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A network-based assessment approach for change impacts on complex product

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Abstract The complex product design is a continuously changing process from customer requirements to a maturity design. During this process a change of one part will, in most cases, causes changes in other parts and even the whole product. The assessment for the impacts of such changes can support designers' designing and help manager to manage redesigning. A complex product can be considered as a weighted network of parts, subassemblies, or subsystems. Based on the theory of weighted networks, three changeability indices (degree-changeability, reach-changeability and between-changeability) are presented. Degree-changeability is used to calculate the direct change impacts. Reach-changeability is used to assess the indirectly change impacts because of propagation. If a part influences the other parts dramatically and it is also influenced by them, this part can be predicted by between-changeability. Finally, the three changeability indices are proven to be effective for the change impact assessment through a real-world case of Roots Blowers. With the analysis, the designers can avoid changing to "expensive" parts or subsystems.

Keywords Complex products · Change propagation · Networks · Change impacts · Changeability indices

Introduction

Changes are the rule and not the exception in product development processes in all companies and in all countries (Clark and Fujimoto 1991). The designers must change the product due to many new requirements, e.g. customer needs and certification requirements, at the early design stage. On the other hand, mistakes may not come to light until late in the whole product development process. The designers must change the product to eliminate the mistakes. Especially for a complex product, design is often accomplished through incremental changes to an existing product (Eckert et al. 2006).

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Generally, a complex product consists of thousands of parts which connect with each other in different ways. The connections integrate the parts together and realize different functions. Simon (1996) defined the complexity of a product in terms of the connections between its parts and claimed that connections between parts of a product can never be fully avoided in engineering products. In Eckert et al. (2004) view, complexity was the structural complexity of parts and connections, and the dynamic complexity of behavior. The connections between parts determine the functions and constraints. However, due to the tight connections within complex products, the dynamic behavior (change to a part) may result in changes to another part, which is called change propagation. The designers find it difficult to systematically evaluate the potential change impacts due to knowledge or experience limitations. They cannot easily follow the propagation paths of changes and their knock-on effects; nor can they easily explore the space of possible designs (Keller et al. 2005).

A change rarely occurs alone, and it may cascade through the connections between parts, which was called a complex change network by Eckert et al. (2004). In the network, changes may be propagated to many different areas in multiple steps which are not expected, and in some cases change propagation may result in "avalanches". Eckert et al. (2001) categorized change propagation into three types with regards to their change properties:

Absorbers: can absorb more changes than they themselves cause. Absorbers lessen the complexity of the change issue.

Carriers: neither reduce nor add to the change problem. They merely transfer the change from one part to another.

Multipliers: expand the change problem and make the situation more complex. Such changes may lead to an avalanche situation arising. Although not all propagation produces an avalanche, change propagation incurs significant cost to fix problems caused by the initial change, because a simple and cost-effective change in a part of the design may have knock-on effects incurring significant cost elsewhere in the product (Giffin 2007). Furthermore, the later the time of changes raising, the more the additional costs. Therefore, the prerequisite for effective change management is that change impacts and propagation can be predicted or measured.

Suh (1990) presented an Axiomatic approach to reduce the product complexity and change propagation. Complex products are hardly designed to satisfy the principles completely. Modular product design (Ulrich and Tung 1991; Mikkola and Gassmann 2003) is a method which enables firms to reduce the physical changes and promotes flexibility during change whether this change may occur during iterations in a single design project or over a broader period of product redesign and evolution (VanWie et al. 2007). Product variants are often achieved through modular product architectures where changes in a part do not lead to changes in other parts. But, it is not always possible to fully modularize products owing to its design requirements. Moreover, trying a modular architecture beyond an optimum range will actually generate unwanted additions to product cost (Krishnapillai and Zeid 2006). Furthermore, Suh et al. (2007) also recognized the importance of change propagation even in platform design which is based on modular design.

Some analysis and predicting methods for the change propagation are developed to avoid potential changes and costly change avalanches by which change process can be handled or design can be guided. Cohen et al. (2000) presented Change Favorable Representation (C-FAR) to capture possible change consequences to a product. Existing product data information and EXPRESS were used to model the product which was broken down into parts and attributes. The attribute interactions of any two parts were translated into a C-FAR matrix, which provided a qualitative linkage measure (high, medium, low) to relations. Change propagation from a source part to the target part was defined as a set of multiplication of C-FAR matrix. But C-FAR's computational complexity makes it appropriate for small or relatively simple products (Clarkson et al. 2004). Ollinger and Stahovich (2001) developed a computer program (RedesignIT) to generate the proposals for achieving redesign goals and suggest the additional changes. Model-based reasoning and a qualitative measure were introduced to describe changes in RedesignIT. This approach focuses on physical quantities and the causal relationships between them, but they are huge for a complex product. Keller et al. (2005), Clarkson et al. (2004) and Jarratt et al. (2002) developed a Change Prediction Method (CPM) to predict the scale of change propagation called risk, and this method was used to model the design of ARMAR-III robot (Keller et al. 2007). The risk was defined as the product of likelihood and impact of change. In CPM, Design Structure Matrices (DSM) was used to model the change relationships between parts, extent to likelihood and impact matrices combining the terms of likelihood and impact. CPM provides a quantitative measure for change prediction, but it predicts the changes between two parts rather than for the whole product. Lee et al. (2010) used an analytic network process (ANP) approach to measure the relative importance of parts and modules in a modular product in terms of design change impacts and propagation. Because this method was based on modular products, it has small advantage for the products which are hardly modularized. And, the elements need to be compared pairwisely with respect to their impacts on other elements; this is a huge work for the complex product. In addition, Flanagan et al. (2003) modeled a function-part matrix which analyzed change propagation paths, but the scale of a change is not addressed.

In summary, most existing approaches analyze the propagation paths from the change of a part to the target part and quantitative impact assessment. However, few are suited to a complex product. None are dedicated to analyzing the influence of a change on the whole product, not to mention the quantitative impact assessment.

This study develops a quantitative method based on complex networks theory to measure the change impacts on the whole product. Connections of a complex product form a complex network structure rather than a tree structure, called *product network* in our paper. The last few years have witnessed substantial and dramatic new advances in understanding the large-scale structural properties of many real-world complex networks (Strogatz 2001; Albert and Barabási 2002; Newman 2003). Especially, many real networks display a large heterogeneity in the capacity and the intensity of the connections, such as social networks, technological networks, unequal traffic on the Internet and transportation networks. These systems are all described in terms of weighted networks in which a real number is associated to each link. A product network is also heterogeneous and has the same statistical characterizations of weighted network to identify the topology structure.

Centrality measures can identify "the most important" nodes in a network based on their interactions. Freeman (1979) firstly clarified the concept and general ways to measure it converged into three categories of centrality: degree, the optimum path, and betweenness. For the weighted network, the degree is extended to node strength which integrates the information on the number (degree) and the weights of links incident in a node (Boccaletti et al. 2006). Doreian (1974) defined the reachability for a pair of nodes as the value of an optimum path which is the most probable path. According to complex networks theory, the betweenness centrality of a node i is the number of optimum paths between other vertices that run through i (Freeman 1977).

Based on the centrality concept of weighted networks, this paper develops the quantitative method to measure directly and indirectly change impacts and make change analysis more objectively. Three assessment indices of change impacts for the whole product—Degree-changeability which assesses the direct change impacts, Reach-changeability which is used to assess indirectly change impacts, Between-changeability which predicts which parts will change other parts and be changed by other parts dramatically—are proposed in the proposed method.

The remainder of this paper is organized as follows. Section "Product network models" models the product network. A general expression is presented to define the change impacts and measure changeability of a part based on the product networks in Sect. "The network-based change impact assessment approach". In Sect. "Case study", a case of Roots Blower is discussed to illustrate the method. Conclusions are then presented in the final section.

Product network models

Suppose that a product consists of m parts, $N = \{n_1, n_2, \ldots n_m\}$ and a part has e_i links, $L = \{l_{i1}, l_{i2}, \ldots, l_{ij}, \ldots, l_{ie_i}\}$, where l_{ij} denotes the link from part i to part j which means i provides information to j. A set of values $W = \{w_{i1}, w_{i2}, \ldots, w_{ij}, \ldots, w_{ie_i}\}$ are real numbers attached to the links where w_{ij} denotes the connection strengthen from part i to part j. Therefore, the product network S is defined as:

$$S = (N, L, W) \tag{1}$$

Ulrich (1995) viewed the issue of design change impacts as coupling, which is the connection of items. Martin and Ishii (2002) proposed that the stronger the coupling between parts, the more likely a change in one will cause a change in the other. The weight W is defined as the degree of coupling between parts. Constructing the product network involves these steps:

1) **Break down a product.** A product is broken down into assemblies or subsystems, and each assembly or subsystem is composed of parts and subassemblies which consist of components. The granularity of decomposition is determined by the demand of assessment. In our method introduction of change impact assessment (Sects. "Product network models", "The network-based change impact assessment approach"), "part(s)" is just a generic expression. Then, each part is presented as a node of the network.
2) **Develop relationships between parts.** The dependency relationship between parts is documented based on structured interviews with experienced engineers and design documentation data. It is developed based on the different interactions types, such as Specification flows (Martin and Ishii 2002) and spatial/energy/material/information dependencies (Pimmler and Eppinger 1994). A quantification schema is used to weight the dependencies. Thus, in product networks the links and their values are the dependency relationships and their weights, respectively.
3) **Calculate weighted value.** Define the kth coupling that part j depends on part i is presented as $w_{ij}^k (k = 1, 2, \ldots)$. Therefore, the weighted value from part i to part j is the sum of the coupling strength between the two parts.

$$w_{ij} = \sum_{k \in l} w_{ij}^k \tag{2}$$

where l is the number of the couplings from part i to part j. Apparently, the stronger weighted value between two parts, the more easily changes propagate from the initial node to the target, thus the higher the sensitivity is. In this research, the sensitivity is equal to the weighted value, which means w_{ij} denotes the sensitivity of part j referred to the change of part i. The process of modeling a product network model is shown in Fig. 1.

The network-based change impact assessment approach

In a product network, change impacts of a part are determined by its connections with all other parts. Hence, a part's changeability is defined based on the coupling strength that the part depends on the others within a product. The high coupling of the part means that it has a large change impact. Assume a product network S is characterized by a single variable $\Phi(S)_i$, the coupling strength that part i depends on the other parts of S. $\Phi_{actual}(S)_i$ and $\Phi_{\max}(S)_i$ express coupling strength caused by actual connection of part i and maximum possible connection of i, respectively. The changeability of part i $C(S)_i$ can be defined as

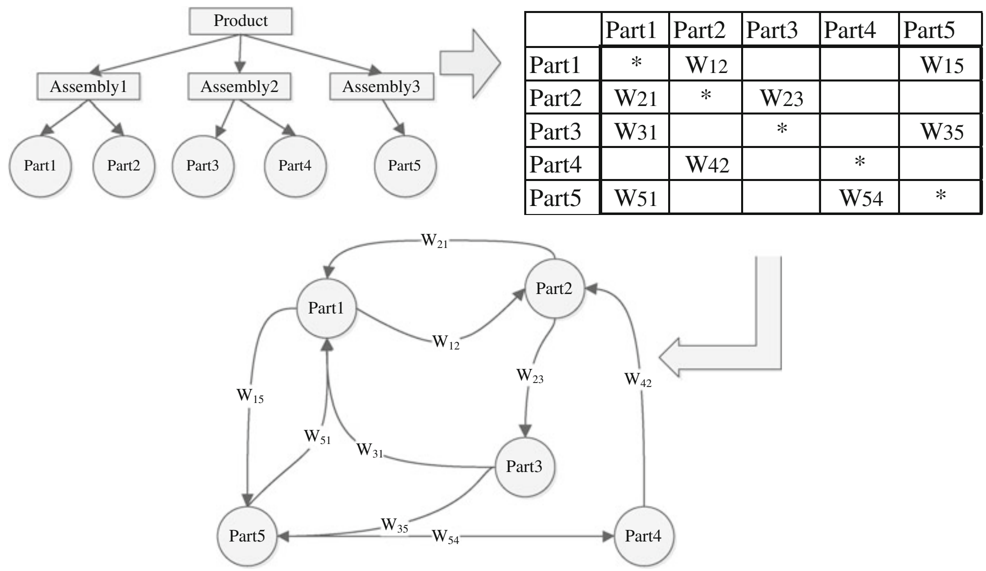

Fig. 1 The process of modeling product networks

$$C(S)_i = 1 - \frac{\Phi_{actual}(S)_i}{\Phi_{\max}(S)_i} \tag{3}$$

Expression (3) offers a common expression of part's changeability. The variable values in Expression (3) depend on product networks and the calculating models based on the centrality and cohesion concepts of networks. Three distinct intuitive conceptions of centrality and cohesion measures are developed: Degree-changeability, Reach-changeability and Between-changeability. These centrality and cohesion properties represent the degree of change propagation from one part to others in a product network. Lager the value of centrality and cohesion properties, the lower $C(S)_i$ is.

Changes of a part in a product not only directly impacts to other parts (Degree-changeability), but also indirectly propagate to others because of design dependencies (Reach-changeability), or a part can also bridge two other parts to transmit changes (Between-changeability). The centralities provide insight into the parts' location in the whole product. If a product network is very central, dominated by one or a few very central nodes, the changes of the central nodes would impact the whole product and even make it failed. For example in a star graph, the central node directly connects to all other parts (causes Degree-changeability), it is the closest node to all other nodes (causes Reach-changeability), and the only node that is between any two other nodes in the graph (causes Between-changeability). Its change will impact all other parts. Therefore, this paper borrows the centrality concept (degree, reachability/shortest path and betweenness) to measure direct and indirect change impacts.

Degree-changeability

As for the directed networks, the concept of node strength is extended to *out node strength* OD_i and *in node strength* ID_i in this paper which are defined as:

$$OD_i = \sum_{j \in N_i} w_{ij}$$
$$ID_i = \sum_{j \in N_i} w_{ji} \tag{4}$$

OD_i denotes the sum of links weights which part i connects to directly in a product network. In the definition of direct impacts, the performance caused by actual connection of parts $\Phi_{actual}(S)$ is defined as:

$$\Phi_{actual}\,(S_{OD})_i = \sum_{j \in N_i} w_{ij} \tag{5}$$

where N_i is the neighborhood of node i. According to Eq. (3), the changeability measure of degree centrality $C(OD)_i$ takes the form as follows:

$$C(OD)_i = 1 - \frac{\Phi_{actual}\,(S_{OD})_i}{\Phi_{\max}\,(S_{OD})_i} = 1 - \frac{\sum_{j \in N_i} w_{ij}}{w_{\max} \cdot (n-1)} \tag{6}$$

where $w_{\max}$ is the maximum value of w_{ij}. The node strength caused by maximum possible connection, $\Phi_{\max}(S)$ in Eq. (3), occurs when each of the strength value between parts is $w_{\max}$ and part i connects with all other $(n-1)$ parts. $C(OD)_i$ ranges from 0 to 1. A high value of OD_i indicates that part i supplies more constraints to other parts. That is to say that a change of part i may dramatically cause the changes of many other parts connected with it directly if the Degree-changeability $C(OD)_i$ is low.

Undirected impact assessment

In practical design, direct connections are usually distinct enough that the designers can immediately recognize. However, the indirect links are most likely to be overlooked by the designers. Degree-changeability can measure the direct impacts caused by the source change, but does not consider any indirect link by which one part may affect other more parts of a product. Indirect impacts can be measured through reach-changeability and between-changeability.

Reach-changeability

In information networks, reachability affects the motivation of an individual to transfer knowledge to a coworker or colleague, although the source of the motivation differs. Whereas the knowledge sender's relationship with the recipient is the source of motivation with tie strength, strong ties to mutual third parties are the source of motivation in a dense social network (Reagans and McEvily 2003). Similarly, reachability affects the change propagation from a part to other parts no matter what the causes are in the product networks. The further one part can achieve, the more widely its changes may propagate.

In product networks, the coupling strength between parts is proportional to propagate probability. Propagate probability is defined as the likelihood that a change of one part will lead to another change along connections between parts and restricted to [0,1]. Propagate probability includes direct probability and indirect probability. The direct probability is the likelihood caused by direct connection and equals to the normalized weights $p_{ij} = \tilde{w}_{ij} = w_{ij}/w_{\max}$. If node j doesn't connect with node i directly, the probability of change reaching from node i to node j is indirect probability P_{ij}. In a product network, P_{ij} is defined as:

$$P_{ij} = \sigma_{iu} p_{uj} \tag{7}$$

where u is the penultimate part in the path from part i to part j, σ_{iu} is the probability of change reaching part u from i, p_{uj} denotes the direct probability of change propagation from u to j. The *out-reachability impact strength* OR_i of part i is defined as the sum of the reachability from i to the other nodes in the network, the form is:

$$OR_i = \sum_{j \in N, j \neq i} Max\{P_{ij}\} \tag{8}$$

Similarly, *in-distance impact strength* IR_i becomes

$$IR_i = \sum_{j \in N, j \neq i} Max\{P_{ji}\} \tag{9}$$

In the definition of Reach-changeability, the performance caused by actual connection of parts $\Phi_{actual}(S)$ is defined as:

$$\Phi_{actual}(S_{OR})_i = \sum_{j \in N, j \neq i} Max\{P_{ij}\} \tag{10}$$

Changes between two parts should propagate along the most possible path. If one of the propagate probability is very low in the propagation path from part i to part j, the change of i could not propagate to j. The most extreme case is that one of the probabilities along the propagation path from part i to part j is 0. In this case, the change of part i can't reach part j through the node with probability 0. So, the most probable propagation will be calculated.

Most products are designed to include certain tolerance margins which can absorb some degree of changes (Eckert et al. 2004). Therefore, the probability of change propagation from part i to part j decreases with the increasing of the propagation steps in any propagation path. With the growth of the numbers of connections and parts, the numbers of the propagation paths are increasing, so are change propagation probabilities. Furthermore, with the increase of the parts which part i can reach there was a corresponding growth of change impacts caused by part i.

Based on Eq. (3), the Reach-changeability takes the form:

$$\begin{aligned} C(OR)_i &= 1 - \frac{\Phi_{actual}(S_{OR})_i}{\Phi_{\max}(S_{OR})_i} \\ &= 1 - \frac{\sum_{j \in N} Max\{P_{ij}\}}{n-1} \end{aligned} \tag{11}$$

A high value of OR_i means that the change of part i can easily propagate to the others. Therefore, its changeability is low. In a product network, the most probability of the link from part i to pat j is 1. The maximum OR_i equals $(n-1)$, which occurs when part i can reach the other $(n-1)$ parts with probability 1. In this situation, the changeability of part i is 0, which means that the other parts must be changed once part i is changed.

Distance d_{ij} from part i to part j is the number of links contained by the optimum path. The average distance $\overline{d_i}$ from part i to the other $(n-1)$ parts is:

$$\bar{d}_{Out-i} = \frac{\sum_{j \in N, j \neq i} d_{ij}}{n-1} \tag{12}$$

By plotting $\frac{OR_i}{n-1}$ against $\bar{d}_{Out-i}$, a visual method is proposed to assess the change impacts as shown in Fig. 2. Figure 2 can be divided into four domains. The parts in A domain characterize high probability and low distance which means most of them mainly affect on the parts connected directly or the nearest neighbors. The parts in B domain also need to be concerned by designer because they have high probabilities and a wide range of change propagations (high average distances). The parts in domain C and D have lower probability, so their changes are most likely to be absorbed.

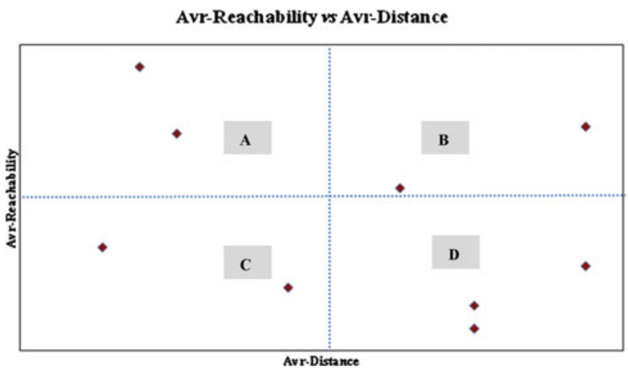

Fig. 2 Avr-Reachability vs. Avr-Distance

Between-changeability

The communication of two non-adjacent nodes depends on the nodes belonging to the path connecting the two nodes (Boccaletti et al. 2006). In social networks, when a person is strategically located on the communication paths linking pairs of others, that the person is central who can influence the group by withholding or distorting information in transmission (Bavelas 1948; Shaw 1954). In traffic networks, the order of nodes betweenness is similar to the vulnerability of networks when nodes are damaged (Latora and Marchiori 2005). Similarly, the part with high betweenness is central of the product network in change propagations.

Considering the strength of design dependencies in a product network, an alternative definition of shortest paths is the path with the maximum likelihood $\left(\max\{L_{ij}\}\right)$ from part i to part j. Therefore, our measure of between-changeability $C(b)_i$ takes the form

$$C(b)_i = 1 - \frac{\Phi_{actual}(S_b)_i}{\Phi_{\max}(S_b)_i} = 1 - \frac{b_i}{(n-1)(n-2)} = 1 - \frac{\sum_{j,k\in N, j\neq k} \frac{n_{jk}(i)}{n_{jk}}}{(n-1)(n-2)} \quad (13)$$

where n_{jk} is the number of the shortest paths connecting node j and node k, $n_{jk}(i)$ is the number of shortest paths connecting j and k and passing through node i.

When node i is the centre of a star or wheel network, the betweenness of i is maximum which equals $(n-1)(n-2)$ (Freeman 1977). When most of parts integrate together by connecting to a part, any change of the part can cause huge influence and it is unsuitable to change. For example, the chief shaft of machine tools is the design reference for many other parts. If it changes, all of the related parts should be changed.

Complexity analysis

The proposed approach studies the change impact assessment based on the availability of complex network theory for the complex problem. So, it is implemented by using the common graph algorithm. Define the number of the nodes and links as N and M, respectively. Breadth-first search (BFS) is adopted for searching the network. Using BFS to scan each node, Degree-changeability sums the weights each nodes directly link and the time complexity is $O(N)$. The algorithm of Reach-Changeability works by first searching the optimum path (i, j, k) which is the most probable path from i to j using only vertices 1 to k as intermediate nodes along the way (where i, j, k are the indices of nodes, respectively), and the most probable path is computed by Eq. (7); this process continues until $k = N$, and the most probable path and the reachability for all (i, j) pairs are found by using any intermediate vertices. This algorithm is similar with Floyd–Warshall algorithm, but the recursive formula is changed:

$$\begin{aligned} &\text{the-most-probable-path}(i, j, k) \\ &\quad = \max\{\text{the-most-probable-path}(i, j, k-1), \\ &\qquad \text{the-most-probable-path}(i, k, k-1) \\ &\qquad *\text{the-most-probable-path}(k, j, k-1)\}. \end{aligned}$$

So, the time complexity is O(N^3). The algorithm of Reach-Changeability centrality works in two steps: compute the reachability and number of the most probable paths between all pairs; then sum all pair-dependencies. The complexity of Between-Changeability is $O(N * N^3) = O(N^4)$.

According to the analysis above, the algorithm efficiency is not very high in theory, so how to improve the algorithm efficiency needs more studies in the further. However, for sparse networks, that is, networks with far fewer than $O(N^2)$ edges, the algorithm can be implemented more efficiently by storing the network in the form of adjacency lists and using a binary heap or Fibonacci heap as a priority queue to implement extracting minimum efficiently. For adjacency-list, the amount of memory is $O(N + M)$. The time complexity of Reach-Changeability is $O(N^2 \lg N + NM)$ and the Between-Changeability's is $O(N^3 \lg N + N^2 M)$.

Case study

Roots Blower is widely used in sewage treatment, pneumatic conveyor, dust collector, electric power, vacuum packaging, vacuum dryer, and so on. Roots Blower also offers an extensive range of standard air blower packages for a wide variety of applications and industries. Roots Blower is characterized by high precision and being well sealed which make the parts interact with each other closely, so one change most probably results in large-scale changes propagation. Therefore, designers need to evaluate the degree of the change impact before changing the design.

The proposed network-based approach is used to evaluate the change impacts of Roots Blower. In order to calculate the impacts based on the changeability assessment indices, the product networks models are first constructed. Two different dependency relationships, specification flows and spatial dependencies, are used to develop the dependency relationship. Furthermore, the change impact assessment is discussed with regard to the models.

Modeling

Product network based on specification flow

Specification flows are defined as design information that must be passed between designers in order to design their respective parts (Martin and Ishii 2002). Different parts are dependent through their specification including geometric dimensions, material, and so on. In order to construct specification flow model, one type of the Roots Blower is broken-down into 10 main parts. Among these ten parts, there are eight parts (rotor, casing, shaft, seal, side cover, bearing, gear and cooling system) composing the blower as shown in Fig. 3 and two extended parts (motor and silencer) which connect the blower and affect the blower's design parameters (not shown in Fig. 3). After documenting the general decomposition of the product, specification flows between the main parts and the external parts are used to develop the dependency matrix and a non-zero mark signifies the dependency of one part on another as shown in Table 1. Reading across a column down reveals what other elements the part in that row provides information to; scanning a row reveals what other parts the element in this column receives information from. For example, the shaft provides different specification flows to the rotor, bearing, gear and seal, and receives different specification flows from the rotor, side cover, bearing, gear and seal in Table 1. For each specification, the sensitivity of each part to a change is estimated by using a numerical rating system where the numerical value is 9, 6, 3, 1 and 0 as shown in Table 2 (Martin and Ishii 2002). For example, in order to build two cavities between the rotor and casing, the spatial specifications of the rotor should be defined, such as area coefficient λ, the clearance δ and outside diameter D. Furthermore, small changes in λ, δ or D impact the casing changes. The rating of the casing's dependency on the rotor's specification (λ, $\delta \& D$) is 9 as shown in Fig. 3.

During identification and documentation of design dependencies, an important issue is how to deal with product-level requirements, such as flow capacity and differential pressure. In this paper, product-level performances are treated as possible external constraints on all the parts of the product. In general, these constraints are not directly expressed the dependencies between parts; they should be translated into different specifications of the parts. The constraints should be so clear that the dependencies caused by those constraints are determined easily. For example, flow capacity which is a product-level specification can cascade down into theoretical flow and leakages. Further, theoretical flow is translated into area coefficient, length, outside diameter and the rotational speed of the shaft; Leakage is determined through the clearance δ between the rotor and the casing, the rotor and the side cover which should be defined as a strong bidirectional spatial design dependency between them.

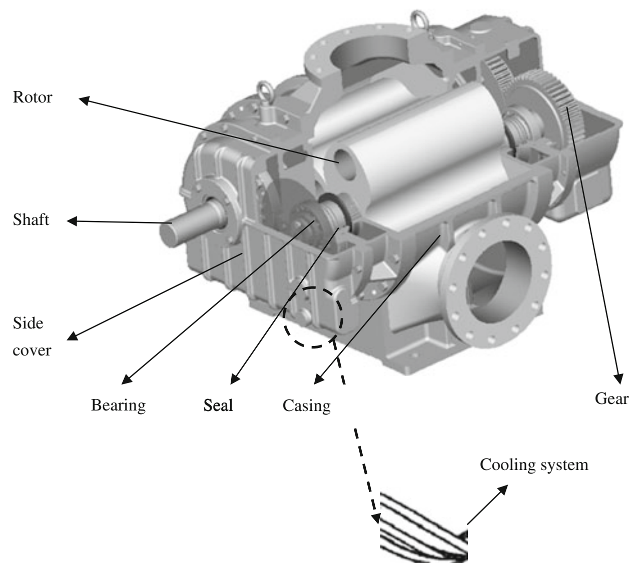

Fig. 3 Structure of Roots Blower

After identifying the dependency relationship between the parts, weighted values of the connections can be calculated which are the sum of all the sensitivities values between two parts. For example, the rotor connects to the casing with weight value 42(9+9+6+9+9). The product network of Roots Blower is built shown in Fig. 4. Figure 4 contains 10 nodes which express the key parts composing the Roots Blower and the links are the dependencies. The arrows of the links are the direction of specification flows, and the value presents the relative dependency strengths. For example, the link connecting the rotor and casing means that there are specification flows between the rotor and casing, and the dependency strengths from the rotor to the casing is 42.

Product network based on spatial dependencies

Spatial constraint is one of the most important dependencies between parts. Spatial dependencies make the product not only achieve the functions, but also assemble together which affects the assembly process. In the spatial dependency model, the minimum granularity of decomposition is

Table 1 Dependency relationships of Roots Blower based on specification flow

	Rotor	Casing	Shaft	Seal	Side cover	Bearing	Gear	Motor	Silencer	Cooling system
Rotor		λ 9; D 9; L 6; δ 9; Thermal-Expansion 9	Fit 9; Torque 9; δ 9; Rotation-Speed 6		δ 9; Thermal-expansion 6		δ 3; Torque 9	A 9; Rotation-Speed 9	λ 6	Thermal-Expansion 9
Casing	D 6; X-dim 6; δ 9; Thermal-Expansion 9; λ 9		Thermal-Transmittal 3		D 9; Thermal-Expansion 9; fit-tolerance 9; oil-seal 9				Inlet/outlet-size 9	Thermal-Expansion 9
Shaft	D 6; Torque 9; Rotation-Speed 9; Fit 3			D 9	X-dim 3;D 6; Fit-tolerance 3; Thermal-Expansion 3	Fit-tolerance 9; Rotation-speed 6	Power-transmit-type 9; Fit-tolerance 9;Rotation-speed 6		Silencer type 6	
Seal			Fit tolerance 6		X-dim 3; D 3; a 6					
Side cover	δ 9	D 3; Thermal-Expansion 9; fit-tolerance9; oil-seal 9	X-dim 3; Thermal-Expansion 9; fit-tolerance1	X-dim 6; D 6; a 9		Oil-seal 9				Thermal-Expansion 9
Bearing			Fit-tolerance 6		D 6; Fit-tolerance 6, oil-seal 9					
Gear	δ 9		Fit-tolerance 9; Torque 9; Rotation-Speed 9; Gear-type 3					Rotation-Speed 6	Noise 3	
Motor	W 9						Rotation-Speed 9; type 9, w 9			
Silencer		Dischare/suction-size 3								
Cooling system		Type 6								

Table 2 Rating of the dependency

Rating	Description
9	Small change in specification impacts the receiving part (high sensitivity)
6	Medium-high sensitivity to change
3	Medium-low sensitivity to change
1	Large change in specification impacts the receiving part (low sensitivity)
0	No specification impact the receiving part

components. According to the assembly structure, the dependency relationships of the parts are documented. The rating system of the sensitivity is three-point scale (2 = high sensitivity, 1 = medium sensitivity and 0 = no sensitivity) (Pimmler and Eppinger 1994). The product network based on spatial dependency is shown in Fig. 5. Figure 5 contains 36 nodes which express the parts composing the Roots Blower and 128 links. The arrows and value of the links present the direction and the relative dependency strengths of spatial dependency.

Changeability analysis

According to the various indices, the critical parts in design can be judged. The designers can choose the parts which have less impact on the product to redesign or change on the premise of the same performance and functions.

Degree-changeability analysis

Degree-changeability supplies the direct change impact assessment. Table 3 lists the out degree and Degree-changeability of the parts in specification flow model shown in Fig. 4. For example, the out degree of the rotor is 135(42+33+15+12+18+6+9) and the Degree-changeability is $0.643 (= 1 - 135/42 * 9)$. According to Table 3, the rotor has the minimum Degree-changeability. In actual design, the rotor has tight connection to the casing, side cover and shaft which causes the most out degree and the minimum changeability. A small change of the rotor's specification may results in the changes of the casing, side cover and shaft. The silencer is the most changeable from the Degree-changeability perspective, because it is an aided part in Roots Blower and its changes are usually caused by other related parts but less likely to impact the other parts.

Reach-changeability analysis

Reach-changeability provides the measurement of the indirect impacts, which defines the probability of the change of a part flowing to another part along the connections. In Table 4, one part can reach the other parts with different probabilities, though most of them do not connect directly as shown in Fig. 4. For example, the most possible path between the rotor and bearing is from the rotor to the shaft to the bearing with 2 steps (Table 5). So, the probability of propagation is 0.785714*0.357143 = 0.281 as shown in Table 4, where 0.785714(=33/42) and 0.357143(=15/42)

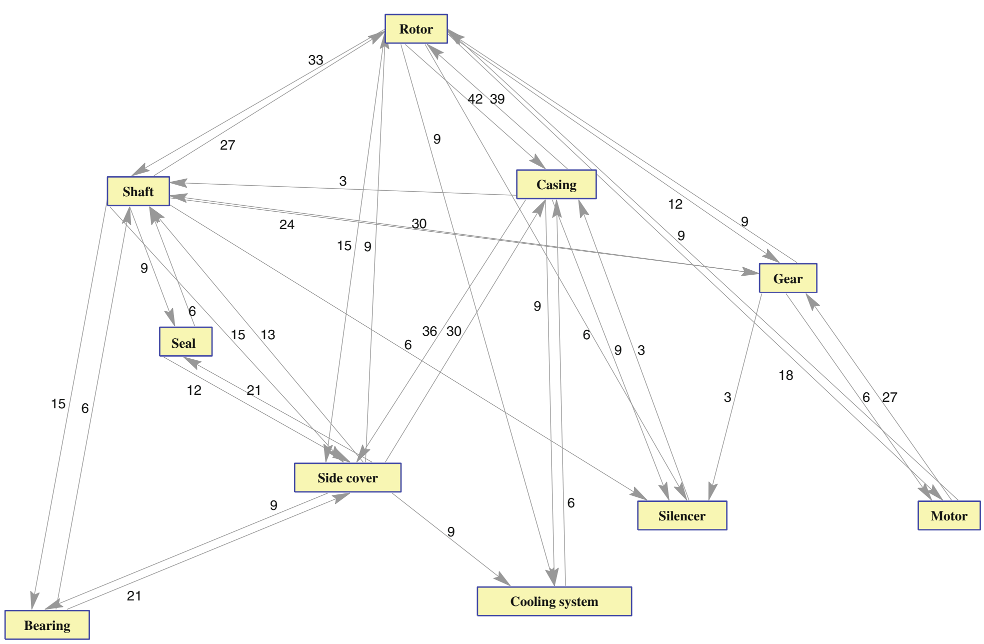

Fig. 4 The product network of Roots Blower based on specification flow

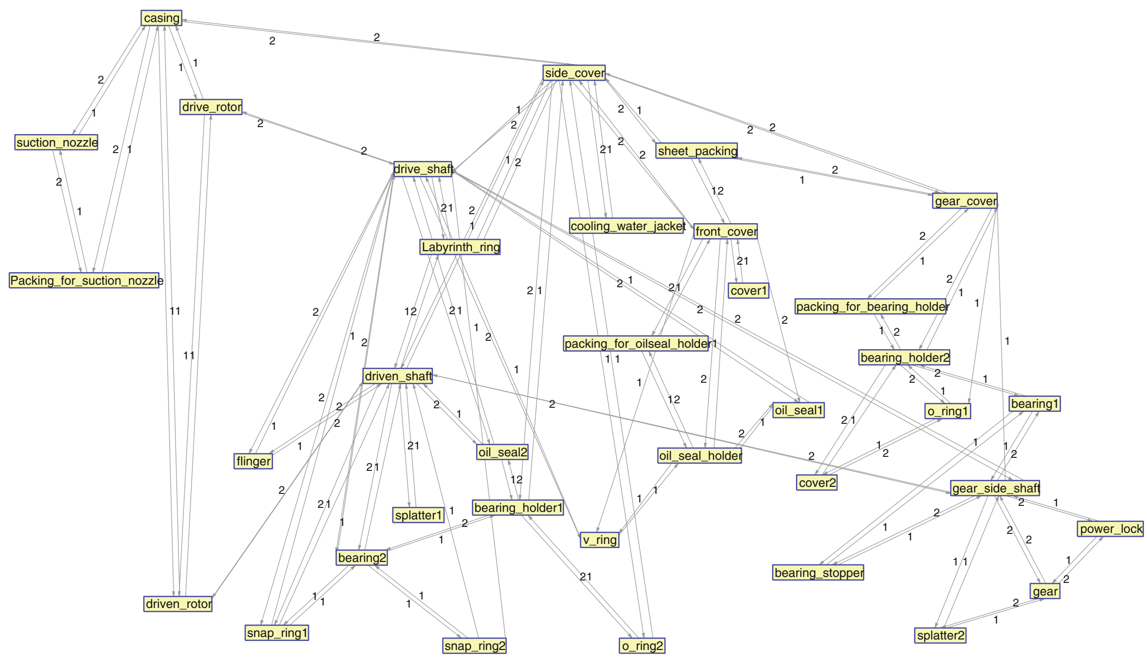

Fig. 5 The product network of Roots Blower based on spatial dependency

Table 3 Degree-changeability of specification flow model

	Out degree	$C(OD)_i$
Rotor	135	0.643
Casing	96	0.746
Shaft	96	0.746
Seal	18	0.952
Side cover	91	0.759
Bearing	27	0.929
Gear	48	0.873
Motor	36	0.905
Silencer	3	0.992
Cooling system	6	0.984

are the direct propagate probability from the rotor to the shaft and from the shaft to the bearing, respectively. In specification flow model, the rotor has the minimum $C(OR)_i$ $\left(1-\frac{1+0.786+0.429+0.857+0.281+0.449+0.429+0.214+0.214}{9}=0.482\right)$ as shown in Table 6, its changes impact the casing, shaft and side cover through direct parametric relationship and forward to the others—the bearing, gear and seal, and in consequence impact the whole Roots Blower. In the real world, if two products belong to different types, they have significant variants. Different types of rotors are almost not used in the same type of Rotors Blowers. In another word, the change of the rotor has a strong effect on the whole product.

Figure 6 shows the average reachability plotted against the average path. In Fig. 6, the vertical dashed line and the horizontal dashed line indicate the mean value of the average optimum path and the average reachability, respectively. The dashed lines divide the figure into four domains. In A domain, the parts have high reachability but low distance; their changes more likely propagate to the others quickly. The rotor, shaft and casing can reach all other parts in 3 steps with high probability, so the changes may highly impact on the product. The gear transmits power by connecting the power resource and the shaft. It may connect few parts directly, but its change can be propagated widely. This situation occurs in domain B. The changes of the parts in this area are dangerous which may cause avalanche. In C and D domains, the parts have low impact probability, so their changes have little impact on the whole product.

Between-changeability analysis

Between-changeability is an additional indirectly impact assessment. The parts with high betweenness locate in the centre of the links. In specification flow model, the parts with high betweenness mean that most of the design parameters are transformed and transferred through them, for example the shaft ($C(b)_{shaft} = 0.333$) in Table 7. In design process, the shafts transform the energy of the motor to the rotor by rotating. Furthermore, center distance between the driving and the driven shaft is the design standard which constraints the design parameters of the rotor, side cover and gear and their assembly location. So, the shaft has also high betweenness in spatial dependency model (Table 8). On the other hand, the changes of many parameters, such as rotation speed,

Table 4 Reachability of specification flow model

	Rotor	Casing	Shaft	Seal	Side cover	Bearing	Gear	Motor	Silencer	Cooling system
Rotor	0	1	0.786	0.429	0.857	0.281	0.449	0.429	0.214	0.214
Casing	0.929	0	0.73	0.429	0.857	0.261	0.417	0.398	0.214	0.214
Shaft	0.643	0.643	0	0.276	0.551	0.357	0.571	0.276	0.143	0.138
Seal	0.19	0.204	0.149	0	0.286	0.061	0.085	0.081	0.044	0.061
Side cover	0.663	0.714	0.521	0.5	0	0.214	0.298	0.284	0.153	0.214
Bearing	0.332	0.357	0.261	0.25	0.5	0	0.149	0.142	0.077	0.107
Gear	0.459	0.459	0.714	0.197	0.394	0.255	0	0.197	0.102	0.098
Motor	0.295	0.295	0.459	0.127	0.253	0.164	0.643	0	0.066	0.063
Silencer	0.066	0.071	0.052	0.031	0.061	0.019	0.03	0.028	0	0.015
Cooling system	0.133	0.143	0.104	0.061	0.122	0.037	0.06	0.057	0.031	0

Table 5 Distance of specification flow model

Parts	Rotor	Casing	Shaft	Seal	Side cover	Bearing	Gear	Motor	Silencer	Cooling system	$\overline{d_{Out-i}}$
Rotor	0	1	1	3	2	2	2	1	2	1	1.667
Casing	1	0	2	2	1	2	3	2	1	1	1.667
Shaft	1	2	0	3	2	1	1	2	1	2	1.667
Seal	3	2	4	0	1	2	5	4	3	2	2.889
Side cover	2	1	3	1	0	1	4	3	2	1	2
Bearing	3	2	4	2	1	0	5	4	3	2	2.889
Gear	2	3	1	4	3	2	0	3	2	3	2.556
Motor	3	4	2	5	4	3	1	0	3	4	3.222
Silencer	2	1	3	3	2	3	4	3	0	2	2.556
Cooling system	2	1	3	3	2	3	4	3	2	0	2.556

Table 6 Reach-changeability of specification flow model

Parts	OR_i	$C(OR)_i$
Rotor	4.659	0.482
Casing	4.449	0.506
Shaft	3.598	0.600
Seal	1.161	0.871
Side cover	3.561	0.604
Bearing	2.175	0.758
Gear	2.875	0.681
Motor	2.365	0.737
Silencer	0.373	0.959
Cooling system	0.748	0.917

torque and center distance, propagate to other parts through the shaft. So, the shaft may be changed due to receive these changes.

Result

According to the proposed indices, the assessment of a part's changeability can be defined as a triple $< C(OD)_i, C(OR)_i, C(b)_i >$. If the three indices of the triple are all small, the corresponding parts are low changeability and are recommended to be frozen as early as possible, for example the rotor (<0.643,0.482,0.375>) and shaft (<0.746,0.600,0.333>) in the specification flow model. According to Table 9, $C(OD)_i$ and $C(OR)_i$ have a high correlation coefficient, so the situation that $C(OD)_i$ is large while $C(OR)_i$ is small does not exist in specification flow model. $C(OR)_i$ and $C(b)_i$ have a smaller correlation coefficient, which is a part with low reach-changeability does not have low between-changeability. For example, the whole Roots Blower (the Rotor, shaft, side cover, bearing and so on) will be changed if the shape of the casing (<0.746,0.506.0.5>) is changed. But, it is not very central in the specification flow model because it has not very low between-changeability.

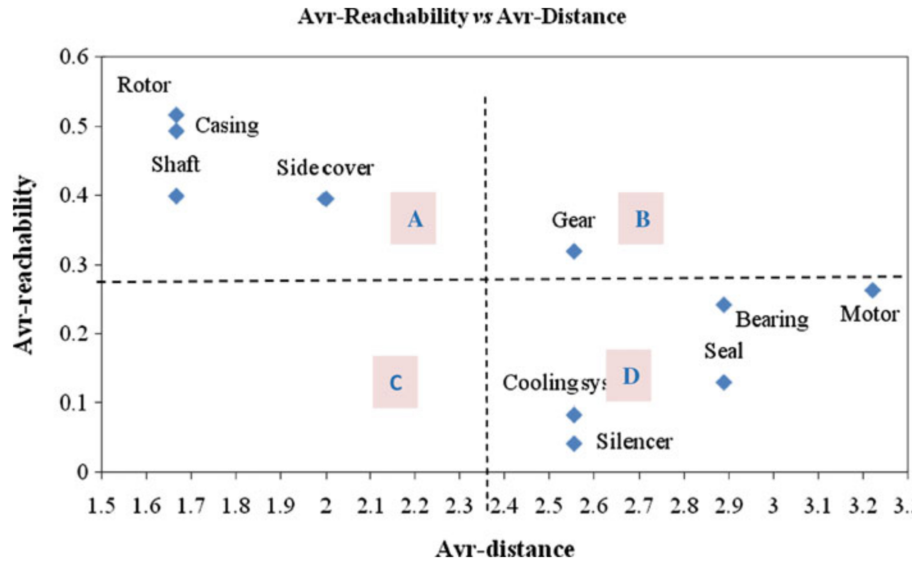

Fig. 6 Average Reachability vs. Average distance of specification flow model

Table 7 Between-changeability of specification flow model

Parts	Betweenness	$C(b)_i$
Rotor	45	0.375
Casing	36	0.5
Shaft	48	0.333
Seal	3	0.958
Side cover	44	0.389
Bearing	3	0.958
Gear	25	0.653
Motor	9	0.875
Silencer	7	0.903
Cooling system	9	0.875

Table 8 Between-changeability of spatial dependency model

Parts	Betweenness	$C(b)_i$
Gear_side_shaft	650	0.454
drive_shaft	465	0.609
Gear_cover	426	0.642
Driven_shaft	396	0.667
Side_cover	395	0.668
Bearing_holder2	364	0.694
Casing	329	0.724
Front_cover	256	0.785
Oil_seal_holder	184	0.845
Bearing1	154	0.871
⋮	⋮	⋮
Cooling_water_jacket	0	1

The changes of other parts (for example the diameter of the shaft) will not affect the casing.

Besides change propagation impact assessment, the assessment indices can be a guide to design. For example, the parts with high betweenness are the datum in design. The specifications or the structures of the parts reach the others mostly through the parts with high betweenness. The parts in A domain of Fig. 6 are usually the main parts in design process, because they provide more specification for the product functions.

Table 9 Correlation coefficients between the three indices based on specification flow model

	$C(OD)_i$	$C(OR)_i$	$C(b)_i$
$C(OD)_i$	1	0.9564	0.9273
$C(OR)_i$	0.9564	1	0.8548
$C(b)_i$	0.9273	0.8548	1

Conclusions

Connections can cause change propagation from one part to the other parts, and then time is delayed and cost is increased in design. Impact assessment of change propagation can help the designers know which parts should be assigned additional resources to respond to likely changes, and create cost-efficient project plans, and ultimately design solutions, more quickly.

A quantitative approach is proposed to determine the position of a part in change propagation which can analyze the issue more objectively and convincingly. First, the connections of parts are identified and the product network is modeled. Second, quantitative model to the impact assessment of change propagation is developed based on weighted networks theory. Three assessment indices, Degree-changeability, Reach-changeability and Between-changeability, are proposed for change impact assessment of the complex product. Degree-changeability assesses direct change, Reach-changeability assesses indirect change, and Between- changeability is to judge the parts that will change and be changed dramatically. Finally, a case study is used to illustrate the proposed method in assessing the change impacts.

How to integrate the other studies of the network for better change management and use the assessment for improving the design should be considered in future work. On the other hand, How to cut down the man-made factors about the weight definition should be further considered during modeling the product network.

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