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Developing a parameter linkage-based method for searching change propagation paths

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Abstract Changes are unavoidable during the product evolution process, and the propagation of changes leads to an augmentation of the design complexity. The acquisition of an optimal change solution provides a significant challenge for designers due to the non-uniqueness of change propagation paths. This paper aims to develop a method to search for change propagation paths. A product model from the parameter linkage perspective is constructed, through which the propagation mechanism of changes is analyzed. Then, a searching method is proposed based on the product model and change propagation mechanism. It is found that the parameter linkages in designs can be organized in a structured manner with two types of parameter linkages, and the change propagation is an alternate process of influence diffusion and change routing. A case study presented in this paper indicates that this method can provide support for the searching and optimal selection of change propagation paths.

Keywords Change · Change propagation · Parameter linkage · Parameter linkage network model · Influence diffusion · Change routing · Searching of change propagation paths

1 Introduction

Design changes are key driving factors of product evolution. An effective and controlled design change is helpful to satisfy customer requirements, reduce product defects, improve product quality, and promote product innovation (Eckert et al. 2004). Given the complexity of product operation mechanisms and the extensive connections within the product, design changes may lead to change propagation, i.e., a change to one part of a system will trigger a series of changes in other parts. Change propagation may bring the potential risk of jeopardizing the integrity of the whole product. However, a recent study by the Aberdeen Group (Brown 2006) shows that only a few companies are able to assess the consequences of changes properly. If the designer can predict the path, scope, and risks of the change propagation before a change takes place, and find the optimal change solution based on the propagation analysis result, the change risks can thus be reduced or prevented, so that the quality of the design change can be assured.

In general, the studies of change propagation can be summarized into the following three aspects:

1. Phenomenon of change propagation

Eckert et al. (2004) describe the change propagation systematically based on a case study of a helicopter manufacturing company, including the description of linking parameters as the causes of propagation and the classification of propagation arising from it. Giffin et al. (2009) analyze the historical change data of a complex technical system, decompose the change network into three types of motifs, and develop a set of indices to identify propagation properties in different areas of the system. Martin and Ishii (2002), in the study on product platform architectures, point out that the specification flow between the components causes the change propagation and develops the coupling index to assess the propagation properties of the components.

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2. Evaluation of change influence

Cohen et al. (2000) propose the C-FAR method to compute the change impact in terms of fixed change propagation paths. The attribute associations between different entities are recorded in C-FAR matrixes and are used to predict the change impact of one attribute on another. Ollinger and Stahovich (2001) represent the causal relationship between physical quantities in a directed graph, which can be used to predict qualitatively the variation of target quantity caused by exogenous quantity. Samling and de Weck (2007) develop a component-based change design structure matrix (DSM) to assess quantitatively the amount of design changes required to accommodate the new technology.

3. Prediction of change propagation risk

Clarkson et al. (2004) propose the change prediction method (CPM) to predict the risks of change propagation in terms of likelihood and impact of the change. They then develop a prototype computer support tool to calculate the propagation risks for a specific product. The model characteristics-properties modeling/property-driven development (CPM/PDD), used to represent the relationships between characteristics and properties, is combined with FMEA methodology to analyze the propagation path triggered by the property change and to assess the potential risks (Conrad et al. 2007; Kohler et al. 2008).

Simon (1996) points out that the complexity of a product comes from the connections between its parts, and engineering products are "almost decomposable systems" because their connections can never be fully avoided. Here, we use the term linkage, which is firstly used by Cohen et al. (2000) and then is used by Jarratt et al. (2004), to mean connection, association, or relationship within the design. Linkages in designs are the medium of change propagation. There are multidisciplinary, multi-level design linkages, which disperse in different computing models, design documents, and designers' brains. In order to analyze change propagation from a global perspective, designers should collect these design linkages and integrate them together. Therefore, scholars have proposed new product models to integrate multidisciplinary design linkages and express their change relationships.

These product models can be classified into models of component linkages and models of parameter linkages. In this paper, parameter is the synonym for property, characteristic, attribute, or physical quantity appeared in other works. Parameter is the most basic object in designs, and the daily engineering decision making deals chiefly with the determination of engineering values of parameters (Rouibah and Caskey 2003). Parameter linkage refers to the relationship between parameters. The representations of parameter linkages are various in models of parameter linkages. Component refers to all levels of nodes in product structures, including system, sub-system, assembly, and part. A component has many parameters, and component linkage is the generalization of parameter linkages between two components. DSMs are commonly used to represent component linkages in models of component linkages (see Steward 1981; Browning 2001). Jarratt et al. (2004) discuss the associations between component linkages and changes and give a comprehensive classification of component linkages. The product models for changes are summarized in Table 1. Because of the differences in product models, the descriptions of propagation phenomenon and the analysis methods for propagation are dissimilar in these studies.

This paper tries to develop a method for searching change propagation paths from the perspective of parameter linkages to help designers search and find optimal change solutions. It first constructs a product model based on parameter linkages and then discusses the propagating mechanism of changes through the product model, finally derives the searching method according to the product model and propagating mechanism.

There are various parameters in the design and the linkages among them are complex. In order to reflect the hierarchical structure and reveal the propagation features of the parameter linkages, a new categorization of the parameter linkages is proposed to sort out and integrate various parameter linkages in the design and based on which a new product model—the parameter linkage network (PLN) model—is constructed.

When we observe the change propagation intuitively, there seems to be two different types of change propagation, i.e., the subsequent changes decided by designers and the subsequent changes caused by the internal relationships of the design. On the other hand, change propagation is dynamic and emanative in nature as there are multiple change solutions for one change, which may break different

Table 1 Summary of product models for changes in related works

Model of component linkage	Model of parameter linkage
Design structure matrix (Clarkson et al. 2004; Eckert et al. 2004, 2006; Samling and de Weck 2007; He et al. 2008; Giffin et al. 2009)	General relationships between attributes of entities (Cohen et al. 2000) Causal relationship between physical quantities (Ollinger and Stahovich 2001) Mapping relationship between characteristics and properties (Conrad et al. 2007; Kohler et al. 2008) Association between component interface parameters (Martin and Ishii 2002)

linkages within the design and bring different change impacts. The generating process of the changes in change propagation is critical for the searching of change propagation paths. In order to explain these phenomena, this paper analyzes the propagating mechanism of changes based on the product model proposed and establishes the theoretical basis for the development of the searching method.

Considering the non-uniqueness of change propagation paths, the searching method needs to solve problems like searching for possible change propagation paths and finding the optimal path from these paths. According to the product model proposed and the propagating mechanism explained, this paper proposes a searching method for possible change propagation paths and puts forward the idea that evaluates the paths and select the optimal path according to the change propagation scope, the change impact, and the change expense of the paths.

The remainder of the paper is structured as follows. The derivation and features of the product model are described in Sect. 2. The propagating mechanism of changes in the product model is explained in Sect. 3. The searching method of change propagation paths and its application in the change of a clutch design is discussed in Sect. 4. The paper ends with conclusions.

2 Parameter linkage network model for change propagation analysis

This section categorizes the parameter linkages of the design into two types, discusses their propagation features, and proposes a structured product model called PLN model for the study of change propagation.

2.1 Types of parameter linkages

In the product design, designers utilize and combine physical laws flexibly to produce artifacts for people's special requirements. Therefore, the parameter linkages in the design can be classified into two categories, i.e., the parameter linkages determined by physical laws and the parameter linkages configured by designers.

2.1.1 Fundamental linkage and its propagation features

The parameter linkages determined by physical laws are intrinsic relationships between parameters, which are named fundamental linkages in this paper. The fundamental linkage is composed of a parent parameter and several child parameters. The parent parameter is a dependent parameter whose value is determined by those independent child parameters according to the rules of physical laws. For example, a fundamental linkage exists between acceleration, force, and mass of an object. The acceleration is the dependent parent parameter whose value is determined by mass and force as independent child parameters according to Newton's second law. A fundamental linkage exists between deformation, force, material characteristics, and geometry of a part. The deformation is the dependent parent parameter whose value is determined by geometry, force, and material characteristics as independent child parameters according to material mechanics.

The fundamental linkage can be represented as $y = f(X)$ where y is the parent parameter, $X = (x_1, x_2, \ldots, x_i, x_n)$ is the vector of child parameters, and f is the rule of the relation. The graphical notation of the fundamental linkage is shown in Fig. 1, and the simplified notation is used when the simplified form is better for depiction or the explicit form of relation is hard to express.

The propagation feature of the fundamental linkage is shown in Fig. 2. A change to a child parameter will not impact other child parameters because of their mutual independence, but will cause the parent parameter to change according to the rule of relation; a change to the parent parameter cannot be implemented directly and should be translated into a change to its child parameters, which should be balanced and decided by designers. For example, the strength of a part is determined by its geometry parameters and material characteristics. A change to a material characteristic will impact the strength parameter, while the geometry parameters are not influenced as independent parameters; a change to the strength cannot be implemented directly but should be translated into a change to a material characteristic or a geometry parameter.

2.1.2 Constraint linkage and its propagation features

The parameter linkages configured by designers are the relationships set up by designers artificially for the purpose

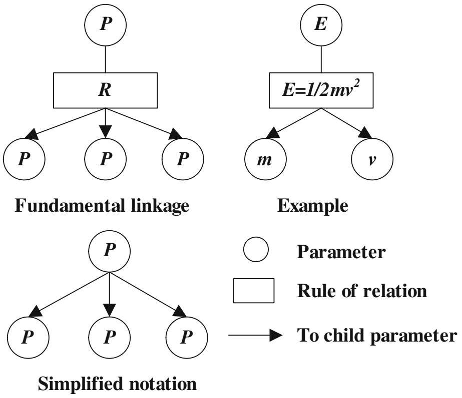


Fig. 1 Representation of the fundamental linkage

of part assembly, interface matching, performance guarantee, or function combination, which are named constraint linkages in this paper. For example, the diameter of a shaft is required to be slightly larger than the inner diameter of a bearing for the interference fit between them; the actual stress of a part is required to be smaller than its allowance stress for the security requirement of the part; the output power of a motor is required to be equal to the input power of an equipment for interface matching and so on.

The constraint linkage can be represented as $g(X) \geq 0$, where $X = (x_1, x_2, \ldots, x_i, x_n)$ is the vector of constrained parameters, g is the rule of relation. The value of $g(X)$ indicates the status of the linkage. As the constraint parameter can be changed independently, the satisfaction of $g(X) \geq 0$ cannot be ensured. The graphical notation of the constraint linkage is shown in Fig. 3, and the simplified notation is used when the simplified form is better for depiction or the explicit form of relation is hard to express.

The propagation feature of constraint linkage is shown in Fig. 4. The status of the linkage is consistent with the preset status before the constrained parameter is changed; then, a change to a constrained parameter breaks the consistency between the current status of the linkage and the preset status; hence, other constrained parameters in the constraint linkage should be changed, so that the status can be adjusted to be consistent with the preset status again. For example, the diameter of a shaft is slightly larger than the inner diameter of a bearing for the interference fit between them. When the diameter of the shaft is changed to a smaller value, the status of the linkage can no longer satisfy the matching requirement, and therefore, the inner diameter of the bearing should be changed, so that the status is consistent with the matching requirement again.

2.1.3 The transformation of constraint linkages into fundamental linkages

Parameters in fundamental linkages are related to each other inherently, so designers cannot change the linkages at random, while parameters in constraint linkages are connected by designers factitiously relying on their knowledge to realize specific function or behavior. If we use y to represent $g(X)$ in constraint linkages, i.e., to introduce a new parameter y as the parent parameter, and take X as the vector of child parameters, then the constraint linkage can be represented as $y = g(X) \geq 0$, which has the same expression as the fundamental linkage, as shown in Fig. 5.

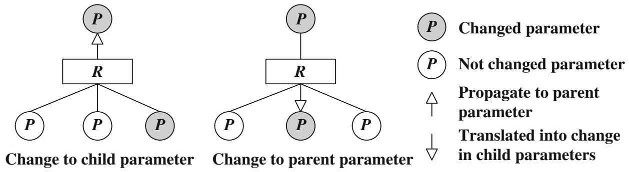


Fig. 2 Propagation feature of fundamental linkage

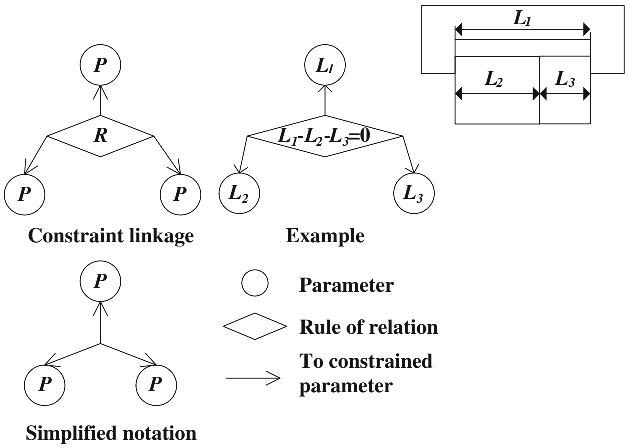


Fig. 3 Representation of constraint linkage

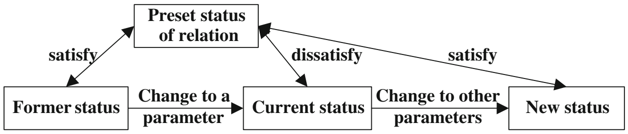


Fig. 4 Propagation feature of constraint linkage

The propagation analysis changes as the constraint linkage is transformed into a fundamental one. Take the linkage in Fig. 5 as an example. When L_1 is changed, the analysis process in the left part of Fig. 5 is that L_2 or L_3 should be changed to keep the linkage in the preset status. The analysis process in the right part of Fig. 5 is that a change to L_1 causes ΔL to change, but the value of ΔL should be 0, so an active change to ΔL is initiated to ensure the value of ΔL. ΔL being a parent parameter, the change to it should be translated into a change to L_2 or L_3. The comparison of these two processes is shown in Fig. 6.

2.2 PLN model

2.2.1 Composition of the PLN model

The parameter linkages in designs are connected with each other through common parameters and constitute a product model that is called the PLN model in this paper.

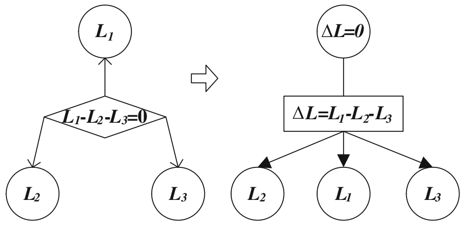


Fig. 5 Transformation of constraint linkages into fundamental linkages

The fundamental linkage is a kind of directional linkage as the propagation of the parent parameter is different from that of the child parameter. However, the constraint linkage is a kind of non-directional linkage as the propagation of each constrained parameter is similar. Therefore, the PLN model composed of both directional fundamental linkages and non-directional constraint linkages has a motley structure. If the constraint linkages are transformed into fundamental ones, a PLN model composed of simplex fundamental linkages can be obtained, which has a clearer hierarchical structure. Correspondingly, the change propagation can be analyzed with a single manner. Figure 7 shows the comparison of these two kinds of models, which are elicited from the bending resistance design of a cylinder, where the actual stress of the cylinder wall is restricted to be smaller than the allowable stress. In the following research, all the constraint linkages are transformed into fundamental linkages for the convenience of propagation analysis.

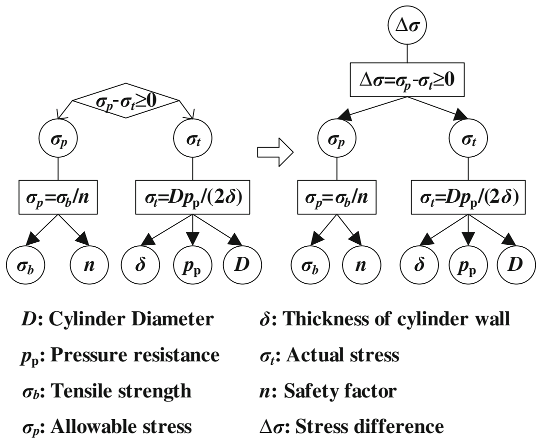


Fig. 7 The comparison of models before and after transformation

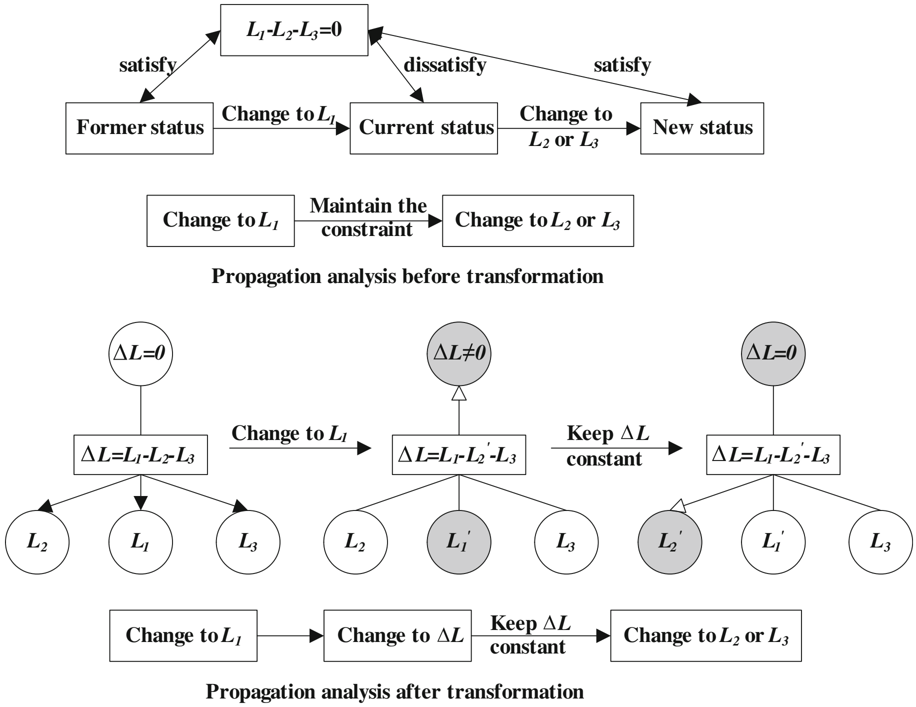
The parent parameter and child parameters in the fundamental linkage are two kinds of roles of a parameter. A parameter can be both a child parameter in one fundamental linkage and a parent parameter in another, like the parameters σ_p and σ_t in Fig. 7. A parameter can be a child parameter in multiple fundamental linkages, but can only be a parent parameter in one fundamental linkage. The parameter being a child parameter in multiple fundamental linkages is called a coupled parameter, as the fundamental linkages involving it are coupled together. Parameters in the PLN model can be divided into two groups, i.e., parameters which are both parent parameters and child parameters, and parameters which are only parent parameters or child parameters. The parameters having a single role form the boundary of the model.

Parameter linkages in designs may come from various disciplines and have different meanings; the PLN model integrates all of them through simplex fundamental linkages. It provides a good model basis for the parameter linkage-based change propagation analysis.

2.2.2 *Construction of the PLN model*

The construction of the PLN model is an important preparation work as the change propagation analysis needs to

Fig. 6 The difference in propagation analysis before and after the transformation



be implemented in the model. In order to ensure the accuracy and integrity of the analysis, designers need to capture parameters and their linkages as comprehensively as possible from the design.

The parameters and their relationships are definite and non-ambiguous; therefore, there is a unique PLN model corresponding to the design. However, in the real design process, it is difficult to acquire because of the following reasons:

1. Designers can rarely acquire the whole knowledge about parameter linkages. Generally, their knowledge increases along the product evolution and the PLN model approaches entirety continuously.
2. The knowledge of parameter linkages generally disperses in different departments or designers; it is unavoidable to omit some parameter linkages.

One important piece of daily work for designers is to analyze the relationships between the parameters and to decide the engineering values of the parameters; therefore, designers are capable of obtaining the main parameter linkages of the design, which are sufficient to ensure the accuracy of the change propagation analysis. The missed or undiscovered linkages can be integrated into the model at any moment during the evolution of the model along the product life cycle.

A working team consisting of designers from different disciplines is necessary to capture various linkages. The team can take the top-down manner or enumeration manner or both to capture parameter linkages. If the team takes the top-down manner, they should find the top level parameters first and then find the child parameters recursively until the bottom level parameters are found. If they take the enumeration manner, they should list all the known parameter linkages and then integrate them into a single PLN model. Methods like brainstorming and mindmapping are beneficial to collect linkages. Similar design cases, technology literatures, and other design data are useful references. During the construction process, two questions can be used as guidelines to avoid omitting important parameter linkages: (1) Which parameters belong to this linkage? (2) What linkages does this parameter join?

There may be some differences among models built by different teams considering the possibility of omitting some parameter linkages. However, these models are compatible with each other on the premise that there is only one correct interpretation for a parameter linkage and designers have the correct understanding of a specific parameter linkage. In nature, these models are all captured from different parts of the unique global PLN model.

2.3 A case of PLN model

This section shows a PLN model captured from the design of a pre-extended single acting cylinder. Figure 8 shows the schematic diagram of the pre-extended single acting cylinder. The PLN model is constructed according to the design formulas of the cylinder (Cheng 2010).

Figure 9 shows the sub-PLN model of the output force design. The theoretical output force of the cylinder is the difference between the air pressure and the counterforce generated by the spring; meanwhile, the spring provides a restoring force for the piston reset.

In order to ensure the working stability of the cylinder, the piston rod cannot be bended under the effect of disturbing forces. Hence, the maximum axial force of the piston rod should be smaller than the theoretical axial limit force. Figure 10 shows the sub-PLN model for the working stability design of the cylinder.

The design of the air inlet port should ensure that there is enough air to push the piston, the intake flow rate thus should be equal to the cylinder displacement. Figure 11 shows the sub-PLN model for the air inlet port design.

The sub-PLN models shown in Figs. 7, 8, 9, 10, and 11 can be integrated into a single PLN model that describes the parameter linkages in the cylinder design, as shown in Fig. 12. This model is only one part of the global PLN model for the cylinder design, but it has included the main parameter linkages and can be expanded to join more parameter linkages.

2.4 Classification of parameters in the PLN model

The PLN model shows how parameters in the bottom layer determine parameters in the top layer. According to their different roles in the propagation of changes, the parameters can be classified into direct parameters, target parameters, and transition parameters.

1. Direct parameters lie on the bottom of the PLN model, including geometry (like diameter, stroke, thickness, and length), material characteristics (like elastic modulus, allowable stress, and stiffness), safety factors, and environmental parameters (like pressure, temperature, and air velocity) (Andreasen and Hein 1987).

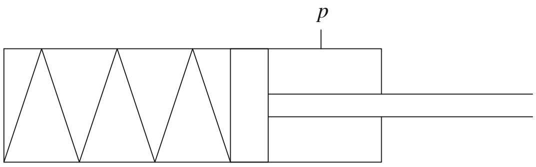


Fig. 8 Single acting cylinder (pre-extended)

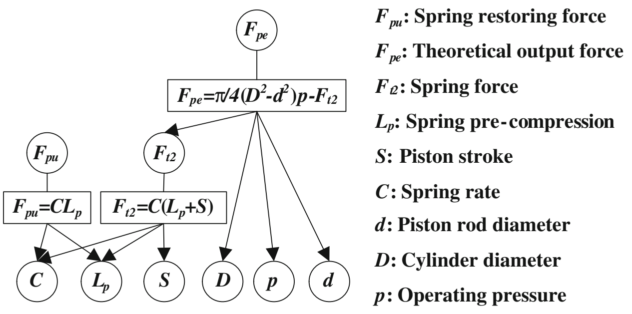


Fig. 9 Sub-PLN model for the output force design

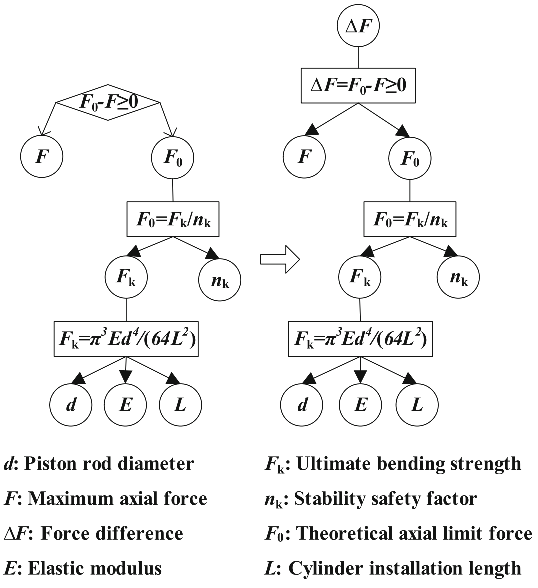


Fig. 10 Sub-PLN model for the working stability design

   Direct parameters can be adjusted directly by designers.

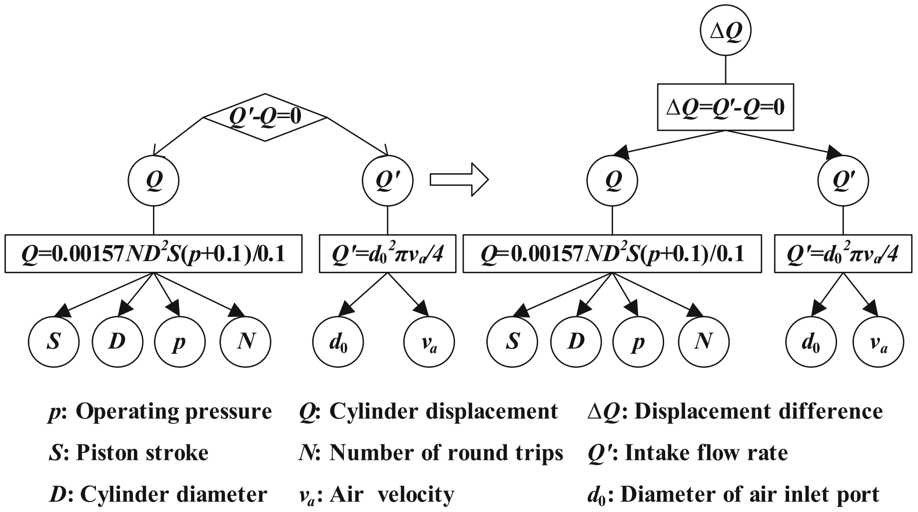
2. Target parameters lie on the top of the PLN model and represent the design specifications that should be satisfied. For example, the target parameters of an engine contain output power, security, and durability; the target parameters of a cylinder contain output force, working stability, and safety. The target parameter cannot be realized directly; instead, its realization should be translated or decomposed in terms of parameter linkages, until the direct parameters are fixed. According to their value property, target parameters can be classified into nominal-the-best, larger-the-best, and smaller-the-best parameters.
3. Transition parameters lie between the direct parameters and the target parameters. They are clues of change propagation analysis as they describe how the direct parameters determine the target parameters.

Designers mainly initiate two kinds of changes during the product design process, i.e., changes to the product performance and changes to the product concrete structure. In the PLN model, a change to the product performance corresponds to a change to a target parameter, which should be implemented indirectly through translating it into changes to direct parameters. A change to the product concrete structure corresponds to a change to a direct parameter, which will influence the upper layer parameters and cause them to change.

3 Propagating mechanism of changes

In this paper, change propagation is thought as a process during which an initial change causes a series of subsequent changes. An initial change is a change decided by the designer to meet a change requirement. A series of subsequent changes are the by-products of the initial change. The goal of change propagation is to adjust the design to incorporate the change requirement, and meanwhile, to enable the design to evolve to a new stable status.

Fig. 11 Sub-PLN model for the design of the air inlet port



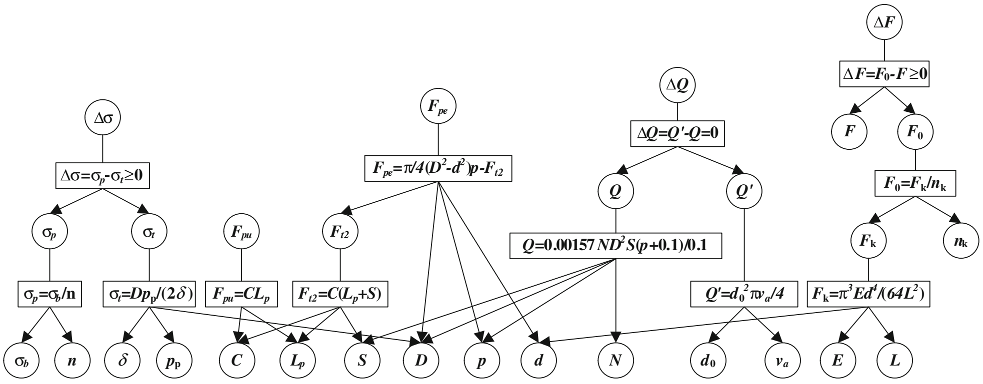


Fig. 12 PLN model for the cylinder design

3.1 Types of basic propagation

Basic propagation refers to the propagation occurring in single parameter linkages. Two types of basic propagation can be elicited in terms of the propagation features of fundamental linkages.

1. A change to a child parameter will cause the parent parameter to change subsequently. It is a kind of objective propagation which can be confirmed directly; therefore, it is named the direct propagation.
2. A change to a parent parameter has to be translated into a change to its child parameters. Generally, there are multiple child parameters for one parent parameter; designers thus have to decide which child parameters need to be changed through decision analysis. It is a kind of subjective propagation which is decided by designers; therefore, it is named the decision propagation.

3.2 Change propagation patterns

In real change propagation processes, basic propagation happens successively, from which two change propagation patterns can be identified.

3.2.1 Change routing

A change to a target parameter should be translated into a change to its child parameters, which should be decided by designers. If the child parameter is also a parent parameter in other linkages, the child parameter's change should also be translated into a change to its child parameters, and the propagation will not finish until the bottom direct parameters are changed. This kind of propagation is triggered by a change to a target parameter, terminates at changes to the direct parameters, and is composed of a succession of decision propagation. It shows how designers choose the path to implement the change to a target parameter, so it is called change routing. Figure 13 illustrates the change routing caused by a change to the stress difference $\Delta\sigma$.

Change routing can be analyzed from another perspective. The sub-PLN model of a target parameter can be thought to be composed of multiple parameter linkage chains that are parameter paths from the target parameter to the direct parameter. A parameter linkage chain is called a feasible routing branch in this paper as it is a feasible path for the change routing of a target parameter. The feasible routing branch of the target parameter p_i is represented as $r(p_i)$, and all $r(p_i)$s constitute the feasible route branch set $\mathrm{R}(p_i)$. Then, the change routing can be described as finding a feasible routing branch subset $\mathrm{R_s}(p_i)$ as the change routing path, so that the value of the target parameter p_i can be changed from $V(p_i)$ to $V'(p_i)$, as shown in Fig. 14.

3.2.2 Influence diffusion

A change to a child parameter causes its parent parameters to change, and if the parent parameters are also child parameters in other linkages, the change in the parent parameters will also cause their parent parameters to change, and the propagation will not finish until the top target parameters are changed. This kind of propagation

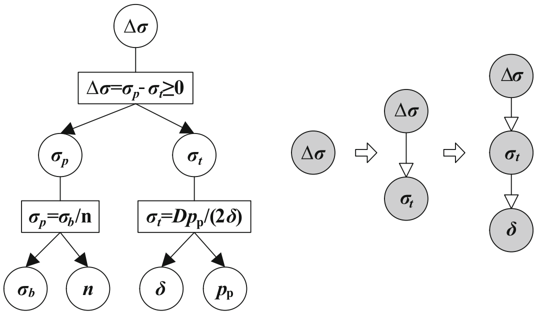


Fig. 13 Sub-PLN model of the parameter $\Delta\sigma$ and its change routing

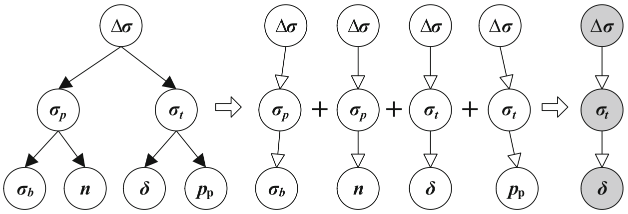


Fig. 14 Change routing from the view of feasible routing branches

starts with a change to a child parameter, terminates at changes in the target parameters, and consists of a succession of direct propagations. It shows how a change to a child parameter influences other parameters, so it is called influence diffusion. Figure 15 illustrates the influence diffusion caused by a change to the diameter D of the cylinder. It should be mentioned that the child parameter initiating the influence diffusion can be direct parameters or transition parameters. For example, if the change routing path contains a transition parameter, which is a coupled parameter, its change can also trigger influence diffusion.

Suppose when a child parameter p_i is changed, all the parent parameters that are influenced by p_i constitute the influence domain $\mathrm{ID}(p_i)$, then

$$\mathrm{ID}(p_i) = \{p | p \in P_D(p_i)\} \tag{1}$$

where $P_D(p_i)$ is the parameter set composed of the parent parameters from the fundamental linkages that involve p_i as a child parameter. This paper further defines

$$\begin{aligned} \mathrm{ID}^2(p_i) &= \{p' | p' \in \mathrm{ID}(p) \vee p \in \mathrm{ID}(p_i)\} = \mathrm{ID}(\mathrm{ID}(p_i)) \\ \mathrm{ID}^n(p_i) &= \mathrm{ID}\left(\mathrm{ID}^{n-1}(p_i)\right) \end{aligned} \tag{2}$$

Then, the influence diffusion can be represented as $p_i \rightarrow \mathrm{ID}(p_i) \rightarrow \mathrm{ID}^2(p_i) \rightarrow \ldots$It can be found that the influence diffusion range of a direct parameter depends on the number of layers between the direct parameter and target parameters and the number of parameters in the influence domain.

3.3 Change propagation process

Based on the change propagation patterns presented, the detailed propagating process of changes can be derived.

1. When a target parameter is changed, its change routing will lead some direct parameters to change, which will trigger influence diffusion if there are coupled parameters in the change routing path.
2. When a child parameter is changed, its influence diffusion will cause some target parameters to change. Then, the designer has to judge whether impact mitigation is required. Here, impact mitigation means to change the target parameter in opposite direction, so that the impact brought about by the previous change can be reduced or eliminated. Impact mitigation will initiate change routing. If the target parameter approaches its ideal value, the change will bring positive impact; otherwise, the change will bring negative impact. When the change in a target parameter brings positive impact or small negative impact, no impact mitigation is needed. However, when the negative impact is too big to be accepted, designers should import opposite changes to mitigate the negative impact, i.e., to raise a new change routing.

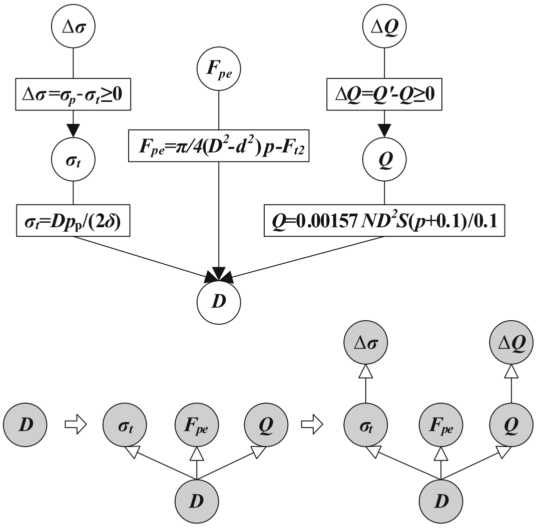


Fig. 15 Sub-PLN model of the parameter D and its influence diffusion

Therefore, influence propagation and change routing occur alternately, which forms the change propagation process shown in Fig. 16. At first, the designer should determine which parameter should be changed in terms of the change requirement received. As discussed in Sect. 1.3, the initial changed parameter can be a direct parameter or a target parameter. Then, the designer should analyze the propagation caused by the initial change.

When the initially changed parameter is a direct one, its change will trigger influence diffusion, which in turn will cause target parameters to change. If the change impact can be accepted, the change propagation will end. If the impact mitigation is required, change routing will be initiated, leading some direct parameters to change. If there are no coupled parameters in the change routing path, the change propagation will end; otherwise, new influence diffusion will be triggered, and a new cycle begins. When the initially changed parameter is a target parameter, the only difference is that change routing will be initiated firstly.

When the change propagation finishes, the design evolves to a new stable status. The changed parameters form the change propagation path, which is a possible path

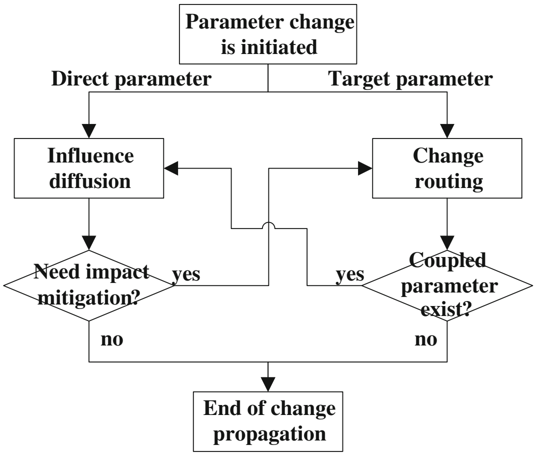


Fig. 16 Propagating process of changes

solution for the change task. Hence, the change propagation path can also be called the change path solution.

It can be found that the change propagation has both objectivity and subjectivity. The objectivity means that the influence diffusion is determined by the inherent linkages within the design, which cannot be modified by designers. The subjectivity means that the change routing is chosen by designers, and the designer's decision changes the direction of propagation. The change propagation path is the mixture of objective propagation paths caused by influence diffusion, and subjective propagation paths caused by change routing. Because of the subjective property of the change propagation, there are multiple ways to implement a change, each leading to a different change propagation path. Therefore, designers should try different feasible routing branches to find multiple propagation paths and select an optimal path from them, as shown in Fig. 17.

During the searching of change propagation paths, the designer may encounter some parameters that are not allowed to change, like the frozen parameters (Eger et al. 2005), and have to give up the current search. Under extreme conditions, there is a large number of parameters which cannot be changed, and consequently, the designer cannot implement a change to a parameter no matter how he adjusts the strategy. It means the current design cannot accommodate the change requirement.

3.4 A case of change propagation

This section analyzes qualitatively the change propagation of a parameter based on the PLN model given in section 1.2.3. Suppose the cylinder is required to work in a complicated environment with many disturbing forces. Then the designer decides to increase the stability safety factor n_k to get higher stability and analyze the change propagation caused by n_k.

According to the PLN model, the increase in n_k causes F_0 to decrease, which ultimately leads ΔF to decrease. The value of ΔF is required to be larger than zero, so impact mitigation should be imported to increase the value of ΔF. There are many ways to change the value of ΔF, and here, suppose the designer chooses to increase the rod diameter d. As a coupled parameter, the increase in d will cause the output force F_{pe} to decrease, which is not permitted in the design specification; therefore, impact mitigation should be imported to increase the value of F_{pe}. There are also many ways to change the value of F_{pe}, and suppose the designer chooses to increase the cylinder diameter D here. As a coupled parameter, the increase in D will trigger new influence diffusion and cause $\Delta\sigma$ and ΔQ to increase. Generally, the actual thickness of the cylinder wall is much larger than the theoretical thickness δ, so the change impact of $\Delta\sigma$ is acceptable. However, ΔQ should be kept to 0, and impact mitigation should be imported. Suppose the designer chooses to increase the diameter of the air inlet port d_0. The change to d_0 will not cause influence diffusion and the change propagation finishes.

Figure 18 illustrates the change propagation of n_k. It can be found that change propagation is the alternation of influence diffusion and change routing. The coupled parameters in the PLN model cause the alternation from change routing to influence diffusion, and impact mitigations cause the alternation from influence diffusion to change routing. Meanwhile, the change propagation path is not unique as there are multiple feasible routing branches for the designer to choose during the process of change routing.

4 A method of searching for change propagation paths

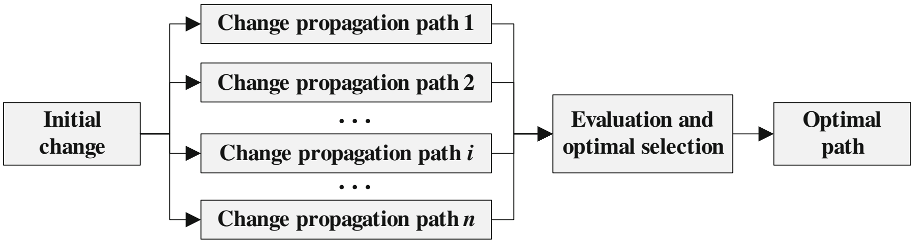
4.1 Procedure of the method

Based on the PLN model presented in Sect. 2 and propagating mechanism of changes presented in Sect. 3, a method is proposed for the searching and the optimal selection of change propagation paths. The procedure of the method is illustrated in Fig. 19.

The procedure for searching a possible change propagation path is as follows:

1. Determine the type of the initially changed parameter. If the parameter is a direct one, go to step 2; if the parameter is a target one, go to step 3.
2. Search the influence propagation path and judge the necessity of impact mitigation. If impact mitigation is needed, go to step 3. Otherwise, end the search and obtain a possible path.

Fig. 17 Multiple searching and optimal selection of change propagation paths



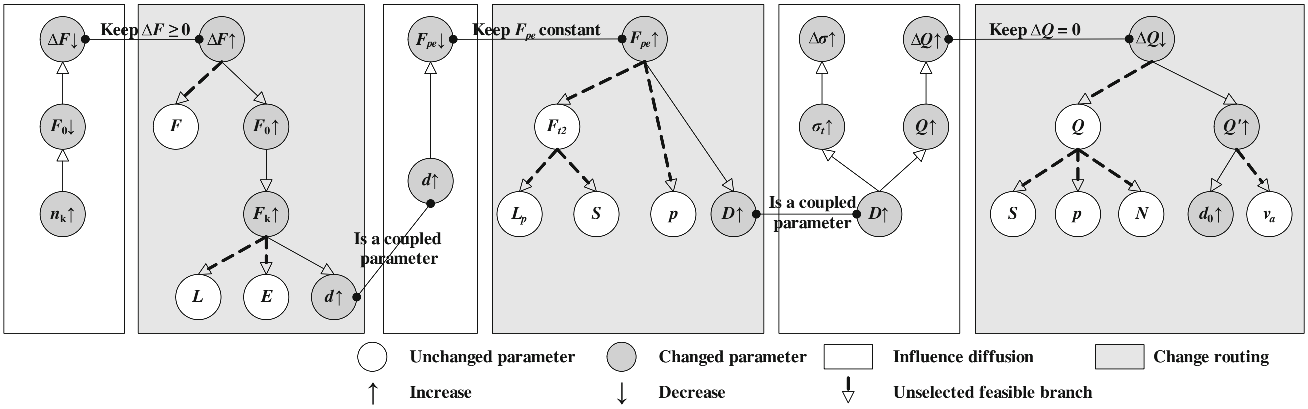


Fig. 18 Change propagation of n_k

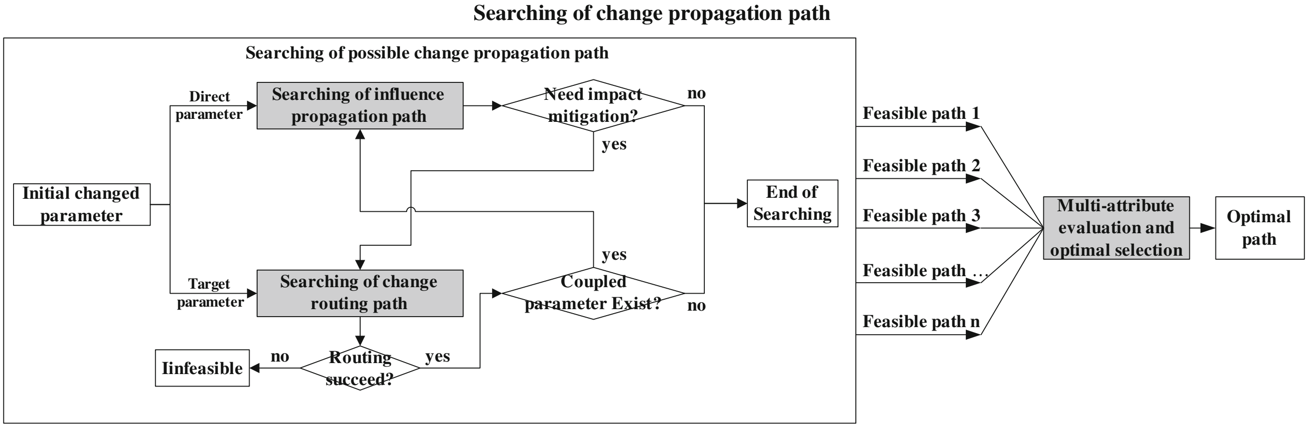


Fig. 19 The procedure of the searching method

3. Search the change routing path. If the searching fails, it means the current search is infeasible and the designer should terminate the current search. If the searching is successful, go to step 4.
4. If there are coupled parameters in the change routing path, go to step 2; otherwise, end the search and obtain a possible path.

The search should be performed in a serial manner because of the coupled parameters in the PLN model; otherwise, the paths in different parallel searches may interfere with each other. For example, when there are multiple target parameters, which need to be mitigated, the change routing for the target parameters should be finished one after another.

There is a global optimal path for an initial change theoretically. However, due to the dynamic and uncertainty of the change propagation, it is difficult for designers to search all the change propagation paths to identify the global optimal path. Generally, designers can only finish limited searches to find a relative optimal path for an initial change. When designers search all the possible paths, the relative optimal path becomes also the global optimal path. Therefore, the designer should repeat the searching procedure to acquire as many paths as possible through adjustment of the change routing path. After the searching, the designer should perform evaluation and optimal selection of these paths and choose the optimal path as the final change solution.

4.2 Data preparation for the searching method

In order to realize the searching and evaluation of a change propagation path, some data should be collected, including the data for computing the variation of a parameter, attributes data of a direct parameter for the estimation of the change expense, and attributes data of a target parameter for the estimation of the change impact.

1. Data for computing the variation of a parameter

Some data should be collected to estimate the variation of a parameter caused by a change in another parameter. Suppose the formula of a parameter linkage is $y = f(X)$, where y is the parent parameter and X is the parameter vector of child parameters. Then, the partial derivative of y with respect to the parameter x_i is:

$$\mathrm{d}y = \frac{\partial f(X)}{\partial x_i}\mathrm{d}x_i = f'_{x_i}(X)\mathrm{d}x_i \tag{3}$$

The real formulas of parameter linkages are usually complicated in designs; for convenience of analysis, formula 3 can be linearized for an approximate evaluation of the parameter variation. Suppose X_0 is the current value of child parameters, the variation of y caused by the change in x_i and the new value y' can be represented as:

$$\begin{aligned}\Delta y &= f'_{x_i}(X_0)\Delta x_i = K_i \Delta x_i \\ y' &= y + \Delta y = y + K_i \Delta x_i\end{aligned} \tag{4}$$

K_i should be collected for computing the variation of a parameter.

2. Attributes data of a direct parameter for the estimation of the change expense

The expense of changes can be estimated through the variations of direct parameters, as direct parameters are the parameters designers can adjust directly. The data about attribute U and E of a direct parameter should be collected. U is the unit variation quantity of the change, which is used to compare the changes to parameters with different dimensions and quantities. For example, for a plate whose radius is 10 cm and whose thickness is 10 mm, the U for the radius may be 0.1 cm and the U for the thickness may be 0.1 mm. E is the change expense of U, whose rating is set as an integer between 1 and 10. Then, the change expense $\mathrm{CE}(x_i)$ of a direct parameter x_i can be calculated through $U(x_i)$, $E(x_i)$, and the magnitude of change $\Delta(x_i)$, i.e.,

$$\mathrm{CE}(x_i) = \frac{\Delta(x_i)}{U(x_i)} \times E(x_i) \tag{5}$$

In addition, a change to a direct parameter cannot exceed its restriction scope S_V, so the permitted change quantity of a direct parameter is limited, which can be calculated through the difference of attribute V_{cur} and S_V, where V_{cur} is the current value of the direct parameter. Therefore, a direct parameter can be expressed as $p = (V_{\mathrm{cur}}, S_V, U, E)$.

3. Attributes data of a target parameter for the estimation of the change impact

The impact of changes can be assessed through the variations of target parameters, as target parameters indicate the performance of the design. Generally, the change impact varies non-linearly when the value of the target parameter departs from its ideal value. This paper applies the quality loss function (Taguchi 1992) to express the relationship between the change and the economic loss and defines change impact as the difference of quality loss before and after the change, as shown in Fig. 20. Suppose the values of a target parameter x before and after the change are x_{cur} and $x_{\mathrm{cur}} + \Delta x$ and the quality loss are $L(x_{\mathrm{cur}})$ and $L(x_{\mathrm{cur}} + \Delta x)$, then change impact $\mathrm{CI}(x) = L(x_{\mathrm{cur}}) - L(x_{\mathrm{cur}} + \Delta x)$.

Take nominal-the-best parameter as an example, its quality loss function is:

$$L = k(x_1 - x_0)^2 \tag{6}$$

where L is the quality loss, x_1 is the current value, x_0 is the nominal value, k is the proportional constant. Then, the change impact of x is:

$$\begin{aligned}\mathrm{CI(x)} &= k(x_{\mathrm{cur}} - x_{\mathrm{ideal}})^2 - k(x_{\mathrm{cur}} + \Delta x - x_{\mathrm{ideal}})^2 \\ &= -k\Delta x^2 - 2k\Delta x(x_{\mathrm{cur}} - x_{\mathrm{ideal}})\end{aligned} \tag{7}$$

$\mathrm{CI}(x)$ being plus means the change impact is positive and $\mathrm{CI}(x)$ being minus means the change impact is negative. Hence, the target parameter can be expressed as $p = (V_{\mathrm{ideal}}, V_{\mathrm{cur}}, k)$, where V_{ideal} is the ideal value of the parameter, V_{cur} is the current value of the parameter. The

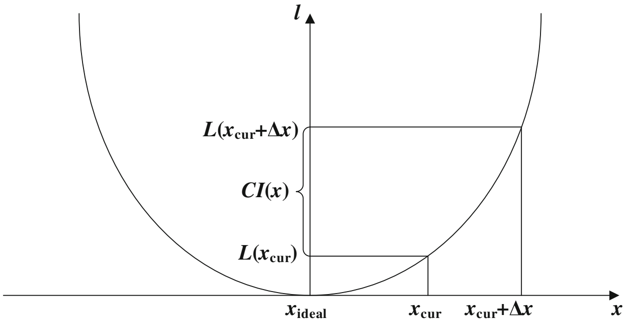


Fig. 20 Calculation of the change impact

monetary unit of change impact can be ignored as it does not affect the comparison of the change impact.

4.3 Searching of influence diffusion paths

The concept is to execute recursive searches in terms of influence domain of a parameter until the target parameters are influenced, and the steps are shown in Fig. 21. When a direct parameter is changed and its change exceeds its restriction scope, the change is infeasible and should be rejected. Through the recursive analysis, designers can get the influence diffusion path and the variation quantity of target parameters.

4.4 Searching of change routing paths

Figure 22 illustrates the procedure of searching change routing paths. The designer should identify feasible routing branches of the target parameter and judge whether the mitigation volume is enough for the change. If the mitigation volume is not enough, it means the change to the target parameter is infeasible; otherwise, the designer can choose a branch set as the routing solution in terms of the branch selection strategy.

4.4.1 Feasible routing branches

A feasible routing branch has the following attributes.

1. Feasible mitigation quantity

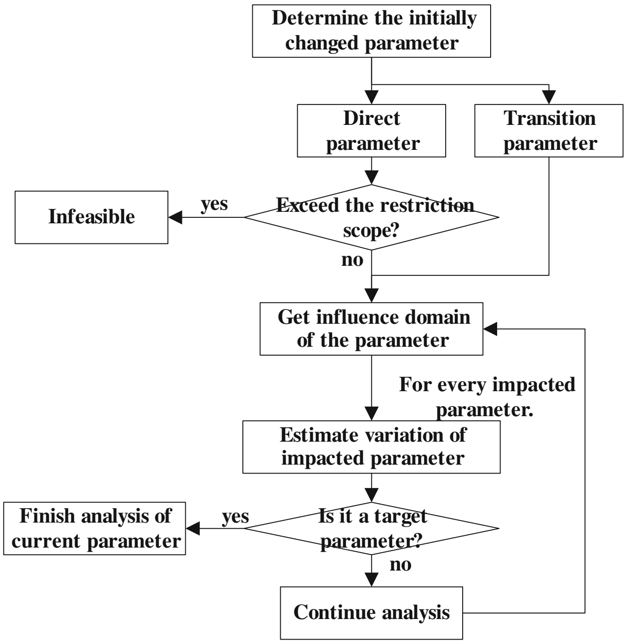


Fig. 21 Searching of influence diffusion paths

A change to a direct parameter is forbidden to exceed its restriction scope. Hence, the variation quantity of a target parameter, which can be realized by the change to the direct parameters, is a limited quantity, which is called the feasible mitigation quantity.

Suppose the amount of feasible routing branches of a target parameter is n, the feasible mitigation quantity for each branch P_i is $M(P_i)$, then the sum of these branches M is:

$$M = \sum_{i=1}^{n} M(P_i) \tag{8}$$

M is called the mitigation volume of the target parameter. Suppose the mission is to change a target parameter with a quantity of M', then $M < M'$ means the mission mitigation quantity is larger than the mitigation volume and the change requirement cannot be realized; otherwise, the change requirement can be realized.

2. Mitigation efficiency

The mitigation efficiency of a feasible routing branch can be categorized into absolute mitigation efficiency Ka and relative mitigation efficiency Kr. Ka is used to compare different feasible routing branches of the same target parameter. Considering the differences in dimensions and values of direct parameters, it is defined as the variation quantity of the target parameter corresponding to a change in the direct parameter with the unit variation quantity U. Kr is used to compare different feasible routing branches passing through the same coupled parameter. The branches passing through the same coupled parameter lead to different target parameters, which are differentiated with each other in dimensions and values; therefore, Kr is defined as the ratio of Ka and the current value of the target parameter V_{cur}. Suppose a feasible routing branch from the direct parameter p_i to the target parameter p_j is $p_i \rightarrow \cdots \rightarrow p_m \cdots \rightarrow p_j$, then the relationship between the variation of p_i and the variation of p_j can be represented as:

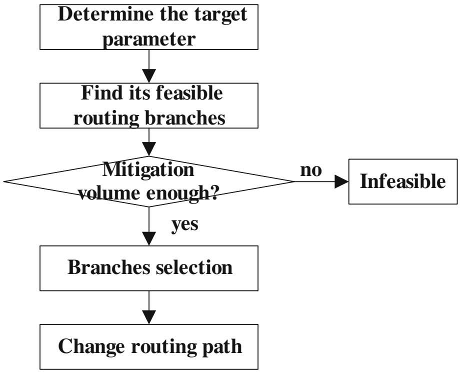


Fig. 22 Searching of change routing paths

$$\Delta p_j = \prod_{m=i+1}^{j} K_{m\cdot m-1}\Delta p_i = K_{ji}\Delta p_i \tag{9}$$

Ka and Kr of the branch can be represented as:

$$\begin{aligned} Ka(p_j, p_i) &= K_{ji}U(p_i) \\ Kr(p_j, p_i) &= \frac{Ka(p_j, p_i)}{V_{\text{cur}}(p_j)} \end{aligned} \tag{10}$$

The variation of a parameter can also be computed with the following formula.

$$p_j' = p_j + Ka(p_j, p_i) \cdot \frac{\Delta p_i}{U(p_i)} \tag{11}$$

3. Diffusion property of a feasible routing branch including a coupled parameter

When there is a coupled parameter in the feasible routing branch, the change routing passing through this branch will trigger a new round of influence diffusion, as shown in Fig. 23. The degree of the diffusion can be assessed through a diffusion coefficient.

Suppose branch P is chosen for the change routing of a target parameter, the relative mitigation efficiency of P is $Kr(P)$, and diffusion branches of P is P_1, …, P_m, then its diffusion coefficient $S_{\text{cp}}(P)$ is:

$$S_{\text{cp}}(P) = \frac{Kr(P)}{\sum_1^m Kr(P_i)} \tag{12}$$

The magnitude of $S_{\text{cp}}(P)$ shows the degree of diffusion. The bigger it is, the smaller the diffusion it causes. $S_{\text{cp}}(P) > 1$ means the diffusion is attenuating while $S_{\text{cp}}(P) \leq 1$ means the diffusion is augmenting.

4.4.2 Selection of feasible routing branches

It is difficult to determine which feasible routing branch should be chosen as the change routing path, as feasible routing branches differ from each other in change expenses, mitigation efficiency, and diffusion property. Designers hope to accomplish the routing task with lower variation quantity, fewer change expenses, and less diffusion, but often these goals cannot be satisfied at the same time. Some synthetical evaluation methods can be used to confirm the optimal routing path; however, the final change propagation path is still unpredictable as the change routing may trigger new influence diffusion and new change routing in succession. The current optimal routing path cannot guarantee that the holistic change propagation path is optimal.

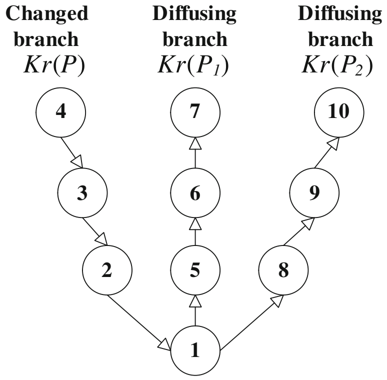


Fig. 23 Influence diffusion caused by a coupled parameter

As introduced in Sect. 4.1, the searching method evaluates paths and selects the optimal path after the searches for holistic change propagation paths are completed. Therefore, it is not necessary to find the optimal change routing path during the searching for a certain change routing, and designers need only to find various change routing paths for the change routing. There may be many feasible routing branches for a target parameter; the number of searching times will increase greatly if all the branches are traversed. In the practical design change situation, designers generally choose the feasible routing branches in terms of some criteria, for example, the expense should be low, the propagation should be small, or the modification should be little. In this paper, they are summarized as selection strategies to help designers sort the selection priority of branches.

Four selection strategies are presented here, they are as follows: efficiency priority strategy, cost priority strategy, uncoupled-branch priority strategy, and nearby-branch priority strategy. The first two are main strategies, used to determine the selection order, and the latter two are auxiliary strategies, which can be used to group the branches before determining their order.

1. Efficiency priority (EP) strategy

In EP strategy, the absolute mitigation efficiency Ka is used to sort the branch sets and the branches with a large Ka being adopted preferentially, so that a change to a target parameter can be achieved with a smaller variation quantity. However, the branch with a large Ka may have small permitted quantity of change and its feasible mitigation quantity may not be large.

2. Cost priority (CP) strategy

In CP strategy, the change expense E of the direct parameter in the branch is used to sort the branch sets and the branches with a small change expense being adopted preferentially. Along with the product design, the coupling between the design process and other processes continues to strengthen, which makes E different in each branch. The total change expense can be reduced if the branch with a lower E is chosen.

3. Uncoupled-branch priority (UP) strategy

The introduction of the branch including a coupled parameter will cause further change diffusion, which means more parameters will be changed. In order to control the change propagation scope, designers incline to choose uncoupled branches to avoid influence diffusion. However, the coupled branch may have higher mitigation efficiency and larger diffusion coefficient; therefore, the solution obtained through the UP strategy may not be optimal. UP is an auxiliary strategy, which should be used together with the main strategies.

4. Nearby-branch priority (NP) strategy

As shown in Fig. 24, suppose a change to parameter 1 influences parameter 4 through parameter linkage chain 1 → 2→3 → 4, then the change of parameter 4 should be mitigated through other branches. The NP strategy means the branches containing the influenced parameters should be selected preferentially, such as branches 5 → 2→3 → 4 containing 2 and 3 or 6 → 7→3 → 4 containing 3, so that the change in 4 can be interdicted before it is influenced, and therefore, the propagation scope can be reduced. For example, if a change to parameter 5 is opted, then the influence diffusion can be interdicted at parameter 2 and the propagation scope is reduced to 1, 2, and 5. NP is also an auxiliary strategy, which should be used together with the main strategies.

The using of selection strategies is summarized in Table 2. After the designer chooses the strategy, the branches can be chosen by the following steps:

1. Get the sort array of branches based on the strategy chosen.
2. Intercept a branch subset from the sort array, whose summation of feasible mitigation quantity is equal to the mission mitigation quantity.

4.5 Evaluation and optimal selection of change propagation paths

A path solution can be evaluated synthetically by four attributes, i.e., change propagation scope, negative change impact, positive change impact, and change expense.

1. Change propagation scope

The change propagation scope is assessed by the number of changed parameters (CN), which is defined as the summation of changed direct parameters N_{dic} (related with design measures) and changed target parameters N_{dec} (related with design requirements). That is:

$$\text{CN} = N_{\text{dic}} + N_{\text{dec}} \tag{13}$$

The more changed parameters there are, the wider the change propagation scope is. In order to keep the design process stable and reduce the risk of changes, designers incline to choose the solution with a smaller propagation scope.

2. Negative change impact

The negative change impact cannot be summed up with the positive change impact. Because, for a path solution with both a large negative change impact and a large positive change impact, its incorporated change impact may be small, which seems acceptable; however, its large negative change impact is unacceptable in the practical change process. The negative change impact and the positive change impact are both by-products of the initial change. In order to keep the product design stable, the negative change impact should be reduced, while the positive change impact, being not the key point of the change, can be reserved. When choosing the path solution, the negative change impact should be paid more attention to.

Suppose the number of target parameters with negative change impact is N_n, according to the calculation formula of the change impact, the total negative change impact of the path solution CI_n is:

$$\text{CI}_n = \sum_{i=1}^{N_n} \text{CI}(x_i) \tag{14}$$

3. Positive change impact

Suppose the number of target parameters with positive change impact is N_p, then the total positive change impact of the path solution CI_p is:

$$\text{CI}_p = \sum_{i=1}^{N_p} \text{CI}(x_i) \tag{15}$$

4. Expense of change

The total expense of change for the path solution CE is the summation of expenses of all changed direct parameters. Suppose the number of changed direct parameters is n, then:

$$\text{CE} = \sum_{i=1}^{n} \text{CE}(x_i) \tag{16}$$

Therefore, a path solution can be represented as PS = (CN, CI_n, CI_p, CE), based on which the comprehensive evaluation of path solutions can be made so that the optimal solution can be chosen. The optimal selection of path solutions is a

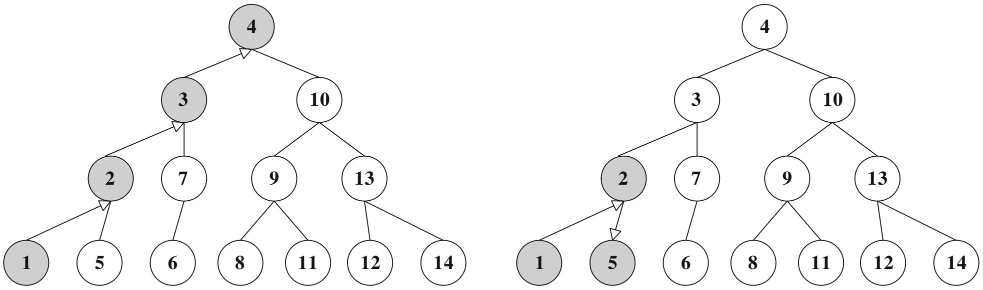


Fig. 24 Example of the nearby-branch priority strategy

Table 2 Instruction of selection strategies

Main strategy	Auxiliary strategy	Sorting rule
EP		Sort the branches by mitigation efficiency
EP	UP	Firstly, group the branches in terms of their coupling attributes and then sort the branches in each group by mitigation efficiency
EP	NP	Firstly, group the branches according to whether the influenced parameters are included and then sort the branches in each group by mitigation efficiency
CP		Sort the branches by the expense of change
CP	UP	Firstly, group the branches in terms of their coupling attribute and then sort the branches in each group by the expense of change
CP	NP	Firstly, group the branches depending on whether the influenced parameters are included and then sort the branches in each group by the expense of change

multiple attribute decision-making problem, which could be accomplished using analytic hierarchical process (AHP) method, multi-attribute value theory (MAVT) or the technique for order preference by similarity to the ideal solution (TOPSIS) method (Yoon and Hwang 1995).

4.6 A case study

In this section, a diaphragm clutch design is introduced to demonstrate the application of the path searching method. In the mechanical transmission system taking the internal combustion engine as power, the clutch is an independent assembly deployed between the engine and the transmission to connect or disconnect the engine from the transmission. The sketch of the clutch is shown in Fig. 25.

4.6.1 Construction of the PLN model and data collection

The top-down manner is used to capture the sub-PLN model of target parameters according to the clutch design (Liu 2001). The target parameters of the clutch include the pressure plate lift, the wear rate of clutch, the torque capacity of the clutch, and the operation convenience. As most parameter linkages of clutch designs are too complicated to be represented with explicit formulas, the simplified notation in Fig. 1 is used to express the fundamental linkages.

The pressure plate lift is related to the thermal deformation of the pressure plate, the deformation of the housing, and the working travel of the control mechanism. The thermal deformation of the pressure plate depends on the stiffness, the toe angle, and the temperature rising of the pressure plate. The stiffness of the pressure plate is related to the elastic modulus and the cross-section shape of the pressure plate, and the temperature rising is related to the quality and the dimension for cooling. Therefore, the sub-PLN model for the pressure plate lift is the model shown in Fig. 26.

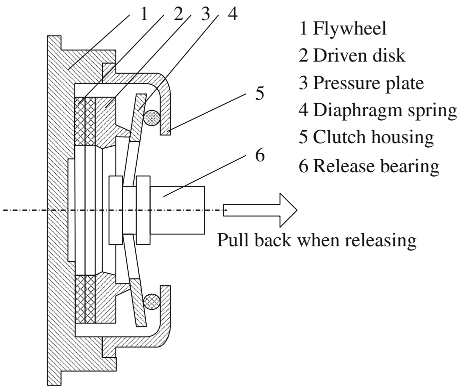


Fig. 25 Sketch of the diaphragm clutch (from Liu 2001)

In order to ensure operation convenience of the clutch, the total travel of the pedal should be constrained in a certain range. The total travel of the pedal is the summation of working travel and free travel of the pedal. Therefore, the sub-model for operation convenience is the model shown in Fig. 27.

The wear rate of the clutch depends on the clearance of the clutch, the impact intensity, the hardness, and the working temperature of the friction plate; and the working temperature of the friction plate is related to the thermal conductivity, the thickness, and the special heat of the friction plate. Therefore, the sub-model for the wear rate of the clutch is the model shown in Fig. 28.

The torque capacity of the clutch refers to the range of the torque that can be transferred from the engine to the transmission, which is an important performance criterion of the clutch design. The torque capacity is the product of the friction coefficient, the unit pressure, and the area of the friction plate. The friction coefficient is related to the working temperature of the friction plate, and the unit pressure depends on the compressed height of the diaphragm spring. Therefore, the sub-model for the torque capacity of the clutch is the model shown in Fig. 29.

The clutch transfers the torque through the engagement between the friction plate and the pressure plate. Hence, the diameter of the friction plate is required to be equal to that of the pressure plate. Clutch housing is the cover of the clutch; its diameter is required to be larger than that of the pressure plate. Therefore, the sub-model for the diameters in the clutch design is the model shown in Fig. 30.

The sub-PLN models shown in Figs. 26, 27, 28, 29, and 30 can be integrated into a single PLN model, which describes the parameter linkages in the diaphragm clutch design, as shown in Fig. 31. This model is only a part of the global PLN model, but it has included the main parameter linkages in the diaphragm clutch design and can be expanded to join more parameter linkages when more knowledge of the clutch design is acquired.

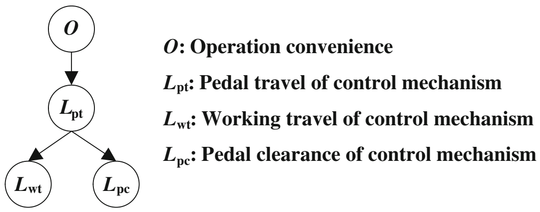


Fig. 27 Sub-PLN model for the operation convenience

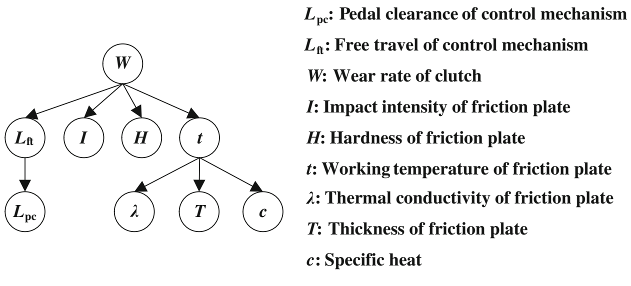


Fig. 28 Sub-PLN model for the wear rate

Some data should be collected for the searching of change propagation paths after the PLN model for the diaphragm clutch design is constructed, including the attributes data of direct parameters used to compute change expenses, the attributes data of target parameters used to compute the change impact, and data for computing the variation of a parameter. We collect these data from related literatures (see Liu 2001; Liu and Hu 2009; Tang et al. 2009), make approximate treatment, and then elicit the example data shown in Table 3, 4, and 5.

4.6.2 *Searching of change propagation paths*

Suppose a new type of friction plate is adopted, whose thermal conductivity decreases from 40 to 38 W/m°. Then, the change propagation caused by the change in thermal conductivity should be analyzed, so that the change impact can be assessed and the corresponding change measures can be fixed.

1. Searching of influence diffusion paths

The influence diffusion path should be searched firstly since thermal conductivity is a direct parameter. According

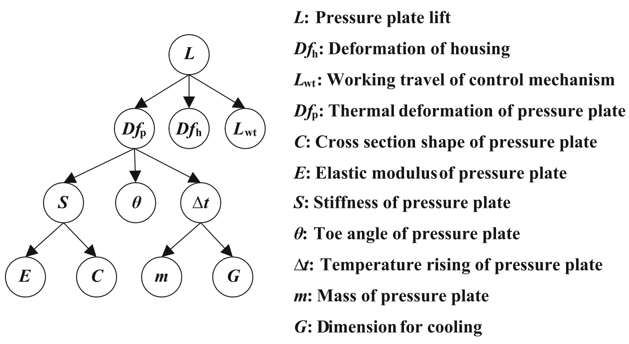


Fig. 26 Sub-PLN model for the pressure plate lift

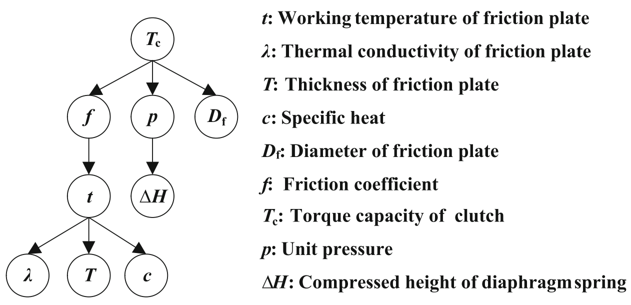


Fig. 29 Sub-PLN model for the torque capacity

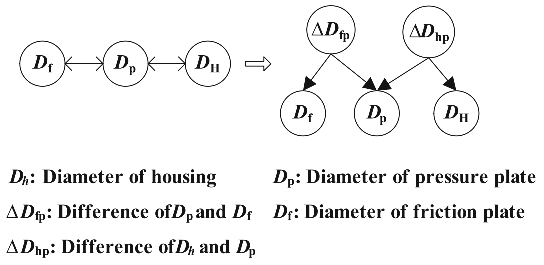


Fig. 30 Sub-PLN model for diameters of the clutch

to the procedure described in Sect. 4.3, the change in thermal conductivity will finally influences the wear rate and torque capacity of the clutch, as shown in Fig. 32. With the data in Table 3, 4, and 5 and the formulas 7 and 11, it can be estimated that the mean value of the torque capacity will increase to 124 from 120 N.m, which produces a positive impact with a quantity of 10.4, and the mean value of the wear rate will decrease to 17,800 from 19,000 km/mm, which produces a negative impact with a quantity of 19.2. The negative impact produced by the change in thermal conductivity is too large to accept; therefore, the designer should mitigate the change in the wear rate through the change routing.

2. Searching of change routing paths

Suppose the wear rate needs to be changed to 18,800 km/mm through the change routing. In terms of the data and the model given in Sect. 4.6.1, the feasible routing branches and their change quantity can be elicited, which are shown in Fig. 33. Among these branches, the free travel of the pedal is a coupled parameter, whose change will trigger a new round of influence diffusion and influence the target parameter operation convenience.

3. Searching of possible change propagation paths

As shown in Fig. 34, by choosing different feasible routing branches as change routing paths in light of selection strategies introduced in Sect. 4.4.2, the possible change propagation paths of thermal conductivity can be obtained. With the data in Table 3, 4, and 5 and the formulas 7 and 11, it is estimated that the change in the free travel will cause operation convenience to decrease from 7.5 to 7.1, which produces a negative impact with a quantity of 1.1. As the negative impact is acceptable, there is no need to make further impact mitigation.

4. Evaluation and optimal selection of change propagation paths

According to attribute computing formulas introduced in Sect. 4.5, the change propagation scope, positive change impact, negative change impact, and change expense for each path solution can be acquired, which is shown in Table 6.

In order to get the optimal path solution, TOPSIS method (Yoon and Hwang 1995) is adopted for multiple

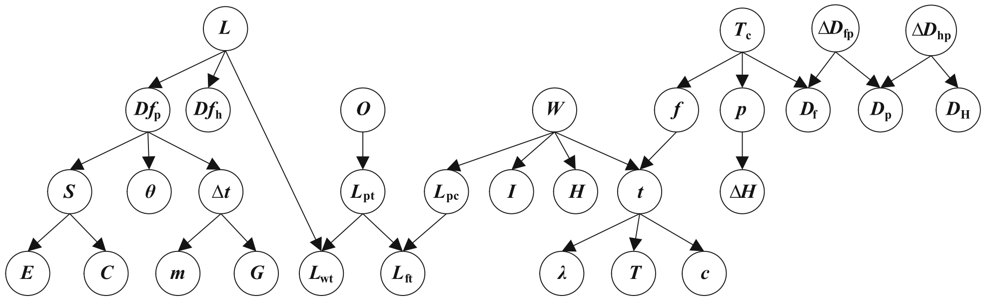


Fig. 31 PLN model for the diaphragm clutch design

Table 3 Data of direct parameters

Parameter name	Dimension	V_{cur}	S_V	U	E
D_H	mm	185	160–200	0.1	4
D_f	mm	185	160–200	1	5
H	HRL	75	65–85	1	4
c	J/kg °C	460	400–600	10	5
λ	W/m °C	40	35–45	1	7
T	mm	3.5	3.2–4	0.1	6
I	J/cm^2	1.4	1.3–1.6	0.01	9
L_{ft}	mm	35	30–45	1	2
…					

Table 4 Data of target parameters

Parameter name	Dimension	V_{cur}	V_{ideal}	k
L	mm	4.5	5	100
O	1	7.5	8	2
W	km/mm	19,000	20,000	5×10^{-6}
T_c	N.m	120	135	0.1
…				

Table 5 Data for computing the variation of a parameter

Direct parameter	Target parameter	*Ka* (absolute mitigation efficiency)
λ	W	600 km/mm
T	W	2,500 km/mm
c	W	20 km/mm
H	W	200 km/mm
I	W	50,000 km/mm
L_{ft}	W	250 km/mm
L_{ft}	O	−0.1
c	T_c	−2 N.m
…		

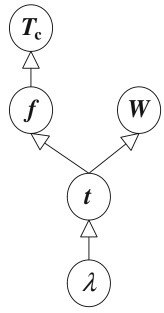


Fig. 32 Influence diffusion caused by change in thermal conductivity

attribute decision making, where the weight vector of (CN, CI$_n$, CI$_p$, CE) is set as (0.2, 0.3, 0.1, 0.4). The closeness degree of each solution to the optimal vector can be obtained through calculation, which is (0.68, 0.51, 0.72, 0.61, 0.48). The path solution 3 is the nearest one and should be selected as the optimal path solution.

5 Conclusions

The parameter linkages are reduced to two types of linkages—fundamental linkage and constraint linkage—which have different propagation features. Through the transformation of the constraint linkage to the fundamental linkage, a PLN model with simplex fundamental linkages is constructed.

Two basic propagation types are identified from the PLN model, which form two propagation patterns, i.e., influence diffusion and change routing. It is observed that change propagation is an alternate process of influence diffusion and change routing, and the propagation will not finish until the design achieves a new stable status.

Based on the PLN model and the change propagation process, a method of searching for change propagation paths is proposed for the searching, evaluation, and optimal selection of change propagation paths.

The method presented contained many assumptions, the validity of which needs to be further explored and more work remains to be done. At the same time, some promising areas have been identified for further development.

1. The case studied in this paper is relatively simple with only a few coupled parameters, while the structure of real PLN models is various. For example, a direct parameter may influence the same target parameter through multiple parameter linkage chains. Therefore, the searching method should be further perfected through more case studies.
2. The number of parameters, parameter linkages, and the complexity of linkages increase remarkably in complex designs. The extension of this method to complex designs may bring new research opportunities.
3. The computer support tool for this method is under development. Generally, the parameters in the real design disperse in different computing models. We plan to take the PLN model as an integration framework to organize the parameter linkages stored in different computing models, so that the change propagation can be analyzed in a comprehensive context. The accuracy of the analysis can also be improved as computing models can provide precise change quantities of the parameters.

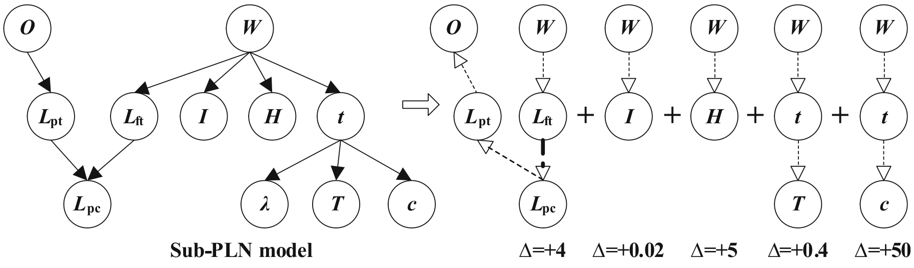


Fig. 33 Feasible routing branches and relevant change quantity for the change routing of the wear rate

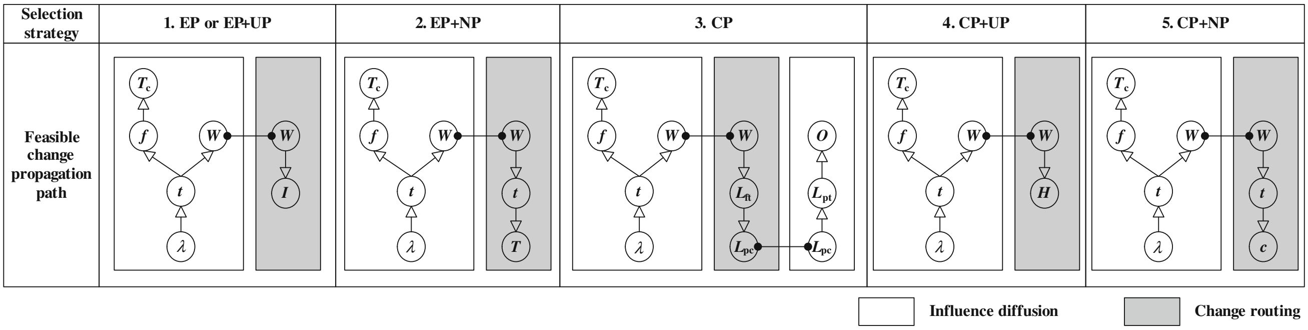


Fig. 34 Possible change propagation paths of thermal conductivity

Table 6 Attributes of each path solution

Path no.	Adjusted parameter	Adjustment quantity	CN	CI_n	CI_p	CE
1	Impact intensity	+0.02	4	2.2	10.4	18
2	Thickness of friction plate	+0.4	4	2.2	10.4	24
3	Pedal clearance	+4	5	3.3	10.4	8
4	Hardness	+5	4	2.2	10.4	20
5	Specific heat	+50	4	2.2	10.4	25

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References

Andreasen MM, Hein L (1987) Integrated product development. IFS (Publications) Ltd, Bedford

Brown J (2006) Managing product relationship: enabling iteration and innovation in design. Aberdeen Group, Boston

Browning T (2001) Applying the design structure matrix to system decomposition and integration problems: a review and new directions. IEEE Trans Eng Manag 48(3):292–306

Cheng D (2010) Hand book of mechanical design: pneumatic Transmission, offprint, 5th edn. Chemical Industry Press, Beijing (in Chinese)

Clarkson PJ, Simons C, Eckert CM (2004) Predicting change propagation in complex design. ASME J Mech Des 126(5): 765–797

Cohen T, Navthe S, Fulton RE (2000) C-FAR, change favorable representation. Comput Aided Des 32:321–388

Conrad J, Deubel T, Kohler C, Wanke S, Weber C (2007) Change impact and risk analysis (CIRA)—combining the CPM/PDD theory and fmea-methodology for an improved engineering change management. In: International conference on engineering design, ICED'07, Paris, France

Eckert C, Clarkson PJ, Zanker W (2004) Change and customisation in complex engineering domains. Res Eng Des 15(1):1–21

Eckert C, Keller R, Earl C, Clarkson PJ (2006) Supporting change processes in design: complexity, prediction and reliability. Reliab Eng Syst Saf 91:1521–1534

Eger T, Eckert C, Clarkson PJ (2005) The role of design freeze in product development. In: International conference on engineering design, ICED'05, Melbourne

Giffin M, de Weck O, Bounova G, Keller R, Eckert C, Clarkson PJ (2009) Change propagation analysis in complex technical systems. ASME J Mech Des 131(8):1–14

He R, Tang D, Xue J (2008) Engineering change propagation based on design structure matrix. Comput Integr Manuf Syst 14(4): 656–660 (in Chinese)

Jarratt T, Eckert CM, Clarkson PJ (2004) Development of a product model to support engineering change management. In: Proceedings of the TCME 2004, Lausanne, Switzerland

Kohler C, Conrad J, Wanke C, Weber C (2008) A matrix representation of the CPM/PDD approach as a means for change impact analysis. In: International design conference—design 2008, Dubrovnik, Croatia

Liu W (2001) Automotive design. Tsinghua University Press, Beijing (in Chinese)

Liu W, Hu Y (2009) Study on the effect of filler particle size on the performance of clutch friction materials. Fiber Compos 1:19–23 (in Chinese)

Martin M, Ishii K (2002) Design for variety: developing standardized and modularised product platform architectures. Res Eng Des 13(4):213–235

Ollinger G, Stahovich T (2001) RedesignIT—a constraint-based tool for managing design changes. In: Proceedings of the ASME international design engineering technical conferences, design theory and methodology, Pittsburgh, USA

Rouibah K, Caskey KR (2003) Change management in concurrent engineering from a parameter perspective. Comput Ind 50:15–34

Samling R, de Weck O (2007) Assessing risks and opportunities of technology infusion in system design. Syst Eng 10(1):1–25

Simon H (1996) The sciences of the artificial, 3rd edn. MIT Press, Cambridge

Steward D (1981) The design structure system: a method for managing the design of complex systems. IEEE Trans Eng Manag EM-28(3):71–74

Taguchi G (1992) Taguchi on robust technology development: bringing quality engineering upstream. ASME Press, New York

Tang C, Qi J, Lv J, Mo Y (2009) The influence of friction surface temperature on friction coefficient of clutch friction pair. Lubr Eng 34(7):66–69 (in Chinese)

Yoon K, Hwang CL (1995) Multiple attribute decision making: an introduction. Sage Publications Inc., Beverley Hills