Application of a Digital Twin Model in the Packaging Process of the Panel Furniture Industry

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Abstract

The packaging process in panel furniture manufacturing enterprises is the final process in production. However, there exists a lack of effective interaction and integration between the manufacturing processes and the information system. This challenge becomes more significant in the context of intelligent manufacturing. To address this, we propose a generalized digital twin workshop model for the packaging process in panel furniture manufacturing enterprises. Using this model, we establish a digital twin workshop for Company W's packaging process, which improves interaction and integration with the information system. By analyzing the data from the workshop service system and the workshop twin data, we identify inefficiencies in the automatic packaging line and propose an optimization scheme using the digital twin workshop model. Through simulation in the virtual workshop and actual verification, we demonstrate that the proposed scheme improves the production efficiency of the automatic packaging line by approximately 20 percent and reduces the need for 5 to 6 packaging workers. Our study presents a new solution for upgrading the information system in the packaging process of panel furniture, contributing to the development and optimization of the furniture industry in the era of intelligent manufacturing.

In recent years, panel furniture enterprises that have adopted the mass customization mode for production have sprung up in the industry, and their product types are mainly detachable structured panels (Xiong and Yue 2022). After going through the four links of cutting, edge-sealing, drilling, and packaging, the panel can enter the warehouse for delivery (Xiong et al. 2020). Within the context of "Internet +," "Industry 4.0," and "Made in China 2025," most of the top outstanding enterprises at this stage have initially completed the transition from digital manufacturing to intelligent manufacturing in the three processes of cutting, edge-sealing, and drilling (Labuschagne et al. 2012, Jia et al. 2023). In the packaging process, however, the overall intelligence level is still low (Gomez-Rocha et al. 2021).

The packaging process includes two specific processes of sorting and packaging. In order to improve the utilization rate of panels, panel furniture enterprises generally adopt the operation mode of kneading orders for production (Lin et al. 2020). Before packaging, the panels must be sorted according to the order or packaging information. The packing process is carried out by either manual or automatic packing line (Wang et al. 2020). The panel furniture enterprises provide customized design services, which results in different sizes of the panels and at the same time greatly increases the difficulty and complexity of the packaging (Chen 2020). Therefore, the packaging process has problems such as complex information, high reliability requirements, large space requirements, and requiring a large number of personnel (Xiong and Wu 2011). Especially in the information system, it is difficult for the packaging process to achieve a high degree of interaction and integration with the physical workshop (Zhu and Wang 2021).

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The digital twin concept was first proposed by Dr. Michael Grieves in 2003 as a "mirror space model" (Tao and Qi 2019). Defined as "a virtual digital representation equivalent to a physical product," his model can be considered as the prototype of the digital twin concept (Qi and Tao 2018). The original digital twin concept is a synthesis of comprehensive multiphysics, multiscale, and probabilistic simulation vehicle or system. Using the best physical models, sensors, vehicles, etc., it is possible to mirror the activity of the actual vehicle to which it corresponds (Tao et al. 2019). The sensor perception technology, digital twin modeling technology, data management technology, digital twin service technology, and communication connection technology that are implicitly embedded in the digital twin concept have been used in many fields (Tao et al. 2019).

At present, the application of digital twin technology has been explored in aerospace, transportation system, health care, agriculture, and other fields. Zhuang et al. (2018) presented a detailed implementation process of the proposed digital twin–based smart production management and control approach in a satellite assembly shop-floor scenario. Xu et al. (2022) proposed a computation offloading and service caching method, named CODT, which uses decision theory in intelligent transportation systems with digital twins, and extensive simulations based on real-world data sets demonstrated that the proposed CODT outperforms other baselines. Corral-Acero et al. (2020) proposed to construct digital twins for each patient to improve the ability of diagnosis and prognosis through the synergies between mechanistic and statistical models. They can also use model predictions to accurately predict the path to recovery, so that treatments can be tailored to each patient. Verdouw et al. (2021) analyzed how digital twins can advance smart farming and defined the concept, developed a typology of different types of digital twins, and proposed a conceptual framework for designing and implementing digital twins. The framework is applied to and validated in five smart farming use cases of the European IoF2020 project.

However, the practical application of digital twin technology in panel furniture industry is still limited; only some scholars in Guangdong University of Technology have done related research. Yan et al. (2021) proposed a rapid custom-design method for panel furniture production lines based on digital twin technology. It could provide design guidance and decision-support services in the design phase, yield the engineering analyzing ability to solve coupled problems, and finally generate the authoritative design scheme of the manufacturing system; Yan et al. used a panel furniture production line as an example to verify the effectiveness of the method.

Previous research has indicated that digital twin technology has been applied and explored in various industries including panel furniture enterprises. However, it has not been applied to the detailed packaging process. Currently, the integration of the information system and physical workshop in the packaging process of panel furniture enterprises is relatively low. Furthermore, there may be potential problems when transitioning to intelligent manufacturing.

Therefore, this paper aims to apply digital twin technology to the packaging process of panel furniture enterprises. The research is divided into two main parts. First, a model of digital twin workshop for the packaging process of panel furniture enterprises will be built. Second, based on this model, the digital twin workshop for the packaging process will be built in Company W to improve the connection between the enterprise's information systems and physical workshops and to verify the feasibility of optimizing the packaging process.

Model Building

The digital twin model of the packaging workshop has been built based on various factors, such as the production line layout, equipment parameters, model size, personnel ratio, and production information (Wang et al. 2019, Yan et al. 2021). In theory, this model could represent all the relevant knowledge and information about the packaging workshop from a geometric, physical, behavioral, and regulatory perspective (Liu et al. 2021, Moser et al. 2021). However, panel furniture is produced through a mass customization model; therefore, there are significant variations in data such as panel size, complete sets of information, sorting information, production rhythm, packaging planning, and packaging efficiency. These variations can lead to unusual combinations of variables even if each individual variable falls within the normal range, resulting in a multivariate outlier scenario where the model's performance quickly becomes inadequate. Therefore, real-time updates and iterations are necessary to keep the digital twin model of the packaging process up to date with changes in actual production data (Qi et al. 2019). To address these challenges and achieve an accurate and effective digital twin model, there is a need to develop a manufacturing platform that characterizes materialization, virtualization, servitization, collaboration, and intelligence (Wu et al. 2021).

Model framework

The framework of the digital twin workshop consists of several essential components, namely the physical packaging workshop, virtual packaging workshop, packaging workshop service system, packaging workshop twin data, and their interconnections (Qi et al. 2018). To cater to the packaging process of panel furniture products, a five-dimensional model of the digital twin workshop for packaging workshops has been established, as shown in Figure 1.

Physical packaging workshop.—The physical packaging workshop refers not only to the workshop itself but also the collection of real physical elements such as all equipment, personnel, products, materials, networks, and more within the workshop (Tao et al. 2022). Its primary function is to receive production tasks from the workshop service system and execute them based on the optimized production instructions generated by virtual workshop simulations (Reiche et al. 2021). To establish extensive connections between various elements of the physical entity layer, it is necessary to overcome the information bottleneck between various elements, enabling the connection of multisource heterogeneous data, and achieving real-time and accurate collection, generation, and storage. Sorting and packaging equipment must meet not only production needs but also transmit production data in real-time, expanding the interface between other equipment and the information system, thereby achieving real-time monitoring, intelligent management, and control. Consequently, the physical packaging workshop has facilitated the development of a new generation of packaging equipment and created new opportunities for improving the level of informatization and intelligence in the packaging process.

Virtual packaging workshop.—The virtual packaging workshop is a digital replica of the physical workshop, which

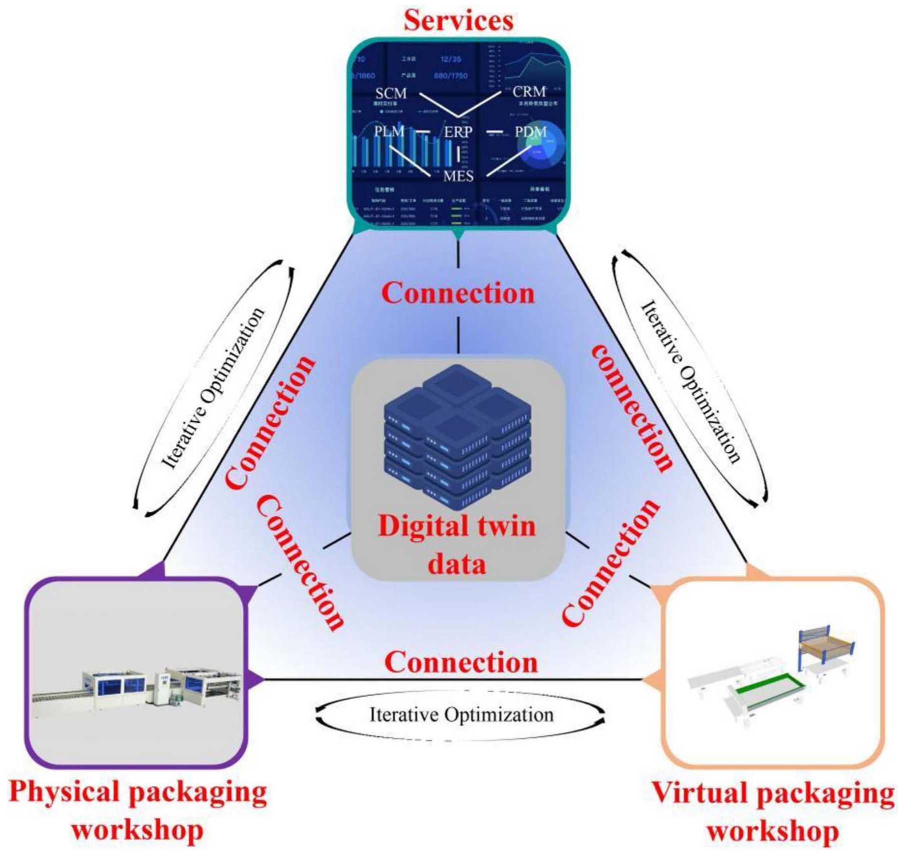

Figure 1.—Five-dimension digital twin model.

is described and characterized from multiple perspectives including geometry, physics, behavior, and rules (Konecny et al. 2023). Information collected by onsite equipment can be reflected in real-time on the corresponding twin model, enabling monitoring and control of the actual production process. Additionally, it also can simulate, optimize and evaluate the physical workshop through the workshop service system and workshop twin data. The virtual workshop can identify potential problems in the physical workshop process, and after proposing an optimization scheme in combination with the workshop service system and workshop twin data, the scheme's feasibility can be verified through simulation.

Packing workshop service system.—The packaging workshop service system is a collection of various service functions that rely on data as a support. It retrieves and packages the data required by the twin workshop to form functional and operational services, such as operation guidance services, intelligent decision-making services, model management services, and data management services. Of particular significance are the operation guidance service and the intelligent decision-making service, which serve as the core pillars of this system.

The operation guidance service assumes the responsibility of providing operators with real-time and personalized guidance and suggestions, contingent upon the prevailing production situation within the workshop. Through an intricate analysis and optimization of the production process, this service aids operators in effectively accomplishing their tasks, thereby augmenting both production efficiency and quality.

On the other hand, the intelligent decision-making service assumes a pivotal role in continuously monitoring and predicting the operational status of the workshop. By harnessing the power of machine learning and artificial intelligence technologies, this service harnesses production data to furnish managers with scientifically sound decision-making support. Consequently, managers are empowered to better oversee workshop production, optimize efficiency, and curtail costs.

Additionally, the system incorporates model management service and data management service, which are indispensable components. The model management service is entrusted with the responsibility of governing workshop production models, encompassing aspects such as model creation, editing, validation, and publication. Conversely, the data management service assumes the onus of administrating the acquisition, storage, processing, and analysis of workshop production data.

Packaging workshop twin data.—The twin data of the packaging workshop is a collection of physical packaging workshop, virtual packaging workshop and packaging workshop service system-related data, domain knowledge, and derived data. It is the integration and fusion of all-process and all-element data, characterized by being multisource, massive, and high-speed. The data of the physical workshop are the real data generated during the packaging process. The data of the virtual workshop and service system are not only directly collected from the production process but also can be obtained by model simulation, data processing, etc., based on the information collected in the physical workshop, which supplements the data in the physical workshop (Lin and Low 2021).

Connection.—Connection refers to the interconnection of various parts of the digital twin workshop (Zolin and Ryzhkova 2022). It includes the connection between physical

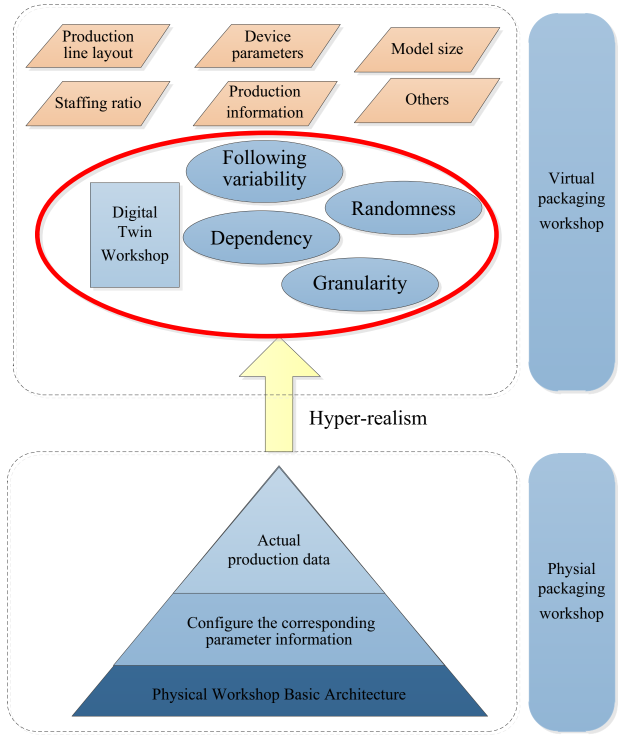

Figure 2.—Digital twin features.

workshop and virtual workshop, the connection between physical workshop and workshop twin data, the connection between physical workshop and workshop service system, the connection between virtual workshop and workshop twin data, and the connection between workshop service system and workshop twin data.

The digital twin workshop uses Internet technology as a support to connect all stages of panels production, open up the information flow of the entire manufacturing system, and realize the horizontal, vertical, and end-to-end interconnection of the packaging process (Park et al. 2021). In this way, it can not only promote the optimization and improvement of the design and management of the packaging process, but also better assist the manufacturing upgrade of the entire production line.

Model properties

The digital twin five-dimensional model of the packaging workshop is hyper-realistic and can reflect the real state of the physical workshop. It can not only describe the state at the physical level of the workshop, but also reflect the real production situation at the product level (Zhang et al. 2019). In addition, the digital twin model of the packaging workshop has these properties: following variability, randomness, dependency and granularity (Fig. 2).

Following variability.—The term “following variability” refers to the ability of the digital twin model of the packaging workshop to always change in real-time in response to changes in the physical workshop and production data, ensuring its hyper-realism. Additionally, this following variability also reflects the ability for a fast response. Whenever there is a change in the physical workshop or in the actual production, the model will promptly adjust to ensure the timeliness of the digital twin.

Randomness.—The digital twin model of the packaging workshop is a faithful reflection of the actual workshop, and any changes in it will be reflected in the model. Meanwhile, for panel furniture enterprises that adopt mass customization production, most of their products exhibit randomness, and accordingly, the model also possesses such randomness. Under the influence of randomness, the model reflected in the packaging process of each panel is unique.

Dependency.—The digital twin model of the packaging workshop is heavily dependent on comprehensively detecting and collecting physical workshop parameters and real-time data during the actual production process. Therefore, a high degree of integration between equipment and informatization is required (Madni et al. 2019).

Granularity.—In addition, the digital twin model also must focus on another important property, which is granularity (Steinmetz et al. 2022). Granularity is the level of detail that describes the various aspects of the target system, and choosing an appropriate level of granularity is very important for building a digital twin workshop model of the packaging process (Zhang et al. 2019). For the packaging process, the selection of model granularity should be considered from the panel level, packaging level, and order level.

To determine the appropriate level of granularity for the digital twin model of the packaging process, several factors should be considered, including the intended purpose of the model, the availability of data, and the computational resources at hand. For instance, if the objective of the model is to provide an overall assessment of the packaging process’s performance, a lower level of granularity may suffice. Conversely, if the aim is to capture detailed information on each component of the packaging process, a higher level of granularity becomes imperative.

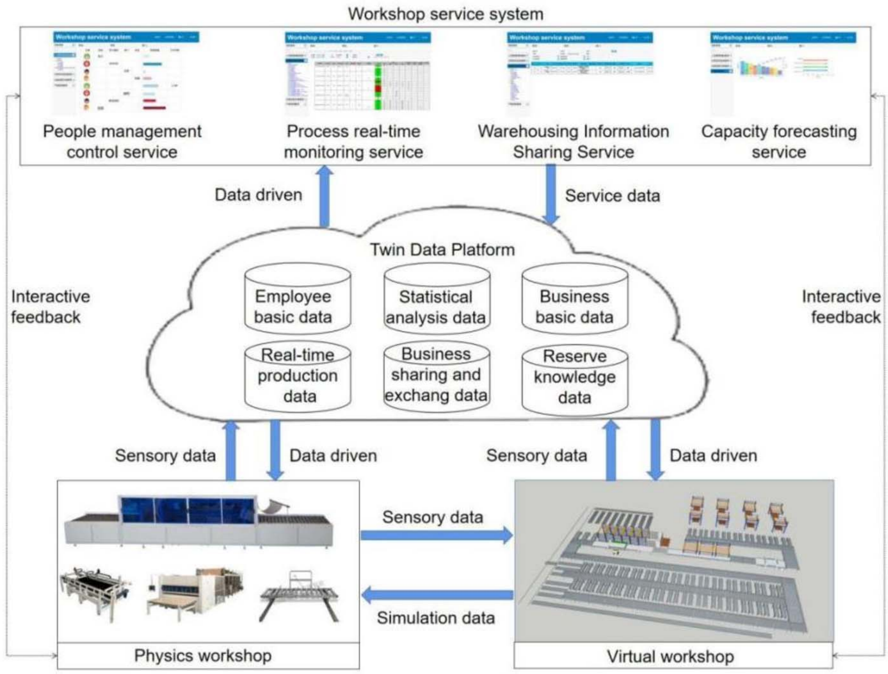

Figure 3.—Digital twin workshop.

Operation and regulation of digital twin workshop

The operation of the digital twin workshop of the packaging process is driven by the data generated and demanded through the physical workshop. After the twin model is built, the real-time control of the production site can be realized by continuously enriching and improving the twin data according to the data generated in the system and the actual production process (Tao and Zhang 2017).

After continuous iteration of data and the continuous upgrading of regulation, the workshop service system can establish special reports and data models to analyze the workshop's operation status and uncover potential problems. Once the problem is discovered, the information flow and panel flow of the packaging workshop can be analyzed through the integration of the physical entity layer and the twin model layer. When an appropriate solution is found, it can be simulated and verified in the virtual workshop layer. If feasible, the solution can be fed back to the production site for regulation and control and, depending on the situation, it can be decided whether to coordinate the entire production line to optimize and upgrade synchronously.

Experimental

Building the digital twin workshop

Nanjing W Home Furnishing Manufacturing Company (Company W) is a customized home furnishing enterprise. The production of its panel furniture has basically achieved full automation and informatization in the process of cutting, edge sealing and drilling. However, the integration and interaction between the physical workshop and the information system in its packaging process are relatively low. For this reason, Company W specially set up a project and decided to use the digital twin five-dimensional model to build a digital twin workshop, in order to improve the connection and the intelligence level of the packaging process. The framework of the digital twin workshop is shown in Figure 3.

Packaging virtual workshop.—There is currently almost no practical application of digital twin technology in the furniture industry, so it is unknown whether it can lead to improved benefits. Therefore, at the start of building of the digital twin workshop, Company W only built a basic framework at the corresponding level to control costs. The virtual model of the packaging workshop was built. The real-time transmission of sensory data from the physical workshop to the virtual workshop and real-time feedback of simulation data from virtual workshop to physical workshop were achieved. However, it is the first attempt to build a twin workshop; therefore, data transmission level is limited to the transmission of production nodes, and the real-time connection between the physical packaging workshop and virtual packaging workshop has not yet been achieved.

Packaging workshop twin data.—Based on the characteristics of Company W's packaging production line, the twin data platform provides employee data, real-time production data, business sharing and exchange data, statistical analysis data, business data, and knowledge repository data.

Packing workshop service system.—According to the characteristics of Company W packaging production line, the model provides personnel management and regulation services, real-time process monitoring services, warehousing information sharing services, and capacity forecasting services.

The personnel management and control services are necessary because of the high labor turnover rate of the workers in the enterprise, and the different methods of manual packaging and automatic packaging used in the packaging operations that lead to different requirements for the proficiency of workers. The system can predict and evaluate the proficiency of workers and adjust the ratio of personnel and positions according to the actual production.

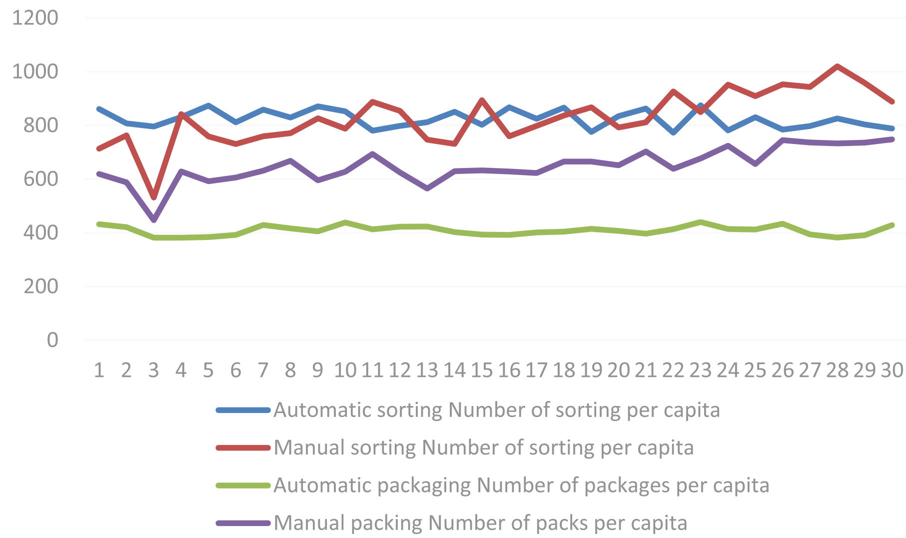

Figure 4.—Packaging-process data analysis.

A key feature of the digital twin workshop is its ability to achieve real-time monitoring of the production process. However, Company W is still in the trial stage; therefore, only the start and completion times of key processes are selected as monitoring nodes for data collection, thereby reflecting partial real-time monitoring of the process.

After the packaging is completed, there is a need to quickly transfer and store the products on the shelves to alleviate the space constraints. This necessitates real-time and shared access to warehouse information.

The production capacity forecast is mainly based on historical data analysis, combined with the number of workers in the packaging workshop at the time of prediction and their respective proficiency levels. The corresponding production capacity forecast data is given to the planning department, so that it can accurately issue tasks.

Company W used the five-dimensional model of the digital twin workshop to initially build the digital twin workshop of the panel furniture packaging process, recognizing the connection between the physical workshop and the virtual workshop. According to actual needs, a dedicated workshop service system is established to meet the needs of different groups of people for guidance and management of production. In addition, it has a twin data platform that can collect all the data of the physical workshop, virtual workshop, and workshop service system, which provides a data foundation for business analysis, model establishment, virtual simulation, and other requirements. It provides new technical support and general models for enterprises.

Practical verification of packaging process

After initially building a digital twin workshop, Company W has improved the integration and interaction between physical and information workshops, and also expects these to be verified in the actual production. So the company attempts to use the digital twin workshop to find out whether there are potential problems in the production process and optimize them, thereby completing the verification of the digital twin workshop.

Potential problems.—Potential problems must be found by analyzing the twin data and using the workshop service system. Through the personnel management and regulation service in the workshop service system, the stage at which the number of employees in the packaging process is stable within the enterprise Office Automation system is retrieved. After determining the range of data values from the real-time production data of the twin data platform, the 30-day production data of the packaging process of the YG production line during this stage are retrieved and analyzed (Fig. 4).

Company W divides sorting into two methods: automatic sorting and manual sorting; and the packaging process is also divided into two methods: automatic packaging and manual packaging. In addition, the automatic sorting line and the automatic packaging line are connected, and the rhythm of the automatic sorting and automatic packaging connection line can be kept consistent via on-site observation, and can run smoothly. However, Figure 4 shows that the efficiency of manual sorting and automatic sorting are similar, but efficiency of the automatic packaging line is significantly lower than that of manual packaging, which reduces the overall efficiency of the packaging process.

The traditional idea that using machines to replace people can improve efficiency has not been reflected in the packaging process of Company W. The investment in equipment, venues, information systems, personnel, funds, etc., not only failed to

Table 1.—Automatic packaging operation units.

Unit	Operating unit name
x1	Fill the foam
x2	Measure and cut paper
x3	Manual place the corner protector
x4	Case sealing

Table 2.—Automatic packaging-line time analysis.

Variable	x1 (s)	x2 (s)	x3 (s)	x4 (s)
$\bar{x}$	19.841	140.634	110.039	41.929
σ	22.971	80.264	44.725	6.824
UCL	88.755	381.425	244.214	62.401
LCL	−49.073	−100.156	−24.135	21.456
Outliers	No	No	No	No

Table 3.—Manual packaging-line time analysis.

Unit	Operating unit name
i1	Take the panel from the tray to the operating table
i2	Organize the panels on the operating table according to the packaging plan
i3	Fill the foam and place the corner protector
i4	Cut paper and tape packing
i5	Take the packaging from the operating table to the tray

improved efficiency, but has become a fetter. The inefficiency of automatic packaging lines has become a potential bottleneck problem in the packaging process of Company W.

Scheme formation

The appearance of the product produced by the automatic packaging line is more aesthetically pleasing and firmer than that of manual packaging, but efficiency is 37 percent lower than that of manual packaging. At this stage, it is impossible to achieve a win–win situation between efficiency and beauty. Company W plans try to use the digital twin workshop to propose solutions and simulate their feasibility.

Using digital twin workshop to solve problems requires observation and analysis of virtual workshop and physical workshop. It can be seen from the virtual workshop that the distance between the measuring station and the case sealer is long, and the panels must pass through nine stages of power rollers to reach the case sealer after coming out of the measuring station. From the observation in the physical workshop, it was found that the four actions of paper feeding, folding box, nailing corner protection, and plugging edge should be completed between the two work nodes, and the connection between the nodes was not close enough.

Therefore, the stopwatch test analysis was carried out for the automatic packaging line, the packaging time was divided into four operation units, the operation unit number was x, and 20 packages were randomly tested (Glonina and Bahmurov 2017). The division of the operation units is shown in Table 1.

A continuous test method was used in the time measurement. A Casio stopwatch was used for observation, and the actual working time was obtained. The triple standard deviation method was applied to find and remove outliers. For the calculation of outliers, the average ($\bar{X}$) and standard deviation (σ) of each operating unit were calculated.

The upper limit of deviation (UCL) $= \bar{X} + 3\sigma$, and the lower limit of deviation (LCL) $= \bar{X} - 3\sigma$; values that are not in this area are outliers and should be eliminated. After calculation, there were no abnormal values (Table 2).

At the same time, the manual packaging line was analyzed, and its packaging time was divided into five operation units, and the operation unit number was i. The division and results of the operation units are shown in Table 3 and Table 4.

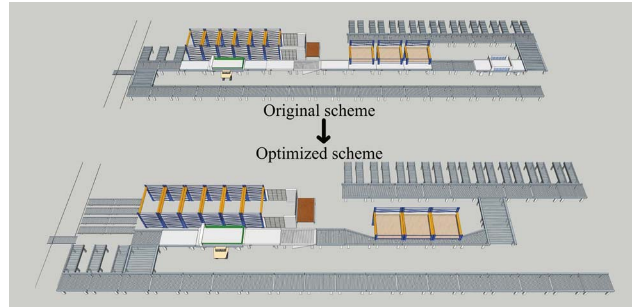

Figure 5.—Simulation verification and comparison in the virtual model.

When observations are uploaded to the digital twin workshop for model and data analysis, it is found that the time of x3 is greater than the average value of i3, and the action of filling foam of the automatic packaging line had been completed in advance in the x1 operating unit. This means fewer operational units but more time used in the automatic packaging line.

Therefore, it is proposed that when the x2 operation unit is completed, the packaging can be carried out in a completely manual way. In other words, it is the combination of automatic packaging line and manual packaging. After the simulation is carried out at the virtual model layer to confirm that the scheme is feasible (Fig. 5), the actual test is carried out in the physical workshop.

Results and Discussion

The new automatic packaging line can be divided into three operating units; the first two operating units are consistent with x1 and x2. Therefore, the stopwatch test analysis was carried out for the third unit j3, and the time j3A and j3B operated by one person and two persons were tested separately. The results are shown in Table 5.

According to Table 5, the time for the j3 process to be completed by two people is less than that of one person. However, overall efficiency will not be greatly improved. Therefore, it is suggested that Company W adopt a one-person operation method during specific implementation.

Combining Table 5 and Table 3 shows that the average operation time of j3 is significantly lower than that of x3 + x4. Total manual packaging time (TM) is $\sum_{i=1}^{i=5}\overline{\sigma}$, total packaging time before automatic packaging optimization (TA) is $\sum_{x=1}^{x=4}\overline{\sigma}$, and total time after automatic packaging optimization (OT) is the sum of x1 + x2 + j3. The total time for different packaging methods is shown in Figure 6.

According to analysis in Figure 6, the overall packaging times of the optimized automatic packaging line are reduced by 19.5 percent and 23.6 percent, respectively, which greatly

Table 4.—Manual packaging-line time analysis.

Variable	i1 (s)	i2 (s)	i3 (s)	i4 (s)	i5 (s)
$\bar{i}$	15.801	24.998	103.772	91.577	4.394
σ	10.396	11.664	43.205	18.303	1.203
UCL	46.990	59.990	233.386	146.486	8.005
LCL	−15.388	−9.993	−25.842	36.668	0.784
Outliers	No	No	No	No	No

Table 5.—Time analysis of j3.

Variable	j3A (s)	j3A-Fix (s)	j3B (s)
$\bar{j3}$	95.646	90.989	78.138
σ	28.083	19.910	17.783
UCL	179.895	150.718	131.487
LCL	11.397	31.259	24.789
Outliers	Yes	No	No

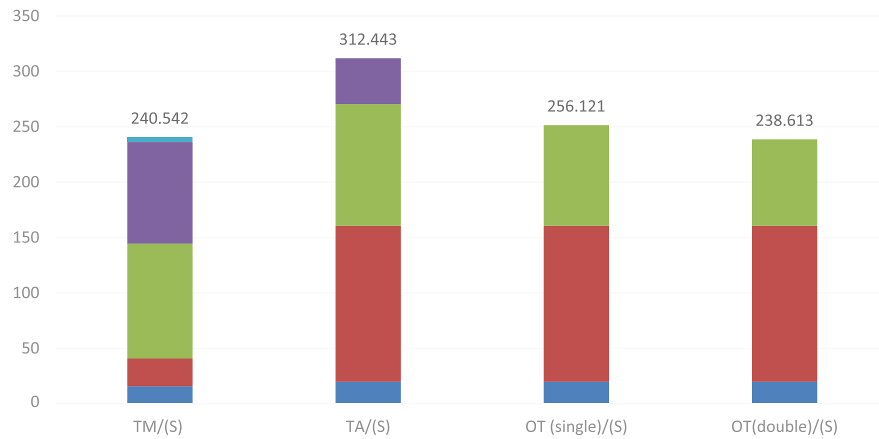

Figure 6.—Total packaging time.

improves the production efficiency of the automatic packaging line. The overall time required is essentially the same as manual packaging and the overall aesthetic degree is guaranteed because the carton is cut by the machine. However, the time of the x2 operation unit is still long, and this can be used as a point of optimization research for in-depth exploration in the future.

Based on data collected in Company W, there are 1,417,534 packages that can be packaged using automatic packaging line in 2022. The annual production is about 300 days, and the daily production is about 4,725 packages. After the efficiency is increased by 20 percent, 5 to 6 packaging workers can be reduced (Table 6).

Through the constructed digital twin workshop in Company W, not only has the integration and interaction between the physical workshop and information systems in the packaging process been improved, but the potential problem has also identified, validated, and resolved through the use of the digital twin workshop.

Conclusions

1. This paper uses digital twin technology to build a digital twin workshop framework for the packaging process of panel furniture, and the model characteristics, operation, and regulation are analyzed.
2. According to this framework, a basic digital twin workshop for the packaging process was built in Company W. Potential problems associated with the packaging process were found with the help of the digital twin workshop.
3. Combined with the virtual workshop of digital twin workshop, a solution to the problem is proposed and implemented in the physical workshop of Company W. Through verification of the improvement scheme, it is found that the production efficiency of the automatic packaging line has been improved by approximately 20 percent, 5 to 6 workers have been reduced, and a win–win situation of efficiency and aesthetic appeal has been achieved.
4. Through actual verification in Company W, it is shown that the digital twin workshop framework of packaging process can be applied to panel furniture enterprises, and can play a positive role in the integration of information system and physical workshop during the packaging process.
5. There are still several areas for further optimization in this study. For instance, the sensitivity analysis of the digital twin model was not conducted in this study, which is an aspect that should be addressed in future research. Additionally, Company W could consider implementing a more flexible mobile mode. Lastly, there may be potential for further efficiency improvements in the "measurement and cutting" stage of the automated packaging line. The goal of this paper is to provide reference and inspiration for relevant scholars to carry out further research, so as to realize intelligent manufacturing of the furniture industry as soon as possible.

Table 6.—Packaging data analysis.

Total package quantity/day	Increase quantity (20%)/pack	Average number of individual packages/day	Reduction in number of people
4,725	945	164	5.76

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