Research in Engineering Design (2020) 31:491–503
https://doi.org/10.1007/s00163-020-00344-7

ORIGINAL PAPER

An analysis method for change propagation based on product feature network

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Received: 16 August 2019 / Revised: 18 August 2020 / Accepted: 2 September 2020 / Published online: 17 September 2020

Abstract

At present, how to evaluate the impact of product design changes in product development process has been a problem to be solved. The research on product design changes has gradually shifted from the component level to the product feature level. Therefore, the components are divided into feature level, and a product feature network is built to analyse the propagation of changes. Because it is not unique to divide features of the component, three-dimensional (3D) entities are used to transit components into 2D features. The strong and weak ties are defined according to the relationship between the divided features, the product feature network is constructed by the divided features and defined ties. Three discrete states of feature nodes are defined based on the change propagation model and the meaning of change propagation index (CPI) in the feature network is proposed. By analysing two types of product feature change propagation and calculating its change probability, the impact of change propagation in the network can be evaluated. Finally, the feasibility of the proposed model is verified by constructing a featured network of a pumping unit and analysing its change propagation.

Keywords Component features · Complex networks · Change propagation · Propagation impact

1 Introduction

In the product design process, designed products are often changed for various reasons, such as demand changes, design errors, etc. (Hu and Cardin 2015). Product design changes need to balance change costs, implementation risks, design plan, product quality, and more (Cheng and Chu 2012). And parts of products, especially the parts of complex products, are usually closely connected. Changes in one component can affect other components and eventually propagate among parts widely (Eckert et al. 2004). So product design changes often lead to unpredictable results due to change propagation. Eckert et al. (2001) and Jarratt et al. (2002) divided the change propagation into a ripple of change, blossom of change, and avalanche of change according to the change impact during the change propagation process. They found that, during the change propagation process, ripple of change and blossom of change would decrease or keep changes within an acceptable range, and avalanche of change would eventually lead to uncontrollable changes. In actual production, product design changes are essential processes for eliminating initial design errors and adapting products to new requirements (Lindemann and Reichwald 1998). Design changes are closely related to time, cost, resources, benefits, product quality, etc. (Cheng and Chu 2012; Eckert et al. 2004; Morris et al. 2016), and design change propagation will lead to design time, cost and quality uncertainty (Hamraz et al. 2012). For enterprises, design change propagation should be limited to the ripple of change, and blossom of change rather than an avalanche of change. Therefore, it is of great significance to accurately analyze the design change process, predict the design change path, and evaluate the design change impact.

At present, faster product updates and shorter product design cycles have become key elements of corporate market competition and how to shorten product design cycles has become an important research topic for enterprise development. Making changes to existing similar designs based on customer requirements may be a good idea for designers, but the impact of change propagation is often difficult to evaluate. And research on product change propagation from

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the product feature level may be a good idea. Koh (2017) showed the feasibility of feature modelling and also discussed feature modelling is good for variant design but less suitable for an adaptive design where the product features may no longer be relevant. And for the idea to make changes to existing similar designs based on customer requirements for function, appearance, and etc., feature modeling can be useful to model the product and analysis the impact of change propagation. Because the feature is a detailed level of the product, how to model the relationship between features and show the information contained by the feature connections may be the first problem to study change propagation by features.

To study the impact of the internal changes in products, a product feature partitioning rule is proposed in this paper to divide components into product features, so the study of change propagation can be ranged from components into a product feature. Based on the complex network theory, the product feature network model is established with the relationship between product features. By analyzing the change propagation mechanism of the product feature network, an analysis method for evaluating the impact of change propagation on feature level is proposed.

The rest of the paper is organized as follows: methods to study design change propagation and some researches on are reviewed in Sect. 2. In Sect. 3, the product feature partitioning rule and product feature network modelling method are proposed. Based on the change characteristics of the product feature network, the change analysis model is constructed and the change propagation impact evaluation method is presented in Sect. 4. In Sect. 5, a pumping unit is taken as an example to verify the product feature network and the analysis method proposed in this paper. Finally, the conclusion and contribution are summarized in Sect. 6.

2 Related works

In the early research, the main task is to construct various matrices for modeling the relationship of products, for example, using design structure matrices (DSMs) to model and analyze complex products. According to different modeling contents, DSMs can be divided into product architecture DSMs, organization architecture DSMs, process architecture DSM, etc. (Browning 2015). Researchers have used matrices to do a lot of research on product design changes.

In software development, Rao et al. (2008) used bad smells to detect the design defects during software development and maintenance and proposed a quantitative method to evaluate the design defects by using the design change propagation probability matrix (DCPP matrix). Fu et al. (2012) established a probabilistic model based on DSM to evaluate the change propagation risk and used the schedule and cost of the development project to optimize their model for predicting the potential risk of change propagation for each component.

In the design task change propagation, Wynn et al. (2014) presented a design workflow network to show the relationship of tasks, deliverables, and gateways. To facilitate the change propagation analysis, additional information and DSMs were added to the network and they finally predicted design workflow changes by CPiW algorithm proposed in the paper. Chua et al. (2012) proposed a method including a change propagation model and a scheduling model for predicting the propagation and impact of changes in design progress due to external changes. The change propagation model was mainly used to predict the change propagation on downstream activities. The scheduling model was used to evaluate the impact of change propagation on design completion, redesign or loss of productivity.

In the design change of engineering products, Clarkson et al. (2004) assessed product change propagation risk by using combine likelihood and combine impact on constructing product risk matrices. Koh et al. (2012) showed a model built on the house of quality (HOQ) and change prediction method to assess the effect of engineering change propagation. In order to reflect the relationship between potential changes and product requirements, their model used the main matrix to represent the relationship between requirements and changes and used the roof matrix to show the effect of change propagation. Duran-Novoa et al (2018) studied engineering change (EC) and its propagation by using some examples, in these examples, matrices and graphs were used to model the relations between components.

Matrix methods are intuitive in describing associations of design changes. Because reasons causing design changes of complex products are more extensive, the relationships between the components of complex products are more complex, and the number of parts in the change propagation may also be very large, it may be a difficult problem to build matrices. Moreover, Computational speed has also become a bottleneck in the matrix approach.

Graph-based models can also express the complexity of product design changes (Li et al. 2012). Although the matrix-based method can show the relationship between components, the information contained in the components cannot be expressed by matrices, and graph-based method can show the internal information of components, that is, graph-based methods can contain more information than matrix-based methods. Therefore, product changes are gradually studied by using graph models. Li et al. (2012) used “And/Or” graph to denote the input–output relationship of tasks in design process. Propagation probability and propagation impact were used to describe the relationship between tasks in their mathematical model and the change completion time was calculated to select the optimal design change path.

In recent years, researchers have gradually discovered that product structure, part connection, design tasks, processing and production are more complex than they thought before, and these complexities were similar to the complexity of complex networks, so network-based change propagation became a new research area of graph-based models. Giffin et al. (2009) proposed a network-based method, which was based on graph theory and pattern analysis, to analysis change request, and they defined Change Propagation Index (CPI) to assess the strength of changes. Cheng et al. (2012) modelled a weighted network by the relationship between products and their components. Based on the weighted network theory, degree-changeability, reach-changeability and between changeability were used to assess the impact of direct changes, to evaluate the impact of change propagation, and to predict the impact on other components, respectively. Ma et al. (2016) constructed a design change analysis model based on design property network. The model expressed design attributes by weighted linkages and by analyzing the weighted network, Change Propagation Index (CPI) was used to evaluate the impact of change propagation.

Design changes are often complex processes with multi-sectoral cooperation, and the process is to balancing multiple factors such as cost, quality, time and etc. And in previous studies, the association between different types of elements was often neglected, so multi-layer network models were built to show the hidden relationships between different elements. Hamraz et al. (2012) combined function-behavior-structure model (FBS model) proposed by Gero and the change prediction method (CPM) proposed by Clarkson, and presented a FBS connection network model, which used functional, behavior, and structure to build a multi-layer network and to express hidden connections between multiple levels, and predicted the risk of design changes with CPM. Pasqual et al. (2012) showed a multi-layer network model for change propagation and they predicted the impact of change propagation by considering Engineer-Propagation Design Structure Matrix (Engineer-PDSM), Engineer Change Propagation Index (Engineer-CPI) and Propagation Directness. Rebentisch et al. (2017) established a multi-layer network model based on the relationship between product elements and production processes. Based on the proposed network model, an alternative plan to solve the change propagation problem and production cost were evaluated.

The product contains many information, such as geometric parameters, machining accuracy, surface roughness, machining process, machining attributes and etc. Since a product consists of many components, and a component can be viewed as a collection of multiple features, the product features contain the necessary information to define the assembly and components. In the early years of computer-aided design (CAD) development, the constructive solid geometry (CSG), B-rep, and sweeping were widely used to model the part features and Boolean connections among features is used to describe the modelling results in mathematics (Requicha 1980; Hui and Tan 1992). With the development of computer-aided design (CAD), the product information contained in the feature is gradually enriched and gradually plays an important role in engineering projects. The expression of product components based on features has been continuously improving and researchers are gradually focusing on the application of features. Kardos et al. (2017) proposed a decomposition scheme for assembly sequence planning (ASP) and this method solved the collision problems of fixtures, tools, etc. based on features to ensure the feasibility of the planned assembly sequence. Louhichi et al. (2014) presented a Digital Mock-Up Association Management Model (DUM-AMM) to evolve the relationship between digital simulation and CAD work packages into the change propagation problem of CAD work packages, for example, CAD surface change problem described in their paper. Eltaief et al. (2018) studied the change propagation management method of CAD assemblies. By obtaining the feature change information of the parts in the sub-assembly, the remaining parts in the sub-assembly are adjusted to the changed parts. The key to this technology was to maintain the consistency of CAD change data in the process of change propagation.

In summary, the matrix-based approach is widely used in the study of design change propagation and the main applications are software design, design tasks and component changes, etc. Graph-based methods are less used in design changes. Moreover, no matter whether it is a matrix-based method or a graph-based method, there are few researches on change propagation inside the product. Therefore, features of product components are taken into consideration in this paper, and the relationship between features is used to construct the product feature network, which is used to study the change propagation in product feature level, that is, the change propagation inside the product.

3 Feature network model for complex products

3.1 Partitioning rule for component features

CSG, B-rep, and sweeping are widely used modeling methods. CSG describes the three-dimensional (3D) geometric features of components, which can be divided into essential features and supplementary features. Essential features are used to construct the overall shape of components, while the supplementary features are used to modify the essential features. B-rep is used to represent the geometric shape of the constructed feature. Sweeping is to form 3D model by taking a 2D model as a section along a certain path.

At present, research on CAD modelling has changed from the global to the feature level. And the problem of product change propagation from the feature level would be studied. The first step to study this problem is to divide the features of components. Although CAD modelling method can divide components into features, the component features divided by CSG, B-rep and sweeping are often not unique (Requicha 1980; Hui and Tan 1992). Because of the different modelling methods, components can often be divided into different combinations of various features, so a partitioning rule is required for the components divided into features. In this paper, essential features and supplementary features are used to classify 3D entities with different attributes. 3D entity is used as the transition, that is the component is first divided into simple 3D solids, and then the 3D solids are finally divided into 2D features and their connections. The partitioning rules are shown as follows.

- First, the components of the product can be divided into some transitional 3D entities. A component can be divided into sets of essential features and supplementary features, and the combined features and duplicate features in the component can be expressed by essential features and supplementary features, so dividing a component into 3D solids is to divide a component into sets of essential features and supplementary features. To classify these features well, the essential features and supplementary features should be judged by the team. Essential features and supplementary features used in this paper are some basic entities we summarized, as shown in Fig. 1.
- Then, if the component has a modelling process, the component can be divided into 3D entities according to the modelling process (The combined features and replicated features in the modelling process need to be replaced with corresponding essential features and supplementary features). If the modelling process cannot be known, it is necessary to consider the physical characteristic, process requirements and assembly requirements to divide the component. The physical characteristic of the components means that there is no need to add supplementary features when dividing components into 3D entities. The requirements of processing and assembly mean features contain different requirements such as processing, assembly, etc. should be divided into different entities based on their connection relationships.

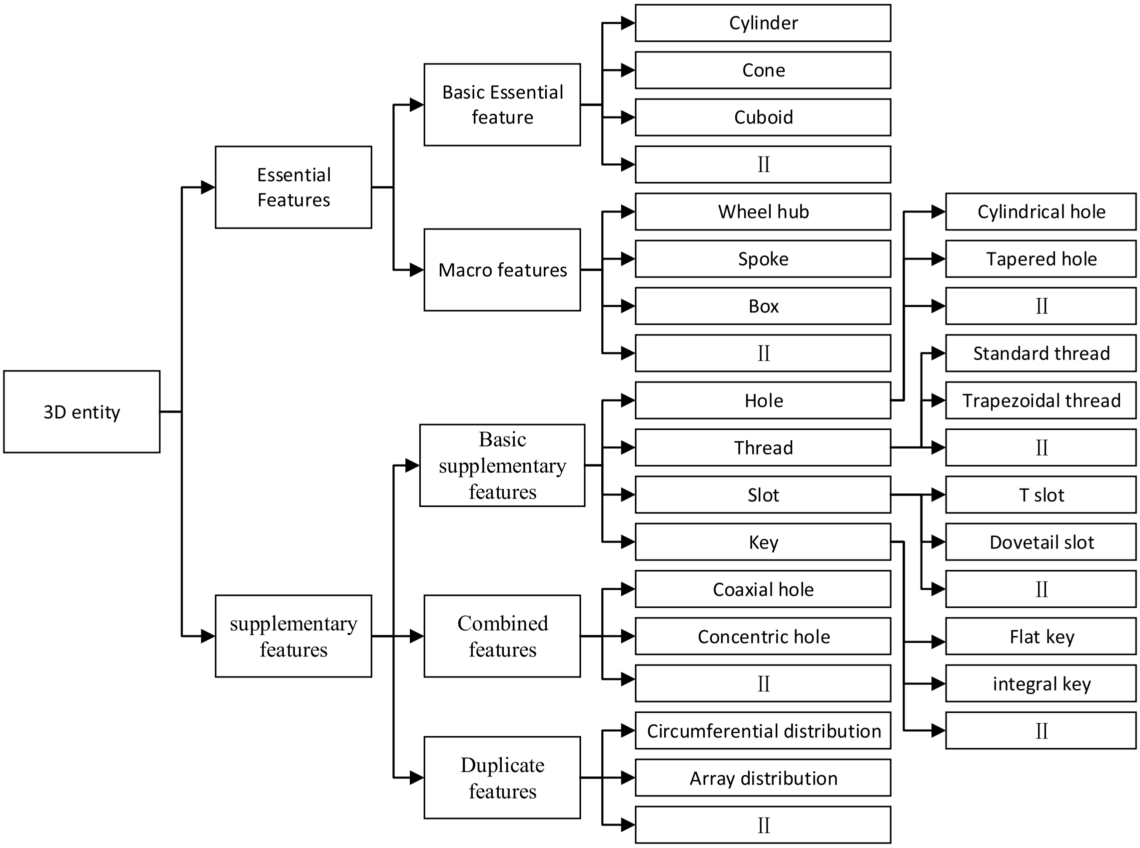

Fig. 1 Partition of component 3D entities

- Divide divided 3D entities into 2D features. Components are divided into sets of essential features and supplementary features according to the above two rules. Depending on the geometrical morphology, if the process information is not included in the features, all these features can be expressed by combinations of points, lines, and planes, i.e., these 3D features can be divided into combinations of 2D features, as shown in Fig. 2.
- The rule for special entity partitioning. Because some entities are too special to express them with rules in Figs. 1 and 2, the 2D feature division of these special entities can use the sweeping method to express the entities better on the 2D feature level.

According to the above rules, Figs. 1 and 2 show the division of component features and Fig. 3 shows the divided component feature structure.

So a product can be divided into 3D entities and these entities can be divided into many 2D features. The number of features can be calculated according to the following equation.

$$N_f = \sum_{j=1}^{n} \sum_{i=1}^{n_j} f_i.$$

Here, N_f denotes the total number of features divided by the product. n denotes the number of components. n_j denotes the number of entities divided by the component j. f_i denotes the number of features contained in the entity i, and the number of features is determined by the shape of the divided entity.

Similarly, the number of feature connections in a product can be calculated by the following equation.

$$N_c = \sum_{j=1}^{N_f} \sum_{i=1}^{N_f} \delta_{ij}.$$

Here, N_c represents the total number of feature connections. δ_{ij} denotes whether there is a connection between feature i and feature j. When i is connected to j, result of δ_{ij} is

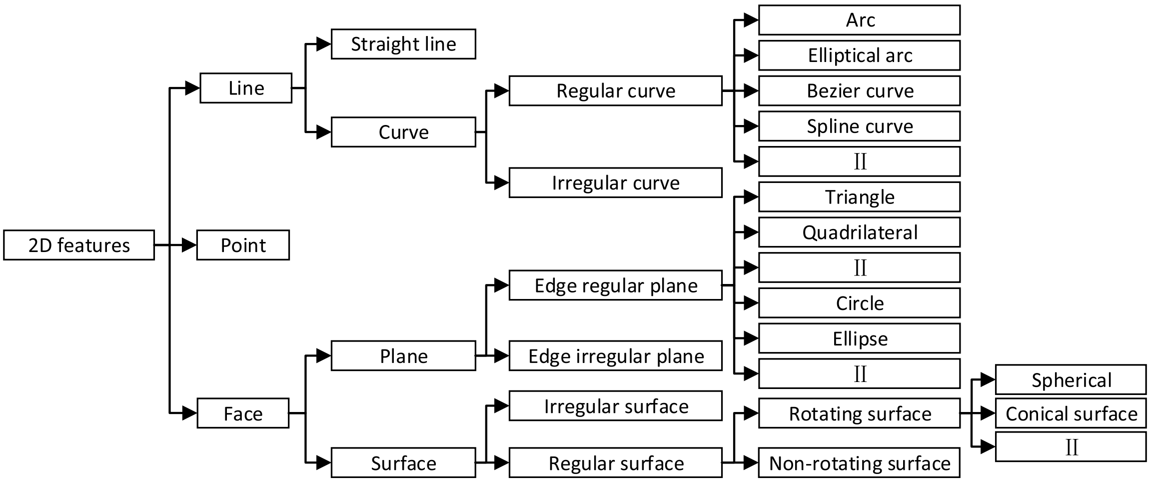

Fig. 2 Partition of component 2D features

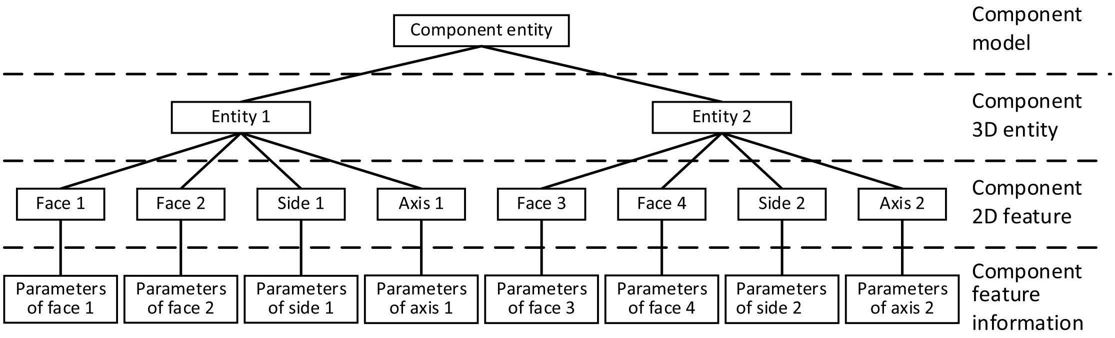

Fig. 3 Component feature partitioning structure

1. Otherwise, δ_{ij} is 0. While $i=j$, features cannot connected to itself, δ_{ij} is 0.

The total number of feature connections can also be expressed as two parts. One part is the connection within the divided 3D entity. the other part is the connection between these 3D entities, as shown in the following equation.

$$N_c = \sum_{j=1}^{N_f} \sum_{i=1}^{N_f} \delta_{ij} = \sum_{j=1}^{n} \sum_{i=1}^{n_j} c_i + \sum_{a=1}^{n_j} \sum_{b=1}^{n_j} w_{ab}.$$

Here, c_i denotes the total number of feature connections within the divided 3D entity. w_{ab} denotes the total number of feature connections between the divided 3D entity.

3.2 Construction of feature networks for complex products

In early stage, the research subject of complex networks is the human society. Sociologist Granovetter (1973) discussed that when people were looking for work, the general friends were more effective than the close friends. He defined the close social relationship as “strong tie” and the weak contact social relationship as “weak tie”. Haythornthwaite (2005) described the sociological differences between “strong tie” and “weak tie” in his paper. Similarly, based on the relationship between features, the physical connection relationship and the functional connection relationship between features can be defined as strong ties and weak ties, respectively. Strong ties mean two features connected with each other directly, for example, two features connected with each other by fit, coincidence, orientation, alignment, inclusion, etc. The spatial constraints of components and products can be described by the decomposed 2D features and strong ties between these 2D features. Weak ties can describe the implicit functions between feature connections, that is, the weak tie means a feature connection path that generates the implicit function through the strong ties, which is mainly represented by the physical function constraint of the feature parameter. The functions produced by the assembly of components can be described by weak ties.

Based on graph theory, the strong tie can be expressed as the following equation.

$$S_k = \{G, V, R\},$$

where, S_k denotes the k-th strong tie. $G = \{F_i, F_j\}$ denotes a 2D feature set associated with the strong tie S_k. F_i denotes the i-th feature and F_j denotes the j-th feature. $V = \{(F_i, F_j)\}$ denotes a feature connection set of S_k, (F_i, F_j) denotes the strong tie of feature F_i to feature F_j. While the connection is a strong tie, there are only two features and a connection in one strong tie. $R = \{R_{ij}\}$ is the geometric restriction set. Constraints R_{ij} in R are conditions for the connection. R_{ij} denotes the geometric restriction between F_i and F_j, such as, perpendicular, parallel, inclusive, incident, or intersecting, etc.

A 3D entity can be expressed by the coupling of multiple strong connections, i.e. $S_i \cup S_j \cup S_k \cdots$, so $G = \left\{F_i, F_j, F_k \cdots\right\}$ contains all 2D features divided from the 3D entity,$V = \left\{\left(F_i, F_j\right), \left(F_i, F_k\right), \left(F_j, F_k\right) \cdots\right\}$ contains all feature strong ties of these features and $R = \{R_{ij}, R_{ik}, R_{jk}\}$ contains all the constraints corresponding to strong ties.

Similarly, the weak tie can be expressed as the following equation:

$$W_k = \{G, V, T\},$$

where, W_k denotes the k-th weak tie, $G = \left\{F_i, F_j, F_l \cdots\right\}$ denotes a 2D feature set associated with weak tie W_k, Fi denotes the i-th feature, $V = \left\{\left[\left(F_i, F_j\right), \left(F_j, F_k\right), \cdots\right]\right\}$ denotes the feature connection path of weak tie W_k. A weak tie contains many feature and can be regarded as a chain of many "strong tie". $T = \left\{T_k\right\}$ denotes the functional constraints set., Constraints T_k in T is the functional constraints formed by between features G and their connection path V. For example, the weak tie of bolt and nut connection includes the tightening force between the threads and the friction between the nut and the surface of the workpiece.

Considering the strong and weak ties between features, after the product is decomposed into 2D features, it can be re-expressed by these strong and weak ties, as the following expression shows.

$$\left(S_i \cup S_j \cup S_k \cdots\right) \cup \left(W_a \cup W_b \cup W_c \cdots\right).$$

In the feature network, each node denotes a feature in a product. Strong and weak ties are used to show the structures and functions in feature granularity. Compared to other modelling method, although feature network has a large number of modelling elements, product information can be divided into each feature and more product information can be contained at the feature level. However, if the complex product consists of many components or some components are complicated, the number of the divided features and feature connections will be very large. While most features of the product are considered for calculation, large computing resources may be required, computation will be complicated and it is difficult to analyze some problems, such as calculating the whole product cost in the network.

The assembly of two plates with a hexagon bolt and nut is used as an example. The rule to partition components is used to compose the hexagon bolt, hexagon nut and two plates. For example, the plate can be divide into a plate with a hole, and these two features are the essential features and the supplementary features in 3D entities level, respectively. And the 3D entities can be divided into many 2D features. Similarly, the hexagon bolt and hexagon nut can be divided into 2D features, as shown in Fig. 4. The bolt and nut pairing consists of 4 components. By dividing these 4 components into 8 3D entities, 51 2D features are finally divided. There are 115 strong ties between these 2D features, and 3 weak ties are found in the product. Codes in Fig. 4 mean the division of these components and each code denotes a feature we obtained from the parts.

The divided features can be connected by strong ties and weak ties. The strong ties are used to express the positional relationship of divided 2D features and the weak ties are used to express the function of the assembly. The strong ties in the network are the feature connection between each other and the weak tie is the function of the bolt connection, which is from the bottom of the hexagon head of the hexagon bolt to the top of the hexagon nut. As shown in Fig. 5, the components can be modeled as a feature network. Each node of the network denotes a feature divided in Fig. 4 and the code on the node is the same as the code of the feature. The purple line in the network denotes the strong tie between two features and the black line denotes the weak tie formed by the feature connection path.

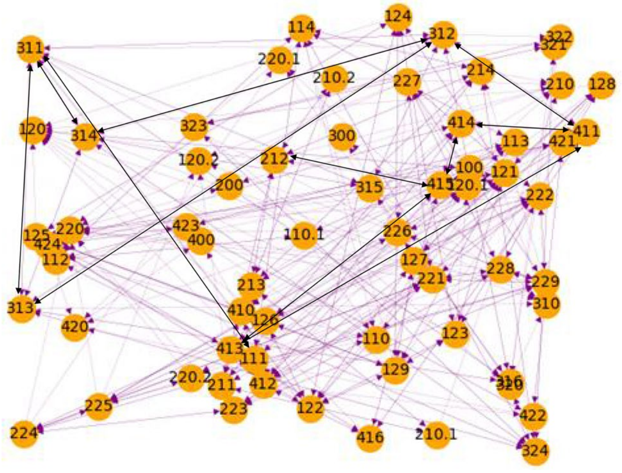

Fig. 5 Feature network of a bolt and nut assembly

4 Complex product design change propagation impact assessment

4.1 Change propagation model for complex product design

The change propagation becomes complex due to multiple factors, multiple dimensions. Therefore, it is difficult to make a precise prediction of change propagation in

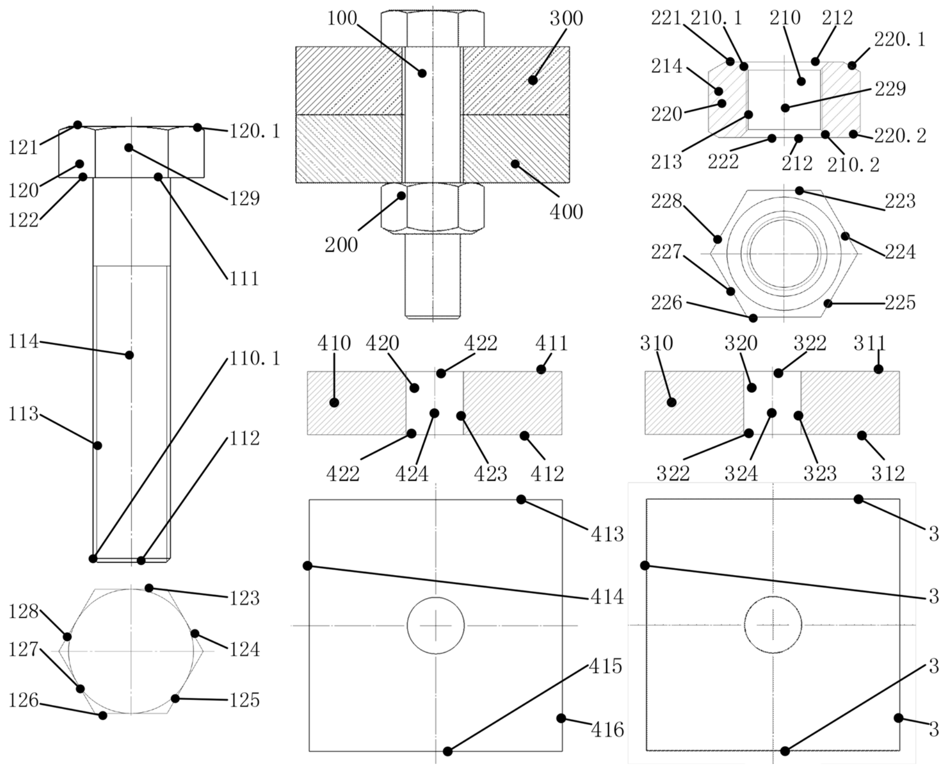

Fig. 4 Feature division of parts used in bolt connection

complex product design. By the methods mentioned above, the change impact of the product can be considered from feature level, and changes of features can be transformed into changes of nodes in the network, so change possibility may be predicted by considering the connection between product features and their change characteristic.

Although complex networks lacked research in the field of product design change propagation, the modelling of complex networks in the epidemic spread fully described the spread patterns of the epidemic and one of the models is the SIRS model which is used to describe the transformation pattern between the susceptible (S), the infected(I), and the recovered (R). Because of the different network structures, the results of the epidemic spread and the steady-state are also slightly different, such as the epidemic propagation of SIRS models in complex heterogeneous networks studied by Li et al. (2014) and the epidemic propagation in small-world networks.

The product feature change propagation pattern is similar to the epidemic spread in complex networks. Therefore, if the product feature network is modeled, the feature nodes can be described in three discrete states: normal state(S), change state(I) and change-prohibited state (R). Normal state nodes in the feature network denote the original features nodes in the product, which can be regarded as the susceptible in the SIRS model. Change state nodes denote the feature nodes that need to be changed, which can be regarded as the infected in SIRS model. Change-prohibited state nodes denote those feature nodes that cannot be changed in the network, which can be regarded as the recovered. Therefore, change propagation between features is similar to the epidemic spread in SIRS model.

Before the product design change occurs, all nodes in the feature network are normal nodes. Due to the new customer requirements, the product needs to be redesigned. Some features need to be changed in the original product. The first change features, that is, the source change features, can be marked by the designer. These features are all expressed as source nodes in the feature network, Change propagation in the network is caused by these source nodes. The source nodes may transfer their adjacent normal nodes into change nodes and the normal nodes which are adjacent to those changed nodes may be transferred into change nodes. Due to the tolerance set by designers, the features from component decomposition have the capability of change absorption. A normal node may transfer an adjacent node into change nodes with probability β. The probability β of each connected feature may be different from each other and the probability should be determined by rules and knowledge accumulated by experienced engineers. Different from normal nodes transferred to change nodes, change nodes may be transferred into change-prohibited nodes because the constraints or design requirements inside the feature and the change may not propagate to other nodes. Change nodes will be change-prohibited nodes with probability δ. Most of the initial change-prohibited features maybe some design benchmarks. As the change propagates, some features will be changed to change- prohibited features, such as features in weak ties, which are related to functions or features that designers think cannot be changed. Similar to change nodes transferred into change-prohibited, change-prohibited nodes may be transferred into normal nodes because of design requirements, and change-prohibited nodes will be transferred into normal nodes with probability γ. Similar to the probability β, the probabilityδandγshould be determined by rules and knowledge accumulated by experienced engineers. The change propagation model is shown in Fig. 6.

Because a product contains many information, such as structure, function and etc., the change propagation may not be analyzed from one dimension. Based on Function–Behavior–Structure (FBS) framework, Koh (2017) discussed change propagation by functional, behavioral, and structural dependencies between components. Design change is constrained by structural and functional constraints. And some functions of a product may be generated by the structure of the product. So model in the feature level can show the relationship, while the strong ties in the network show the structural relationship of features and the weak ties express the functional constraints formed by the structure of the product. When changes propagate in features connected be strong ties, the structure and shape of the product will be affected. And when features in weak tie are changed, many related features will be changed and some functions of the product may be changed.

4.2 Evaluation of change propagation for complex product design

From the change propagation model mentioned above, it is obvious that change propagation can end in two different ways.

In the first way, the change is gradually absorbed through a series of nodes until there is no further impact

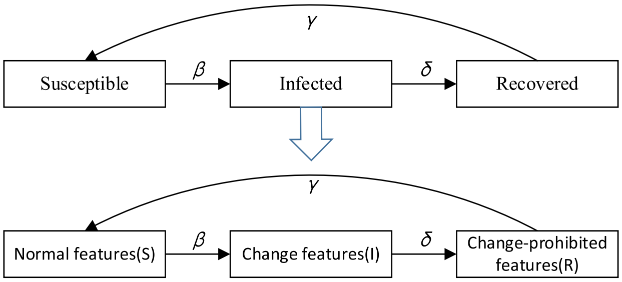

Fig. 6 Change propagation model of product features

in the propagation path. Due to the machining tolerance set during the design process, the features of a component have the capability to absorb the change. The change probability of feature change propagation will decrease as the length of the change chain increases. The change in component feature nodes will be fully absorbed before reaching the change-prohibited node. The propagation probability can be expressed as Eq. (1).

$$p_{ij} = \prod_{k=1}^{n-1} \beta\left(F_k, F_{k+1}\right) = \prod_{l\in M} \gamma_l \prod_{k=1}^{n-1} \beta_{k(k+1)}, \tag{1}$$

where, F_k denotes the k-th feature of components, which is a feature node in the feature network. p_{ij} denotes the change possibility propagated from F_i to F_j. n denotes the number of features propagated from F_i to F_j. $\beta(F_i, F_j)$ denotes the probability that the change in feature F_i leads to a change in feature F_j and changes from change-prohibited nodes to normal nodes are included. β_{ij} denotes the probability that the change in feature F_i leads to a change in feature F_j directly. When $i = j$, the change in a feature cannot propagate to itself, i.e. $\beta_{ij} = 0$. M denotes the set of change-prohibited nodes transformed into normal nodes on the propagation path. l is the l-the node transformed into a normal node in M. γ_l denotes the probability that a change-prohibited node is transformed into normal nodes.

In the second way, the change propagation would reach the change-prohibited node. In this way, the change must be eliminated when the change propagates from the source node to the change-prohibited node. If the change cannot be eliminated when the change propagation reaches the change-prohibited node. Redesign of the product will fail because features are incompatible, so the entire change chain may be considered again. In the network, functions of the product are shown by weak ties. While the change propagates through weak ties, the end feature of the weak tie could be transferred into the change-prohibited state, the change propagation will end at the end feature of the weak tie. In this case, the propagation probability can be expressed by Eq. (2).

$$p_{ij} = \prod_{k=1}^{n-1} \beta\left(F_k, F_{k+1}\right) = \delta_j \prod_{l\in M} \gamma_l \prod_{k=1}^{n-1} \beta_{k(k+1)}, \tag{2}$$

where, δ_j denotes the probability that the change of j-th node propagates to the change-prohibited nodes.

Change may propagate from F_i to F_j through multiple pathways, as Fig. 7 shown. Each pathway may propagate the change from F_i to F_j. So the propagation probability can be expressed by Eq. (3).

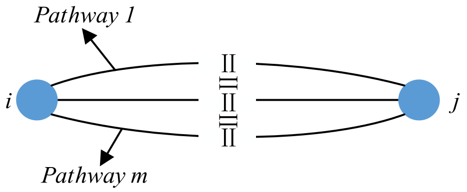

Fig. 7 Change propagates through multiple pathways

$$p_{ij} = 1 - \prod_{k=1}^{m}\left(1 - p_{kj}\right) = 1 - \left(1 - p_{ij}\right) \cdots \left(1 - p_{mj}\right). \tag{3}$$

Here, p_{ij} denotes the propagation probability that change propagate from Fi to Fj through multiple pathways. m denotes the number of paths that change propagates from F_i to F_j. p_{kj} denotes the k-th pathway to propagate the change.

Considering the change propagation in the network, numbers of three types of nodes in the network at the j-th step can be denoted as $S(j), I(j), R(j)$. The total number of nodes in the network is $N(j) = S(j) + I(j) + R(j)$. Although the similarity between SIRS model and the change propagation model proposed in this paper was clarified in Sect. 4.1, the product feature network do not have the random connection and the change of various nodes is different from the SIRS model. The number of these nodes during the change propagation process in the feature network can be described as Eq. (4) shown.

$$\begin{cases} \Delta S(j) = S(j) - S(j-1) = -\sum\limits_{a=1}^{S(j-1)} \beta_a \langle k_a \rangle + \sum\limits_{b=1}^{R(j-1)} \gamma_b \\ \Delta I(j) = I(j) - I(j-1) = -\sum\limits_{c=1}^{I(j-1)} \delta_c + \sum\limits_{a=1}^{S(j-1)} \beta_a \langle k_a \rangle \\ \Delta R(j) = R(j) - R(j-1) = -\sum\limits_{b=1}^{R(j-1)} \gamma_b + \sum\limits_{c=1}^{I(j-1)} \delta_c \end{cases} . \tag{4}$$

Here, $\Delta S(j), \Delta I(j), \Delta R(j)$ denote the change value of nodes S, I, R, respectively. $\langle k \rangle$ denotes the degree of feature nodes and subscript denotes the corresponding node. β_a denotes the number of change nodes changing from normal nodes. γ_b denotes the number of normal nodes changing from change-prohibited nodes and its value is 0 or 1. δ_c denotes the number of change-prohibited nodes changing from nodes change and its value is 0 or 1.

Many people used many metrics show the characteristics of design change in the product, for example, Koh et al. (2015) used the engineering change forecast (ECF) matrix to show the component dependency and based on the ECF matrix, ECF index is used to assess the priority of each component to be made more modular in Koh et al. (2015). In this paper, the density of different types of nodes is used to show the changing status of this change propagation. The normal density can be denoted as $\rho_S = S(j)/N(j)$, which denotes the proportion of normal nodes to the total nodes at the j-th step of the design change propagation. The stability of the initial design can be assessed by this density. The density of change nodes can be denoted as $\rho_I = I(j)/N(j)$, which represents the proportion of change nodes to the total nodes at the j-th step of the design change propagation. The impact of change in one redesign can be evaluated. Similarly, the density of change-prohibited can be denoted as $\rho_R = R(j)/N(j)$, which represents the proportion of nodes in the change-prohibited state to the total nodes at the j-th step of the design change propagation. The impact of change caused by human design factors can be evaluated. When the product change propagation reaches a steady-state, all nodes turn into normal nodes. In this situation, the changing density is taken as $\rho_I = 0$ and the change-prohibited density is taken as $\rho_R = 0$.

The product feature network is built by the divided features of product components. Therefore, it can be analyzed and evaluated by relevant indicators of complex networks. Here, the properties of node degrees are selected to evaluate the impact of change propagation. For the change propagation of network nodes is a dynamic process, the changes in network nodes are transmitted across the edges. During the change propagation process, the affected characteristics of nodes can be described by in-degree and out-degree of nodes. Hence, the in-degree $ID_i(k)$ denotes the number of other features that affect the i-th feature in the change propagation process. Likewise, the out-degree $OD_i(k)$ denotes the number of other features that are affected by the i-th feature, which is also the number of nodes that turn into change nodes. The number of normal nodes in the network that turn into change nodes during the propagation from step k-1 to step k can be expressed as $\Delta I(k) = \sum_{i=0}^{k} \Delta I_i(k) = I(k) - I(k-1)$. During the propagation, the change amount of change density can be denoted as $\Delta\rho_I = \Delta I(j)/N(j)$. The change density can then be expressed as the sum of these change amounts, which is $\rho_I = \sum_{i=0}^{k} \Delta\rho_I(i)$.

The in-degree and out-degree of nodes can also reflect the property to impact other nodes. If $ID_i(k) = 0$ and $ID_i(k) > 0$, the feature node will cause the change of other nodes without being affected by other nodes, i.e., the feature node is the source of propagation. If $ID_i(k) > 0$ and $OD_i(k) = 0$, the feature node will no more cause the change of other nodes, i.e., the change will be fully absorbed by this node and end at this node. From the above illustrations, it is obvious that out-degree of nodes is closely related to the increase in the change density of the network. However, it only describes the increase in change density of the entire network without accurately describing the impact on the change density of each node. Hence, $K_i = OD_i - ID_i$ should be taken into consideration and the impact can be evaluated by the difference between in-degree and out-degree. When $K_i > 0$, the change of this node will cause multiple nodes to change. The change diverges at this node and the degree of increase in the change amount of change density demonstrates an increasing trend. When $K_i < 0$, multiple nodes will cause this node to change and the change will contract at this node. An increase in the change value tends to decrease the change density.

The change propagation index(CPI) was defined by Suh et al. (2007) to classify different elements. And CPI was also defined to classify nodes with different properties (Giffin 2007). To describe the growing trend of changing density, in-degree and out-degree of a node should be normalized according to the definition of CPI proposed by Giffin (2007), as shown in Eq. (5). The ratio of the difference and sum between in-degree and out-degree are calculated and denoted as CPI, which lies in the range of − 1 to 1. Considering the propagation properties of the network, when $-1 < C_i < 0$, the change in this node is caused by change in multiple nodes and the change shrinks at this node. When $Ci = -1$, the propagation ends at this node. When $0 \leq C_i < 1$, the change in this node causes other nodes to change and the change diverges at this node. Finally, when $Ci = 1$, the propagation starts from this node. The change propagation path, scope, and degree of impact on the nodes can be evaluated if change propagation probability, change density and CPI are taken into consideration.

$$C_i = \frac{OD_i - ID_i}{OD_i + ID_i}. \tag{5}$$

5 Case study

A pumping unit is taken as an example to verify the proposed method in this paper. The pumping unit consists of 225 parts and its assembly model is shown in Fig. 8. The components of the pumping unit are divided into 2D features based on the feature Partitioning rules in Sect. 3.1. By dividing these 225 components into 727 3D features, 3606 2D features are finally divided. There are 8978 strong ties between these 2D features, and 157 weak ties are found in the product. The model of the pumping unit is expressed by the features and strong ties, and weak ties are used to express the product function. Finally, the feature network of the pumping unit can be modelled. A part of the pumping unit feature network is shown in Fig. 8. Each node in Fig. 9 denotes a 2D feature of the pumping unit components. Nodes with different colors denote features of different components. And the blue lines

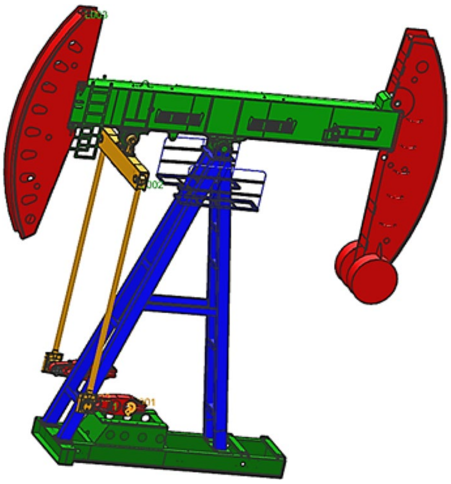

Fig. 8 Assembly model of pumping unit

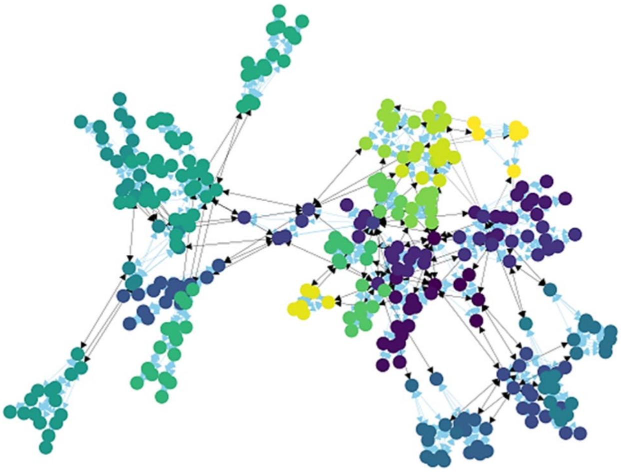

Fig. 9 A part of the pumping unit feature network

between nodes denote strong ties between features, and the black lines denote weak ties between features.

In Fig. 9, it can be seen that connections of features within a component are more complicated than the connections among components. Usually, few features are involved in the connections among components, and these features are included in the weak ties within the product. It seems that the feature connection rules in the feature network are the same as those in reality.

The impact of network changes can be evaluated based on the study of product feature network change propagation. Whether a designed feature can be defined as a "change-prohibited feature" depend on whether the change in design has a significant impact on the desired functions of the physical structure. Initial change-prohibited features can be some design benchmarks. As the change propagates, according to specific design requirements, some features, which designers think do not need to be changed, will be changed to change-prohibited features. These features can be some features in strong ties or in weak ties. For example, if designers want to change some structures that do not affect the structure of a function, such as the logo of the product, features in weak ties can be changed into change-prohibited features. If the designers do not want to change some structures and functions, such as maintaining the appearance and adjusting internal structure of the product, even if designers set the function remains unchanged, the changed feature will affect the features in the weak tie and the function may be changed. At this time, the features in weak ties need to be changed to meet the functional requirements and they cannot be set as the change-prohibited features. Therefore, whether features can be defined as change-prohibited features depends on whether the change of them affects the specific design requirements on the functions. Moreover, it is less likely that change-prohibited nodes can be converted into normal nodes, and changed nodes are less likely to be changed to change-prohibited nodes because change-prohibited nodes contain some design constraints set by designers. Due to lacking a large number of change cases and experienced engineers, the propagation probabilities between features cannot be obtained in detail, so the propagation probabilities in the model are assumed to be $\rho = 0.5$, $\beta = 0.5$, $\lambda = 0.5$. Although the benchmark and some features that designers think cannot be changed can be viewed as the change-prohibited features in design, these features are only a small part of overall features. it is assumed here that the ratio of the change-prohibited nodes to the overall features is about 0.1.

The circular hole of the connecting bracket and the circular hole of the connecting rod are selected as the starting features to propagate the design change. The probability of the change propagation can be calculated by using the method mentioned in Sect. 4. If the length of the propagation chain is controlled within seven. the probability distribution can be obtained, as shown in Fig. 10. If change propagates through one pathway, the longer the propagation path is, the lower the change probability is, and if changes propagate

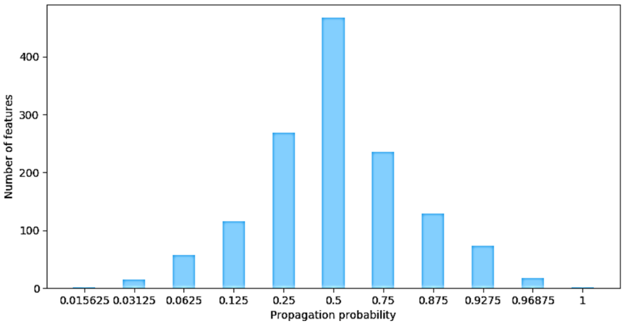

Fig. 10 Propagation probability distribution of change propagation

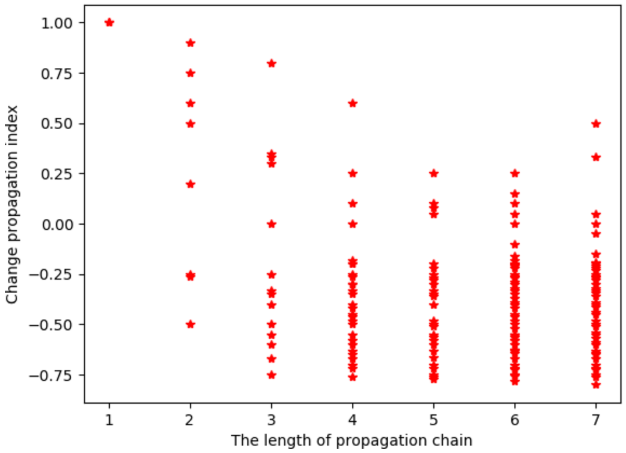

Fig. 11 CPI of nodes during the change propagation process

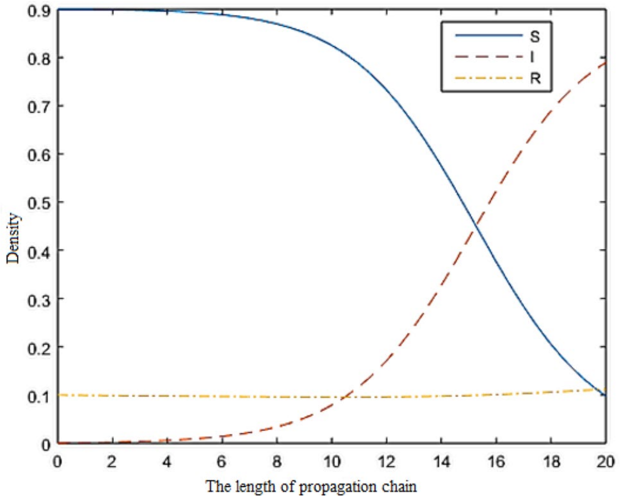

Fig. 12 Density changes of various nodes during the change propagation process

through multiple pathways, the propagation probability of feature will increase. And in the product, more features are connected with each other in through a property, such as length, width, diameter, and so on. Most of the structural change will only propagate one step. If structural changes affect the function and stiffness of the product, the propagation chain will be longer.

And CPI of each feature can be computed, as shown in Fig. 11. Nodes in Fig. 11 denote the CPI of each feature during the change propagation process. CPI of source change nodes are 1, and source change nodes will affect their adjacent nodes. As change propagates, the change will shrink in more and more nodes. And the longer the propagation path is, the more obvious the contraction tendency of the node change impact.

The density change of various nodes during the change propagation process can be calculated, as shown in Fig. 12. According to the connection between the features, the features would affect each other. If change cannot be absorbed, minor changes will change the whole product and change propagation eventually be stable by the large-scale change of the product.

6 Conclusion

With the wide application of digital technology, the research on product models has shifted from components to features, so products can be expressed not only by voxels and boundaries but also by complex and dynamic networks of features which can contain information about structure, function and process. The change propagation of products studied in this paper is based on features. To model the feature network of the product, a partitioning rule for component features is given based on CAD models. The definitions of strong ties and weak ties in the network are proposed by the connection relationship between the features. On the basis of the network, two types of change propagation modes are proposed by referencing the SIRS model in complex networks. Change propagation can be evaluated by the possibility and propagation impact in the feature network, so the efficiency of decision-making can be enhanced.

Based on the product feature network, relevant research may be further carried out in the future, for example, processing technology and cost can be combined with product feature network to form a complete evaluation system for the decision-making of product design change. Based on customer requirements, the personalization of the same product will become possible. Combined with advanced technologies, such as 3D printing technology, these methods may be used to make decision optimizing defective products or repairing damaged products.

Acknowledgements This work was supported by National Natural Science Foundation of China [Grant No. 51505286] and Shanghai Key Lab of Advanced Manufacturing Environment.

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