

Research on DSM-based Product Development Coupling Activity Overlapped Execution Model

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Abstract. Aiming at the problem of overlapping execution of coupling activities in the product development process, using Markov Chain method to describe the iterative process of coupling activities based on the design structure matrix (DSM). Then introduced the information output, input time factor matrix and rework risk matrix to describe the complex information interaction between design activities, constructed a model of rework time caused by design activity coupling and iteration by quantifying the overlap of design activities, and then established the entire project time cost model for coupled activity sets. Finally, an application analysis was performed with examples. The research shows that this method can effectively reduce product development time and provide a certain theoretical basis for the rational planning and scientific guidance of the overlapping execution mode of coupled activities in the product development process.

Introduction

Concurrent engineering is one of the effective ways to shorten the product development cycle, but the parallelism and overlap between activities in the product design process also accelerates the update and feedback of design information and increases the risk of activity iteration and rework. From the perspective of product design information interactions, there are three basic information dependencies between design activities, namely: independent relationships, one-way dependencies, and two-way coupled dependencies. Among them, the coupling dependency is more complicated due to the frequent information interaction between its design activities, which makes the design process iterative. Reasonably and effectively controlling the information interaction between activities can optimize the product development process.

For the research on the overlap of coupling activities in the product development process, domestic and foreign scholars have achieved many results. For example: Lim Tae-Kyung et al. [1] gave a simple description of the overlapping attributes of activities, analyzed the time cost trade-off problem, gave a mathematical expression of rework time and duration, and determined it without allocating additional resources. In order to reduce the time and cost, the best overlap of activities is achieved. Reza Dehghan et al. [2] described the overlapping execution characteristics between design activities, analyzed the overlapping costs and time trade-offs of the activities, proposed the concept of equivalent rework time, and gave the calculation of time and cost trade-offs in the case of multiple activities overlapping model. Chu Zihao et al. [3] described the multi-mode problem of overlapping activities, constructed a multi-mode rework time factor matrix with overlapping activities, and arranged an appropriate execution mode for each activity to achieve the goal of minimizing project duration. A multi-mode active overlapping project scheduling model is constructed.

The Design Structure Matrix (DSM) can effectively represent the information flow between design activities and the cyclic relationship between design activities [4]. In recent years, many domestic and

foreign scholars have extended it to describe the complex process of product development. For example: MAHESWARI et al. [5] used DSM to plan and compress the project duration to estimate the duration of natural overlapping projects involving minimal risk; HISHMMA et al. [6] used the division operation in DSM to cleverly process the order of the matrix rows and columns to make the information feedback distance between activities Effectively shorten and reduce iterations and rework between activities. Xin Junjie et al. [7] conducted an in-depth analysis of the update and feedback of information between design activities, and proposed an improved product development process model. DSM was used to extend the model to multiple design activities, and a mathematical model of time and cost was established. Zhang Youxin et al. [8] described the construction and optimization of DSM and made suggestions for DSM expansion.

This article aims to reduce product development time. Based on DSM, the Markov Chain method is used to describe the information flow during the iterative cycle. The Gaussian elimination method is used to solve the linear equations in the iterative process to obtain the initial execution order of the coupled activities. Then, by introducing information output, input time factor matrix, and rework risk matrix to describe the complex information interaction between design activities, quantify the overlap of design activities, build a rework time model due to coupling and iteration of design activities, and then establish The time cost model of the coupled activity set in the entire project, and finally, the application analysis is performed with examples.

Determination of Initial Execution Order of Coupling Activities

For multiple serial coupling activities overlapping execution models, in order to make the information transmitted between design activities as accurate as possible and reduce the update and feedback of later information, the initial execution order of coupling activities is determined before the design activities overlap. Reference [9] uses the Gaussian elimination method to solve the total execution time of the coupling activities, then adjusts the execution order of the coupling activities and finds its completion time, and finally determines the initial execution order of the coupling activities with the goal of the shortest completion time. Taking a simple 3×3 DSM shown in Fig.1 as an example, serial execution is performed in the order of coupling activities A-B-C, and a third-order Markov Chain iterative model is established as shown in Fig.2.

	A	B	C
A	8	0.5	
B	0.2	5	0.3
C	0.4	0.1	6

Figure 1. 3×3 design structure matrix.

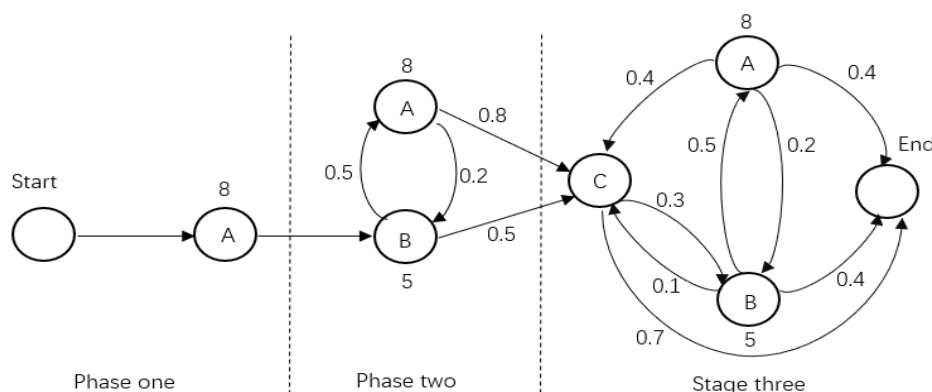


Figure 2. Schematic diagram of the third-order Markov Chain iteration.

Fig.2 shows the coupling activities of three loop iterations. The iterative process between design activities is roughly divided into three phases: the first phase executes activity A and enters the second

phase after completion; in the second phase, activity B completes execution. After that, there is a 50% probability that it will directly enter the third stage to execute activity C, and a 50% probability that it will return to execute activity A. After the execution of activity A is completed, it will have a 20% probability to execute activity B again, and an 80% probability will be transferred to the Perform design activity C in three phases. In the third stage, after the execution of activity C is completed, there is a 70% chance that the design process will be directly completed to complete the design project, and at the same time, there is a 30% chance that the iteration between the coupling activities A, B, and C will eventually complete the design project. According to this cyclic iterative mode between design activities, each activity may have multiple iterations and rework. In the end, the design activity achieves convergence and completes the iterative cycle process in a certain iteration process.

To calculate the expected total completion time of the model, the execution duration of each phase needs to be calculated separately. Because the model is executed serially according to A-B-C, design activity C finds that the iteration results do not meet the requirements, and it will feed back information to design activity A or B, resulting in rework of design activities A and B, and finally design activities Part of C will also be redone, so the calculation process calculates the duration of each phase from phase three to phase one in reverse order. Suppose that the execution durations of design activities A, B, and C in phase three are T_A , T_B , and T_C , respectively. From this, three linear correlation equations are obtained:

$$\begin{cases} T_A = 8 + 0.2T_B + 0.4T_C \\ T_B = 0.5T_A + 5 + 0.1T_C \\ T_C = 0.3T_B + 6 \end{cases}$$

The above linear equations are converted into a matrix form and simplified by Gaussian elimination:

$$\begin{bmatrix} 1 & -0.2 & -0.4 \\ 0 & 0.9 & -0.3 \\ 0 & 0 & 0.9 \end{bmatrix} \begin{bmatrix} T_A \\ T_B \\ T_C \end{bmatrix} = \begin{bmatrix} 8 \\ 9 \\ 9 \end{bmatrix}$$

Because the iterative process of phase three is performed from design activity C, only the execution duration of design activity C needs to be solved, and design activities A and B do not need to calculate and retain the results. $T_C = 10$ at this stage is obtained. Similarly, for the execution time of phase two, let the execution periods of design activities A and B of phase two be S_A and S_B , respectively. The calculation process is similar to that of phase three, and the phase $S_B = 10$ is obtained. For the execution time of phase one Since there is only one execution task for design activity A at this stage, let the execution period of this stage be R_A , that is, $R_A = 8$. So the total completion time of serial iteration of the entire coupled activity set is $T_C + S_B + R_A = 28$. This method is used to solve all the

Table 1. Execution order and its total completion time of Coupling activity set.

Execution order	A—B—C	A—C—B	B—A—C	B—C—A	C—A—B
Completion Time	28.00	27.33	25.00	27.40	29.73

different execution sequences and their corresponding total completion times. The results are shown in Table 1. As can be seen, the completion time of the execution sequence B-A-C is at least 25, so the initial execution sequence of the coupling activity is determined as B-A-C.

Analysis of Overlapping Characteristics of Coupling Activities Based on DSM

Coupling Activity Overlap Description

In the traditional serial execution model, all the accumulated information is passed to the downstream activities after the upstream activities have completely ended, and the design work begins after the downstream activities have obtained the information. However, in order to shorten the product development cycle, downstream activities are intervened in advance before the upstream activities have ended. At this time, the upstream and downstream activities will overlap and execute on the time axis. Fig.3 (a) shows the overlapping design activities without considering the rework time, where T_1 , T_2 and T_3 are the expected completion time of the design activity, and T_{12} and T_{23} are the design activities A and B, B and C formed on the time axis, respectively. For the overlapping part, NT is the total time for iterative execution of each design activity without considering the rework time.

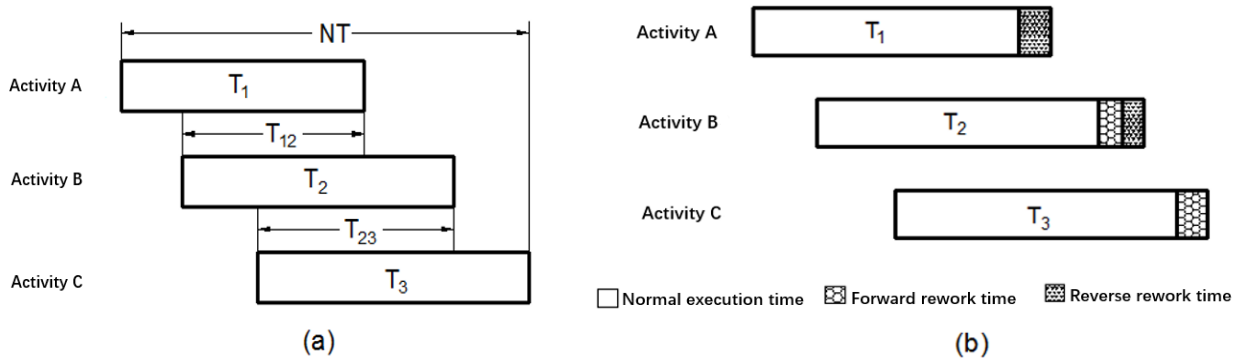


Figure 3. Schematic diagram of the coupling activity overlap execution.

Compared with the overlap of uncoupled activities, the overlap of coupled activities must not only consider the impact of upstream design activity information updates on downstream design activities, but also consider the impact of downstream design activity information updates on upstream design activities, and Rework caused by iterative design activities. Fig.3 (b) is a schematic diagram of overlapping design activities considering rework time. Due to the coupling relationship between design activities, upstream activities cannot obtain all the information about the smooth progress of downstream activities in advance, and can only make appropriate assumptions about the information they need. When this assumption is unreasonable, there will be imperfections or errors in the information passed by upstream activities to downstream activities during the overlapping execution phase. These erroneous information will inevitably cause rework of downstream activities, which is the positive result in Fig.3 (b). Time to rework. If the imperfect or incorrect knowledge of the upstream design activity is found during the iterative solution of the downstream design activity, and the wrong information is passed back to the upstream design activity, then the upstream design activity needs to perform the previously assumed error information. The modification caused the rework of the upstream design activity, which is the reverse rework time in Fig.3 (b).

Description of Overlapping Process of Coupling Activities Based on Dsm

DSM initially used a Boolean matrix to represent the dependency of information between design activities in the product development process. After expanding to a digital matrix with special meaning, it can not only represent the strength of the dependency of information between design activities, but also the interaction time of information, Probability of rework for design activities, etc. This paper refers to the information output, input time factor matrix, and rework risk matrix proposed in [10] to describe the complex information interaction between design activities. Fig.4 (a) is the information output time factor matrix IO , where the diagonal elements are the estimated completion time of the design activity, and the non-diagonal elements $IO(i, j)$ represent the earliest information output time from design activity j to design activity i . The following triangular element $IO(3,2) = 0.3$ indicates that when design activity B reaches 30%, information can be transmitted to design activity

C. The upper triangular element IO (2,3) = 0.6 indicates that design activity C reaches 60%. Information can be passed back to design activity B. Figure 4 (b) is the information input time factor matrix II. The non-diagonal element II (i, j) represents the earliest information input time from design activity i to design activity j, that is, design activity j starts to accept the information output by design activity i. For example, if element II (2,1) = 0.2 means that design activity B reaches 20%, the information of design activity A can be accepted.

Because the risk of rework is related to the impact of rework probability and the information transmitted between activities, this paper uses the rework probability RP matrix and the rework impact strength RI matrix to represent the rework risk due to overlap in design activities. Fig.4 (c)

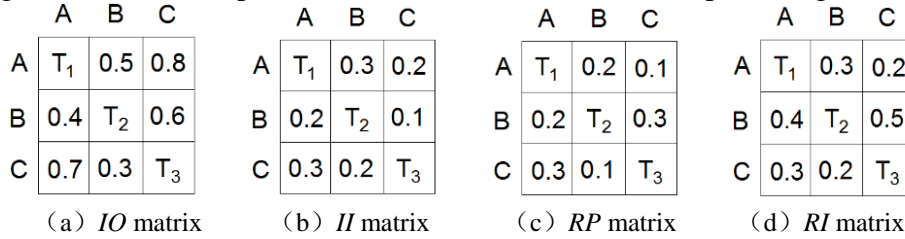


Figure 4. Various DSMs for coupled activity overlap processes.

is the RP matrix. The off-diagonal element RP (i, j) represents the probability that the design activity i needs to be reworked after the design activity j is completed when the designer executes activity j first and then activity i. The lower triangle element indicates the forward rework probability. For example, the element RP (2,1) = 0.2 means that when the designer performs activity A first and then activity B, the probability that design activity B needs to be reworked is 0.2 after design activity A is completed. The upper triangle element indicates the probability of reverse rework. For example, the element RP (2,3) = 0.3 means that when the designer performs activity A and then activity B, the feedback information is provided to design activity A after design activity B is completed. Design activity A requires The probability of rework is 0.2. Fig.4 (d) is the RI matrix. The off-diagonal element RI (i, j) indicates that if rework occurs in design activity i, the rework amount accounts for the proportion of the total workload of the design activity. It indicates that design activity B has reworked, and the amount of rework is 40% of the total work of design activity B.

Construction of Coupling Activity Overlap Execution Time Model

In the case of overlapping activities, the total development time cost of the project is ST. It consists of the normal activity execution time NT and the rework time cost RT caused by the overlap:

$$ST = NT + RT \quad (1)$$

According to Figure 3 (a), the overlap β is defined as the percentage of the overlap between the two design activities in the downstream design activity:

$$\beta_1 = T_{12} / T_2 \quad (2)$$

Overlap measures the overlap between two consecutive design activities. According to Fig.4 (a), the IO matrix is used to describe the degree of overlap between design activities. The design activity i immediately upstream and the design activity j immediately downstream The degree of overlap β_i :

$$\beta_i = \frac{IO(i,i)(1-IO(j,i))}{IO(j,j)} \quad (3)$$

Describe normal activity execution time NT by overlap:

$$NT = T_1 + T_2(1 - \beta_1) + T_3(1 - \beta_2) \quad (4)$$

Use IO matrix to describe normal activity execution time NT:

$$NT = \sum_{i=1}^n IO(i, i) - \sum_{\substack{i=1, \\ j=i+1}}^{n-1} IO(i, i)(1 - IO(j, i)) \quad (5)$$

The information that the upstream design activity passes to the downstream design activity during the overlapping execution phase will inevitably cause the rework of the downstream design activity, that is, the forward rework. The cost of forward rework time for the entire project

$$RT_s = \sum_{j=1}^{n-1} \sum_{i=j+1}^n (II(i, j) \times II(i, i) + (1 - IO(i, j)) \times IO(j, j)) \times RP(i, j) \times RI(i, j) \quad (6)$$

is: Where $II(i, j) \times II(i, i)$ represents the time that has been executed when the downstream activity started to accept the information passed by the upstream activity, and $(1 - IO(i, j)) \times IO(j, j)$ represents the time iteratively executed after the downstream activity accepted the information.

$$RT_c = \sum_{i=1}^{n-1} \sum_{j=i+1}^n (IO(i, j) \times RP(i, j) \times RI(i, j)) \quad (7)$$

The total time cost of the overlapping activities is:

$$ST = NT + RT_s + RT_c \quad (8)$$

Case Analysis

Taking the development process of a certain type of camera as an example to analyze the application. Four coupling activities including shutter device design (design activity A), viewfinder design (design activity B), camera body design (design activity C), and film device design (design activity D) were selected as the research objects. The corresponding initial design structure matrix obtained according to relevant expert opinions is shown in Fig.5.

	A	B	C	D
A	20	0.1	0.2	0.3
B	0.3	35	0.4	0.2
C	0.1	0.3	21	0.5
D	0.1	0.1	0.2	18

Figure 5. Initial design structure matrix.

First, determining the initial execution order of the coupling activities. According to the method introduced in the first section, use Gaussian elimination to solve the total execution period of the coupling activities. The different execution sequences and their corresponding results are shown in Fig.6.

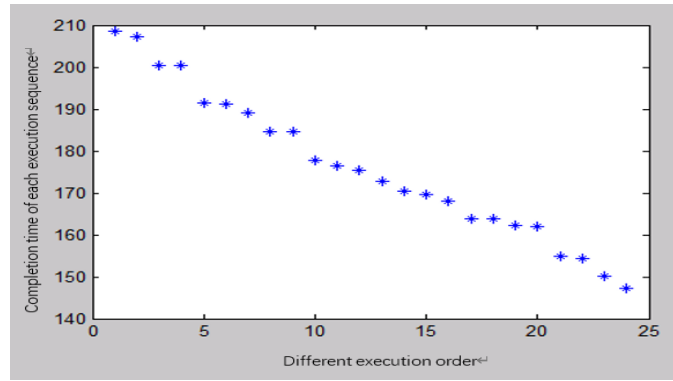


Figure 6. Execution time of different execution order.

It is known from Fig. 6 that the minimum time cost of the adjusted camera development process is 147.14, and the corresponding execution order is D-A-C-B. Among them, the time cost of the execution sequence A-B-C-D before the adjustment was 200.36, compared with the reduction of 53.22 and the time cost by 26.56%. The initial execution sequence of the final coupling activity is D-A-C-B.

According to relevant expert opinions, the corresponding time factor IO matrix, II matrix, rework probability RP matrix, and rework impact intensity RI matrix are shown in Fig.7.

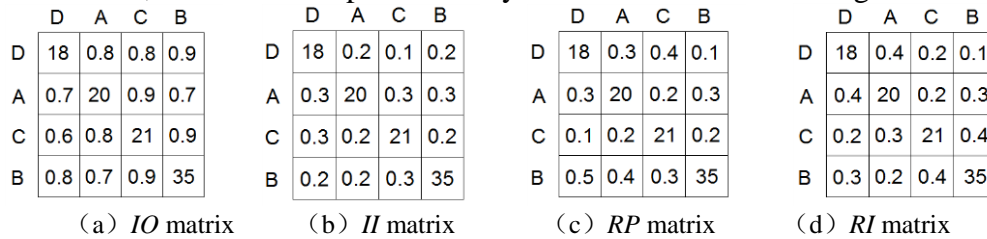


Figure 7. Camera development process various DSM.

According to the matrices of the camera development process in Fig.7, the normal activity execution time NT, forward rework time cost RTS and reverse rework time cost RTC in the entire project are calculated from the formulas (5) to (8). The time cost is 90.26. The solution results of overlapping execution of design activities before and after the initial execution sequence adjustment during camera development are imported into Table 2:

Table 2. Corresponding results during camera development.

Execution plan	Before performing sequence adjustment	After performing sequence adjustment	After overlapping activities
Time cost	200.36	147.14	90.26

From Table 2, it is known that the time cost of DSM-based activity overlapping execution proposed by this article is 90.26, which is 56.74 less than the time cost of 147.14 before activity overlap, and the time cost is reduced by 38.56%. The time cost decreased by 110.10, and the time cost decreased by 54.95%. Therefore, the DSM-based activity overlapping execution model proposed in this paper can effectively reduce product development time, thereby shortening the product development cycle.

Conclusion

Coupling between design activities is the main reason for the complexity of the design process. This paper makes a reasonable plan for the overlap of coupled design activities in the product development process. The traditional serial design pattern does not consider the time delay caused by iteration and iteration between activities. The model proposed in this paper not only considers the rework time cost of coupling activities due to iteration, but also uses the overlapping execution between design activities to shorten the product development cycle more effectively. The calculation method is more

practical than the traditional method. Research shows that this method can effectively reduce product development time, and has a certain reference for the rational planning and scientific guidance of the overlapping execution mode of coupled activities in the product development process. However, this method is mainly aimed at the study of simple projects, and it has a large amount of calculation for development projects with more design activities. The subsequent application of the model and the efficiency of the algorithm need to be further improved.

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