A Process Simulation-Based Method for Engineering Change Management

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Abstract: Engineering change management is a special form of problem solving where many rules must be followed to satisfy the requirements of product changes. As engineering change has great influence on the cycle and the cost of product development, it is necessary to anticipate design changes (DCs) in advance and estimate the influence effectively. A process simulation-based method for engineering change management is proposed incorporating multiple assessment parameters. First, the change propagation model is established, which includes the formulation of change propagation influence, assessment score of DC solution. Then the optimization process of DC solution is introduced based on ant colony optimization (ACO), and an optimization algorithm is detailed to acquire the optimal DC solution automatically. Finally, a case study of belt conveyor platform is implemented to validate the proposed method. The results show that changed requirement of product can be satisfied by multiple DC solutions and the optimal one can be acquired according to the unique characteristics of each solution.

Key words: change propagation; simulation; ant colony algorithm; design change solution

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0 Introduction

Engineering change management is a special form of problem solving where many rules must be followed to satisfy the requirements of product changes. Triggers of design change (DC) can be incorrect assumption about market conditions, future customer needs and available technology[1-3]. It has been suggested that DCs can consume one-third of the engineering design capacity[4]. The later product changes are detected, the more cost it takes to implement them[5]. Thus, it is necessary to anticipate DCs in advance and estimate the risk effectively. Designers mostly have limited choices of DC solutions with manual forecasting. Available choices may be referring to similar cases or DC solutions with the incorporation of personal or co-workers' experiences. However, traversing all the solutions and acquiring the optimal one are difficult for unaided designers or design teams.

To address the challenge, researches in the academic can be classified into three areas: DC object, DC relation and change propagation analysis. DCs can be modifications of dimensions, performance indices, materials and so on, which are dependent on the specific DC cases. Cohen et al.[6] proposed a change favorable representation (C-FAR) method from the perspective of product entity and its attributes. Griffin et al.[7] studied 41 500 changed requirements and introduced three types of node motifs of requirements. Yin et al.[8] applied the topology faces to model geometrical change propagation. Koh et al.[9] drawn on the individual components to estimate the system changeability. However, the de-

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tailed process of change propagation is not given when an initial change is triggered.

Multiple forms are applied to describe the DC relation, e. g., design structure matrix, network. Chen et al.[10] constructed the module relations in the form of matrix to analyze the change propagation. Hamraz et al.[11] recorded the relations among multiple entities (i.e., function, behavior and structure) in the matrices. Network is widely used to represent the design data. Smith et al.[12] organized the relations among function, attribute and structure in the network. Li et al.[13] applied the network to record the mutual relations among components. Referring to the research of Li et al.[13], the network is incorporated to demonstrate the product DC relations in the paper.

As change propagation can enlarge the scope and influence, the prediction is the core of engineering change management. Based on the DC relations, computational tools have emerged to aid designers to explore possible DC solutions and acquire the optimal one. Koh et al.[14] proposed a prediction method to model the effects of potential change propagation brought by different change options quantitatively. Clarkson et al.[15] developed mathematical models to predict the risk of change propagation in terms of change likelihood and impact. Wynn et al.[16] introduced a simulation model to predict resource requirements and schedule change process risk. Li et al.[17] applied the resource constraint in the prediction of change propagation. Tang and Yin[18] proposed a collaborative change method to analyze the changeability of aircraft assembly tooling. Zheng et al.[19] assessed the impact of configuration changes in complex product. However, multiple indices for the risk analysis of change propagation are rarely studied.

Considering the above problems, this paper proposes a process simulation-based method to predict and acquire the optimal DC solution. Network is applied to detail the product relations. The change propagation model is proposed to predict the possible DC solutions. The improved ant colony optimization (ACO) incorporating the DC characteristics of iteration, change propagation, and learning factor is developed to obtain the assessment scores of DC solutions. And DC solution of the largest score can be regarded as the optimal one for designers' decision-making. A case study is conducted to verify that the proposed method can effectively help designers manage the engineering change.

1 Change Propagation Model

1.1 Change propagation influence

In product DC, the initial change is triggered and it can be propagated due to complex product relations. The relations are recorded in the form of network as shown in Fig. 1. In Fig. 1, $R(F_k, C_n)$ and $R(C_i, C_j)$ represent the funtion-component and component-component relatives, respectively. These two types of relations, i.e., $R(F_k, C_n)$ and $R(C_i, C_j)$, are introduced by

$$R(F_k, C_n)=\left\{C_n \rightarrow F_k|(cf_{nk}^{1}, cf_{nk}^{\mathrm{i}})\right\} \tag{1}$$

$$R(C_i, C_j)=\left\{C_i \rightarrow C_j|(cc_{ij}^{1}, cc_{ij}^{\mathrm{i}})\right\} \tag{2}$$

where F_k represents the function, and C_i, C_n and C_j

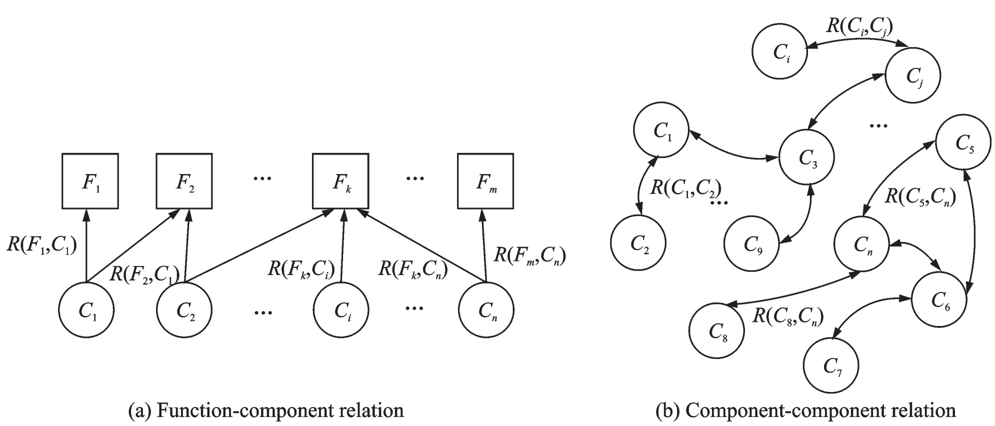

Fig.1 Product change relations

represent the components. The change likelihood and impact between function and component are depicted with cf^{l}_{nk} and cf^{i}_{nk}, which implies the possibility and impact of changed component on the function. The component relations are depicted with change likelihood cc^{l}_{ij} and change impact cc^{i}_{ij}.

During the change propagation, initiating changed component is modified to satisfy the functional requirement. Changed components can further affect other coupled ones. Meanwhile, the affected component can cause related functions to deviate from the optimal status, which implies that more work is required to maintain the performance of affected functions. On this basis, the propagation influence of C_i on C_j is calculated by

$$PI(C_i, C_j) = cc^{l}_{ij} * [(cc^{i}_{ij})^{z} + \sum_k cf^{l}_{jk} * (cf^{i}_{jk})^{h}] \quad (3)$$

where z is the quantity of influence iteration of C_i on C_j, h the quantity of influence iteration of C_j on function F_k, and k the serial number of functions affected by C_j.

1.2 Assessment score of DC solution

Satisfaction of functional change is the target of product DC. A functional change can be realized by different solutions, and each solution is different from others. According to the unique characteristics of each solution, the optimal one can be identified. The changed function can be satisfied by multiple components and the DC of component can be evaluated with multiple parameters. For example, the component DC can be assessed with cost, duration, or environment factor. Corresponding to a function, the weightings P^{p}_{nk} of one type of parameter are valued and the summation is 1. Besides, the assessment value A^{p}_{n} is introduced to assess the component influence in the DC process. For example, assessment value of motor's cost is larger than that of blade in terms of duration, then the blade can be given priority in the DC process to cause lower risk. The weightings and values are estimated according to engineer's experiences, which reflect the product characteristics and engineer's creativity. On this basis, the assessment score (AS) of components for a DC solution can be formulated as

$$\mathrm{AS} = 1 / \sum_{n=1}^{m} [\sum_{k=1}^{q} (\sum_{p=1}^{s} \mathrm{DC}_n * A^{p}_{n} * P^{p}_{nk})] \quad (4)$$

where DC_n is the design change of component C_n, p the serial number of assessment parameter, n the serial number of component. For a change propagation path (i.e., DC solution), the assessment scores of changed components for the corresponding functions are summed. With the proposed assessment score model, all the DC solutions can be assessed for the decision-making of engineers.

2 Optimization of DC Solution

A functional change can be realized by multiple DC solutions. Each DC solution is composed of multiple affected components and requirements. It is necessary to optimize the DC solutions to acquire the least risky one. In this paper, the ACO is applied to optimize the DC solutions. The optimization process can be vividly demonstrated as shown in Fig.2. A virtual initial node is added in the beginning of each change propagation path. With the ACO, the paths are traversed from node C_0 by all the ants according to the rules of pheromone update and selection probability. Each column represents a DC solution, and the element (F_k, C_i) represents the affected component and function in a propagation step.

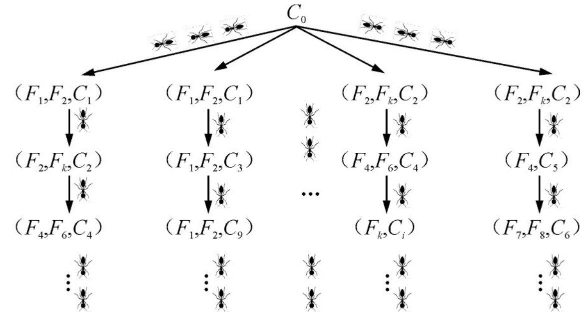

Fig.2 Optimization process with ACO

According to Section 1.2, the assessment score with ACO can be formulated by

$$\mathrm{AS}_a = \mathrm{AS} + \sum_{i=1}^{n} w_{ij} \quad (5)$$

where AS_a is the assessment score with the improved ACO, and i, j are the components of DC solution. The reachability of ant between components can be demonstrated by the change propagation influence. The assessment score for the path travelled by an ant is calculated with $\vartheta \sum_{i=1}^{n} w_{ij}$, where w_{ij} is the reciprocal of $PI(C_i, C_j)$, and ϑ a coefficient adjusting AS and $\vartheta \sum_{i=1}^{n} w_{ij}$ in the same order of magnitude.

In order to guide the ant colony to traverse the components, the rules of pheromone update and selection probability are introduced and improved, which are formulated by

$$\Delta\rho_{ij}(c)=\begin{cases}\mu^* \sum_{a=1}^{z} AS_a & \text{ant } a \text{ passes the path } (C_i, C_j)\\ 0 & \text{else}\end{cases} \tag{6}$$

$$\rho_{ij}(c+1)=\tau^*\rho_{ij}(c)+\Delta\rho_{ij}(c) \tag{7}$$

where $\Delta\rho_{ij}(c)$ is the variation of pheromone caused by all the ants in the cth cycle and $\rho_{ij}(c)$ the amount of pheromone after the cth cycle. μ and τ are the concentration and volatilization coefficients of pheromone, respectively. Based on the assessment score, the pheromone is updated iteratively.

The ant's selection of each step path, i. e., (C_i, C_j), is dependent on the amount of residual pheromone and change propagation influence, which is formulated by

$$SP_{ij}^{a}(c)=\begin{cases}\dfrac{[\rho_{ij}(c)]^{\alpha *}[1/PI(C_i, C_j)]^{\beta}}{\sum_{C_l \in G}[\rho_{il}(c)]^{\alpha *}[1/PI(C_i, C_j)]^{\beta}} & C_l \in G = \text{allow } a \text{ to pass}\\ 0 & \text{else}\end{cases} \tag{8}$$

where α and β are the pheromone and reachability simulation factors, respectively, and G is the collection of next components through which ant a can pass.

As there are many DC solutions, a termination condition is proposed to improve the efficiency of optimization as shown in Eq.(9).

$$\left|AS^{H}(c)-AS^{H}(c-1)\right| \leqslant \varepsilon \tag{9}$$

where $AS^H(c)$ and $AS^H(c-1)$ are the highest assessment scores with ACO in the cth and the $(c-1)$th cycles, respectively, and ε is the termination coefficient.

To automatically acquire the optimal DC solution, an algorithm is proposed to evaluate the DC solutions as shown in Fig.3, which is detailed as follows.

Step 1 Initialize parameters and acquire the product relations.

The quantity of ant and travelling cycle are set as n and 0. The first component for the ant to pass is C_0. Other parameters are set as follows: $\vartheta=1$, $\mu=1$, $\tau=0.75$, $\Delta\rho_{0j}(c)=0$, $\rho_{0j}(0)=1$, $\alpha=1$, $\beta=1$, $AS^H(0)=0$, which implies that the components in the first change propagation step are randomly selected.

Step 2 Ant (or another ant) selects the next affected component, and the amount of pheromone and selection possibility are updated.

Based on the function-component and component-component relations, the ith ant selects the next component according to the selection possibility. And the change propagation influence is calculated according to Eq.(3). Then the amount of pheromone and selection possibility are updated on the basis of Eqs.(6—8).

Step 3 Judge the optimization process based on the propagation influence.

If the change propagation influence is less than 0.01[9], go to Step 4; Otherwise go to Step 2.

Step 4 Calculate the AS_i of the path travelled by ant i.

Calculate the AS_i according to Eq. (5). If all the ants have finished passing the change propagation paths, go to Step 5; otherwise, go to Step 2.

Step 5 Judge the optimization process based on the termination condition.

If $\left|AS^{H}(c)-AS^{H}(c-1)\right| \leqslant \varepsilon$, go to Step 6; otherwise all the ants start travelling the components another time and go to Step 2.

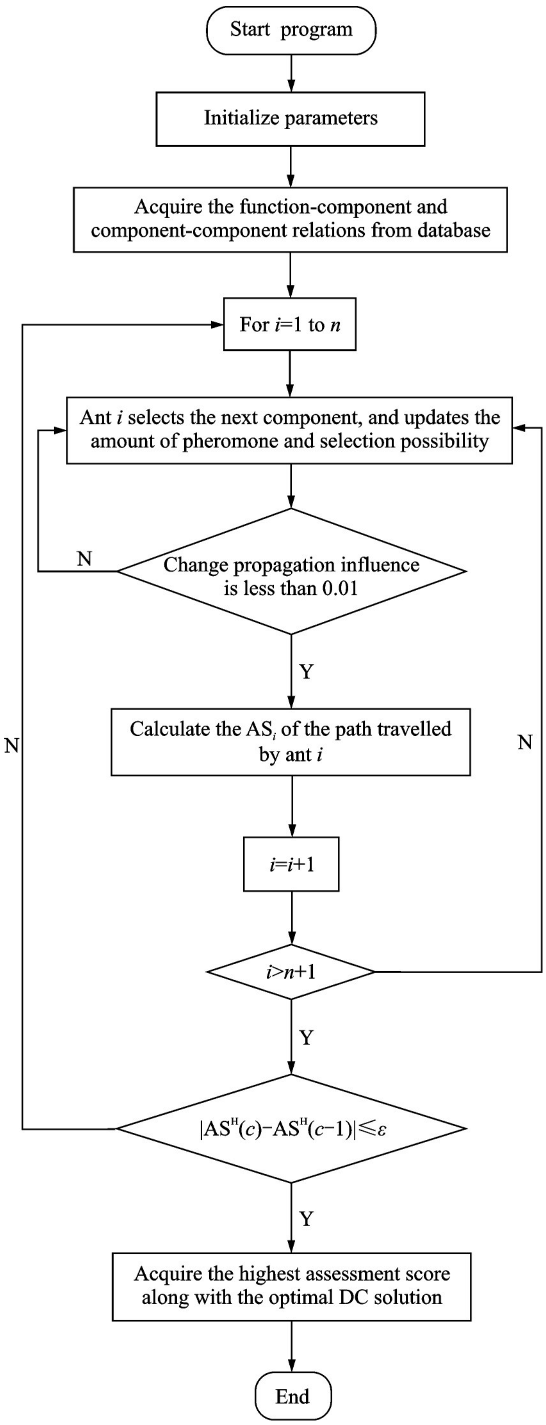

Fig.3 Flowchart of the optimization algorithm

Step 6 Acquire the optimal DC solution corresponding to the highest score.

Step 7 End of program.

With the proposed method, the change propagation paths can be acquired. Meanwhile, DC solutions are evaluated comprehensively with the parameters of cost, duration, etc. In other words, the optimal DC solution incorporates the balance of multiple indices. The DC risk is evaluated in terms of assessment score. The higher the score is, the lower the risk is. The DC solution with the highest score is regarded as the basic one for the designers to decide and implement the design change process.

3 Case Study

A case study of a belt conveyor platform is carried out to demonstrate how the proposed method can assist designers during the early phases of engineering change. The belt conveyor platform is simplified and the weightings of functions are shown in Table 1. Weightings of components along with the couplings between main functions and components are shown in Table 2. The conversion of electrical energy into rotational energy, the adjustment of force and speed transmission, and the conversion of rotational energy into translational energy are the elicited functions of the platform. Three types of parameters, which are cost, duration and resource consumption, are applied to analyze the DC solutions comprehensively. The components are listed according to the functions. Besides, component-component relations (change likelihood and impact) are extracted as shown in Fig.4. Values below the arrow represent the influence relations from the left component to the right one. Values above the arrow represent the opposite relations. Values on the left of the arrow represent the influence relations from the upper component to the lower one. Values on the right of the arrow represent the opposite relations. All the values are evaluated by the senior engineers, who have participated in the similar product design. To guarantee the accuracy as far as possible, these engineers are interviewed separately and the results are discussed in a round-table conference. Different opinions must be unified before the next topic.

As the transmission force is not large enough to carry heavy objects, it is necessary to improve the transmission capacity. The transmission module to adjust the force and speed is required to be changed. That is, the changed function is adjustment of force and speed transmission. After that, the affected

Table 1 Parameter weightings of functions

Function	Parameter		
	Cost	Duration	Resource consumption
Conversion of electrical energy into rotational energy	0.4	0.3	0.3
Adjustment of force and speed transmission	0.2	0.5	0.3
Conversion of rotational energy into translational energy	0.4	0.2	0.4

Table 2 Parameter weightings of function components

Function	Component	Parameter weighting		
		Cost	Duration	Resource consumption
Conversion of electrical energy into rotational energy	Electromotor	0.5	0.4	0.5
	Coupling 1	0.1	0.2	0.1
	Bearing 1	0.2	0.2	0.2
	Bearing 2	0.2	0.2	0.2
Adjustment of force and speed transmission	Shaft 1	0.1	0.1	0.1
	Gear 1	0.2	0.2	0.2
	Bearing 3	0.1	0.1	0.1
	Bearing 4	0.1	0.1	0.1
	Shaft 2	0.1	0.1	0.1
	Gear 2	0.2	0.2	0.2
	Chassis	0.2	0.2	0.2
Conversion of rotational energy into translational energy	Coupling 2	0.2	0.3	0.2
	Roller	0.3	0.3	0.3
	Transmission belt	0.5	0.4	0.5

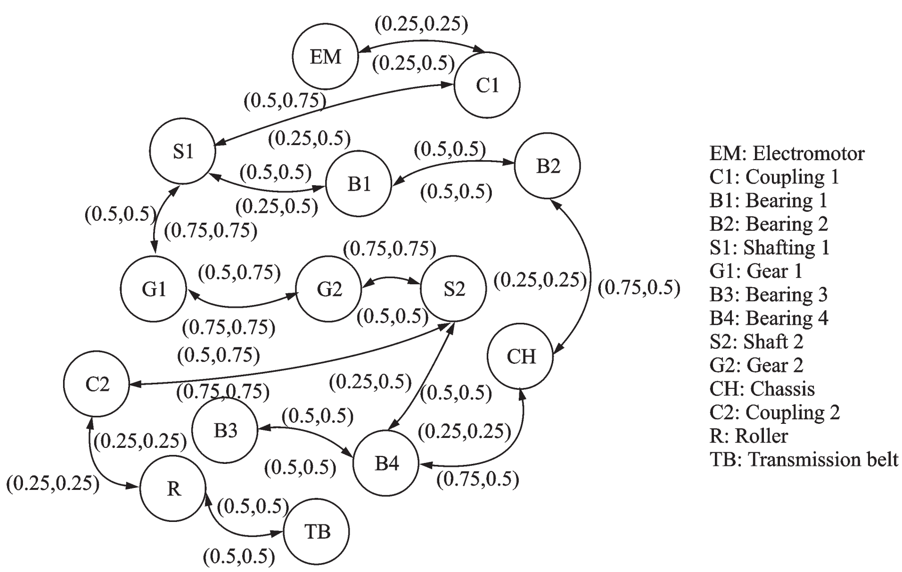

Fig.4 Component-component relations of conveyor platform

components in the first change propagation step are passed by an ant with the same probability. Next, the iteration process of component selection is implemented, and the pheromone and selection possibility are updated. Finally, the component chains constitute the possible change propagation paths and the corresponding assessment scores are acquired with the proposed algorithm.

As shown in Fig.5, the assessment results are plotted. It can be seen that the score of the 36th DC solution is the highest and the change propagation path (i.e., Gear 2→Shaft 2→Coupling 2→Shaft 2

→Coupling 2→Roller→Transmission belt) can be acquired, implying that it is the optimal DC solution. It can be a catalytic idea triggering designers to further analyze and decide the actual implementation plan. To the contrary, the 9th DC solution is the riskiest one, which should be avoided as far as possible. Besides, designers should be alert about the DC solutions in the yellow rectangular box, which are the medium risky options.

Compared with the simulation-based method proposed in the research of Ref.[13], this method combines multiple parameters to comprehensively analyze the DC solution. Besides, the characteristics of iteration, learning factor and change propagation are incorporated with the improved ACO.

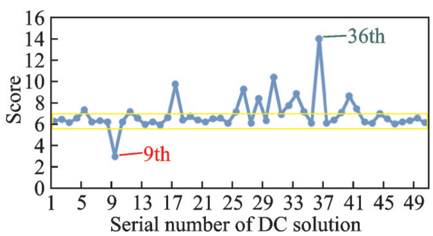

Fig.5 Assessment results of the belt conveyor platform

4 Conclusions

A process simulation-based method for DC solutions is introduced. The purpose is to utilize the existing design information of product to rapidly generate a number of DC solutions and screen out the optimal one in the early DC process. The change propagation model incorporating the iteration influence between functions and components is developed. Multiple product parameters are applied in the assessment score model to rank the DC solutions comprehensively. The solutions can be listed according to the descending order of the scores and the optimal one with the highest score can be acquired. An algorithm of scheduling the DC solutions based on the improved ACO is proposed to schedule DCs in advance and estimate the influence effectively.

Next, more complex products will be tested for the proposed method. Considering the concurrency of tasks, logic relations of product design should be incorporated in the change propagation process. Furthermore, the efficiency of algorithm execution can be improved with respect to the enormous product data. Further research is currently underway.

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Author contributions Dr. **YIN Leilei** conducted the study and wrote the paper. Dr. **ZHU Haihua** completed the interview and assessment. Dr. **SUN Hongwei** designed the case study. Mr. **LIAO Liangchuang** contributed to the conclusion and background. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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基于过程仿真的工程变更管理方法

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摘要:工程变更管理是解决产品设计问题的一种特殊形式,必须遵循许多规则才能满足产品变更的要求。由于工程变更对产品开发周期、成本有很大的影响,因此有必要提前预测设计变更并对其影响进行有效的评估。本文提出一种融合多评价参数过程仿真的工程变更管理方法。首先,建立了变更传播模型,包括变更传播影响的数学模型、设计变更方案的的评价得分;然后介绍了基于蚁群算法的变更方案优化过程,并给出了一种自动获取最优变更方案的优化算法;最后,以带式输送机平台为例验证了该方法的有效性。结果表明,产品的变化需求可以由多个候选变更方案满足,并可根据方案的特性获得最优的结果。

关键词:变更传播;仿真;蚁群算法;设计变更方案