahead scenario, and studied how forecast error could influence the physical system in real time. For on-line scheduling, Yan et al. (2022) built the virtual replica of a job shop system, applied a double-layer Q-learning algorithm to calculate schedules for machines, and collects warning information from the physical system to determine rescheduling and maintenance. Eunike et al. (2022) clearly demonstrated the tasks for physical objects like updating states, virtual objects like sync local file to cloud, and communication like receive signal and send jobs. Liu et al. (2019) designed the virtual system as a combination of upper-level calculation system, semi-physical simulation platform and 3D models, followed by the execution of physical system. The above digital twin design provided effective approaches to coordinate the physical and virtual system, but the newly proposed scheduling methods like ETHS still needs specific digital twin design to improve the applicability.

3. Methods

In this section, two main parts of digital twin design based on ETHS will be proposed, including the design of virtual system and the design of information channel.

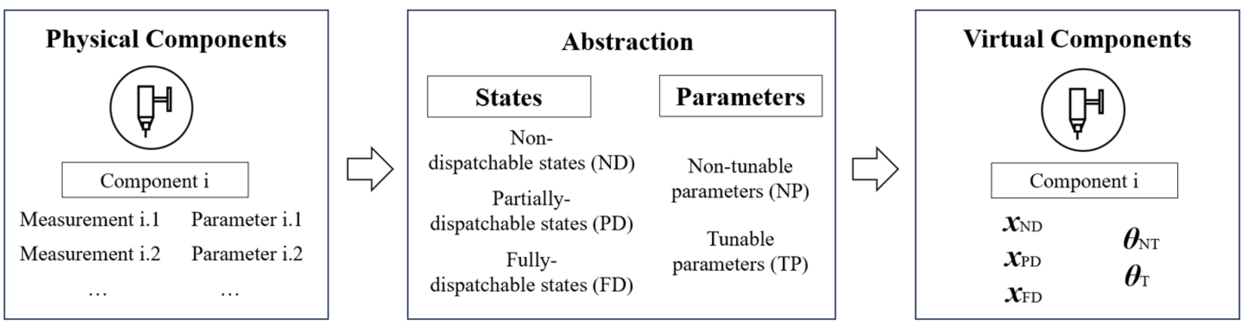

Figure 1. Abstraction of physical components

3.1 Virtual system design

The virtual system design should be based on both the configuration of physical system and the framework of ETHS. In order to efficiently build the virtual replica, we will first propose the methods to abstract the components into categorised states and parameters, then adding the scheduling models into the virtual system.

- <u>Abstraction of the states and parameters</u>

In the physical system, sensors or monitoring systems are assumed to be installed to measure the data of different components, together with the constant parameters for the component. Take battery energy storage system (BESS) as an example, the measurement might include the charging and discharging power, the state of charge (SOC), and the parameter might include the charging efficiency coefficient. The measurement of a single component is simple, but when measuring heterogeneous components in the system, a systematic method to organise these data is required. According to ETHS, the states of components are categorised according to it control flexibility. Non-dispatchable (ND) states means they can only be measured. Fully-dispatchable (FD) states means they are highly flexible and can be controlled at each time step. Partially-dispatchable (PD) states means they can only be controlled when the entire system needs rescheduling. Therefore, one major part of the abstraction is intended measuring and categorising the states into three vectors $\boldsymbol{x}_{ND}, \boldsymbol{x}_{PD}$ and $\boldsymbol{x}_{FD}$, so that different categories of states could be applied into their corresponding scheduling problems. The other part of abstraction is to record all the parameters that will be used in scheduling. Parameters can be categorised into non-tunable (NT) parameters and tunable (T) parameters.

The parameters will also be recorded in two vectors $\boldsymbol{\theta}_{NT}$ and $\boldsymbol{\theta}_T$. When formulating the scheduling problems in the virtual system, $\boldsymbol{\theta}_{NT}$ will remain the same while $\boldsymbol{\theta}_T$ could change according to the specific system configuration. In the end, the virtual components are all represented by their categorised states and parameters, which is shown in Figure 1.

- Scheduling Models

The categorised states and parameters will be assigned to different scheduling problems according to ETHS. Therefore, in the virtual system, we can formulate the scheduling models according to the virtual components. From S1 to S4, the states at each time step will be the input, and the output will be the schedules for the components. We use $\boldsymbol{x}[k]$ to represent the observed value of states at time step k, and we use $\hat{\boldsymbol{x}}\,[k+s|k]$ to represent the predicted or scheduled states at time step $k+s$, while the prediction or scheduling action is completed at time step k. N_s is used to represent the scheduling length. Therefore, as is shown in Figure 2, the scheduling models will generate schedules for components accordingly. S1: Off-line scheduling will input the historical non-dispatchable states and output the predicted states of ND together with the schedules for PD and FD for the entire scheduling horizon. S2: On-line adjustment will input the states for ND and PD at time step k, and output the schedules for FD at time step k. S3: Performance evaluation will input the states from all ND, PD, FD, and decides whether the system needs rescheduling. If the system performance is not satisfactory, S4: On-line rescheduling will be triggered, it will input the ND states and output the schedules for PD and FD for the remaining scheduling horizon. Detailed mathematical formulation from S1 to S4 can be found in ETHS proposed by Zhean et. al (2023).

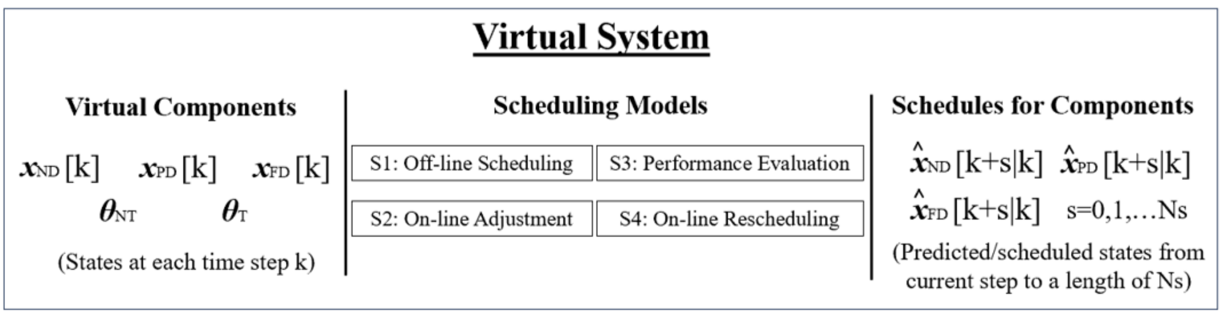

Figure 2. Holistic virtual system design

3.2 Design of Information Channel

According to the virtual system design in 3.1, a clear information channel is needed for the interaction between the physical and virtual system. Even though there are numerous data at both sides, we point out the most critical information to be collected in the information channel in Figure 3. The categorised states and parameters should be measured at the physical system, recorded in the information channel, and imported by the virtual system to calculate schedules. Even though the scheduling models are complex, only the scheduled results for ND, PD and FD states should be input back to the information channel, and the results should be executed by the physical system. The proposed information channel could largely reduce the redundant information in the system, thus improving the efficiency of both physical and virtual system.

Figure 3 also shows the final design of digital twin based on ETHS. In this digital twin, the key states from physical system can be systematically selected and measured, the scheduling in the virtual system can be implemented, and the information between the physical and virtual system can efficiently flow. The proposed digital twin could thus bridge the gap between ETHS and a physical manufacturing system.

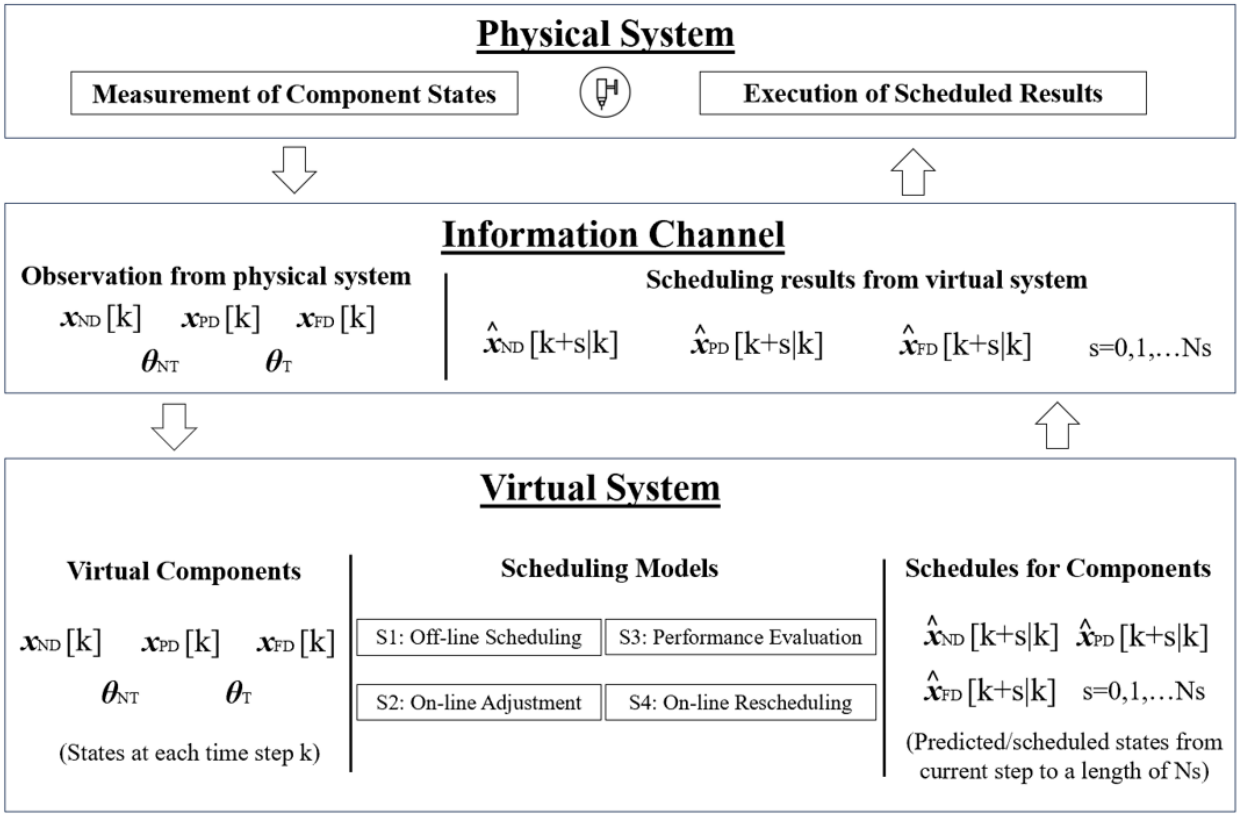

Figure 3. Digital twin design of the manufacturing system

4. Experiments

This section introduces a simulated metal production factory as the experiment for the proposed digital twin. The system configuration will be introduced first, followed by the implementation of digital twin.

4.1 System Configuration

As is shown in Figure 4, the proposed system consists of a 100-kW photovoltaic (PV) system, a 50-kWh battery energy storage system (BESS), a 50-kW gas turbine (GaT), and the system is connected to the grid, which allows electricity procurement and surplus power feed-in. Solar irradiance data are from the Australia Bureau of Meteorology, electricity price and feed-in tariff are from SUMO.

The experiment is an order of 40 products in a 24-hour period, if the 40 products are not all completed, the order cannot be delivered. Job time and machine power consumption will be introduced in the next section.

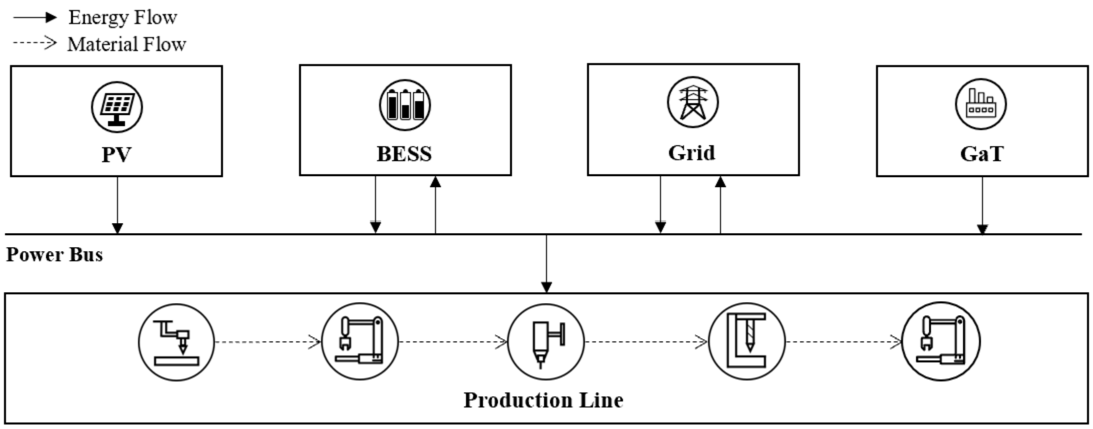

Figure 4. Energy flow of the experimental system

4.2 Digital Twin of the Manufacturing System

In order to build the digital twin, we need to demonstrate the measurement and execution in the physical system, the information channel data and the virtual system development (Table 2).

Table 2. States for the physical system

States	Description
ND States	
$x_1 \in R^1$	Power of PV generation
PD States	
$x_2 \in R^5$	Machine status on or off for each machine
$x_3 \in R^5$	Operation status starts or not starts on each machine
$x_4 \in R^5$	Number of operations finished on each machine
$x_5 \in R^1$	GaT generation power
FD States	
$x_6 \in R^1$	ESS charging power
$x_7 \in R^1$	ESS discharging power
$x_8 \in R^1$	ESS state of charge (SOC)0
$x_9 \in R^1$	Grid electricity procurement power
$x_{10} \in R^1$	Grid feed-in power

Table 3: Parameters for the physical system

NT Parameters	Description	Value
$\boldsymbol{\theta}_1 \in R^5$	Machine power of 5 machines (kW)	[18.5, 9.27, 1.13, 33.9, 26.4]
$\boldsymbol{\theta}_2 \in R^5$	Operation time for 5 jobs (5 minutes)	[2, 1, 2, 3, 2]
$\theta_3 \in R^1$	Gas price ($)	1.83
$\theta_4 \in R^1$	ESS charging/discharging efficiency	0.9
$\theta_5 \in R^1$	ESS fixed operational cost ($/5 min)	0.003
$\theta_6 \in R^1$	ESS charging degradation cost ($/kWh)	0.0006
$\theta_7 \in R^1$	ESS maximum capacity (kWh)	50
$\theta_8 \in R^1$	ESS depth of discharge	80%
$\theta_9 \in R^1$	ESS maximum power (kW)	50
$\boldsymbol{\theta}_{10} \in R^{288}$	Grid electricity procurement price ($/kWh)	0.187: 9 pm-9 am, 0.33: 9 am-9 pm
$\theta_{11} \in R^1$	Grid electricity feed-in tariff ($/kWh)	0.052
$\theta_{12} \in R^1$	Machine breakdown probability parameter	0.05

$\theta_{13} \in R^1$	Machine breakdown time parameter	1
$\theta_{14} \in R^1$	Number of production task	40

According to section 3, the first step to build the digital twin is to abstract the components in the physical system. We select the key states in the system and categorise them in Table 2. All these states will be measured in the physical system, and the measured states at each time step will be recorded in the information channel in the form of three vectors. Similarly, the parameters in the physical system are also recorded in Table 3.

In the virtual system, all the virtual components are now in the form of state and parameter vectors, which will go through the scheduling models. In S1, the off-line schedules from 0th time step to 288th time step will be generated for 5 machines, BESS, GaT and grid, together with the prediction of 24-hour PV generation at 0th time step. In S2, When the disturbances of PV prediction error and machine breakdown occur, the schedules for BESS and grid at each time step will be generated. In S3, the accumulated machine breakdown time and the PV prediction error will be evaluated at each time step and judge whether the rescheduling is necessary. The rescheduling time step numbers are 29, 60, 75, 96, 104, 113, 121, 138, 150, 159, 168, 174, 184, 196, 206, 216, 239, 251, 266 and 283. Finally, S4 outputs the rescheduled results at the above time steps. All the mathematical scheduling models can be found in Zhean et al. (2023). Every time the scheduling outputs a result, only the ND, PD, and FD states are transferred to the information channel, and these states will be executed by the physical system.

5. Results and Discussion

This section reveals the results of experiments. We compare the energy cost, computing time and production completion between two systems with and without the proposed digital twin. The results show significant advantage of using the proposed digital twin.

5.1 Experimental Results

The key performance indicators in this experiment are energy cost, computing time and whether the production order can be completed. We compare the results of the proposed digital twin design of a system without digital twin. The experiments are run 3 times, we record the average values as the results.

Table 4. Comparison between the system with and without proposed digital twin

	Energy cost per product ($)	Computing time (s)	Finished Products
With digital twin	2.42	218	40
Without digital twin	3.06	1	39

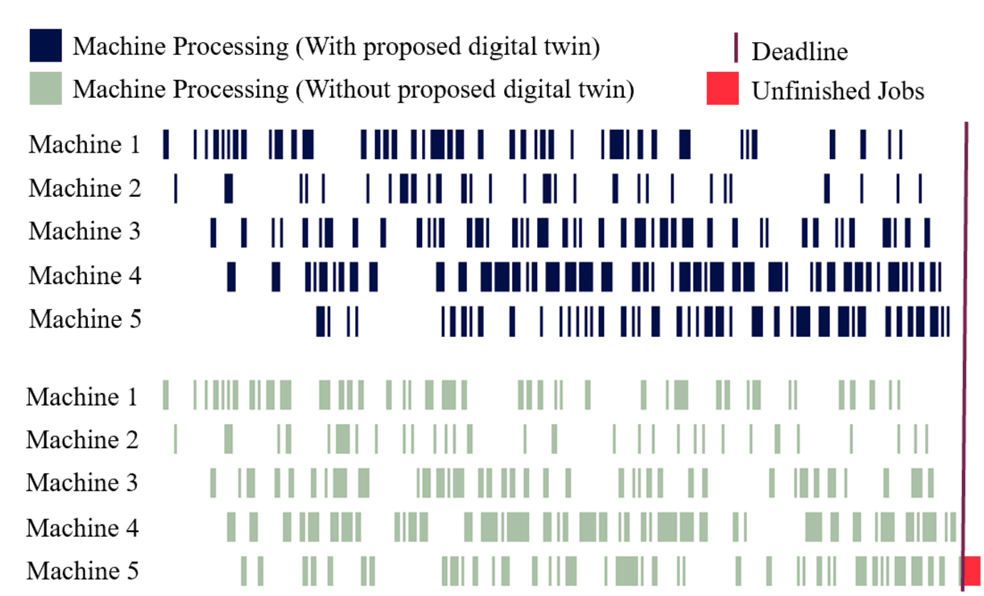

Figure 5. Production Gantt chart comparison between the system with and without proposed digital twin

Results in Table 4 and Figure 5 show that the system with proposed digital twin could largely reduce the energy cost and guarantee a completion of production order. Even though the computing time increases dramatically, it is still acceptable for manufacturing factories. The system benefits from the digital twin in 2 aspects. On one hand, we only select the critical states and parameters to flow in the system, largely increasing the efficiency. On the other hand, all the real-time disturbances can be reflected by the difference between the measured and predicted states in the physical system, the difference is thus transferred to the virtual system and the virtual system is able to return a modified schedule to handle these disturbances.

5.2 Discussion

The results could validate the proposed digital twin, but it still faces several challenges for a wider application in manufacturing factories. On one hand, the model of manufacturing system is case specific, which means the scheduling models vary in different factories, and some might be too complicated to be solved in an acceptable time. On the other hand, the successful operation still requires a robust hardware system, which is not tested in this paper.

6. Conclusion

Facing the gap that ETHS doesn't considers an environment of physical system, this paper successfully built the digital twin of a RESs integrated manufacturing system based on ETHS. Firstly, we designed the virtual system according to the physical system configuration and ETHS. Secondly, we built the channel for data flow between the virtual system and the physical system. The results shows significant advantage of the proposed digital twin.

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