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Information Flow Scheduling in Concurrent Multi-Product Development Based on DSM

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Abstract Multi-product collaborative development is adopted widely in manufacturing enterprise, while the present multi-project planning models don't take technical/data interactions of multiple products into account. To decrease the influence of technical/data interactions on project progresses, the information flow scheduling models based on the extended DSM is presented. Firstly, information dependencies are divided into four types: series, parallel, coupling and similar. Secondly, different types of dependencies are expressed as DSM units, and the extended DSM model is brought forward, described as a block matrix. Furthermore, the information flow scheduling methods is proposed, which involves four types of operations, where partitioning and clustering algorithm are modified from DSM for ensuring progress of high-priority project, merging and converting is the specific computation of the extended DSM. Finally, the information flow scheduling of two machine tools development is analyzed with example, and different project priorities correspond to different task sequences and total coordination cost. The proposed methodology provides a detailed instruction for information flow scheduling in multi-product development, with specially concerning technical/data interactions.

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1 Introduction

With market competition increasing, achieving success with new product development(PD) in mechanic products markets is becoming more and more challenging, and the capability of meeting the diversified customer demands is playing more important role [1]. Due to shortening product life cycles, businesses are also proposing a set of critical success factors to reduce product development time and respond quickly to vibrant customer demand [2].

To meet diversified customer needs while shortening product development cycle, the product developers should concentrate on development of multiple products simultaneously and improve process efficiency and quality [3], rather than focusing on one product at-a-time. However, the resource conflict among multiple PD projects often leads to the delay of project schedules, and the number of parts, tools and materials also increases linearly with number of products. Ensuring concurrent multiple PD progress [4, 5], and managing the information difference and similarity of multiple products are the key problem of concurrent multi-product development project management.

The Design Structure Matrix(DSM), also called the dependency structure matrix, has become an used modeling framework of product development management [6]. DSM is a matrix representation of a directed graph, which allows the project or engineering manager to represent important task relationships in order to determine a sensible sequence for the tasks being modeled [7, 8]. As compared to Critical

Path Method (CPM) and Program Evaluation and Review Technique(PERT), DSM is more suitable for planning information flow in PD project [9–11]. The rows and columns of DSM correspond to the tasks, and the matrix reveals the inputs and outputs of tasks, by manipulating the matrix, the feedback marks can be eliminated or reduced, this process is called partitioning [12, 13]. According to the input/output, the subsets of DSM elements that are mutually exclusive or minimally interacting should be determined, this process is called clustering [14–16].

In recent years, some multiple project scheduling models and methods based on DSM was brought forward, to ensure multi-project progress. P H Chen et al. proposed a hybrid of genetic algorithm and simulated annealing (GA-SA Hybrid) for generic multi-project scheduling problems with multiple resource constraints [17]. C Ju and T Chen developed an improved aiNet algorithm to solve a multi-mode resource-constrained scheduling problem [18]. T Gaertner et al. presented a generic project scheduling technique for functional integration projects based on DSM, to improve the planning of delivery dates and required resources and capacities, to ensure tighter synchronization between project teams, and prioritize tasks in parallel projects [19]. T R Browning proposed an expandable process architecture framework (PAF), which organizes all the models and diagrams into a single, rich process model with 27+ new and existing views, to synchronize various aspects of process (activity network) information in large, complex projects [20]. The above research aims for decreasing project progress delay by arranging task sequences and allocating project resources reasonably, but the influence of task interactions on material flow or product information flow was not taken into consideration.

The product information clustering technologies based on DSM were also presented [21–23], DSM was adopted to cluster product components into modules with minimum interfaces externally and maximum internal integration, but these model aimed for information interaction in the single product, lacked the research about the information difference and similarity among multiple products. Such as, E P Hong and G J Park proposed a new design method to design a modular product based on relationships among products functional requirements, to overcome the difficulty of modular design, with combining axiomatic design, the function-based design method and design structure matrix [21]. A H Tilstra et al. presented the high-definition design structure matrix (HDDSM) to captures a spectrum of interactions between components of a product [22]. T AlGeddawy and H ElMaraghy proposed a hierarchical clustering (cladistics) model to automatically build product hierarchical architecture from DSM [23].

Different from one PD project, information flow planning in concurrent multi-product development should emphasis on two factors: first, partitioning tasks sequences according to tasks relationships and project priorities to decease influences of information feedback on project schedules. Second, clustering the similar tasks [24] of multiple PD projects to reduce number of parts and tools, decrease interaction cost and improve development efficiency.

2 Task Relationships in Multiple Projects

2.1 Relationships Among Projects and Products

The concurrent multiple PD project management is the management mode of screening, evaluating, planning, executing and controlling all the projects during a certain time period, from the enterprise or department perspective. The relationships among projects and products in multi-project environment [25] can be divided into the following three types:

(1) Multiple projects for single product development. Each project is responsible for the development of one or more subsystems, and multiple projects cooperate with each other, to complete the development of a complex product. Cars, airplanes, and other complex PD often use this kind of management mode.

(2) Multiple project for the interrelated multiple products. Each project is responsible for the development of one or more products, and there exist the technical or information interaction among multiple products, such as the same product structure, the similar design technology, etc. The new product is often developed based on product families, so this relationship is very common, which was the main research object of the paper.

(3) One project for one product, and each product is independent. There exists no the same and similar parts or sub-systems among multiple projects, which only occurs in the process of few new product development.

2.2 Input/Output Relationships Description

Input/output relationships of tasks in concurrent multi-product development can be divided into four types: serial, parallel, coupling and similar, as shown in Fig. 1. Fig. 1(a) shows the serial relationship, output of t_i as the input of t_j, t_i have to finish before t_j. Fig. 1(b) shows the parallel

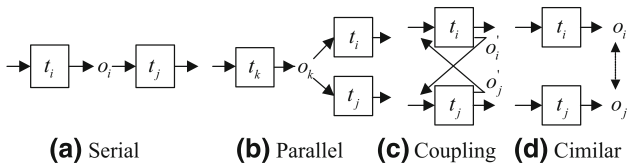


Fig. 1 Input/output relationships in multi-project situation

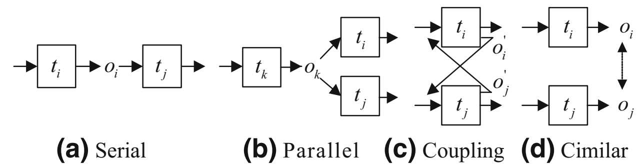


Fig. 2 DSM description of tasks dependencies

relationship, output of t_k as the input of t_i and t_j, t_i and t_j can be executed concurrently after the previous task t_k, the dependency between t_i and t_j corresponds parallel. Fig. 1(c) shows the coupling relationship, o_i',o_i' denotes the output of t_i and t_j, o_i',o_i' as the input of t_j and t_i separately. Fig. 1(d) shows the similar relationship, the output of t_i and t_j is identical or similar, or similar technology was adopted during perform t_i and t_j. The first three types of relationships in Fig. 1 exist both in one-project and multi-project environment, similar relationship is the special relationship in concurrent multi-product development projects.

2.3 Task Relationships in Multiple Projects

The output of PD project includes design schemes, product drawings, process files, parts, sub-systems, semi-finished parts or products, bill of material, etc., which were labeled as product information, the input/output relationships of tasks can be expressed as the dependencies of product information.

$$I(P_i) = \{e_1, e_2, \ldots, e_n\},$$
$$R(P_i) = \begin{pmatrix} ri_{11} & \ldots & ri_{1n} \\ \vdots & & \vdots \\ ri_{n1} & \ldots & ri_{nn} \end{pmatrix}, \tag{1}$$

where $I(P_i)$ and $R(P_i)$ denotes product information set and information dependencies set respectively, ri_{ij} is dependency of information element e_i on e_j, ri_{ij} can be expressed as $0 \sim 5$ integer,

$$ri_{ij} = \begin{cases} 1 \sim 5, \text{there is information from } e_j \text{ to } e_i, \\ 0, \text{there is no information from } e_j \text{ to } e_i, \end{cases} \tag{2}$$

There exist many identical or similar parts, components and development technologies, etc. in different projects. The task dependencies in multiple projects can be expressed as:

$$mrt_{gk} = f(ri_{gk}) = \begin{cases} 1 \sim 5, \text{there is information from } e_k \text{ to } e_g, \\ -5 \sim -1, e_g \text{ and } e_k \text{ is indentical or similar}, \\ 0,\ e_g \text{ and } e_k \text{ is irrelevant }. \end{cases} \tag{3}$$

3 Extended DSM Model

DSM represents the system, product or process by aggregating individual interactions among components, people, activities, or parameters. DSM is essentially an N^2 diagram that is structured in such a way as to facilitate system-level analysis and process improvement. The mark in cell i, j of DSM indicates that the item in row i requires information from the item in column j as an input. Under the diagonal corresponds to the forward information flow, and above diagonal shows the feedback.

The task relationships in multiple PD projects were described as serial, parallel, coupling and similar type, the DSM description as shown in Fig. 2, Fig. 2(a)$\sim$2(c) corresponds to serial, parallel and coupling relationship separately, and Fig. 2(d) corresponds to similar relationship.

To describe tasks dependencies in multiple PD projects, one extended DSM(EDSM) was brought forward. $\{t_{a1}, t_{a2}, \ldots, t_{am}\}$, $\{t_{b1}, t_{b2}, \ldots, t_{bn}\}$ denotes the tasks in project P_a and P_b separately, the extended DSM related to P_a and P_b can be expressed as a partitioned matrix.

$$EDSM = \begin{pmatrix} \mathbf{A} & \mathbf{D} \\ \mathbf{C} & \mathbf{B} \end{pmatrix},$$

$$\mathbf{A} = \begin{pmatrix} rt_{a1,a1} & rt_{a1,a2} & \ldots & rt_{a1,am} \\ rt_{a2,a1} & rt_{a2,a2} & \ldots & rt_{a2,am} \\ \vdots & \vdots & & \vdots \\ rt_{am,a1} & rt_{am,a2} & \ldots & rt_{am,am} \end{pmatrix},$$

$$\mathbf{B} = \begin{pmatrix} rt_{b1,b1} & rt_{b1,b2} & \ldots & rt_{b1,bn} \\ rt_{b2,b1} & rt_{b2,b2} & \ldots & rt_{b2,bn} \\ \vdots & \vdots & & \vdots \\ rt_{bn,b1} & rt_{bn,b2} & \ldots & rt_{bn,bn} \end{pmatrix},$$

$$\mathbf{C} = \begin{pmatrix} mrt_{b1,a1} & mrt_{b1,a2} & \ldots & mrt_{b1,am} \\ mrt_{b2,a1} & mrt_{b2,a2} & \ldots & mrt_{b2,am} \\ \vdots & \vdots & & \vdots \\ mrt_{bn,a1} & mrt_{bn,a2} & \ldots & mrt_{bn,am} \end{pmatrix},$$

$$\mathbf{D} = \begin{pmatrix} mrt_{a1,b1} & mrt_{a1,b2} & \ldots & mrt_{a1,bn} \\ mrt_{a2,b1} & mrt_{a2,b2} & \ldots & mrt_{a2,bn} \\ \vdots & \vdots & & \vdots \\ mrt_{am,b1} & mrt_{am,b2} & \ldots & mrt_{am,bn} \end{pmatrix},$$

where $\boldsymbol{A}$ and $\boldsymbol{B}$ indicates input/output dependencies matrix of project P_a and P_b separately, $\boldsymbol{C}$ denotes dependencies of P_b on P_a, and $\boldsymbol{D}$ corresponds to dependencies of P_a on P_b.

4 Information Planning Based on EDSM

Information flow planning based on the extended DSM is different from DSM, which involves four types of computation: merging, converting, partitioning and clustering.

4.1 Merging Converting and Partitioning Regardless of Project Priorities

According to the input/output relationships, $mrt_{ij} = -5$ means output of t_i and t_j is identical. To avoid duplicate work, t_i and t_j can be combined, this process is called merging. Such as $\{t_{ai}, t_{aj}\}$ and $\{t_{bg}, t_{bk}\}$ is tasks set of project P_a and P_b separately, the initial extended DSM model was expressed as

$$\begin{pmatrix} t_{ai} & & & \\ 3 & t_{aj} & & \\ -5 & & t_{bg} & \\ & & 5 & t_{bk} \end{pmatrix},$$

the work content of t_{ai} and t_{bg} is identical, t_{ai} and t_{bg} can be combined into one task, furthermore task dependencies need be to reconstructed. After merging t_{ai} and t_{bg}, the extended DSM model can be expressed as:

$$\begin{pmatrix} t_{ai} & & \\ 3 & t_{aj} & \\ 5 & & t_{bk} \end{pmatrix} \text{ or } \begin{pmatrix} t_{bg} & & \\ 3 & t_{aj} & \\ 5 & & t_{bk} \end{pmatrix},$$

in multi-project environment, $-5 < mrt_{ij} < 0$ means the output of t_i and t_j is similar, and $0 < mrt_{ij} < 5$ means that the output of t_j as the input of t_i.

When converting computation is done, the similar relationships can be converted to $0 < mwr'_{ij} < 5$, so as to partitioning and clustering can be done based on the uniform algorithm, $mrt'_{ij} = f(mrt_{ij})$ is the converting function, the initial extended DSM is:

$$\begin{pmatrix} t_{ai} & & & \\ 3 & t_{aj} & & \\ -3 & & t_{bg} & \\ & & 5 & t_{bk} \end{pmatrix},$$

$mwr_{bg,ai} = -3$ means the work content of t_{ai} and t_{bg} is similar. Supposing converting function follows the linear law, $mwr'_{ij} = k \times mwr_{ij} + b$. Designer can choose the different value of k and b, and analyze influence of numerical value k and b on partitioning and clustering results. Adopting $mwr'_{ij} = -2 \times mwr_{ij} - 3$, the converted extended DSM is

$$\begin{pmatrix} t_{ai} & & & \\ 3 & t_{aj} & & \\ 3 & & t_{bg} & \\ & & 5 & t_{bk} \end{pmatrix} \text{ or } \begin{pmatrix} t_{bg} & & & \\ 5 & t_{bk} & & \\ 3 & & t_{ai} & \\ & & 3 & t_{aj} \end{pmatrix}.$$

Partitioning is the computation of reordering the rows and columns in the DSM with minimizing the number of marks above the diagonal, the result is the optimal tasks ordering, which reduces feedback and rework. According to the partitioned matrix, the serial, parallel and coupling relationship can be identified. Regardless of project priorities, partitioning algorithm of the extended DSM is identical to the common DSM [24, 25]. Tasking the parallel tasks relationships as the example.

$$\begin{pmatrix} t_i & 0 & 5 \\ 0 & t_j & 5 \\ 0 & 0 & t_k \end{pmatrix} \rightarrow \begin{pmatrix} t_k & 0 & 0 \\ 5 & t_i & 0 \\ 5 & 0 & t_j \end{pmatrix},$$

the initial tasks sequence is $t_i \rightarrow t_j \rightarrow t_k$, and partitioned tasks sequence is $t_k \rightarrow t_i \rightarrow t_j$, the relationships between t_i and t_j is parallel, can be performed concurrently.

4.2 Clustering Regardless of Project Priorities

The goal of clustering is to find subsets of the extended DSM (i.e., clusters) so that the tasks within a cluster are maximally interdependent and clusters are minimally interacting. Some researchers have proposed different clustering algorithm based on different principle, such as A Yassine presented a clustering objective function by using the minimal description length principle [26], S E Carlson and N Ter-Minassian proposed a clustering algorithm based on coordination cost [27].

This paper focuses on the information flow in multi-project situation, with the goal of minimizing the influence of information interaction on project schedule, referring the algorithm of Idicula and Fernandez, etc., the clustering object function of the extended DSM was built.

$$Tcc(M) = \sum_{i=1}^{n} cc(t_i),$$

$$cc(t_i) = \sum_{j=1}^{n} (mwr(t_i, t_j) + mwr(t_j, t_i)) \times size(t_i, t_j)^{p\_k}, \tag{4}$$

where $Tcc(M)$ is total coordination cost of model M,which is the objective function that the algorithm attempts to minimize, $cc(t_i)$ indicates coordination cost of task t_i, n is the number of tasks in M, $mwr(t_i, t_j)$, $mwr(t_j, t_i)$ denotes the interaction between t_i and t_j, corresponding to the value in the extended DSM, $size(t_i, t_j)$ is the size of minimum cluster which contains t_i and t_j, p_k is the power coefficient corresponds to the k-th level clusters, value range of p_k is integer from 1 to 5. After merging, converting and partitioning, one extended DSM was obtained:

$$\begin{pmatrix} \boldsymbol{A} & 1 & 2 & & & & \\ & \boldsymbol{B} & 4 & & & & \\ 4 & 2 & \boldsymbol{C} & & & & \\ & & & \boldsymbol{D} & & 3 & 2 \\ & & & 5 & \boldsymbol{E} & 3 & 3 \\ & 5 & & 1 & 3 & \boldsymbol{F} & 2 \\ & & & 4 & 3 & 4 & \boldsymbol{G} \end{pmatrix}.$$

Clustering can be done based on the previous computation, according to Eq. 4, p_k_1, p_k_2, p_k_3 corresponds to different level clusters, p_k_1 indicates the power coefficient of smallest cluster, p_k_2 corresponds to the upper level of cluster, which consists of a series of sub-cluster and tasks, p_k_3 corresponds to the whole extended DSM, adopting $p\_k_1 = 1,\ p\_k_2 = 2,\ p\_k_3 = 3$, the clustered extended DSM can be obtained:

$$\begin{pmatrix} \boldsymbol{A} & 1 & 2 & & & & \\ & \boldsymbol{B} & 4 & & & & \\ 4 & 2 & \boldsymbol{C} & & & & \\ & & & \boldsymbol{D} & & 3 & 2 \\ & & & 5 & \boldsymbol{E} & 3 & 3 \\ & 5 & & 1 & 3 & \boldsymbol{F} & 2 \\ & & & 4 & 3 & 4 & \boldsymbol{F} \end{pmatrix}.$$

Adopting $p\_k_1 = 1,\ p\_k_2 = 1,\ p\_k_3 = 2$, the different clustered extended DSM can be obtained:

$$\begin{pmatrix} \boldsymbol{A} & 1 & 2 & & & & \\ & \boldsymbol{B} & 4 & & & & \\ 4 & 2 & \boldsymbol{C} & & & & \\ & & & \boldsymbol{D} & & 3 & 2 \\ & & & 5 & \boldsymbol{E} & 3 & 3 \\ & 5 & & 1 & 3 & \boldsymbol{F} & 2 \\ & & & 4 & 3 & 4 & \boldsymbol{G} \end{pmatrix},$$

which means that the lower level clusters will contain more tasks as p_k_2/p_k_1 increase, and the upper level will contain more sub-clusters and tasks as p_k_3 increase.

4.3 Merging Converting and Partitioning with Regarding Project Priorities

Regarding project priorities, the duplicate work in low-priority project should be combined into the identical tasks in high-priority project, and tasks dependencies was reconstructed. Such as $\{t_{ai}, t_{aj}\}$ and $\{t_{bg}, t_{bk}\}$ is tasks set of project P_a and P_b separately, pri_a and pri_b denotes priorities of P_a and P_b, $pri_b > pri_a$, the initial extended DSM is:

$$\begin{pmatrix} t_{ai} & & & \\ 3 & t_{aj} & & \\ -5 & & t_{bg} & \\ & & 5 & t_{bk} \end{pmatrix},$$

$mwr_{bg,ai} = -5$ means the work content of t_{ai} and t_{bg} is identical, and t_{ai} and t_{bg} can be combined into one task. To guarantee schedule requirement of high-priority project P_b, t_{ai} should be combined into t_{bg}, the merged extended DSM can be expressed as

$$\begin{pmatrix} t_{bg} & & \\ 3 & t_{aj} & \\ 5 & & t_{bk} \end{pmatrix},$$

converting aims at transforming $-5 < mrt_{ij} < 0$ into $0 < mwr'_{ij} < 5$, so as to partitioning and clustering can be done based on the uniform algorithm, $mrt'_{ij} = f(mrt_{ij})$ is the converting function. Different from computation regardless of project priorities, converting regarding priorities should guarantee the schedule of high-priority project firstly. Such as, project P_b with higher priority, $pri_b > pri_a$, the initial extended DSM is

$$\begin{pmatrix} t_{ai} & & & \\ 3 & t_{aj} & & \\ -3 & & t_{bg} & \\ & & 5 & t_{bk} \end{pmatrix},$$

means the work content of t_{ai} and t_{bg} is similar, adopting $mwr'_{ij} = -2 \times mwr_{ij} - 3$, the transformed extended DSM as follows, because t_{bg} with high priority, t_{bg} was arranged before t_{ai} in task sequence,

$$\begin{pmatrix} t_{bg} & & & \\ 5 & t_{bk} & & \\ 3 & & t_{ai} & \\ & & 3 & t_{aj} \end{pmatrix}.$$

Partitioning regarding project priorities performs the following steps: firstly, reordering the rows and columns of extended DSM, secondly, moving forward high-priority tasks, or moving backward low-priority tasks. For example, $\{t_{a1}, t_{a2}, t_{a3}, t_{a4}\}$ and $\{t_{b1}, t_{b2}, t_{b3}, t_{b4}\}$ is tasks set of project P_a and P_b separately, P_a with higher priority, $pri_a > pri_b$, the extended DSM model before and after partitioning is

$$\begin{pmatrix} t_{a1} & & & & & & & \\ 2 & t_{a2} & 2 & & & & 2 & \\ 5 & & t_{a3} & & & & & 2 \\ & & 5 & t_{a4} & & & & 1 \\ & 2 & & & t_{b1} & & & \\ & 3 & & & 5 & t_{b2} & & \\ 3 & & & & & & t_{b3} & \\ & & & 2 & & & 3 & t_{b4} \end{pmatrix},$$

or

$$\begin{pmatrix} t_{a1} & & & & & & & \\ 3 & t_{b3} & & & & & & \\ 5 & & t_{a3} & & 2 & & & \\ & & 5 & t_{a4} & 1 & & & \\ & 3 & & 2 & t_{b4} & & & \\ 2 & 2 & 2 & & & t_{a2} & & \\ & & & & & 2 & t_{b1} & \\ & & & & & 3 & 5 & t_{b2} \end{pmatrix},$$

tasks sequence $T' = \{t_{a1}, t_{b3}, t_{a3}, t_{a4}, t_{b4}, t_{a2}, t_{b1}, t_{b2}\}$ can be obtained, adjusting tasks order based on project priorities and input/output dependencies, new tasks sequence can be obtained, $T'' = \{t_{a1}, t_{a3}, t_{a4}, t_{b3}, t_{a2}, t_{b4}, t_{b1}, t_{b2}\}$, t_{a2} can not move to the front of t_{b3} because that t_{a2} depends on the output of t_{b3},$mwr_{a2,b3} = 2$. The corresponding partitioned extended DSM regarding project priorities is:

$$\begin{pmatrix} t_{a1} & & & & & & & \\ 5 & t_{a3} & & & & 2 & & \\ & 5 & t_{a4} & & & 1 & & \\ 3 & & & t_{b3} & & & & \\ 2 & 2 & & 2 & t_{a2} & & & \\ & & 2 & 3 & & t_{b4} & & \\ & & & & 2 & & t_{b1} & \\ & & & & 3 & & 5 & t_{b2} \end{pmatrix}.$$

4.4 Clustering with Regarding Project Priorities

The goal of clustering with regarding project priorities is dividing the tasks with similar priorities and high input/output dependencies into the same subsets, to decrease information interaction cost in multi-project situation. The object function takes influence of project priorities on coordination cost into consideration, pri_i and pri_j denotes priority of project P_i and P_j respectively. The clustering object function with regarding project priorities can be expressed as:

$$Tcc(M) = \sum_{i=1}^{n} cc(t_i),$$
$$cc(t_i) = \sum_{j=1}^{n} f_{ij} \times (mwr(t_i, t_j) + mwr(t_j, t_i)) \times size(t_i, t_j)^{p\_k},$$
$$f_{ij} = (|pri(t_i) - pri(t_j)| + 1)^{p\_pri}, \tag{5}$$

where $Tcc(M)$ is total coordination cost of model M, $cc(t_i)$ is coordination cost of task t_i, n is the number of tasks in M, $r(i,j)$, $r(j,i)$ is the interaction between t_i and t_j, p_k is the power coefficient related to the k-th level clusters, f_{ij} indicates impact factor related to project priorities, $pri(t_i)$ and $pri(t_j)$ denotes project priorities, p_pri is the power coefficient related to project priorities, value range of p_k and p_pri is $0 \sim 1$, and $0 < f_{ij} \leq 1$.

Different from clustering regardless of project priorities, by introducing f_{ij}, the difference in project priorities was taken into consideration, with f_{ij} increacing, the tasks with different priorities will be divided into different clusters. Such as, pri_a and pri_b denotes project priority of project P_a and P_b respectively, adopting $pri_a = 3$, $pri_b = 1$, $p\_k_1 = 1$, $p\_k_2 = 2$, $p\_k_3 = 3$, after merging, converting and partitioning with regarding project priorities, the tasks sequence can be determined, and the clustered extended DSM with regarding project priorities can be obtained:

$$\begin{pmatrix} t_{a1} & & & & & & & \\ 5 & t_{a3} & & & & 2 & & \\ & 5 & t_{a4} & & & 1 & & \\ 3 & & & t_{b3} & & & & \\ 2 & 2 & & 2 & t_{a2} & & & \\ & & 2 & 3 & & t_{b4} & & \\ & & & & 2 & & t_{b1} & \\ & & & & 3 & & 5 & t_{b2} \end{pmatrix}.$$

5 Example

Two machine tool products was developed during the same period, the worktable size of one machine tool is 650×650 mm^2, the other is 1250×1250 mm^2, two machine tools have the similar product structures.

The dependencies among tasks in multiple PD projects were determined according to the input/output relationships, the initial extended DSM model can be built:

$$EDSM = \begin{pmatrix} \boldsymbol{A} & \boldsymbol{D} \\ \boldsymbol{C} & \boldsymbol{B} \end{pmatrix}.$$

Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
machine body A	1		2																		
machine column A	2	3																			
spindle box A	3		4					5	1	1											
exchangable working platforn	4					4	4														
turntable A	5	2			3																
working table A	6				4																
spindle A	7			2																	
screw A	8	1	1	1		1															
slide guide A	9	1	1																		
tool changer A	10	1						1													
chip-removal system A	11	3					1														
oil cooler A	12							1	1												
air operated system A	13				1			1													
hydraulic system A	14					3	3														
lubricating system A	15							1	1	1											
electrical cabinet A	16							1	1												
Carriage aprons A	17	2																			
tools measurement device A	18							1													
workpiece measurement syste	19						1														
raster rule A	20									1											

(a) Task relationships in prj_a

Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
machine body B	1		2																		
machine column B	2	3																			
spindle box B	3		4					5	1	1											
exchangable working platforn	4					4	4														
turntable B	5	2			3																
working table B	6				4																
spindle B	7			2																	
screw B	8	1	1	1		1															
slide guide B	9	1	1																		
tool changer B	10	1						1													
chip-removal system B	11	3					1														
oil cooler B	12							1	1												
air operated system B	13				1			1													
hydraulic system B	14					3	3														
lubricating system B	15							1	1	1											
electrical cabinet B	16							1	1												
Carriage aprons B	17	2																			
tools measurement device B	18							1													
workpiece measurement syste	19						1														
raster rule B	20									1											

(b) Task relationships in prj_b

Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
machine body B	1	-3																			
machine column B	2		-2																		
spindle box B	3			-2																	
exchangable working platform B	4				-1																
turntable B	5					-2															
working table B	6						-1														
spindle B	7							-1													
screw B	8								-1												
slide guide B	9																				
tool changer B	10										-3										
chip-removal system B	11											-3									
oil cooler B	12												-5								
air operated system B	13													-5							
hydraulic system B	14														-5						
lubricating system B	15															-3					
electrical cabinet B	16																-5				
Carriage aprons B	17																	-1			
tools measurement device B	18																		-5		
workpiece measurement system E	19																			-5	
raster rule B	20																				

(c) Identical and similar relationships between two projects

Fig. 3 Task dependencies in multiple projects

Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
machine body A	1		2																			1
machine column A	2	3																				2
exchangable working platform A	3				4	4																3
turntable A	4	2		3																		4
working table A	5			4																		5
slide guide A	6	1	1																			6
Carriage aprons A	7	2																				7
spindle box A	8		4				1			5	1											8
spindle box A	9								2													9
screw A	10	1	1		1				1													10
chip-removal system A	11	3				1																11
hydraulic system A	12				3	3																12
workpiece measurement system	13					1																13
raster rule A	14						1															14
tool changer A	15	1								1												15
oil cooler A	16									1	1											16
air operated system A	17			1						1												17
lubricating system A	18						1			1	1											18
electrical cabinet A	19									1	1											19
tools measurement device A	20									1												20
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	

first level cluster

second level cluster

(a) Computation with power coefficient of 2/2/2

Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
machine body A	1		2																			1
machine column A	2	3																				2
exchangable working platform A	3				4	4																3
turntable A	4	2		3																		4
working table A	5			4																		5
slide guide A	6	1	1																			6
Carriage aprons A	7	2																				7
spindle box A	8		4				1			5	1											8
spindle box A	9								2													9
screw A	10	1	1		1				1													10
chip-removal system A	11	3				1																11
hydraulic system A	12				3	3																12
workpiece measurement system	13					1																13
raster rule A	14						1															14
tool changer A	15	1								1												15
oil cooler A	16									1	1											16
air operated system A	17			1						1												17
lubricating system A	18						1			1	1											18
electrical cabinet A	19									1	1											19
tools measurement device A	20									1												20
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	

first level cluster

second level cluster

(b) Computation with power coefficient of 1/2/2

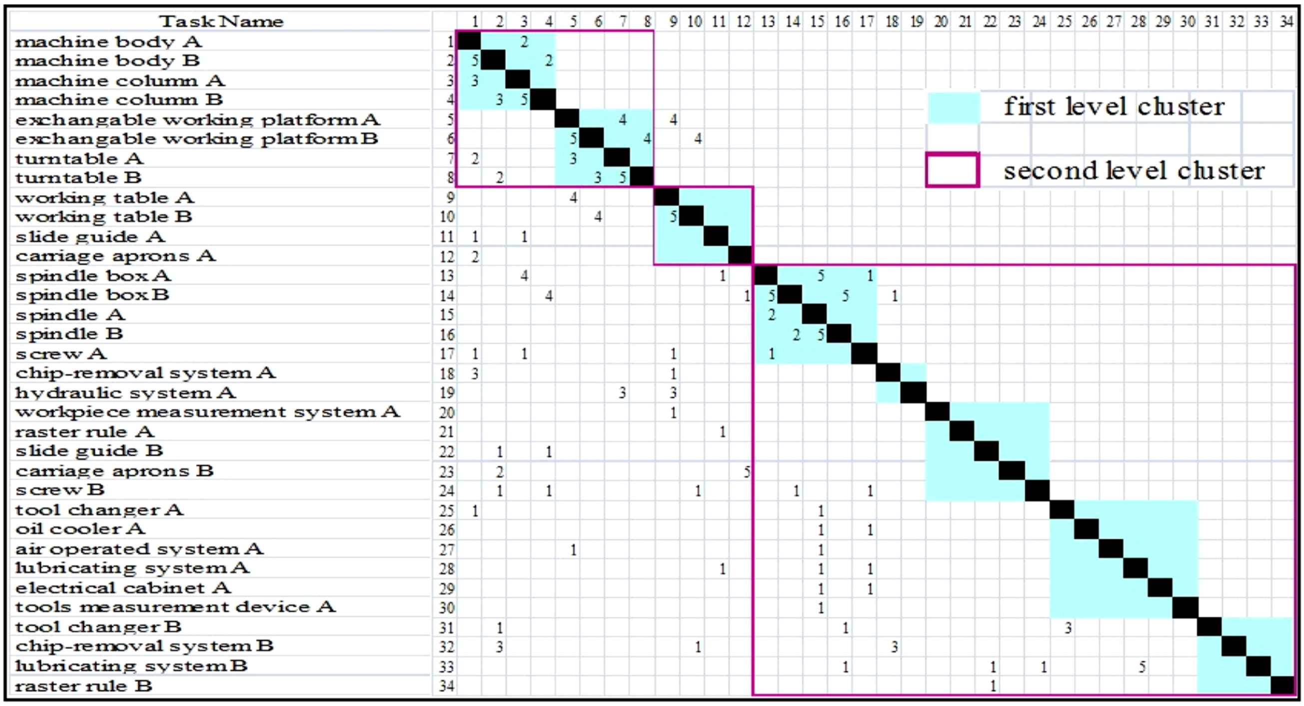
Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
machine body A	1		2																			1
machine column A	2	3																				2
exchangable working platform A	3				4	4																3
turntable A	4	2		3																		4
working table A	5			4																		5
slide guide A	6	1	1																			6
Carriage aprons A	7	2																				7
spindle box A	8		4				1			5	1											8
spindle box A	9								2													9
screw A	10	1	1		1				1													10
chip-removal system A	11	3				1																11
hydraulic system A	12				3	3																12
workpiece measurement system	13					1																13
raster rule A	14						1															14
tool changer A	15	1								1												15
oil cooler A	16									1	1											16
air operated system A	17			1						1												17
lubricating system A	18						1			1	1											18
electrical cabinet A	19									1	1											19
tools measurement device A	20									1												20
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	

first level cluster

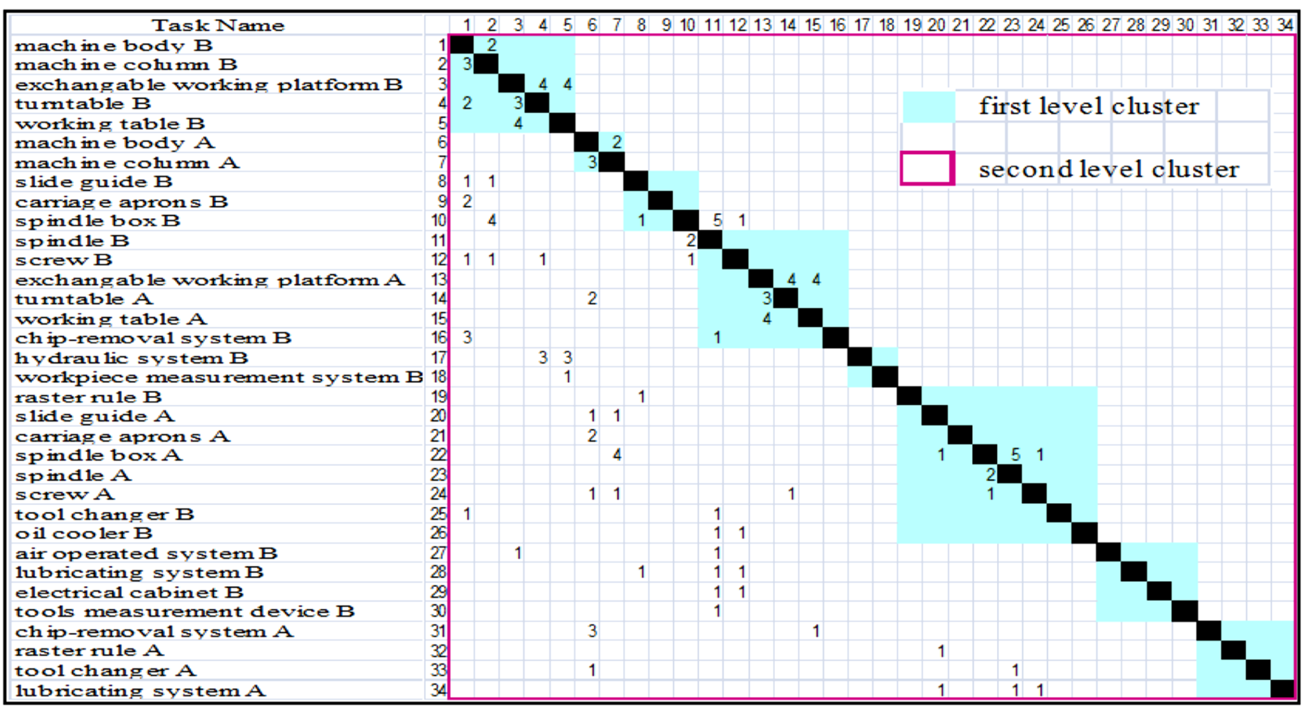
second level cluster

(c) Computation with power coefficient of 1/2/3

Fig. 4 Partitioning and clustering of prj_a



(a) Scheduling regardless of project priorities



(b) Scheduling with regarding project priorities

Fig. 5 Information flow scheduling based on extended DSM

Fig. 3(a), Fig. 3(b) corresponds to dependencies of 650 type (prj_a), 1250 type (prj_b) horizontal machine center separately, Fig. 3(c) corresponds to the identical and similar relationships between two projects, $\boldsymbol{D}$=0.

According to the information planning approach of Extended DSM, the partitioning and clustering computation results related to prj_a can be obtained, as shown in Fig. 4. The values of p_k_1, p_k_2, p_k_3 have significant

Table 1 Total coordination cost with different power coefficient

	1/1/1	1/1/2	1/1/3	1/2/2	2/2/2	1/2/3
con_1	4800	87 480	3 394 680	138 400	138 400	3 445 600
con_2	3828	86 508	3 393 672	109 254	115 000	3 416 454
con_3	2822	64 532	2 162 672	77 230	78 338	2 175 370
con_4	2325	54 306	1 867 320	56 488	68 554	1 963 882

impact on clustering results, the size of second level clusters increases with p_k_3/p_k_2, the size of first level clusters increases with p_k_2/p_k_1.

Merging the duplicate work, and adopting linear function $mwr'_{ij} = k \times mwr_{ij} + b$ to convert the similar relationships. Partitioning and clustering extended DSM with different value of k and b, adopted $mwr'_{ij} = -2 \times mwr_{ij} - 1$ as the converting function, the similar tasks was divided into the same clusters. Regardless of project priorities, adopting $p\_k_1 = 1$, $p\_k_2 = 2$, $p\_k_3 = 2$, merging, converting, partitioning and clustering tasks of two projects based on the extended DSM, the computation result as shown in Fig. 5(a). With regarding project priorities, adopting $pri_a = 1$, $pri_b = 3$, which means that prj_b with high project priority, the computation result based on the extended DSM as shown in Fig. 5(b).

Regardless of project priorities, the similar tasks tend to be divided into the same clusters, to reduce the influence of information interaction on project schedule. the similar tasks tend to be divided into different clusters, to reduce the influence on schedule of high-priority tasks.

Adopting different p_k_1, p_k_2 and p_k_3, $Tcc(M)$ was computed in four types of conditions: ① two project was independent, each project as a cluster con_1, ② two project was independent, clustering without regarding the relationships between two projects con_2, ③ clustering based on the extended DSM model, without regarding project priorities con_3, ④ clustering based on the extended DSM model, with regarding project priorities con_4, computation results as shown in Table 1.

The first two conditions didn't take relationships between two projects into consideration, and the last two conditions was computed based on the extended DSM, with regarding dependencies among multiple projects. The differences of $Tcc(M)$ show that optimizing tasks sequence based on the extended DSM can decrease influence of task interactions on project schedules, and values of p_k influence computation results obviously, the power coefficient should be determinded according the task relationships and PD teams.

6 Discussion

The extended DSM was built to optimizing task-sequences and task-clusters in multiple PD projects, focusing on the technical information interactions and similarities in multiple projects, taking project priorities into consideration, was mainly applied to the mechanical product development projects, such as automobiles, machine tools, construction machines, etc. Although software, construction and other industries also involve multi-project management [26, 28], but the task-relationships are different from mechanical product development projects.

A series of coefficients was introduced in the converting and clustering calculation, such as k and b in converting function $mwr'_{ij} = k \times mwr_{ij} + b$, p_k in Eq. (4), p_k and p_pri in Eq. (5). The calculation results indicated that the value of these coefficients had a great effect on the information planning. It is necessary to determine these coefficients by taking the completed projects as example, changing the values, and judging the rationality of task-sequences and task clusters combined with the expert experience.

Resources sharing and conflicting was the important feature of multi-project management [17, 29], but the extended DSM model didn't take resource allocation into consideration, therefore the information planning results based on extended DSM should not be the final task sequences, the further adjustment according to resource capabilities was needed.

7 Conclusions

(1) Describing task dependencies is the basis of information flow planning based on the extended DSM, the task relationships in multi-project is divided into four types: serial, parallel, coupling, and similar. Similar is the specific dependency relationship of the extended DSM.

(2) The initial extended DSM can be expressed as a partitioned matrix, describing task dependencies in one project and among multiple projects concurrently.

(3) By adopting different power coefficients in converting or clustering function, different task-sequences or task-clusters can be obtained. Determining the appropriate power coefficient is important for information flow scheduling based on the extended DSM.

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