Change Impact Analysis of Complex Mechanical Product Based on Complex Network Theory

Na Zhang, Yu Yang

College of Mechanical Engineering, Chongqing University, NO. 174 Shazhengjie, Shapingba, Chongqing 400044, China

Abstract. In order to reduce the change impact and prevent avalanche, the paper proposes a method for analyzing the change impact based on complex network theory. Firstly, the complex network theory is used to systematically describe the structure of complex mechanical products. Secondly, the change propagation process is analyzed based on propagation dynamics theory, and then, the change propagation rate and changed nodes ratio are proposed for the analysis of change impact based on network evolution theory and network topology properties. Finally, the proposed method is used to analyze the change propagation and change impact of clutch.

1. Introduction
With the diversification and personalization of customer needs, the changes of customer needs have become an inevitable issue in the development of complex products. Due to a complex mechanical product contains a large number of parts and complicated relationships between parts, A change occur in one part will cause a series of changes in others which connected to it, or even will cause avalanche effect. Changes of product structure will eventually lead to the changes of design tasks, and eventually resulting in design delay and extra costs. In this regard, designers require to respond to changes quickly. The response to changes depends on the analysis of change propagation and change impact. Therefore, research on the change propagation and change impact of complex mechanical product design is of great significance to respond to change, control change costs and improve change efficiency.

At present, the existing analysis methods of change impact include risk matrix [1], axiomatic design matrix [2], design structure matrix [3-8], relation matrix [9,10] and complex network theory [11], etc. Due to the diversity, uncertainty and dynamics of changes propagation, complex network theory provides new ideas for solving the issue of change impact assessment. In this study, a method for analyzing the change impact based on complex network theory. Firstly, a network model of complex mechanical product is constructed. Secondly, the change propagation process is analyzed based on propagation dynamics theory, and then, the change propagation rate and changed nodes ratio are proposed for the analysis of change impact based on network evolution theory and network topology properties. Finally, a case study is presented to illustrate the proposed method.

2. The construction of the network model
The construction of network model is the basis of analyzing change impact. Due to the characteristic of complex mechanical products, the complex network is used to describe the structure of complex mechanical products systematically and quantitatively.
In the network model, the parts of complex mechanical product are regarded as nodes, the relationship between parts are regarded edges and the strength of the edges are defined as network weights. Based on this, the network model \( G \) of the complex mechanical product can be defined as follows.

\[
G = (V, E, W)
\]

(1)

where \( V = \{v_i, i = 1, 2, ..., n\} \) is the set of nodes, and \( w \) represents the part \( i \); \( E = \{e_{ij}, i = 1, 2, ..., n, i \neq j\} \) is the set of edges, \( e_{ij} \) is the edge between node \( v_i \) and \( v_j \). \( W = \{w_{ij}, i = 1, 2, ..., n, i \neq j\} \) is the set of weights, and \( w_{ij} \) is the value of relationship between node \( v_i \) and \( v_j \).

The determination of weights is a key step in constructing a network model. In this paper, the weights are determined by considering functional correlations and structural correlations. Therefore, weight is calculated as follows.

\[
w_{ij} = \alpha w_{ij}^{f} + \beta w_{ij}^{s}
\]

(2)

where \( \alpha \) and \( \beta \) correspond to \( w_{ij}^{f} \) and \( w_{ij}^{s} \). \( w_{ij}^{f} \) denotes the structural correlation strength between \( v_i \) and \( v_j \). \( w_{ij}^{s} \) represents the functional correlation strength between \( v_i \) and \( v_j \).

The weight \( w_{ij}^{f} \) is determined by the functional load, and the value is calculated as follows:

\[
w_{ij}^{f} = \sum_{k=1}^{H} \frac{f_k}{F_k}
\]

(3)

where \( f_k \) is the functional load that \( v_j \) can bear for the realization of function \( h \), \( F_k \) is the total functional capacity.

The weight \( w_{ij}^{s} \) is determined by the structural constraints, such as size constraints, shape constraints, etc., and it can be calculated as follows:

\[
w_{ij}^{s} = \sum_{l=1}^{L} w_{ij,l}
\]

(4)

where \( w_{ij,l} \) denotes the correlation strength of the \( l \)--th kind of structural correlations. \( L \) represents the total number of types of structural correlations.

It should be noted that the greater the correlation strength between two nodes, the greater the weight of the node is.

The above analysis shows that the constructed network model is an undirected weighted network. Moreover, it has been proved that the network model belongs to scale-free network. Therefore, the network model which constructed in this paper has the propagation characteristics and evolution characteristics of the scale-free network.

3. The assessment of change impact

3.1. Change propagation process

The changes of customer needs are transformed into the changes of parts. Due to propagation dynamics theory and the evolutionary characteristic of network model, the change propagation can be described as follows: the node that needs to be changed is adding in network as a new nodes and connecting to the other nodes according to rules, and then, the weights are recalculated.

Therefore, combining the evolutionary characteristic and the classical propagation model SI, the change propagation process is analyzed as follows.

(1) The initial network is defined as: \( G_0 = (V_0, E_0, W_0) \), where \( V_0 = \{v_{0i}, i = 1, 2, ..., n_0\} \), \( E_0 = \{e_{ij}, i, j = 1, 2, ..., n_0\} \), \( W_0 = \{w_{ij}, i, j = 1, 2, ..., n_0\} \), \( i \neq j \).
(2) Suppose that there is a change on node $v_{i_0}$ at time $t_0$, and $v_{i_0}$ is transformed to $v_{i_0}'$. As a new node, $v_{i_0}'$ is added to the initial network model and connected to other nodes in initial network model according the. Then, a new network model is formed and the weights are recalculated.

(3) At time $t_1$, change is propagated from node $v_{i_0}'$ to other unchanged nodes (such as node $v_{j_0}$) that connected to it. The propagation probability of node $v_{j_0}$ is calculated as follows.

$$p_j = \frac{\sum_{j \in I(i)} w_{ij}}{w_{j\text{max}}}$$

(4) At time $t_a$, the changed nodes at the previous moment are added to the network model as new nodes, and then, repeat step 2 and step 3 until the network evolution is completed.

3.2. The assessment indexes

The change propagation process is essentially the evolution process of network model driven by changes. Therefore, the change impact can be assessed through parameter changes before and after the network evolution. In this paper, the change impact is evaluated from two aspects: change propagation rate and changed nodes ratio.

Change propagation rate refers to the speed that a changed node causes other unchanged nodes to change at a certain time. The greater the degree of the changed node, the bigger the change propagation rate. Change propagation rate $p(t_a)$ can be calculated as follows.

$$p(t_a) = \frac{\sum_{j \in I(i)} w_{ij}}{w_{j\text{max}}}$$

where $w_{j\text{max}}$ is the largest weight in the network model.

Changed nodes ratio refers to the proportion of changed nodes in the network at a certain moment. The equation for calculating the changed nodes ratio $r(t_a)$ is as follows.

$$r(t_a) = \frac{r(t_{a-1}) + \frac{n_a}{N_a}}{N_a}$$

where $r(t_{a-1})$ is the changed nodes ratio at time $t_{a-1}$. $N_a$ is the total number of nodes in network model at time $t_a$ and $n_a$ is the number of nodes that changed at time $t_a$. The results show that the greater the changed nodes ratio, the greater impact of change is, and the more parts need to be changed.

4. case study

This paper takes the change impact assessment of clutch design as an example. Due to the limitations of the paper length, the ten key parts (as shown in Table 1) of clutch are selected for change impact analysis.

| No | Parts      | No | Parts      |
|----|------------|----|------------|
| $v_1$ | Flywheel   | $v_2$ | Pressure plate   |
| $v_3$ | Clutch cover | $v_4$ | Release bearing   |
| $v_5$ | Spring     | $v_6$ | Bearing ring   |
In this section, firstly, the relationship between parts are analyzed and the network model of clutch are constructed. Secondly, the change propagation and the change impact are analyzed and discussed. According to the design specification and equations (1)-(4), the relationship between parts and the correlation strengths are determined. Based on this, combined with the network construction rules, the network model is drawn by Netdraw (as shown in Figure 1). As shown in Figure 1, the network model contains 10 nodes and 90 edges, moreover, the weights are shown in Figure 1.

| $v_7$  | Separation hook | $v_8$  | Platen  |
|------|----------------|-------|---------|
| $v_9$  | Driven shaft   | $v_{10}$ | Friction plate |

![Network Model of Clutch](image)

Figure 1. The network model of clutch.

On the basis of the network model, the change propagation and change impact are analyzed. Using the method proposed in section 3, the change propagation rate of all nodes are calculated (as shown in Figure 2).

![Change Propagation Rate of All Nodes](image)

Figure 2. The change propagation rate of all nodes.

Furthermore, the change propagation process of different initially changed node is analyzed and the changed nodes ratio of different initially changed node at different time are calculated (as shown in Figure 3).

![Change Propagation Process](image)

Figure 3. The change propagation process of different initially changed node.
Based on the above calculation results, the following conclusions can be drawn:

1. The change propagation capabilities of different nodes are different. The change propagation capability of a node is determined by the node degree and weight. The greater the node degree and weight, the stronger the change propagation capability of the node is. It can be seen from Figure 2 that driven shaft \( v_9 \) and release bearing \( v_4 \) have the strongest propagation capability, which requires enterprises to fully consider the customer requirements that these parts meet in the early stage of design to avoid changes in the later stages of design.

2. For different initially nodes, the number of changed nodes are different at different time and the change completion time are different. Therefore, to reduce the change impact scope and control change costs, the companies is need to stop the change propagation at the right time.

3. When the change propagation period exceeds a certain time, the number of changed parts tends to be stable, that is, all parts are changed. That is to say, as the change propagation cycle increases, any part will change without effective control, and the entire product will change.

5. Conclusions
The analysis of the change impact can provide a basis for companies to make decisions on changes of complex mechanical products. The complex network theory is used to analyze change impact of complex mechanical products in the study. The change propagation process is analyzed based on propagation dynamics theory, and then, the change propagation rate and changed nodes ratio are proposed for the analysis of change impact based on network evolution theory and network topology properties.

The results show that the change propagation capabilities of different nodes are different. The greater the node degree and weight, the stronger the change propagation capability of the node is. For different initially nodes, the number of changed nodes are different at different time and the change completion time are different. In addition, when the change propagates for a certain time, all parts will change, which requires companies to terminate the change at the right time to reduce the impact of the change.

Acknowledgements
This study was supported by National Natural Science Foundation of China under Grant (No. 71571023) and a project supported by graduate research and innovation foundation of Chongqing, China (Grant No. CYB17024)

References
[1] N. Smith, S. Mahadevan, J Spacecraft Rockets 42 4 (2015)
[2] Y. Ma, G. Chen, G. Thimm, Comput Ind 59 2 (2008)
[3] H. Seol, J Eng Design 21 1 (2010)
[4] J. Lee, Y.S. Hong, Res Eng Des 28 4 (2017)
[5] T. Cohen, S.B. Navathe, R.E. Fulton, Comput Aided Design 32 5 (2000)
[6] B. Morkos, P. Shankar, J.D. Summers, J Eng Design 23 12 (2012)
[7] D. Tang, J Mech Eng 46 1 (2010)
[8] C. Eckert, P.J. Clarkson, W. Zanker, Res Eng Des 15 1 2004
[9] S. Tosserams, A.T. Hofkamp, L.F.P. Etman, J.E. Rooda, Struct Multidiscip O 42 5 (2010)
[10] L. Chen, A. Macwan, S. Li, J Mech Des 129 3 (2007)
[11] N, Zhang, Y. Yang, Y.J. Zheng, J.F. Su, J Intell Manf 6 (2017)