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Influence of Multi-component Failure on Mechanical Product Design Change

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Abstract: Design change is one of the most common activities in design and development of mechanical products, and the change will affected by the design and maintenance of the products. It is not uncommon that multiple components might run out of order simultaneously during the use of a product, which would have significant influences on the product performance. Such kind of multi-component failure must be considered early in the product design stage, therefore it is necessary to study multiple design changes incurred by multi-component failure. Existing studies on the design change only focus on single change and ignore multiple simultaneous changes. To address this problem, a change influence network model is establishes, and the propagation path of multiple changes on the change influence network is described according to the change propagation characteristics of mechanical products. By analyzing the degree of dependence between the nodes and the absorption situations of nodes to change propagation, the possible paths of change propagation on the change influence network are determined, and based on which, calculation of the change influence is carried out, which provides decision-making support for product designers. Finally, the feasibility of the proposed methodology is demonstrated by taking a household juicer for case study.

Keywords: multi-component failure; change influence network model; component correlation strength; change propagation absorption

1 Introduction

Design change is imperative during product development process, which may be initiated or triggered by various reasons and on various situations. One of the situations which the designer needs to take into account, and is often unintentionally neglected, is that, it is likely that the product being designed may face component failure during its future usage. As such, it is necessary for the designer to study the influences of such failure and take proper measures early in the design process. By the word "failure", we mean a component changes its behavior from working normally to working abnormally, hence there is a change of working status involved in the situation. If a component fails, it may trigger a series of interlocking and associative changes, which means "change propagation"[1-2]. Change propagation often has a negative influence on the product performance and reliability. To make things more complicated, the relevant components might have different degree of importance, due to different application situations and functional requirements of the product[3-6]. Some components often play a more decisive and critical role than others, which means that failure of important and critical components should be given more attention in the design process of product.

As can be seen, design change due to component failure involves not only design change itself, but also change propagation and component importance. Researchers around the world have studied the characteristics

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and influences of design change at various levels of detail. For example, Eckert et al[7-9] studied the characteristics of change propagation, and summarized the three modes of change propagation: flowering, water wave and avalanche. Tao et al[10] proposed a method for formulating the scope of project change, indicating the scope of influence between the relevant elements. Liu et al[11] proposed a breadth-first traversal algorithm to identify the model-related propagation range. Tang et al[12] calculated the change influence with probability details to predict the degree of influence of engineering changes. Li et al[13] proposed a process simulation approach which selects the most efficient propagation path for complex product design changes.

Most of the above studies are directed to a single change, and it is scarce that multiple design changes are ever addressed, especially for those due to multi-component failure. In actual situations, it is quite often that a product might have multiple component failures at the same time, resulting in multiple changes. As such, it is necessary for considering potential risks of multi-component failure early in the design phase. To tackle this problem, the characteristics of design changes due to multi-component failure in the design phase will bell investigate, and the influence of the design changes by the propagation effect of these changes, so as to provide technical support and related methods in the product design and development.

2 Mechanical component importance

The influence of the design change is not only determined by the propagation path of the change itself, but also by the varied importance of the relevant components. This is because, if the propagation proceeds to important or critical components, the influence from the change will definitely be greater than otherwise to less important components. Hence, it is necessary to study component importance.

2.1 Functional usage

Functional usage refers to the use of a function of a mechanical product through certain period of the product usage[14]. It can be measured by two methods as listed in the following. Assuming that the product has n count of functions, which are recorded as F_1, F_2, F_3, F_4, $\cdots$, F_n, respectively.

1) Measured by feature usage time. Observe the product at its working status for T hours, record the time of using function $F_i(1<=i<=n)$, indicated as t_{Fi}. The function usage of F_i, indicated as W_{Fi}, can be defined as

$$W_{Fi} = t_{Fi}/T \tag{1}$$

Where, $\sum_{i=1}^{n} t_{Fi} = T$.

2) Measured by the number of times the function has been used. Observing the number of times, indicated as M, the product has been used over a period of time. Record the number of times each specific function has been used, indicating as m_{Fi} for function $F_i(1<=i<=n)$. The function usage of F_i is

$$W_{Fi} = m_{Fi}/M \tag{2}$$

Where, $\sum_{i=1}^{n} m_{Fi} = M$.

2.2 The importance of mechanical components

Assume a mechanical product has m count of components, denoted as A_1, A_2, $\cdots$, A_m. There are n count of functions, which are recorded as F_1, F_2, $\cdots$, F_n. The relationships between functions and their corresponding components can be characterized by a function-component correlation matrix, as shown in Table 1. This matrix denotes each function's implementing components, for example, F_1 is delivered by components A_1, A_2, etc., whereas F_2 is delivered by components A_2, $\cdots$, A_m. The implementing component of a function is said to have direct correlation with that function; or in other word, they are correlated with each other.

Table 1 Function and component correlation matrix

	A_1	A_2	A_3	$\cdots$	A_m
F_1	1	1	0	$\cdots$	0
F_2	0	1	0	$\cdots$	1
F_3	1	0	1	$\cdots$	0
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
F_n	1	0	1	$\cdots$	1

The above matrix did not take into account the information relating to functional usage. If functional usage is introduced, the correlation matrix of functions and components can be updated as shown in Table 2, where each element of the matrix is calculated by

$$\overline{< F_iA_j >} = W_{FI} * < F_iA_j > \quad (3)$$

Where: $i=1,2,\cdots,n$; $j=1,2,\cdots,m$; $<F_iA_j>$ stands for the element in Table 1 indicating whether a component A_j is correlated with a function F_i; $\overline{<F_iA_j>}$ stands for the corresponding new element in Table 2. If the function F_i is correlated with component A_j, which means that A_j has directly contributed to delivering function A_i, then $<F_iA_j>=1$; otherwise $<F_iA_j>=0$.

Equation (3) shows that, the transformation of the old matrix (Table 1) to the new one (Table 2) is implemented by using functional usage as the weighting factor. If $W_{Fi}=0$, assume $W_{Fi}=0.01$ instead, so that the components with non-zero values can be retained.

Table 2 Function and component correlation matrix with introduction of functional usage

	A_1	A_2	A_3	$\cdots$	A_m
F_1	W_{F1}	W_{F1}	0	$\cdots$	0
F_2	0	W_{F2}	0	$\cdots$	W_{F2}
F_3	W_{F3}	0	W_{F3}	$\cdots$	0
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
F_n	W_{Fn}	0	W_{Fn}	$\cdots$	W_{Fn}

With the above-mentioned functional usage based function-component correlation matrix, the importance of component can be calculated by

$$I_{Aj} = \frac{\sum_{i=1}^{n} \overline{< F_iA_j >}}{\sum_{j=1}^{m} \sum_{i=1}^{n} \overline{< F_iA_j >}} \times 100\% \quad (4)$$

3 Change propagation path and evaluation of change influence

3.1 Change influence network model and component correlation strength matrix

As the mentioned before, to study the characteristics of change propagation and to explore the change propagation path, we need to develop a change influence network model. This model is used to describe the link or correlation between the components that work with each other to deliver the required functions. The reason that the component correlation information can be employed to build such a model is quite obvious, it is in effect the correlation between components that will determine how a change is going to be propagated from one component to another.

To characterize the degree of correlation between two components, we introduce a concept called component correlation strength. With this concept, we can build up the change influence network by taking each component as a node, whereby the links between nodes are used to represent the correlation strengths between them. Assume $C(x, y)$ is used to indicate the strength of the correlation between two nodes, component x and component y, which is valued within the range $[0, 1]$. With this definition, we can use $C(x, x)$ to indicate the node itself, i. e. the component x, and $C(x, x)=1$. Furthermore, due to the mutual correlation between nodes, $C(x, y)=C(y, x)$.

Figure 1 shows an exemplar change influence network model, by using the information given in Table 3. For example, since the strength of the correlation between component 1 and component 2 is 0. 7 in Table 3, it is denoted in Figure 1 by two nodes and a link, where $C(1, 2)=C(2, 1)=0.7$.

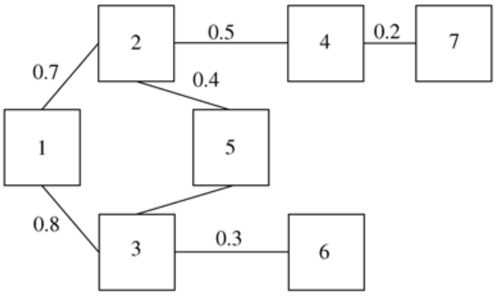

Figure 1 An exemplar change influence network model

Table 3 Component correlation strength matrix $C(x,y)$

	A_1	A_2	A_3	A_4	A_5	A_6	A_7
A_1	1	0. 7	0. 8				
A_2	0. 7	1		0. 5	0. 4		
A_3	0. 8		1		0. 7	0. 3	
A_4		0. 5		1			0. 2
A_5		0. 4	0. 7		1		
A_6			0. 3			1	
A_7				0. 2			1

3. 2 Characterization of change propagation absorption of nodes

The aforementioned network is termed as change influence network, because it can be employed to determine change propagation path and eventually to evaluate the change influence. In fact, the strength of correlation between nodes not only determine how change is being propagated, it also determines how the change propagation is absorbed by the nodes. As can be seen from Figure 1, node 2 absorbs the change propagation of node 5 to node 4 in the propagation chain 1-3-5-2-4-7. If a node absorbs the change propagation from its preceding one, the change propagation will stop accordingly. The situation will turn more complicated when multiple nodes fail at the same time. For example, the change due to the failed node 1 can be propagated to node 2 and node 3, and 4. If node 3 also failed, then propagation will stop at node 3, whereas the change at node 3 will be propagated to node 4 when node 3 works normally. Therefore, in different situations, the absorption of change may be different.

To characterize change absorption situation of each node in the change influence network model, we use $A(x \rightarrow y)$ to indicate how node y is to absorb the change propagation from node x, where the arrow head symbolize the propagation direction. It is assumed that $A(x \rightarrow y)$ takes a value of either 0 or 1. When $A(x \rightarrow y)=0$, node y is not capable of absorbing the change propagation from node x completely, which means the change will continue be propagated to node y. When $A(x \to y) = 1$, the change propagation of node x to node y is completely absorbed by node y, which means the change propagation stops at node y.

To facilitate further discussion, the assumaption are in the following:

1) When the change propagates from node x to node y in the change influence network model, $A(x \to y) = 1$;

2) When the change is propagated by node x to node y, and y is the last or ending node of the network, which means there is no immediate successor of node y, then $A(x \to y) = 1$;

3) When there are 2 nodes x and y change simultaneously, and there are two immediate successors, indicated by node m and n, that are connected with node x and y, then $A(x \to m) = 1$, $A(x \to n) = 1$, $A(x \to m) = 1$, and $A(y \to n) = 1$;

4) When there are 2 nodes x and y change simultaneously, and node x is connected to node y through nodes a, b, c in a row, there would be several situations: (1) If node b connects only with node a and c, then $A(b \to c) = 1$, $A(a \to c) = 1$; (2) If node b is also connected to nodes other than a and c, then $A(b \to c) = 0$, $A(a \to c) = 0$.

Whether a node is capable of absorbing the change propagation from another node should be based on the specific information of the product and the change history of the design, hence it should be specified by the designer by applying his or her own experience or domain-specific design knowledge.

3.3 Evaluation of change influence for multi-component failure

When multiple components fail simultaneously, the change propagation is different from the situation when only one component fails, hence the change influence would be different as well. Besides, the change propagation absorption for those nodes involving multi-component failure will be more complicated as compared with that of only one change. We can employ the concept of Design Structure Matrix (DSM)[15-17] to represent the change propagation absorption situation of all nodes, for which the matrix is termed as change propagation absorption matrix. The dimension of the matrix is indicated by the number of nodes in the influence network model, and each element of the matrix represents whether a node is capable of absorbing another node, whereas those of the main diagonal elements represent the nodes themselves, hence can be ignored in the following calculation.

To facilitate illustration, let's take two component failures as an example. Assume nodes 2 and 3 fail at the same time. Since both nodes failed, the influence of change at node 2 cannot be propagated to node 3. Similarly, node 3 shall not affect node 2. Figure 2 and Figure 3 illustrates examples of change propagation from node 2 to other nodes, and from node 3 to other nodes, respectively.

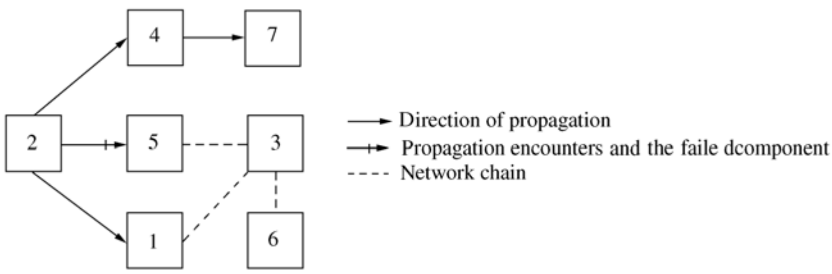

Figure 2 Propagation diagram when node 2 fails

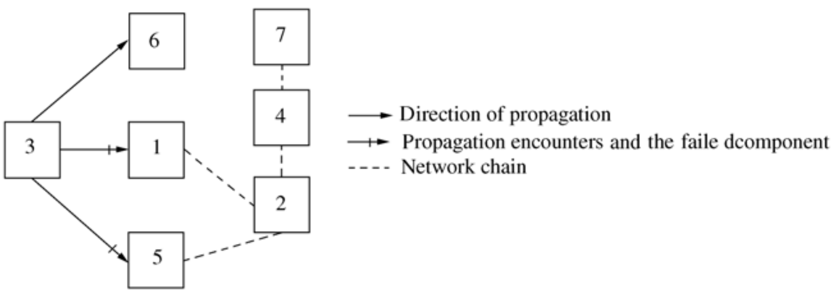

Figure 3 Propagation path diagram when node 3 fails

The change propagation absorption matrices regarding node 2 fail and node 3 fail for this example are shown in Table 4 and Table 5, respectively. For example, in Table 4, the first row shows that the change at node 2 is absorbed completely by node 1, which means the change propagation from node 2 to node 1 is terminated by node 1, as is the situation shown in Figure 2, since node 3 failed, the change at node 1 is not possible to be propagated to node 3, hence node 1 is deemed as terminating change propagation, in other word, node 1 behaves similarly as node 7 does.

Table 4 Change propagation absorption matrix when node 3 fails

$A(x \rightarrow y)$		Node x (change initiator)						
		1	2	3	4	5	6	7
Node y	1		1					
	2	1			1	1		
	3							
	4		0					1
	5		1					
	6							
	7				1			

Table 5 Absorption capacity matrix of change propagation when node 2 fails

$A(x \rightarrow y)$		Change node x						
		1	2	3	4	5	6	7
Node y	1			1				
	2							
	3	1				1	1	
	4							
	5			1				
	6			1				
	7							

With Table 4 and Table 5, it is possible to predict the change propagation path in the change influence network when both node 2 and node 3 fail simultaneously, as shown in Figure 4.

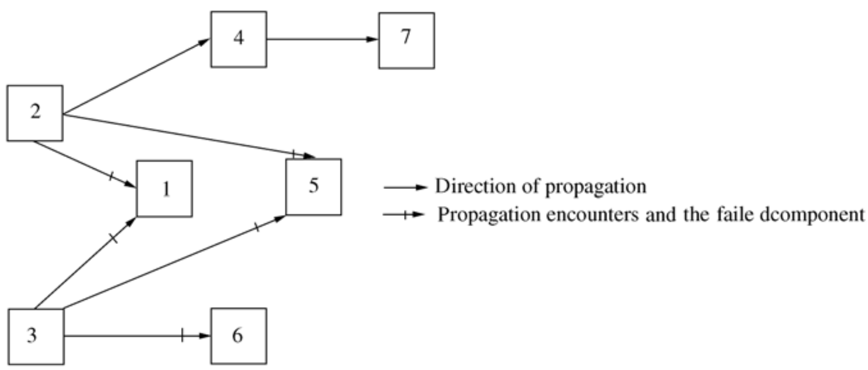

Figure 4 Propagation path diagram when node 2 and node 3 fail simultaneously

With the above results, we can further develop the methodology for evaluation of change influence caused by multi-component failure. To facilitate calculation, let's assume the following:

When nodes x and y both changed, i. e. the two corresponding components both failed, the node x (or y) in the change influence network can reach the node y (or x) through the adjacent node m_i, $R(x, m_i) = 1$.

Based on the change propagation path obtained from the change propagation absorption capacity matrix, the change influence, indicated by D, can be calculated by

$$D = \frac{1}{K}\sum_{j=1}^{n}\frac{\sum_{i=1}^{m}D(x_i, y_j)}{m}\cdot\frac{a^2}{k} \tag{5}$$

Where, K is the total number of products; m is the number of nodes that export changes to node y_j; a is the number of failed nodes; n is the number of changed nodes.

Equation (5) can be normalized as

$$N_D = \frac{D}{\frac{1}{K}\sum_{j=1}^{n}\frac{\sum_{i=1}^{m}D(x_i, y_j)}{m}\times\sum_{a=1}^{k}\frac{a^2}{k}}\times 100\% \tag{6}$$

4 Case study

This section takes the household juicer as an example, as shown in Figure 5, to illustrate the proposed methods. Two products of slightly different configuration, indicated as product A and product B, are chosen for analysis and comparison. For product A, there are in total 13 components, indicated $A_1 \sim A_{13}$, where A_1 is main frame case; A_2 is electric motor; A_3 is rotation shaft; A_4 is switch; A_5 is flywheel; A_6 is juice cup; A_7 is leftover collector; A_8 is central disc; A_9 is mixing cup; A_{10} is filter; A_{11} is push rod; A_{12} is cover; A_{13} is cutting cup.

a) Product A b) Product B

Figure 5 Household juicer

Among these components, the cutting cup can be used for fruit juice extraction; and if the cup is replaced with a meat blade, it can be used for mincing meat. The product uses an electric motor to drive the tool, and the material, either the fruit pellet or meat chop, is processed within the enclosed space of the machine until desired form. Hence, the primary functions of the product include juicing fruit (or juice extraction) and mincing meat.

To study the potential influence of multi-component failure, let's evaluate the component importance first. Observe the product in use for a certain period of time, assuming 100 h, and then record the use of each function, as are shown in Table 6. For those components such as housing and switches that are not directly involved in performing the product's primary functions, their using time can be specified with a fixed and unified amount of hours each, assuming 5 h for this example. The juice extraction function is recorded as F_1, and the meat mincing function is recorded as F_2. By applying Equation (1), Equation (3) and Equation (4), the importance of each component can be calculated, as have been shown in Table 6.

Table 6 Function usage and component importance of the household juicer

Component number	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_{13}
F_1	5	80	80	5	70	30	30	50	90	70	30	40	40
F_2	5	80	80	5	80	5	5	5	90	5	30	40	5
I	0. 9%	15. 2%	15. 2%	0. 9%	14. 2%	3. 3%	3. 3%	5. 2%	17. 1%	7. 1%	5. 7%	7. 6%	4. 3%
Ranging	10	2	2	10	3	9	9	7	1	5	6	4	8

As can be seen from the table, the importance of components A_2, A_3, and A_9 take the top three in the list, in other word, they are regarded as critical components for the product. When they all failed, the change (from normal working status to failed status) from nodes 9 and 3 will be propagated to node 5. Since node 5 is only connected to node 3 and node 9, the propagation will be forced to terminate at node 5, while at the same time the change from node 2 cannot be propagated to node 3 as well. The absorption matrix of the product for change propagation is shown in Table 7, and the propagation path on the influence network model can then be obtained, as shown in Figure 6. Further on, by applying Equation (6), the influence of multiple changes from node 2, node 3 and node 9 can be evaluated as $N_D = 19.7\%$.

For product B, there are in total 11 components. Comparing with product A, there are no push rod and filter cup. Using the same calculation method it can be found that the most important component are electric motor, rotation shaft and flywheel. By applying Equation (6), the influence of multiple changes from the failure of these three components can be evaluated as $N_D = 15.4\%$ (The detailed steps are omitted to save space). As can be seen, the influence of critical component failure of product B is smaller than that of product A. This result is agreeable to our common understanding-both product A and B are used as household juicer, and the number of components in product A is more than that in product B. The influence of multi-component failure of a product with more components would be greater than that of a product with same functionality yet fewer components, should there be same kind of failure, for example, both occur to same kind of critical components. By knowing the influence value, the designers would be informed of the influence situation of multi-component failure for various design alternatives or options, hence facilitating the designers in making up design decisions.

Table 7 Change propagation absorption capacity matrix of the household juicer

$A(x \rightarrow y)$	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_{13}
	1	2	3	4	5	6	7	8	9	10	11	12	13
1		0		1									
2	1			1									
3		1			1								
4	0	1											
5								1	1				
6									1				
7								1					
8					0		1		0				
9					1	1		1		1			
10									0		1		
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12											0		1
13												1	

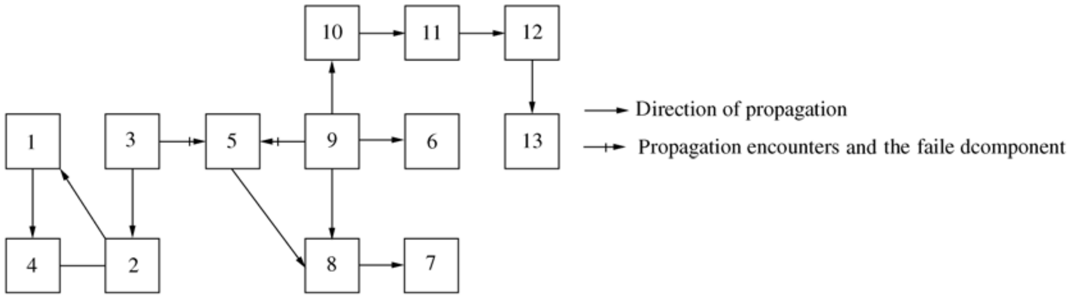

Figure 6 Change propagation path of the studied case

5 Conclusions

Mechanical product designers need to take into account a lot of issues relevant to the product being designed, among which is the one regarding potential risk of multi-component failure during its future use. Due to this reason, it is necessary to study the influence of multiple changes caused by multi-component failures, so that proper measure can be taken early in the design stage. To this end, the importance of product components is evaluated first by taking their functional usage information into account. Subsequently, the correlation between components is evaluated by a correlation strength matrix. With these results, a change influence network model is developed, which is further exploited to study the change propagation absorption situation of the components, resulting in a change propagation absorption matrix. Due to the embedded information of both component correlation matrix and change propagation absorption matrix, the change influence network model can be used to obtain the possible paths of change propagation and to calculate the influence value of change from multi-component failure.

Lastly, the proposed methods are illustrated with a case study of the household juicer. Three critical components are identified first. By assumption of failure of all these components, the influence of multiple changes due to their failure is modeled with a change influence network, whereby the change propagation paths are obtained and the influence is quantitatively evaluated. To demonstrate the usefulness of the influence value, another product of same functionality is also studied, which is of fewer number of components. All these results provide valuable information to the designer in facilitating their decision-making product design process.

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