Hindawi
Scientific Programming
Volume 2022, Article ID 1994257, 10 pages
https://doi.org/10.1155/2022/1994257

Research Article

Analysis of the Impact of Change Propagation within Complex Product Modules

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Received 1 July 2022; Accepted 7 September 2022; Published 30 September 2022

Academic Editor: Lianhui Li

Based on the design structure matrix, the changing dependency analysis method is used to study the law of change propagation between parts in the process of product change, in view of the complexity of the product structure and the strong correlation between parts. First, the product components are divided into different modules according to different requirements, and a design structure matrix with weights is established according to the change dependencies between the components within the modules; then, a part changes propagation network is established to analyze the change dependency degree between parts and the influence of the part propagation mode on change propagation and to analyze the possible change propagation impact of part changes. The feasibility and rationality of the method are verified using the frame module as an example. The experimental results show that the method is effective in predicting the changing risk of a part and analyzing the change propagation impact arising from a part change.

1. Introduction

In the context of economic and trade globalization, manufacturing companies face the challenge of changing market rules, the emergence of relevant new technologies, and the rise of individual customer needs. In order to maintain their competitiveness in the market and to meet the diverse needs of their products, companies inevitably have to make engineering changes to their products. In the engineering change process, module change propagation means that: a change in one component causes a change in other components within the same module, which may also have a change impact on other modules and thus on the whole product [1]. The study of change propagation is a major element in engineering change, and the direction of change propagation affects the outcome of engineering change.

When changes are made to modules, further research is required into the impact of module change propagation, where the prediction of module change outcomes is central to change propagation. In terms of the risk of change communication, Eckert et al. [2] studied the basic causes of product changes and the risks arising from the changes, providing an in-depth analysis of the problems arising from the product change process. Loch et al. [3] used five strategies to reduce the processing time of engineering change orders: capacity flexibility, load balancing, combining tasks, sharing resources, and batch size reduction, with special attention to the impact of engineering changes; Rui et al. [4] predicted the impact of change propagation by clustering and grading parts through a graph-theoretic approach based on a design structure matrix, specifically analyzing the characteristics of three types of change propagation: water-wave propagation, bloom propagation, and avalanche propagation; Xiang et al. [5] constructed a risk analysis model for engineering changes in complex products from two perspectives: direct and indirect impacts between Hub nodes in a complex product design network. Yupeng et al. [6] applied complex network theory to model the structure of complex products by considering three factors, namely, function, structure, and change risk, in the modular division of complex products and established a network model of complex product parts with parts as nodes and the association relationship of parts as edges. Liang et al. [7] analyzed the propagation of engineering changes in complex products by combining the design structure matrix, defined the risk of engineering changes in two dimensions of direct and indirect influence, and constructed a risk analysis model of propagation of engineering changes in complex products of the perspective of comprehensive risk. Fan et al. [8] studied change propagation from the aspect of feature association, classified the types of feature association units in product design, and analyzed the change propagation characteristics, change propagation mode, and change propagation process of association units; Zhongwei et al. [9] analyzed the causes and characteristics of avalanche propagation with respect to the constraint conflicts and the number of affected parts and predicted the avalanche propagation by using the directed graph method and knowledge related to complex networks.

In the context of changing communication research methods, Cohen et al. [10] proposed a C-FAR method to evaluate and predict the results of engineering changes, modeling the product information about the EXPRESS language, demonstrating the propagation process of engineering changes, and qualitatively evaluating the results of engineering changes. Congdon et al. [11] applied multiple network theory about complex product modeling to analyze the influence mechanism of different association relationships of the propagation of engineering changes, in view of the fact that the joint effect of multiple association relationships between parts and components was not considered comprehensively in the traditional complex product engineering change propagation impact assessment process. Yongze et al. [12] developed software for engineering change analysis based on the directed graph method of engineering change propagation analysis, which can analyze the propagation, coordination, absorption, and control of part changes in engineering changes and can improve the accuracy and efficiency of engineering change analysis and evaluation. Qin et al. [13] tracked and collaboratively sensed change propagation and predicted the impact range of change propagation through engineering change management. Mengze et al. [14] established a complex product part network model by taking the part connection relationship as the edge and defining the change propagation intensity as the edge weight while considering the change propagation intensity. Xianfu et al. [15] represented the association relationship between product parts based on the design structure matrix, analyzed the association propagation path of master parts, calculated the module association dependency, and determined the priority order of modules. According to the change propagation characteristics of components, Jianfen et al. [16] constructed a multi-objective optimization model and used a nondominated ranking genetic algorithm to solve the model and obtain the Pareto optimal solution set, which can provide an important basis for designers to select the optimal design change solution. All of the above are studies of change propagation for components or basic elements of a product, whereas in practice, there are numerous components in a product, and it would be a large and difficult task to conduct a change study for each component.

On the basis of the above research, this paper establishes a change propagation model within a complex product module by dividing the complex product into modules and dividing it into a number of basic module units, taking the module as the basic elements of change propagation research, as shown in Figure 1, to research the change propagation impact of the module Firstly, we analyze the change propagation impact on parts and components within the module where the changed parts are located and find out the change impact produced by the changes of the parts in the module.

1.1. Type of Propagation of Component Changes within a Module. There is a strong correlation between the components in any given module. The parts are related to each other in a network, which is complex and uncertain. In the network, when a change occurs to a component, the change will propagate along different paths according to the relationship between the components and will have a change propagation effect on the associated components. How to determine the scope of change that the change may cause is key. Change propagation between components and parts can be divided into six forms: direct propagation, bi-directional propagation, indirect propagation, circular propagation, diffusion propagation, and clustering propagation.

(1) Direct propagation: the effect of a change in part A is propagated in one direction to part B causing a change in part B. This change propagation relationship can be observed directly.

(2) Two-way propagation: the effect of a change in part A is propagated to part B, and the change in part B in turn affects part A. The two affect each other.

(3) Indirect propagation: The effect of a change to part A is propagated to part B and then indirectly to part C. There is no direct link between part A and part C and this change propagation is not easily observed directly.

(4) Circular propagation: The influence of changes in part A is propagated to part B and then indirectly to part C. Changes in part C in turn acts on part A, causing the part itself to change repeatedly and iteratively, but this does not mean that the cycle is dead, and can be stopped by the coordination of changes in part or the absorption of changes by parts.

(5) Diffusion propagation: The effect of a change to part A is simultaneously propagated to parts B and C at the next A level, and change propagation occurs. During the change propagation process, diffusion increases the number of parts involved in and affected by the change propagation, which may eventually lead to an avalanche of propagation, making the change propagation impact uncontrollable.

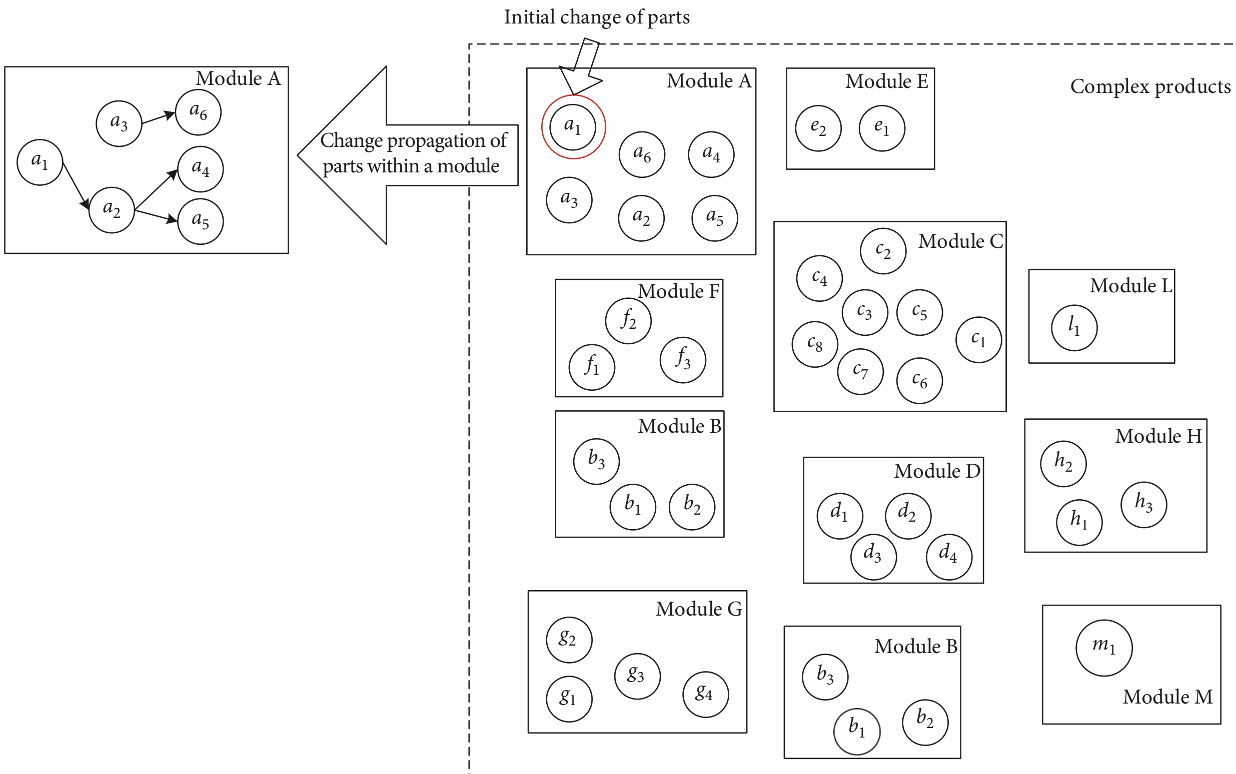
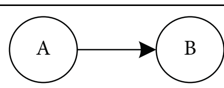
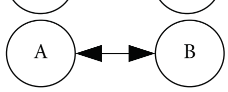
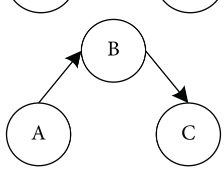
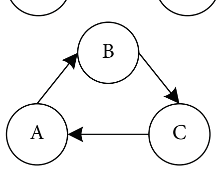
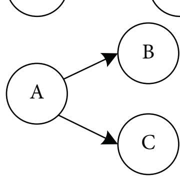
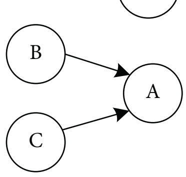


Figure 1: Change propagation model within a complex product module.

Table 1: Types of inter-part change propagation.

Number	Illustration	Type
1		Direct transmission
2		Two-way transmission
3		Indirect transmission
4		Ring transmission
5		Spread transmission
6		Gather transmission

(6) Clustered propagation: The change impact on part A and part B is propagated to part C at the same time, and the change propagation is clustered so that part C has to meet the change design requirements of both part A and part B. In the change propagation process, clustering reduces the number of parts involved in the change propagation and the number of parts affected by the change, reducing the area affected by the change propagation.

The six types of change propagation are represented in a table, as shown in Table 1.

2. Establishing a Parts Change Communication Network

The Design Structure Matrix (DSM) is the primary method for studying the propagation of changes in product design. The link between the elements of the matrix rows expresses the change dependencies that exist on parts. In the binary Boolean DSM, a “0″ means that no change dependency exists on two parts and a “1” means that a changing dependency exists on two parts. In actual manufacturing, the degree of change dependency on parts varies, with some parts having a strong change dependency and others having a weak dependency. It is not possible to classify the dependencies on parts into just two types: those with change dependencies and those without. This is defined by the five-

	a_1	a_2	a_3	a_4	a_5	a_6
a_1	–	1	0.7	0	0	0
a_2	1	–	0.7	0	0	0.5
a_3	0.7	0.7	–	0.3	0.5	0.3
a_4	0	0	0.3	–	0	0
a_5	0	0	0.5	0	–	0
a_6	0	0.5	0.3	0	0	–

Figure 2: Digital DSM.

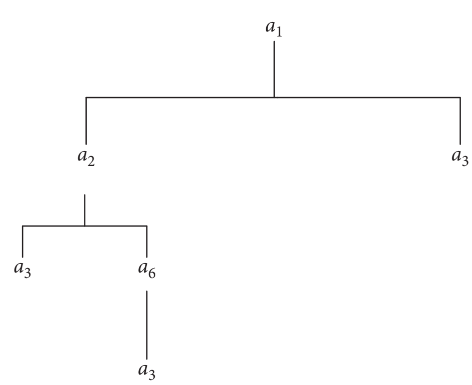


Figure 3: Change propagation impact tree.

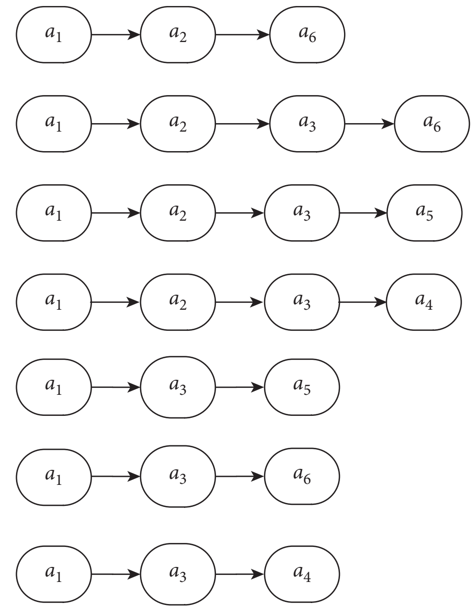


Figure 4: Change propagation chain.

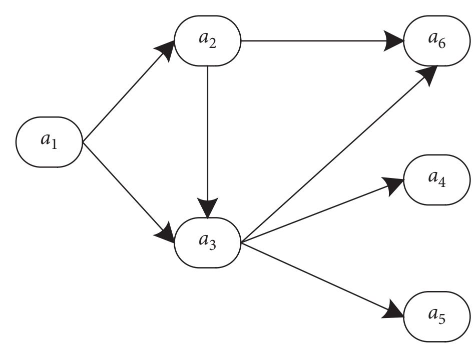


Figure 5: Change dissemination network.

point weighting method [17] using a number between 0 and 1, depending on the strength of the changing dependency on two parts. The number 1 indicates that there is a strong change dependency on two parts, and a change in one part will have a change impact on the other part, while the number 0 indicates that there is no change dependency on two parts, and a change in a part will not have a change impact on the other part. According to the change dependency relationship between parts and the change dependency strength, the numerical design structure matrix is established, as shown in Figure 2.

The change dependency on two elements can be visually represented by a numerical DSM, which reveals the change impact on a change to part a_1 from part a_2. This change propagation influence is a direct change influence and there are also indirect change influences on the change propagation process, for example, a change in part a_1 can cause a change to parts a_3 and a_6 through a change to part a_2. The design structure matrix does not represent the indirect change impact, so a change impact tree is created based on the numerical DSM created. Assuming that part a_1 is the initial changed part and a_3 is the change termination part, create a change impact tree for part a_1 to part a_3 as shown in Figure 3.

During the change propagation process, a part is said to be the initial change part when a change in a part causes the change propagation to occur. Change propagation starts with the initial change part and proceeds according to the change dependencies on the parts until the change is terminated. Firstly, parts in a changing dependency on the initial changed part will have a change impact, with different change dependencies having different change impacts on the part, and secondly, the part affected by the change will also have a change impact on the parts with which it has a changing dependency until the change propagation ends at a particular part. An analysis of the change propagation influenced tree created shows that when the initial parted a_1 starts to make changes, it directly affects parts a_2 and a_3 for changes, while changes to part a_2 affect a_3 and 6 for changes, and changes to part 6 have a change influence on a_3. It can be seen that during the propagation of changes in $a_1 \longrightarrow a_3$, a_1

can affect a_3 directly and a_1 can also have an indirect change impact on a_3 through other parts.

The indirect effects of change propagation cause change to be propagated through a number of different propagation paths, each of which can be represented by a propagation chain, as shown in Figure 4.

Using the digital DSM as a tool, the change propagation network in the network is represented by a directed graph $G(V, \mathrm{E})$, where $V = \{x \mid x = 1, 2, 3, \cdots, n\}$, denotes the set of directed graph vertices and x denotes a part within a module. $E = \{(x, y) \mid x, y \in n, x \neq y\}$ is a directed edge, indicating the existence of a change propagation relationship between part x and part y. In a directed graph $G(V, \mathrm{E})$, the individual change propagation chains described above intersect with each other to form a change propagation network [18]. This is shown in Figure 5.

The change propagation networks to provides a clear view of the initial change parts in a module and the change effects of the initial change parts in other parts, as well as a general view of the paths along which changes are propagated [19]. In the change propagation network, not only direct change effects on parts can be identified, but also indirect change effects. In a network, however, it is not possible to know exactly the magnitude of the propagation dependencies on parts, to determine along which specific paths the change propagation will take, and also to determine the magnitude of the change propagation range. Therefore, there is still a need to study and analyze the change dependencies on parts.

3. Change Propagation Impact Analysis Method Based on Change Dependencies

3.1. Changing Dependencies. When a change activity occurs to a product, due to the high degree of cohesion within the module, there is a high degree of correlation between parts in the module and a high degree of change dependency. When a part starts to change, the change propagates according to the dependencies on the parts, and the complex dependencies between the parts make there are multiple paths for change propagation, the change propagation has a wide range of influence and it is difficult to control the direction of change propagation. If the change propagation path of a part in a module can be determined, the change propagation impact on the part change in the module in which it is located is discovered, the propagation impact between modules is then studied, and the product change results are eventually discovered. If the propagation of change in parts affects the module in which it is located to change in size, structure, or function, then this module will be used as the initial change module, and the propagation impact on the initial change module on other modules will be further investigated between modules to discover the propagation impact on changes in the product. However, when the change propagation of the part will not have a change impact on the module in which it is located, then this module will not change and will not have a change impact on other modules.

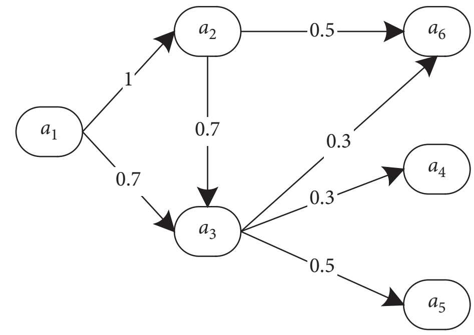


Figure 6: Change dependencies between parts in the change propagation network.

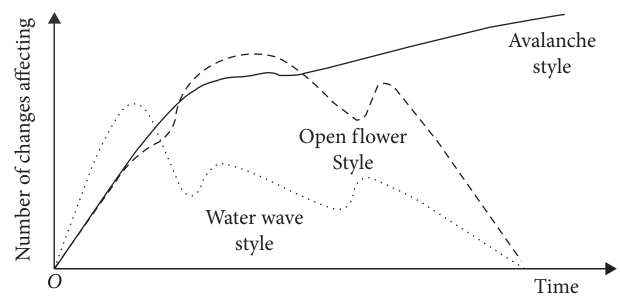


Figure 7: Change propagation impact.

Parts in the same module have strong dependencies on each other, and too much dependency between parts can lead to change propagation going along multiple paths, increasing the scope of change propagation impact. The greater the dependency on parts, the greater the degree to which changes in a part affected changes in another part, and the greater the change transfer of the two parts, making change propagation more difficult to control. Combining the numerical DSM and the change propagation network, the changing dependency on two elements x and y in adjacent cells are represented by $W(x, y)$ and takes a value in the range $[0, 1]$. The value of $W(x, y)$ is obtained according to the numerical DSM established. The value of W is obtained according to the numerical DSM established. $W(x, x)$ represents the degree of change dependency on the component itself and takes the value of 1. Figure 6 shows the addition of change dependencies on the change propagation network [20].

Figure 6 shows that the change propagation of part a_1 spreads and has a simultaneous change impact on parts a_2 and a_3. Due to the close direct change dependency between part a_1 and part a_2, the change impact of part a_1 on part a_2 is greater and change propagation is easily formed.

3.2. Part Change Propagation Impact Analysis. Change propagation impacts are divided into three types: ripple propagation, blossom propagation, and avalanche propagation, as shown in Figure 7.

As can be seen in Figure 7, the water-wave propagation, the initial change causes a part of the parts to be changed, but after a short period of time, the number of parts involved in

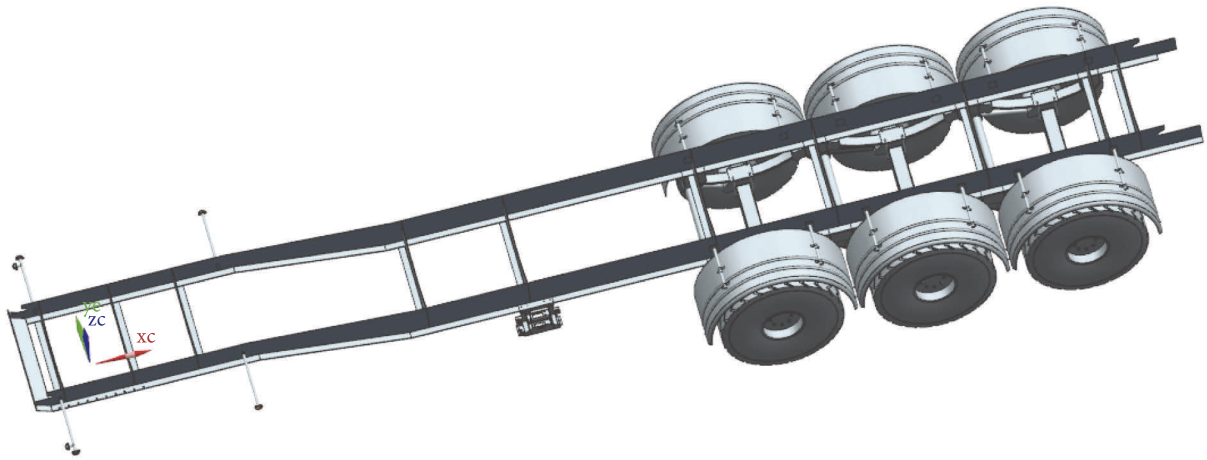


Figure 8: Schematic diagram of the frame module.

the change rapidly decreases and eventually stays at a certain number, because the propagation method of parts is mainly direct propagation, so the change propagation influence is weak. Blossom propagation, where the initial change causes a large number of parts to change, and after a while, the number of parts involved in the change begins to decrease and eventually remains at a reasonable number, due to the existence of indirect and diffusion propagation between parts, which can lead to a rapid increase in the number of changed parts. After a period of time, the number of parts involved in change propagation decreases because, during the change propagation process, some parts have a certain ability to absorb the change. The parts affected by the change propagation absorb the change propagation completely or partially so that the parts with which there is a propagation dependency do not need to be changed or only partially changed, and therefore the change propagation stops or decreases. In avalanche propagation, the initial change causes a large number of parts to change, with the increase of time, the number of changes continues to grow, eventually leading to the number of change impact that is difficult to control, as the avalanche effect, due to the propagation of parts for the diffusion of propagation, the impact of change of a part will be spread to several parts with its change dependency at the same time, making the propagation of change spread, increasing the scope of change propagation impact, and this increases the development cost and reduces the productivity of the product [21]. Therefore, an avalanche of change propagation should be avoided as much as possible.

As can be seen in Figure 6, part a_1 is the initial change part. In the entire change propagation network, the propagation of part a_1 to parts a_2 and a_3 is diffuse, with changes to a_1 affecting changes to both a_2 and a_3, causing changes to propagate along both change paths. The propagation of changes from part a_2 to part a_3 and part a_6 is diffuse, extending the change propagation range. The change propagation of part a_6 is agglomerative and absorbs the change propagation of part a_2 and part a_3, reducing the change propagation impact and creating a blossoming change propagation impact. Part a_3 has both diffuse and convergent propagation. If the change propagation is absorbed in whole or in part at part a_3, the change propagation will be reduced, making the propagation path manageable, but if the change propagation is diffused at part a_3, increasing the range of change propagation, an avalanche of change propagation may occur, making the change propagation difficult to control. Part a_3 is therefore more likely to change and has the greatest impact on changes to the module as a whole. When studying the impact of changes to parts within a module, it is important to prioritize the analysis of the risk of change propagation for part a_3 in order to better control the scope of change propagation.

From the above analysis, it can be concluded that the change propagation impact is mainly determined by the changing dependency between parts and the change propagation mode of the parts. All parts within a module are affected by the initial change. In order to avoid uncontrollable effects of the design change on the product, the changing risk of the part should be analyzed and predicted before the change is made, in order to avoid an avalanche of change propagation effects [22]. In this paper, the change risk value is used to represent the magnitude of the comprehensive change risk of a part, and the change impact that the change propagation of the initial change part will have on the module in which it is located. The changing risk value is expressed in terms of R. Combining the change dependency degree $W(x, y)$ between parts, the changing risk valued calculation formula is obtained as follows:

$$R = \frac{1}{k}\sum_{j=1}^{n}\frac{\sum_{i=1}^{m} W\left(x_i, y_j\right)}{m}. \quad (1)$$

In the formula, k indicates the number of all parts in the module; m indicates the number of parts that have a change propagation effect on the change part; y_j the

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}
a_1	–	1	0.7	0.5	0	0.7	0	0	0.3	0.5	0.3	0.3
a_2	1	–	1	0.5	0	0.5	0	0.3	0	0	0.3	0.3
a_3	0.7	1	–	0.3	0	0.5	0	0.3	0	0.3	0	0
a_4	0.5	0.5	0.3	–	0	0	0	0	0	0	0.3	0
a_5	0	0	0	0	–	0.7	0.7	0	0	0	0	0
a_6	0.7	0.5	0.5	0	0.7	–	0	0	0	0	0	0
a_7	0	0	0	0	0.7	0	–	0	0.5	0.3	0	0
a_8	0	0.3	0.3	0	0	0	0	–	0.5	0	0	0
a_9	0.3	0	0	0	0	0	0.5	0.5	–	0.3	0	0
a_{10}	0.5	0	0.3	0	0	0	0.3	0	0.3	–	0	0
a_{11}	0.3	0.3	0	0.3	0	0	0	0	0	0	–	0.3
a_{12}	0.3	0.3	0	0	0	0	0	0	0	0	0.3	–

Figure 9: Digital DSM for the change of components in the frame module.

number of parts that produce the propagation effects of the change; and *n* indicates the number of change parts in the module.

By calculating change risk values for key nodes and comparing the magnitude of the change risk values, larger values indicate that an avalanche of change propagation impacts are likely to occur, and therefore, changes to the part need to be controlled so that change propagation is within manageable limits.

4. Example Validation

Using the frame module in Figure 8 as an example, the effect of change propagation on the components within the frame module is investigated when the cross member is the initial change part, and the content of this chapter is verified.

As can be seen in the schematic diagram of the frame module, the components contained in the frame module are the wing, web, cross member, front cover, axle, bearings, tires, fenders, struts, spare wheel carrier, front tail light, and side indicators, 12 components.

Due to the change dependencies on components, changes do not occur in isolation. Changes in the initial component will cause changes in other components that are related, and changes will continue to propagate until an equilibrium is reached. In the actual change propagation process, the change propagation method is divided into the direct propagation method and the indirect propagation method. The direct change relationship between two components can be expressed by establishing a design structure matrix with links between the elements of the matrix. The change dependencies on parts result in several different propagation paths, which are represented by the change propagation chain to parts. Finally, the change propagation chains are intersected in a directed graph to form a change propagation network of the parts.

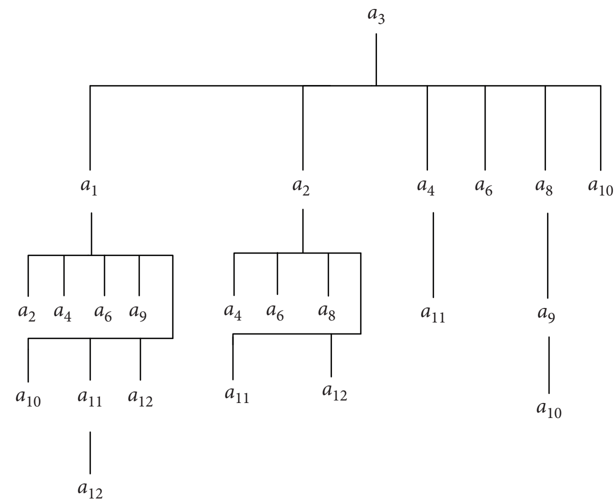


Figure 10: Part change propagation impact scope tree.

4.1. Creation of Digital DSM for Component Changes in the Frame Module. By means of the five-point weighting method, the change dependencies on the 12 components in the frame module are specified by numbers between 0 and 1, and the components are arranged in a uniform order above and to the left of the matrix to create a 12×12order numerical DSM, as shown in Figure 9.

From the diagram it can be observed that the initial change to part beam a_3 has a direct change propagation impact on parts a_1, a_2, a_4, a_6, a_8, and a_{10}, while part a_2 also has a change impact relationship on parts a_4, a_6, a_8, a_{11}, and a_{12}, so a change to part a_3 may also have an indirect change propagation impact on parts a_{11} and a_{12}. A change propagation tree based on the numerical DSM for part changes is shown in Figure 10.

4.2. Chain of Propagation of Component Changes. Through the part change propagation influence range tree, it can be seen that there are multiple change propagation paths to part change propagation. A change propagation chain is used to represent a propagation path to represent all part change propagation paths within the frame module, as shown in Figure 11.

4.3. Establishing a Network for the Dissemination of Component Changes within the Frame Module. The change propagation network in the network is represented by a directed graph $G(V, \mathrm{E})$, where $V = \{x \mid x = 1, 2, 3, \cdots, 12\}$, the set of directed graph vertices, x represents the parts in the frame module, and $E = \{(x, y) \mid x, y \in 12, x \neq y\}$ is a directed edge, indicating that there is a change propagation

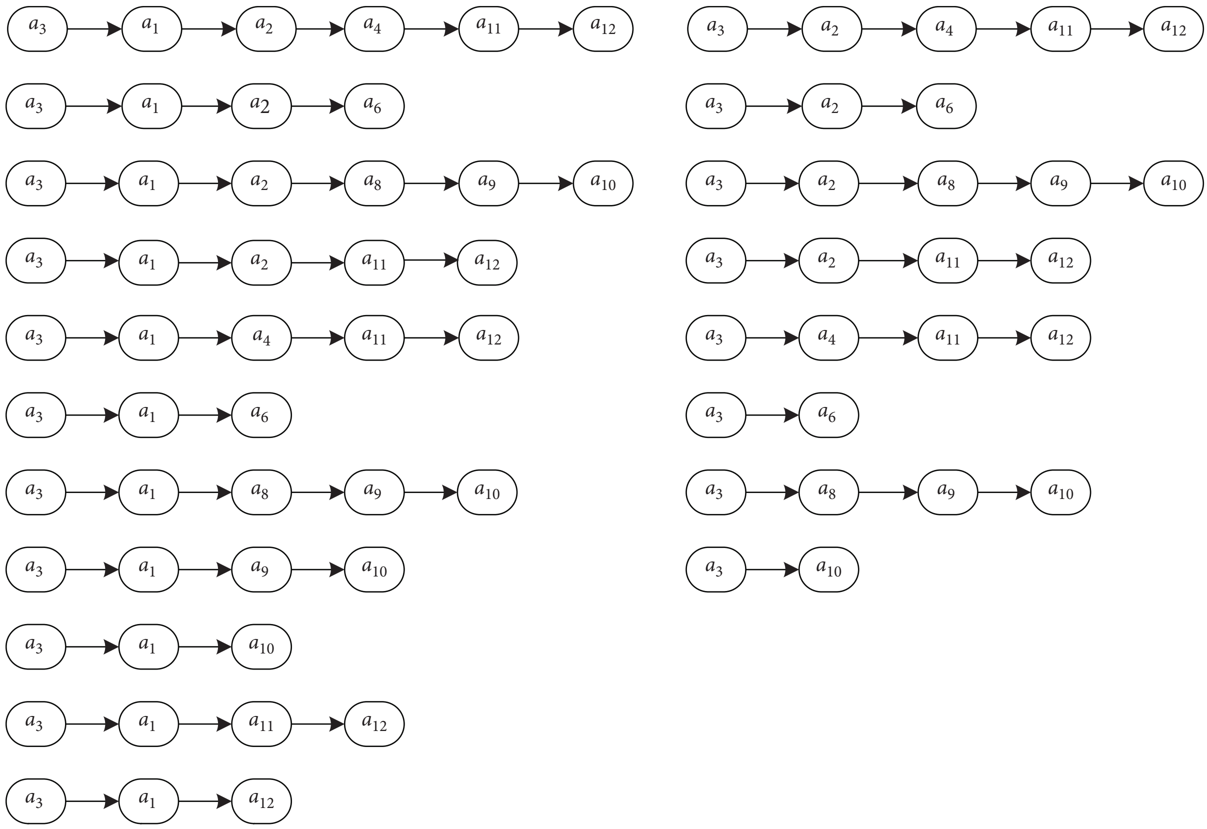


Figure 11: Part change propagation chain.

relationship between parts and parts. In the directed graph $G(V, \mathrm{E})$, the change propagation chains of each part in Figure 11 are intersected to form a part changed propagation network, combined with a numerical DSM, with $W(x, y)$ representing the changing dependency between two elements x and y of adjacent cells, taking a value range of [0, 1], to establish a change propagation network containing change dependencies between parts as shown in Figure 12.

It can be seen from Figure 12 that when the initial change part a_3 produces a change, the change propagation of part a_1 and part a_3 in the whole change propagation network is diffusion propagation, and there are many parts affected by the change of part a_1 and part a_2. Therefore, when studying the change propagation impact on parts in the frame module, the part change risk value [23] is calculated according to (1), and the change propagation risk of part a_1 and part a_2 is analyzed in priority in order to better control the change propagation range.

The change risk value for change propagation through part a_1 after the initial change in part a_3 is:

$$R(a_1) = \frac{1}{12}\left(0.7 + 1 + 1 + \frac{0.5 + 0.5}{2} + \frac{0.7 + 0.5}{2} + 0.3 + 0.3 + \frac{0.5 + 0.3}{2} + \frac{0.3 + 0.3}{2} + \frac{0.3 + 0.3}{2}\right) = 0.45. \tag{2}$$

Then the change risk value for change propagation through part a_2 after the initial change in part a_3 is

$$R(a_2) = \frac{1}{12}\left(\frac{1 + 1 + 0.5 + 0.5 + 0.3 + 0.5 + 0.3 + 0.3 + 0.3/2 + 0.3 + 0.3/2}{2}\right) = 0.196. \tag{3}$$

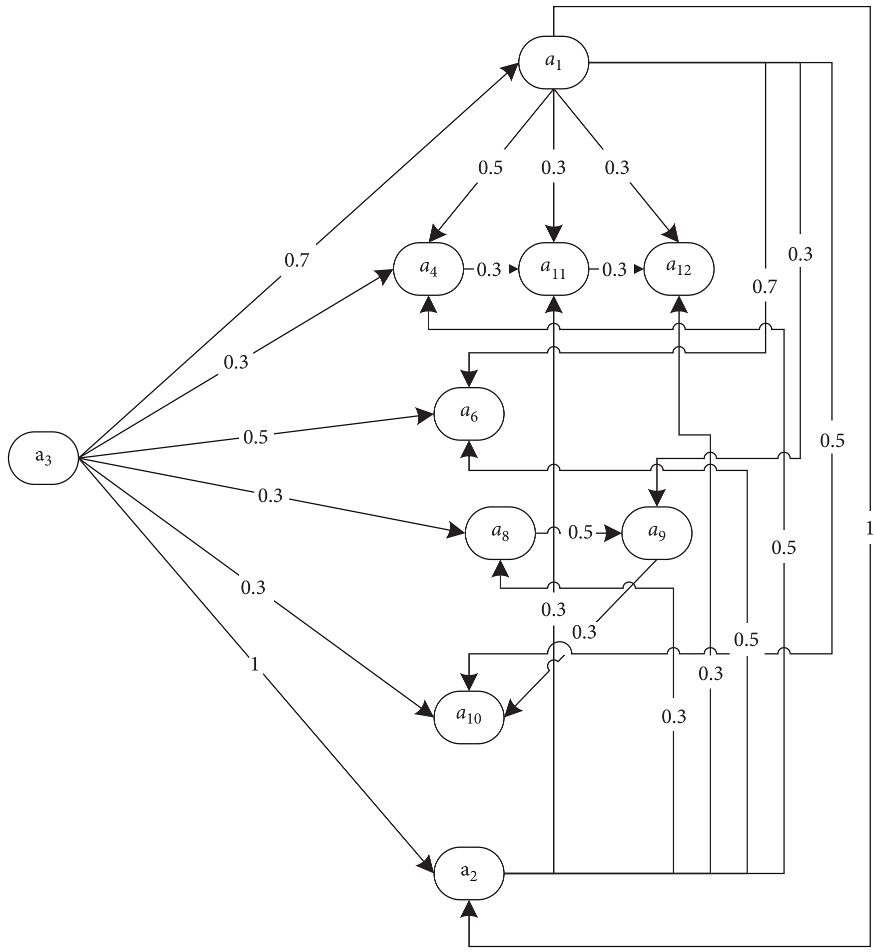


Figure 12: Change propagation network with change dependencies.

It can be seen that $R(a_2) < R(a_1)$, which indicates that the change in the initial part a_3 cross member has a greater impact on the propagation of the change to the part a_2 wings than to the part a_2 web, and therefore the risk of change propagation through part a_1 is greater, indicating that if changes are made to the wing during the frame change process, it may cause the number of change parts to increase, and there is also the possibility of avalanche changed propagation, so attention should be paid to the propagation impact of the change from changes to the wing during the change process.

5. Conclusions

This paper focuses on the change propagation impact on parts within a module. Based on the direct change propagation relationship between parts, a digital DSM of parts is created for parts in the same module, the indirect change propagation relationship between parts is assessed through the DSM, a change propagation chain of parts is constructed, and finally, a change propagation network is formed in the directed graph to describe the propagation path of part changes. By analyzing the degree of change dependency on each part and the impact of the part propagation method on change propagation, the possible paths of change propagation are determined, and based on the calculation of the change risk value, the change risk value of the key node is calculated, the possible change propagation impact of the part change through this node is evaluated, the changing risk of the part is predicted, and the change of the part is controlled in advance to avoid the uncontrollable impact of the change design on the product.

Data Availability

The data used to support the finding of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This project was supported by the Shaanxi Science and Technology New Star Project (Grant nos. 2020KJXX-071), Key R&D Project in Shaanxi Province (2021NY-171), Shaanxi Science and Technology Resources Open Sharing

Platform (Grant nos. 2021PT-006), and Shaanxi Provincial Department of Education Special Scientific Research Project (Grant no. 20JK0075).

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