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Research on kitting evaluation method of complex electromechanical products

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Abstract. Precise and efficient product kitting evaluations are vital for boosting assembly performance and customer contentment for varied, small-batch, and intricate electromechanical products. However, current enterprise resource planning systems (ERP) provide inadequate support for analyzing the kitting of products. How to evaluate the degree to which customers' demands for a complete set of multiple products can be met when adjusting the importance level of customer demands without changing the customer demand date in the production system and affecting the scheduled customer orders has become one of the urgent problems that enterprises need to solve. In response to the above issues, this article presents a method for evaluating product kitting, which takes the maximum quantity of complete sets of products as the optimization objective, considers multiple constraints such as material inventory data and in process business data, and designs a multi-level BOM decomposition algorithm. Finally, a case study of a company producing core components for standard high-speed trains demonstrates the practicality and efficacy of the proposed method.

Keywords: ERP, restrictions, BOM, kitting

1. Introduction

Complex electromechanical products are composed of various types of mechanical parts, electronic components, and raw and auxiliary materials into several components such as mechanical structures, control devices, and electrical equipment, and then the components are assembled into a complex structure assembly according to a certain assembly sequence [1], with a hierarchical structure complicated, complex process, a wide variety of materials, etc. The production mode is gradually changing to a multi-variety and small-batch mode under the dual drive of the market and technology. Facing the complex assembly process and changing assembly mode of complex electromechanical products, the kitting delivery of products has important practical significance for improving product assembly efficiency and customer satisfaction.

With the gradual and in-depth application of enterprise management systems such as ERP in manufacturing enterprises, the production management level of enterprises has been significantly improved, but there are still many deficiencies in the analysis of complete sets of materials. The MRP calculation logic of the traditional ERP system is based on BOM, process, demand date, etc. to reverse the customer demand, calculate the start date of production activities such as raw material procurement, semi-finished product production, and final product assembly, and give priority to satisfying orders with earlier demand dates in the system. However, without changing the existing order demand date in the production system and affecting the already scheduled orders, it is impossible to evaluate whether the constraints such as current material inventory data, in process business data and and other constraints can meet the complete set of customer needs when considering adjusting the priority of customer demand. Aiming at the existing multi-variety and small-batch production mode's increasing requirements for complete delivery of products, and the relatively weak application of completeness analysis in production management software, this article proposes an evaluation method for product kitting. The optimization goal of this method is to maximize the number of complete sets for multiple products by customers, taking into account multiple constraints such as material inventory data and in process business data, and designing a multi-level BOM decomposition algorithm to evaluate the degree to which customers' complete set of needs can be met based on current constraints, providing support for management decisions.

The content of the article is organized as follows. Section 2 introduces the concept of material kitting and the related work of complete set analysis. Section 3 introduces the product kitting evaluation algorithm model proposed in this paper. Section 4 introduces the application of product kitting evaluation methods. Section 5 is conclusion and outlook.

2. Related work

In the 1990s, Ronen [2] put forward the concept and definition of material kitting for the assembly process of printed circuit boards, and analyzed the reasons for the unevenness of materials and its application in various production environments. Hanson et al [3,4] made a comparative analysis of the two modes of material supply and continuous supply, and pointed out that the time required for complete supply of materials is shorter than that of continuous supply. Croci et al. [5] studied the assembly process of printed circuit boards, and proposed that changing batch supply to complete supply can reduce product assembly time and increase production efficiency.

Zhou et al. [6] established a gradual incremental coordination method with the technological process as the node, and expressed the bill of materials and material inventory list required for the assembly task to the i-th process with a matrix. By comparing the two matrices, they can judge the complete set of materials required for this process, and solve the problem of reasonable distribution of materials under limited assembly resources. Zhou et al. [7] studied the scheduling problem of material supply in the automobile mixed-flow assembly line, and proposed an improved complete set of parts strategy, which transformed the problem into an integer programming mathematical model for solving the replenishment task of logistics personnel in supermarkets near the offline side of the strategy. Compared with the traditional online method, the strategy based on full set of parts consumes less labor-intensive. Bortolini et al. [8] proposed a "two-stage" method to solve the problem of material storage and layout under a complete set of material strategy. Based on the results of component commonality clustering analysis and cluster allocation, the size of storage locations and layout methods are determined to reduce the transportation distance of complete sets of materials, making the storage and layout mode under a complete set of material strategies more reasonable and effective. Khajavi et al. [9] studied how to use additive manufacturing to produce small and medium-sized batches of multi-component products. By introducing the cost impact of a complete set of materials on the production process, the inherent information processing is directly embedded in the digital production process and parts produced in co-construction, simplifying preparation work in the production process and saving production costs. Bottin et al. [10] studied the problem of material configuration of complete sets of products under the market demand of small batch customization, and applied TSP to the production process through the integrated multi-clustering model, so that it can find the optimal sequence through the bill of materials matrix. Faccio et al. [11] studied the packaging problem in the production system based on a complete set of materials, constructed a comparison model of the total cost function according to different packaging strategies, and found the optimal complete packaging strategy to provide decision support for operation management. Zhou et al. [12] introduced a robot-manual picking mode based on a complete set of material distribution strategy to solve the problem of high efficiency and high cost of manual picking of a complete set of materials in a mixed-flow assembly line, and used an improved quantum ant colony algorithm to optimize the configuration number and distribution cycle of automatic picking robots and workers, so as to achieve the overall optimal cost of robots, labor and work-in-progress inventory. Li et al. [13] addressed the issue of delayed order delivery caused by uncertain factors such as difficulty in material kitting and long time for remote allocation in the multi-site final assembly process of customized production lines. They considered the final assembly process proactively, inserting reasonable buffer time intervals at the end and start of adjacent tasks, and established a proactive scheduling model for the final assembly process in uncertain environments, the non-dominated sorting genetic algorithm is used to solve the problem, thereby improving the robustness and effectiveness of the overall scheduling scheme.

The above research work mainly focuses on the analysis of the completeness of raw materials and semi-finished products, without considering the completeness of materials at the product level. In response to this issue, many research works have established a complete set of product analysis models with different optimization objectives, but most of them focus on the complete set of analysis models with the goals of minimum cost, minimum delay time, and total product waiting time. Wang et al. [14] developed a complete analysis model with the goal of minimizing the total waiting time of products. Liu et al. [15] studied the homogeneous analysis model with the goal of minimizing ranking bias. With the increasingly intensified competition among enterprises, in addition to pursuing the lowest cost in the production process, more attention should be paid to and timely response to customers' demand for the supply of multiple products in sets. Therefore, establishing a product kitting analysis model with the target of multiple product sets is of great significance in actual production and operation of enterprises. For example, Zhou et al. [16] studied the workshop scheduling model with the goal of maximizing the number of complete sets of orders in production planning and scheduling.

However, the above related studies did not take into account the constraints of materials, especially the materials situation in process at the production site of the enterprise. Aiming at the above problems, this article proposes a product kitting evaluation method considering the main constraints such as material inventory and in-process business data, so as to meet the customer's optimization goal of maximizing the number of complete sets of various products. Through a multi-level BOM decomposition algorithm, the quantity of customers' demand for multiple product sets can be evaluated, so as to provide support for management decisions.

3. Product kitting evaluation algorithm

In the kitting evaluation algorithm, the MBOM structure of the product is represented by the directed dendrogram $G=\{V|B\}$, where V represents the node list, B represents the edge set, and the graph is represented by the adjacency list Adj. Assume that the MBOM structure of product V_1 is shown in figure 1,V_1 is composed of lower-level components V_2 and V_3, V_2(E,2) means that its process division is self-made parts, and the ratio of the quantity to its parent material V_1 is 2, V_4 (F,1) means that the component process is divided into purchased parts, and the quantity ratio of its parent material V_2 is 1, and other nodes are similar.

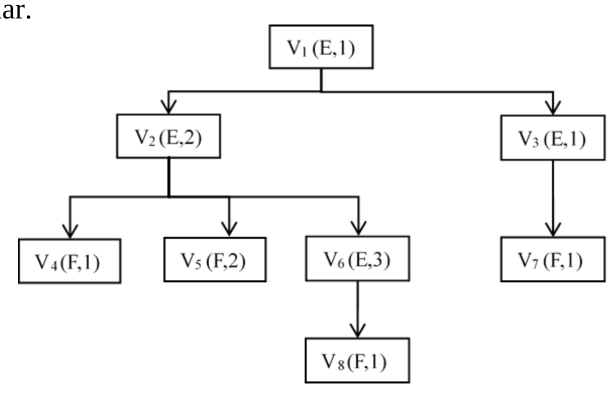

Figure 1. MBOM structure of product V_1.

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Known information at the time of product kitting evaluation:

(a). The inventory quantity of each material in the enterprise;

(b). The quantity of each material put into the production site;

(c). MBOM data of each product;

(d).The proportioning quantity of the customer's demand for a complete set of multiple products.

The known parameter symbols of the algorithm are described as follows:

V: the existing material collection of the enterprise;

U: collection of materials purchased by the enterprise;

V_i: material i that needs to be purchased or produced;

$\pi(V_i)$: the parent material of material V_i in MBOM;

$Bom(V_i, \pi(V_i))$: the ratio of the quantity of material V_i to its parent material $\pi(V_i)$;

$Stock(V_i)$: inventory quantity of material V_i;

$Resb(V_i, \pi(V_i))$: the quantity of material V_i that has been invested into its parent material $\pi(V_i)$ in the production order.

The process value calculated by the algorithm and the symbol of the solution target are described as follows:

$Acc(V_i)$: the cumulative available quantity of material V_i;

$Bom(V_i)$: the ratio of V_i to the root node V_1;

$Kit(V_i|V_i \in U)$: the maximum production quantity of purchased materials;

$Kit(V_1)$: The maximum production quantity of the target product V_1.

Based on the above, use the following equation (1) to calculate the cumulative available quantity $Acc(V_i)$, which is the sum of the inventory quantity of material V_i, the quantity already put into the production order, and the quantity consumed by the parent material $\pi(V_i)$ that has been produced.

$$Acc(V_i) = \begin{cases} Stock(V_i) + Resb(V_i, \pi(V_i)) + Acc(\pi(V_i)) \cdot Bom(V_i, \pi(V_i)) & , \quad i \neq 1 \\ Stock(V_i) & , \quad i = 1 \end{cases} \tag{1}$$

Among them, when i=1, it means that V_i is the product layer material (root node). Calculate the maximum production quantity $Kit(V_i)$ of all purchased materials V_i (leaf nodes, $V_i \in U$) through the following equations (2) and (3), and round down the minimum value in $Kit(V_i)$, which is the maximum quantity that product V_1 can be produced based on known information and parameters.

$$Bom(V_i) = \begin{cases} Bom(\pi(V_i)) \cdot Bom(V_i, \pi(V_i)) & , \quad i \neq 1 \\ 1 & , \quad i = 1 \end{cases} \tag{2}$$

$$Kit(V_1) = \lfloor Min(Kit(V_i \mid V_i \in U)) \rfloor = \lfloor Min(Acc(V_i) / Bom(V_i)) \rfloor \tag{3}$$

The algorithm is described as follows:

```
Kit(G,V1)
for each vertex u in V[G]
    do flag(u)←0
  /*The variable π(u) represents the parent node of u*/
      π(u)←NIL
  /*Initialize the Stock(u), Resb(u,π(u)), Bom(u), Bom(u,π(u)) of the node*/
      Stock(u)←INIT
      Resb(u,π(u))←INIT
      Bom(u)←1
      Bom(u,π(u))←INIT
/*Initialize the value of V1*/
flag(V1)←1
```

```
π(V1)←NIL
Resb(V1)←0
Bom(V1)←1
Kit(V1)←+∞
/*Initialize the root node Acc(V1) value*/
Acc(V1)←Stock(V1)
Q←Ø
ENQUEUE(Q,V1)
While Q≠Ø
    do u←DEQUEUE(Q)
      /*A node without children is a leaf node*/
      if length Adj[u]=0
        then
            /*mark as a leaf node*/
            flag(u)←-1
      else
            /*Iterate over the children of a node*/
            for each v∈Adj[u]
                do if flag[v] = 0
                   then flag[v]←1
                         ENQUEUE(Q,v)
                         /*Calculate the sub-item Acc(v) value*/
                         Acc(v)=Stock(v)+Resb(v,u)+Acc(u)*Bom(v,u)
                         Bom(v)=Bom(u)*Bom(v,u)
                   else
                         flag(v)=flag(v)+1
                         /*same node exists*/
                         Acc(v)=Acc(v) +Resb(v,u)+Acc(u)*Bom(v,u)
                         Bom(v)=Bom(u)*Bom(v,u)+Bom(v)
/*Calculate the minimum production quantity of leaf nodes*/
for each vertex u∈V[G]
    do if flag(u) = -1
        then Kit(u)←Acc(u)/Bom(u)
            if Kit(u)≤Kit(V1)
              then Kit(V1)←Kit(u)
return Floor(Kit(V1))
```

When evaluating the customer's demand for a complete set of multiple products V_1, X_1, and Y_1, by constructing a one-layer MBOM structure (as shown in figure 2), the maximum production quantity of product P_1 can be calculated according to the above algorithm. The production quantity $\lfloor Min(Kit(P_1)) \rfloor$ is to evaluate the complete set of products that can satisfy customers.

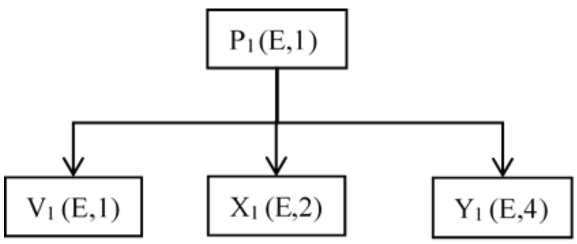

Figure 2. Kitting MBOM for products V_1, X_1, and Y_1.

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4. Instance verification

4.1. Case analysis

The manufacturing of rail transit equipment involves the production and manufacture of multiple subsystems of the vehicle. The main components include vehicle body, bogie, traction transmission, brake device, vehicle-end connection device, current collection device, internal equipment and cab equipment of the carriage, and train control network system, etc. As a provider of core components and equipment for rail transportation such as traction, braking, network, and safety, enterprise Z needs to meet customers' needs for a complete set of subsystem products. Taking the Fuxing CR400AF/BF series short EMUs as an example, the whole vehicle includes 4 sets of traction transmission and 8 sets of brake control device products, among which the traction transmission product involves the self-made and outsourced processing of more than a thousand kinds of parts. The product structure is diverse, and the design and production processes are complex, which in turn leads to a complex structure of the manufacturing bill of materials.

MBOM is the core master data of an enterprise, which not only includes all the constituent materials of the product, but also includes the structure and quantity relationship between these materials, namely the hierarchical membership relationships from raw materials to components and final products. Assuming that the MBOM structure of a product V_1 of enterprise Z is shown in figure 1, then the set of leaf node components $U=\{V_4, V_5, V_7, V_8\}$. The inventory quantity of each node component and the quantity of the order in process are shown in the following table 1 (during the operation of the enterprise, the inventory quantity of materials and the quantity of the order in process at a certain moment will dynamically change with the development of on-site business), and assuming that components V_3 and V_6 are the same component (the same component is used at different levels of MBOM), then V_7 and V_8 are also the same component (the lower structure of the same component in MBOM is also the same), and the maximum number of sets for product V_1 needs to be calculated.

Table 1. Business data in SAP system of enterprise Z.

Materials	Stock quantity (*Stock*)	Quantity put into production order (*Resb*)	Ratio to parent item quantity (*Bom*)
V_1	1	0	1
V_2	2	2	2
V_3	3	2	1
V_4	4	3	1
V_5	4	4	2
V_6	3	1	3
V_7	5	2	1
V_8	5	2	1

The values of $Acc(Vi)$ and $Kit(Vi)$ of each component are calculated using the kitting evaluation algorithm as shown in table 2, where the cumulative available quantity $Acc(V_3)$ of V_3 is 25 (6), which means that the calculated value is 6 when the algorithm traverses V_3, When the algorithm traverses and calculates V_6 (V_6 and V_3 are the same node), calculate and update the value of V_3 to 25.

Table 2. Calculate the number of leaf node sets.

Materials	Cumulative available quantity (Acc)	Compared with the root node V_1 (Bom)	The maximum production value of the leaf node (Kit)
V_1	1	-	-
V_2	6	2	-
V_3	25(6)	7(1)	-
V_4	13	2	6.5
V_5	20	4	5
V_6	25	7	-
V_7	32	7	4.5
V_8	32	7	-

Then $\lfloor Min(Kit(P_1)) \rfloor=4$, that is, when prioritizing the production of product V_1, the maximum number of sets that can be produced is 4 based on business data such as current V_1 and its component inventory, and orders in progress. The above-mentioned product kitting evaluation method comprehensively considers the constraints of material inventory information and in-process business data, achieving product kitting evaluation without changing the business data in the production system. It effectively solves the weak problem of traditional enterprise management software in product kitting analysis and supports managers' business decisions.

4.2. System implementation

By applying the algorithm model proposed in this article to develop a product kitting evaluation and decision-making system, which obtains the online inventory and the current order execution progress by integrating with the underlying management and control system integration. At the same time, it integrates with the inventory management system to obtain the current material inventory, and with the purchase system to obtain in-transit inventory. Then, it realize the flow and interaction of various business process information through a unified data integration platform. The system architecture is shown in figure 3, mainly including the production site layer, workshop control layer and enterprise application layer.

Production site layer mainly covers the manufacturing and assembly workshop, production repair workshop, operation and maintenance workshop of Z enterprise, including the underlying line-side material collection hardware facilities required by the system, such as intelligent material labels, visual electronic labels, material ANDON, code scanning gun, etc., providing the basis for precise control of line-side materials.

Workshop control layer mainly realizes the collection of material inventory at the edge of each production line in the workshop and material inventory data in the warehouse management system. Through the digitalized operation management and control system, the order execution progress, material use quantity, abnormal material quality quantity, material line-side inventory, PTL material inventory and other information of the production line can be accurately collected. The Warehouse management system can accurately collect the current inventory information, the information of materials to be moved, the information of materials to be delivered, and the information of returned materials, so as to provide accurate data for complete analysis and evaluation of products.

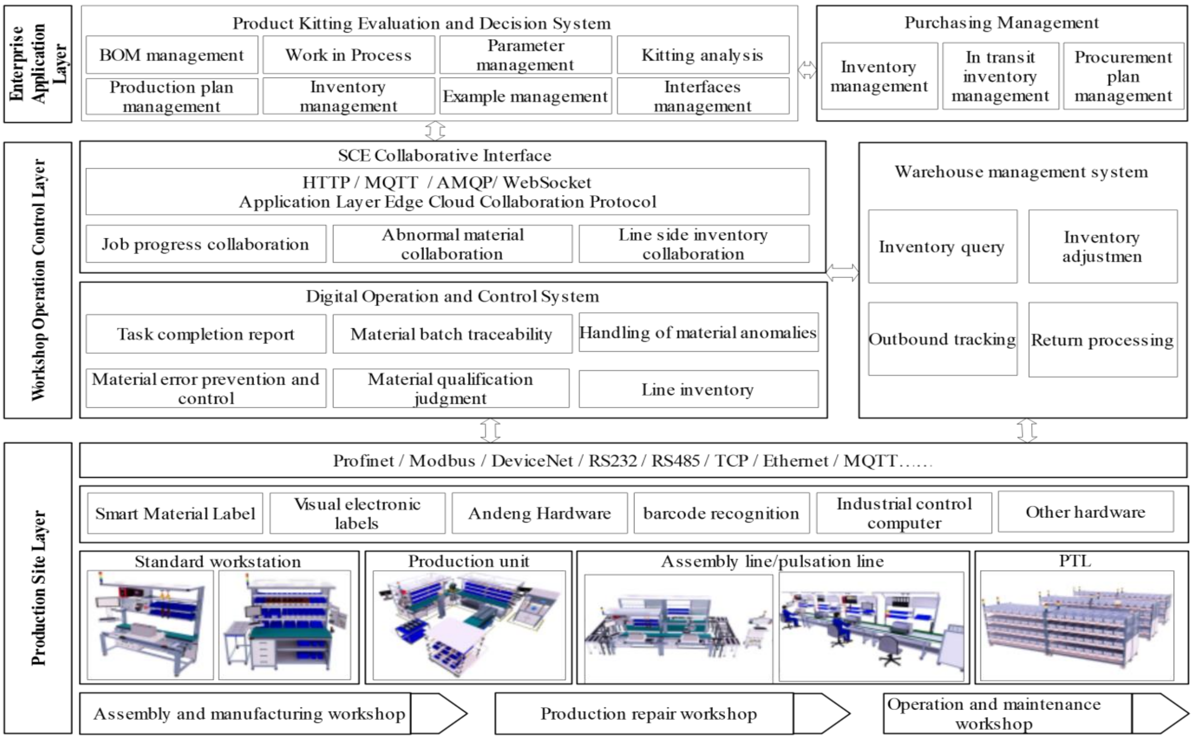

Figure 3. System architecture.

Enterprise application layer realizes the product kitting evaluation and decision-making system with digital operation control, warehouse management, procurement management and other systems. The product kitting evaluation and decision-making system is built on the basis of the SAP platform, so it can directly interact with the procurement management system for data, such as inventory information, in-transit inventory information, etc. Interacting with the digital operation control system and warehouse management system requires the SCE collaboration interface, which supports multiple message transmission protocols such as MQTT and AMQP, and can realize real-time collection of relevant material data.

The partial application interface of the product kitting evaluation and decision-making system is shown in figure 4, in which figure 4.(a) shows the calculation of single product kitting, figure 4.(b) shows the product kitting result interface, figure 4.(c) shows the import of multi-product BOM structure, and figure 4.(d) shows the multi-product kitting result interface. By setting the brake control device product as a high-priority demand, based on the MBOM data of the material in the SAP business system, the number of complete sets of the single product is calculated according to the algorithm model proposed in this article. The "material" column represents the material number of the calculated complete set of products, and the "component" is listed as all the lower-level materials in the material MBOM, and the "quantity of complete sets" is the maximum number of complete sets that can be produced by each component material calculated by the kitting algorithm model, and the minimum value is the maximum complete set number of product materials. For the situation of multi-product sales, assuming that the project S-000370.04.01.01 is a high-priority demand, a multi-product MBOM hierarchy can be built according to figure 2 and import it into the system as shown in figure 4.(c). Based on the built-up supporting sales BOM, the result of calculating the number of multi-product kits is shown in the figure 4.(d).

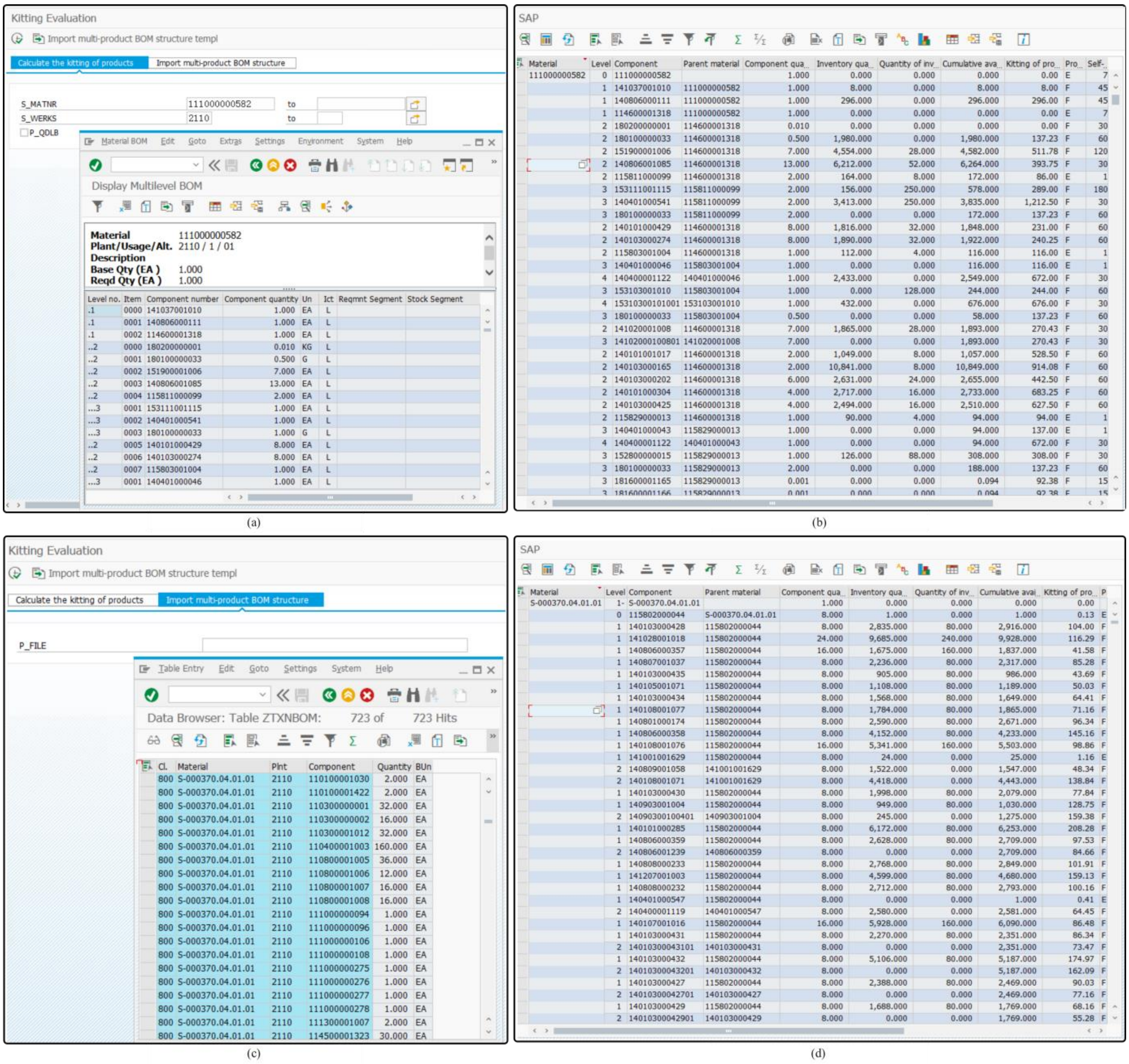

Figure 4. System application interface.

The product kitting evaluation and decision-making system does not need to manually change the business data of the existing system. When faced with changes in the importance of delivered products, it changes from the previous work mode based on manual data calculations to relying on system calculations. The response results are shortened from week level to minute level, while ensuring the accuracy of calculation results in real-time on-site business operations, and providing effective support for quickly responding to customers demand for completeness. After being applied in the actual business of Z enterprise, the algorithm model has been verified to be accurate and effective, providing important data support for timely business adjustment and management strategic decision-making.

5. Conclusion

In this paper, under the condition of providing product priority, based on the constraints of inventory and in-progress business, an algorithm model for calculating product kitting is proposed, which can quickly evaluate the degree of meeting customer product kitting requirements, drive business development with both process and digitalization, laying the foundation for the digital transformation of enterprises. Based on the product process route and procurement cycle, the critical path of the

MBOM tree diagram can be calculated, combined with the minimum set of values calculated by the algorithm model in this article, the key materials that meet the delivery needs of customers under certain conditions can be obtained, and the focus is on the business involving such materials, which can prevent the impact of factors such as shortage of materials on production execution and delivery in advance, and improve the delivery capacity of the enterprise. In addition, key material quality factors are also important factors that restrict production and delivery. How to quickly calculate product uniformity under various constraints will be one of our main follow-up research tasks.

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