A New Design Change Model for Effective Scheduling Change Propagation Paths

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Abstract: Changes in requirements may result in the increasing of product development project cost and lead time, therefore, it is important to understand how requirement changes propagate in the design of a complex product system (CoPS) and be able to select best options to guide design. This paper presents a new design change model to systematically analyze and search change propagation paths. Firstly, a PDS-Behavior-Structure-based design change model is established to describe requirement changes causing the design change propagation in behavior and structure domains. Secondly, a multi-disciplinary oriented behavior matrix is utilized to support change propagation analysis of CoPS, and the interaction relationships of the matrix elements are used to obtain an initial set of change paths. Finally, a rough set-based propagation space reducing tool has been developed to assist in narrowing change propagation paths by computing the importance of the design change parameters. The proposed new design change model and its associated tools have been demonstrated by a case study to show its feasibility and effectiveness. This model is not only supportive to response quickly to diversified market requirements, but also helpful to satisfy customer requirements and reduce product development lead time.

Key words: complex product systems; design change model; propagation path analysis; propagation space reduction; rough set

1 Introduction

In the global product market competition, customer requirements are fast changing. Meanwhile, the product lead time is required to become shorter and shorter. Therefore, effectively making necessary changes to previous designs is a key design process in new product development given the fact that most complex products and systems derive from predecessors and not through clean sheet design[1]. Obviously, changing one component produces knock-on effects on others, generating chain-like change propagations. This knock-on effect may leads to costly rework or jeopardizes the integrity of the whole product[2]. Thus, it is critical that change propagations can be modeled and analyzed effectively in the (re)design process to help correctly identify key and effective change propagation paths and implement necessary changes accordingly. In this way, new product development will reduce design iterations and development time[3].

Fig 1 describes the relationships of change dependency analysis, change processing analysis and change executing in a new product development process.

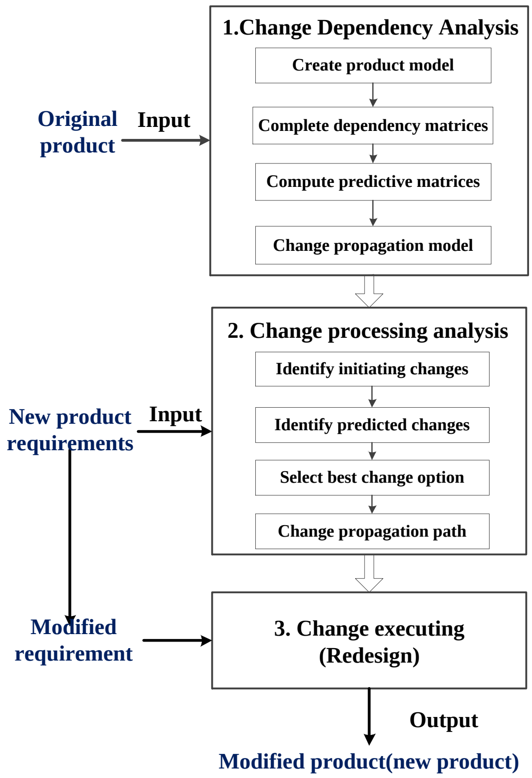

Fig. 1. Relationships of design change model, change propagation analysis and path searching

Firstly, conduct change dependency analysis based on the previous design leading to the development of a design change model. In this analysis, use an original product (product model and data) as the input to establish a

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Supported by National Natural Science Foundation of China (Grant No. 51305367 and Grant No. 51575461), the Doctoral Student Innovation Funds for Zhang Haizhu from Southwest Jiao Tong University, and the Open Outreach Project TPL1501 from the State Key Laboratory of Traction Power.

dependency matrice among the product sub-systems or components, and uses product data and parameters to establish the corresponding predictive matrices based on the parameters' dependency relationships and parameter relations such as explicit or implicit constraints. The dependency matrices and predictive matrices form a design change model, which can be used to predict and examine component relationships[4]. Secondly, put the new product requirements as inputs (identified initiating changes) to the design change model and analyze and identify possible change propagation paths and their impacts because of coupling relationships among parameters in the design change model, and finally select best change propagation path for execution. Thirdly, realize design changes along the selected change propagation path, leading to a new design scheme for evaluation. It is clear that a good design change model is a key enabler for this design process.

Actually, making design changes to previous one is a complex and important process in new product development to industry[5], especially, when designing a complex product system (CoPS)[6]. In fact, in a complex product system, it involves multi-disciplinary and multi-field coupling relationships in functions, subsystems and components[7], featuring not only the diverse functions, but also the complicated and coupling design parameters. Therefore, making a change in customer requirements leads to many change propagations, some propagation paths can be identified easily from their explicit dependences and the others may be difficult because of their coupling relationships. The parameter coupling relationships of design change have a significant effect on the path selection. An improper design change path selection may fails to meet customer demand and generates more iteration of the whole design activities[8]. Thus, there is a challenging need of establishing a change model to properly and systematically analyze the coupling relationships among product functions, structures, manufacturability and costs caused by interdisciplinary and multi-field design spaces. In other words, this design change model is required to be able to systematically analyze change propagation impact for acquiring reasonable change propagation paths.

In this paper, a new design change model is proposed for effectively supporting new CoPS development by helping explore and identify reasonable change propagation paths based on systematic change propagation impact analysis. Our contributions have twofold:

(1) A new design change model is based on the PDS-Behavior-Structure (P-B-S) mappings, which can describe both design change dependency and relations in behavior and structure domains. It can integrally support change propagation impact analysis of CoPS by using multi-disciplinary oriented behavior matrix, and explore an initial change path set by utilizing the interaction relationships of the matrix elements.

(2) A rough set-based propagation space reducing tool associated with this model has been developed to assist in narrowing change propagation paths by computing the importance of the design change parameters, thereby enhancing the decision-making process of design change.

The rest of the paper is organized as follows. Section 2 summarizes related work and section 3 introduces the P-B-S design change model, multidisciplinary behavior matrices and the rough set-based reducing tool. Section 4 takes the design change of a high speed train's bogie as an example to verify the usefulness and effectiveness of the proposed method, and finally conclusions are drawn in section 5.

2 Related work

Design change has increased in prominence as an active academic research area[9]. Many methods and tools have been developed to model design change propagation and support design change prediction and analysis. The key design change modeling methods are listed in table 1.

Table 1. Design change modeling methods

Methods	*Characteristic*
Change favorable representation (C-FAR)[13]	Represented by vectors
Change prediction method (CPM)[4]	Components within design structure matrices
Information structure framework (ISF)[8]	Cross-domain approach
Parameter linkage network (PLN)[14]	Sort out and integrate various parameter linkages
Systems Modeling Language (SysML)[15]	Described modeling approach

C-FAR uses vectors and vector elements to represent components and their attributes, which can not only represent change but also provide a rational qualitative evaluation of the change consequences. CPM makes use of design structure matrices (DSMs) to compute the risk of change propagation between components, which gives indications of the change propagation experienced and much more specific behavior in redesign projects. ISF describes a design and identify possible change propagation linkages within a cross-domain approach which considers the information domains including requirements, functions, components, and the detail design process. PLN is constructed from the parameter linkage perspective in order to show the hierarchical structure and to reveal the propagation characteristics of the parameter linkages. SysML makes use of the port-concept of the system modeling language to describe and analyze change influences in production plants, which is facilitated and can be used to decide on the efficiency or costs of a change of the system. Most of them model a product as a network of linked elements based on their dependences and describe change propagation effects along the paths of this network. But in general, there lacks a system method to describe and analyze a CoPS with coupling system structures, implicit functions and behavior information.

Change propagation paths can be visualized in various forms, including design structure matrices[16], change risk plot[17], propagation networks[18]and propagation trees[19]. When displaying a large and complex product with too many direct and indirect linkages, it is uneasy to see every path clearly[20] and unwise to analyze every propagation path with reduced efficiency. Therefore, there is a need to develop a design change model associated tool to reduce the number of change propagation path candidates for improving task efficiency.

In summary, the following conclusions can be drawn by reviewing the current related work:

(1) In a CoPS, changing any one of requirement parameters may necessitate changes in functions, subsystems and components. In order to evaluate the influences of these changes, a new design change needs to take multi-disciplinary and multi-field coupling relationships into account integrally. In light of the design change impact analysis of multi-disciplinary in the behavior layer for CoPS, we focused on the propagation impact relationship of design parameters in the behavior layer, and then mapping them to the carrier in the structure layer.

(2) In the design change of a complex product system, the number of parameters, parameter linkages, and the complexity of linkages can be significantly high. Moreover, the parameter linkages are coupled and nonlinear. Visualizing and evaluating a large amount of design change information of CoPS is difficult. Thus, a tool to reduce the number of change propagation paths to guide the design change is necessary.

3 New design change model and propagation analysis

In order to support new CoPS development, it is necessary to explore and identify reasonable change propagation paths. The proposed new design change model is to describe both design change dependency and relations, and obtain an initial change path set. In association to this model, a new propagation analysis and space reduction tool is developed to enhance the decision-making process of design change. The method is detailed as follows.

3.1 Design change modeling

The essential process of conceptual scheme design is to map among product design specifications (PDS), product behavior and structure. If changes in requirements in PDS are made, the behavior and structure need respond to the changes. We regard PDS as the initiating layer of design change, behavior as the transfer layer of design change, and structure as the executive layer of design change. Based on the P-B-S conceptual design model[21]and the three level's definition of design change, our P-B-S design change model is developed to show the process of design change and identify change propagation impact(Fig. 2).

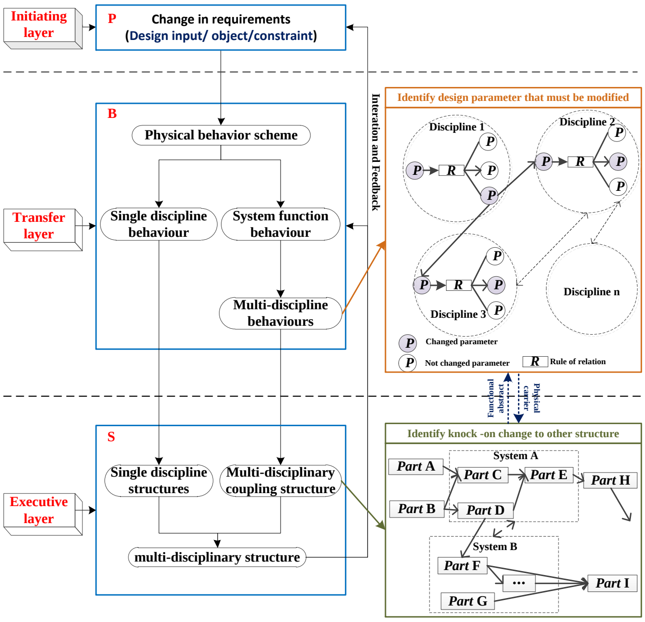

Fig. 2. The design change model based on PDS-Behavior-Structure (P-B-S) relations

The proposed new design change model has three layers (see Fig. 2), namely initiating layer， transfer layer and executive layer. In the initiating layer, the design change model starts with PDS which is regarded not only as a design input, but also objectives and constraints of a design scheme. In the transfer layer, the P-B mapping is applied to obtain the physical behavior scheme, resulting in either a single disciplinary behavior solution or a synthesized system functional behavior solution. The disciplinary behavior matrix technique[22] has been employed to form a matrix for analyzing system functional behavior and to support change propagation impact analysis of CoPS, on the basis of the analysis results, the design parameters that must be modified are identified. In the executive layer, the B-S mapping is conducted to determine the behavior carrier, namely, the structures which can realized requirements change by identifying knock-on changes to other structures. A multi-disciplinary structure is normally composed of single discipline structures and multi-disciplinary coupling structures to support the realization of the system function behavior (SFB).

Therefore, for designing a CoPS, when requirement changes, it needs not only to identify design parameters that must be modified in the behavior layer, but also to identify knock-on change to other structure in the executive layer of design change. In this paper, our main focus is on the former. According to the design change model, a multi-layer network architecture is built to describe the design change and the interaction relationships of behavior to obtain an initial change path set.

In a CoPS, the relationship of structures includes systems, subsystems and parts. In a single discipline behaviour, the fundamental behavior parameters linkage is composed of a parent parameter and several child parameters[14]. The parent parameter is a dependent parameter whose value is determined by those independent child parameters based on the rules. A change rarely occurs alone and multiple changes can have interacting effects on other discipline systems. Thus, it is necessary to be aware of not only individual discipline change chains but also complex multi-disciplinary change networks.

We established a multi-discipline behavior matrix to search influence propagation paths. Discipline areas are assumed to be $D=\{D_1, D_2, \ldots, D_k\}$. For a single disciplinary scheme, its behaviour can be described as a series of state changes in sequence $\{Bv_1, Bv_2, \ldots, Bv_n\}$. For a multi-disciplinary scheme, we examined how behaviors from a discipline can couple with other discipline behaviors to acquire a collaborative multi-disciplinary solution. Let the behavior states for discipline D_i is $\{Bv_1, \ldots, Bv_n\}$, and the behavior states for discipline D_j is $\{Bv_m, \ldots, Bv_l\}$, then the corresponding multi-disciplinary behaviour matrix can be described as D_{ij}. Its element value could be null to represent no interaction relationship between two related behaviour states or a possible interaction relationship (R_{ij}). If there are more behaviors to be coupled in the behavior scheme, the top row can be enlarged. The interaction relationships can be established from cross-disciplinary team efforts.

$$D_{ij} = \begin{array}{c|ccc} & Bv_m & \cdots & Bv_l \\ \hline Bv_1 & R_{1m} & \cdots & R_{1l} \\ \vdots & \vdots & \vdots & \vdots \\ Bv_n & R_{nm} & \cdots & R_{nl} \end{array} \tag{1}$$

Note that the relationships (R_{ij}) in the matrix represent (1) the behavior dependency and (2) their coupling relations.

Because of the complexity of these relationships, it is difficult to find best change propagation paths without proper propagation analysis.

3.2 Propagation analysis and space reduction tool

Our propagation analysis consists of (1) the searching of change propagation paths (2) path evaluation and space reduction.

3.2.1 Searching of change propagation paths

Fig. 3 shows the searching process of change propagation paths. The process starts with initial changed parameters in PDS, which cause changes either in single disciplinary behavior or multi-disciplinary behavior. When the caused changes are in multi-disciplinary behavior, the multi-disciplinary behavior matrix will be used to explore and generate possible behavior propagation paths and then the searching process will proceed down to the structure level. When the affected changes are in single disciplinary, the path searching can go down directly to the structure level. The mappings between behavior and structures are based on our P-B-S conceptual design model [21]. When the searching process is completed, all possible paths will be identified.

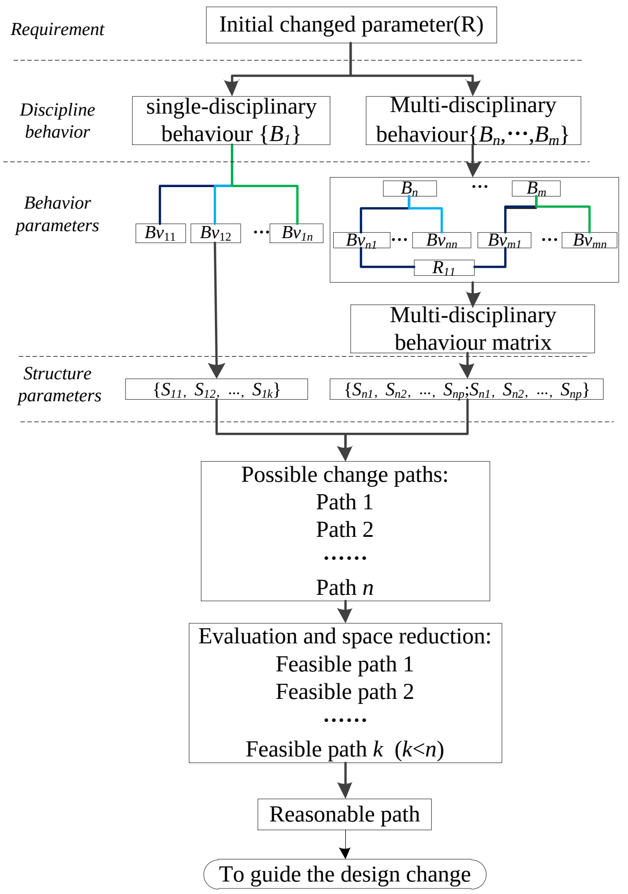

Fig. 3. Searching of change propagation path

Because a change usually has multiple ways to implement, forming different change propagation paths, designers should evaluate them based on a set of measures and select most suitable paths for testing and further development.

3.2.2 Space reduction tool

From Fig. 3, it can be noted that the initial requirement changes may be realized by many structure parameters' changes $\{S_{ij}\}$. The relative importance or sensitivity between the initial changed parameters in PDS and the corresponding structural parameters $\{S_{ij}\}$, is varied and can be evaluated by rough-set theory. Through evaluating their relative importance and sorting them in order, the structural parameters with lower importance can be removed, thus the further investigating space can be reduced.

The Rough set theory[23] is a useful data reduction[24,25] method, without considering the coupling and nonlinear relations between the requirement parameters, and structures.

We applied this method in the following ways to reduce the number of change propagation paths.

(1) Establishing knowledge expression system

First, based on the original product designs (a set of design samples), the requirement parameters, design parameters in behaviors and structures can be obtained as data samples and described as a knowledge expression system, which provides the basis of the data structure for importance analysis. Using formal four tuple to describe:

$$S=(U, A, V, f),\tag{2}$$

where $U=\{x_1, x_2, \cdots, x_m\}$

$A=C\cup D$

$V=\cup V_i\ (1\leqslant i\leqslant k)$

$f=\{f_i \mid f_i: U\rightarrow V_i\}$

U is a finite data (or design) samples set; C is a finite set $\{S_{ij}\}$; D is a data set to describe the concerned behavior parameters $\{B_i\}$; V is the range of value of $\{S_{ij}\}$; f_i is an information function, and defines the mapping relationship between the each record of $\{S_{ij}\}$ and its corresponding parameter values in the set of U.

(2) The importance evaluation based on Rough Set

According to the attribute reduction algorithm based on rough set [23], gain the important degree (w) of $\{S_{ij}\}$ for the target parameters $\{B_i\}$, as follows:

$$w=\gamma_C(d)-\gamma_{C-\{c\}}(d),\tag{3}$$

where $\gamma_C(d)=|pos_C(d)|/|U|$

$\gamma_{C-\{c\}}(d)=|pos_{C-\{c\}}(d)|/|U|$

If $\gamma_C(d)$=1, the knowledge expression system can form a compatible two-dimensional decision table, and from this decision table , the important degree can be calculated.

The normalizing result of w^* is:

$$w^*(c)=w(c)/\sum_{c\in C}w(c),\tag{4}$$

Finally, the quantitative analysis result of the importance of $\{S_{ij}\}$ can be obtained, which can assist in narrowing the selection of target parameters $\{B_i\}$, leading to the reduced change propagation paths. According to their importance of $\{S_{ij}\}$, the structure parameters can be classified as the selectable and discarded parameters. When $w^*(c)$=0, the parameter c is discarded, and it should be deleted from the initial path set; when $w^*(c)\neq 0$, the parameter c is selectable. It a parameter has a higher importance degree; the corresponding change path should be seen as an optional design change path.

All selected change paths can be further tested and evaluated for final design change solutions.

4 Case study —High speed train's bogie

A high speed train's Bogie was selected for our case study of designing change. The proposed method and strategy were verified.

The high speed train's bogie(see Fig. 4) includes a frame, four wheel sets, four primary suspensions and so on, it is a complex product system.

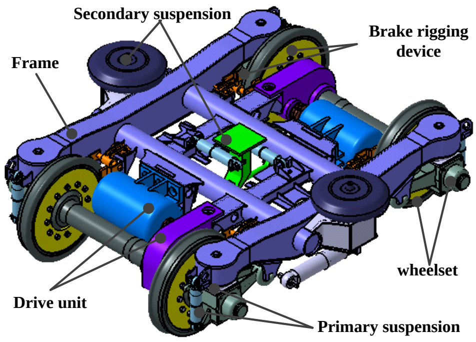

Fig. 4. High speed train's bogie

Firstly, we built a P-B-S design change model(Fig. 5). In the initialing layer, take design speed change as an example; in the transfer layer, we focused on the vehicle dynamic behavior (single discipline behavior), and the brake behavior (multi-discipline behavior); in the executive layer, according to the B-S mapping relationship, we obtained the single discipline structure and multi-discipline coupling structure. The parameters c_1-c_7 are the possible single discipline changeable while p_1-p_5 are the possible multi-disciplinary changeable. Secondly, for multi-disciplinary behaviors, we used the multi-disciplinary behaviors matrix to find the mappings from the behaviors to disciplinary coupling structures. Thirdly, we selected the structure parameters (c_1-c_7) as an example to show how to possibly reduce the parameter space.

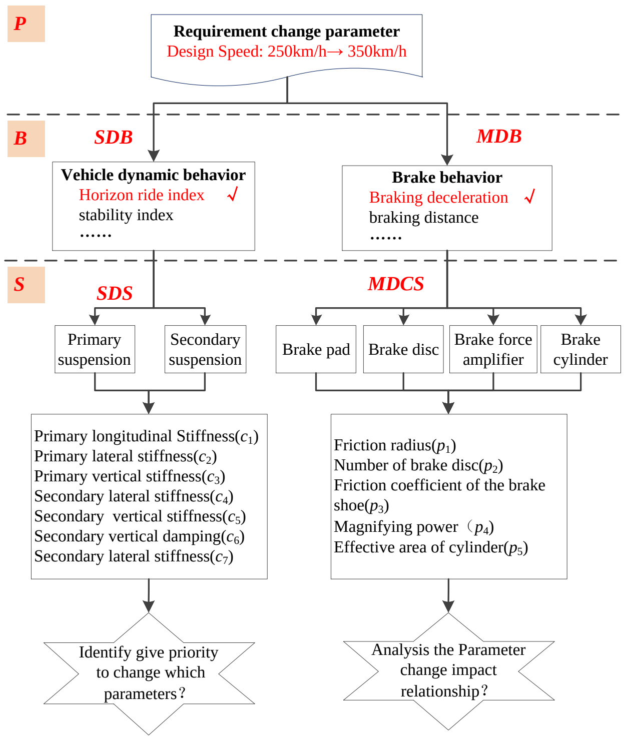

Fig. 5. P-B-S design change model

4.1 Multi-disciplinary behavior matrix analysis.

We analyzed structure parameter change impact for the multi-disciplinary behaviors (B_{v1}-B_{v7}), leading to the identification of structure parameters p_1-p_5.

When designing the braking system, we need to consider collaboration from various disciplines with different physical principles. The braking system includes four disciplines: the control (D_1), mechanical (D_2), pneumatic (D_3) and electrical (D_4). Their multi-disciplinary behavior parameters are interrelated. Fig.6 shows individual disciplinary behavior parameters and the relationships among them. From Fig. 6, we built a multi-disciplinary behavior matrix (DBM) for analysis.

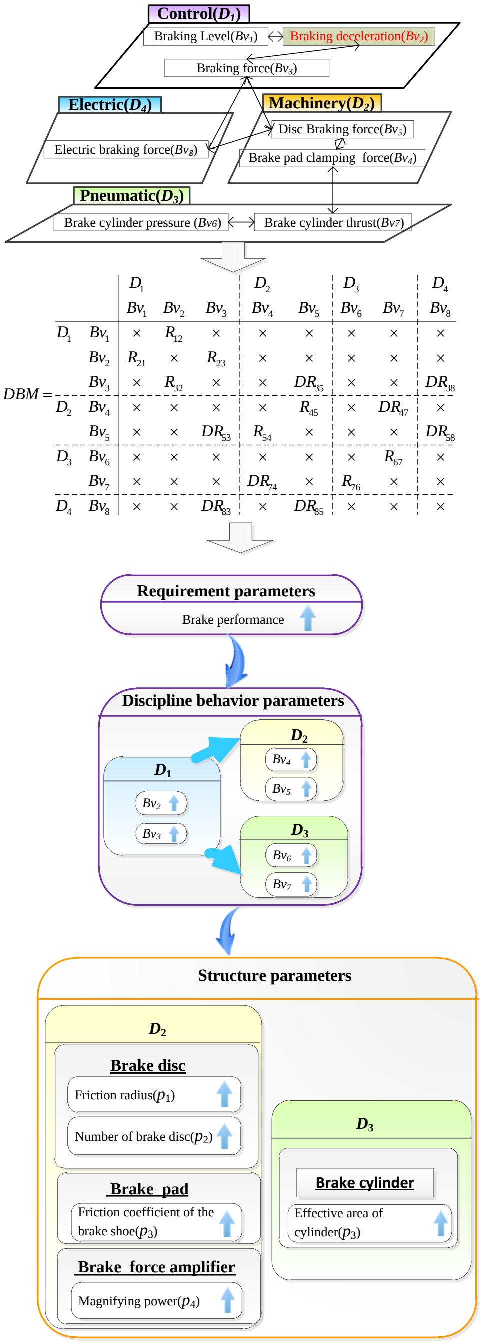

Fig. 6. Multi-disciplinary behavior matrix

According to the *DBM*, the behavior parameters cross disciplines are influenced by each other, and they needs proper structures as a carrier to realize. The relationships among braking behaviors in terms of disc braking force (Bv_5), brake pad clamping force (Bv_4), brake cylinder thrust (Bv_7), and brake cylinder air pressure(Bv_6) are then identified for developing multi-disciplinary coupling structures, including brake disc， brake pad, brake force amplifier and brake cylinder. According to the P-B-S model, the initial change structure parameters sets $\{p_1, p_2, p_3, p_4, p_5\}$ can be obtained. Thus, the multi-disciplinary behavior matrix can express the relationships of disciplines, behaviors and structure parameters, it also indicates the change propagation impact among the requirement parameters, discipline behavior parameters and structure parameters.

4.2 Space Reduction

For the single discipline behavior-the vehicle dynamic behavior, its corresponding structure parameters are $\{c_1, c_2, c_3, c_4, c_5, c_6, c_7\}$. This set of parameters could be reduced because not all of them are equally importance to the behavior parameter.

To do this, we took one previous bogie design as a reference and from its design and simulation model, we created 30 data samples. Firstly, the Latin super cubic experimental design method[26] was used to obtain 30 suspension parameter data set as sample data. Therefore, the $U=\{x_1, x_2, \cdots, x_{30}\}$ was obtained.

Secondly, we used 30 suspension parameters of sample data as input parameters for SIMPACK software to conduct a certain type of dynamics simulation analysis and each simulation analysis result in a horizontal stability index (d_1). Finally, we obtained the knowledge expression system for the vehicle dynamics suspension parameters: $U=\{x_1, x_2, \cdots, x_{30}\}$, $C=\{c_1, c_2, \cdots, c_7\}$, $D=\{d_1\}$, see Table 2.

Table 2. The vehicle dynamics suspension parameters knowledge expression system

Sample sets	Structure parameters value							Behavior value
	c_1	c_2	c_3	c_4	c_5	c_6	c_7	d_1
x_1	831.2	996.1	1339.5	155.4	167.5	45.4	58.6	2.56
x_2	1106.8	1152.2	1001.2	125.1	179.8	39.0	42.7	2.42
x_3	801.8	1115.8	1292.0	162.4	153.7	36.7	52.9	2.53
x_4	1120.1	1099.1	1376.3	166.8	271.8	48.8	44.0	2.49
x_5	902.4	1075.2	1481.3	108.6	201.1	20.2	35.4	2.33
x_6	963.2	1082.5	1493.9	131.9	286.6	36.0	47.7	2.45
x_7	824.7	992.5	1484.6	158.6	160.5	35.3	38.5	2.44
x_8	1026.7	1182.8	1443.9	116.4	157.4	59.8	50.0	2.45
x_9	924.9	880.5	1200.9	117.9	240.0	22.4	55.0	2.50
x_{10}	936.3	846.3	1467.5	101.6	180.2	34.4	53.1	2.47
x_{11}	943.3	1107.9	1054.3	142.8	163.7	42.3	48.9	2.49
x_{12}	1064.6	806.6	1326.7	186.8	278.9	58.4	55.6	2.61
x_{13}	955.5	1034.4	1351.0	133.5	149.3	50.9	57.3	2.53
x_{14}	836.9	1199.1	1248.1	122.9	299.9	51.4	38.6	2.35
x_{15}	1121.6	950.9	1282.4	160.0	138.7	52.8	30.2	2.42
x_{16}	986.0	1042.0	1459.4	178.1	175.0	55.8	50.2	2.54
x_{17}	975.6	1066.8	1064.6	110.6	122.6	32.9	33.2	2.33
x_{18}	892.1	1166.3	1012.1	129.8	261.2	53.8	57.9	2.53
x_{19}	1054.3	1157.1	1431.1	173.4	211.7	54.9	33.8	2.44
x_{20}	1149.5	975.1	1172.9	123.7	200.0	39.5	34.2	2.36
x_{21}	968.2	927.8	1197.9	151.3	229.5	58.9	41.1	2.43
x_{22}	1068.3	869.6	1039.8	107.0	227.0	26.4	40.7	2.38
x_{23}	862.2	981.2	1372.9	191.2	252.6	40.3	37.0	2.48

x_{24}	871.2	940.5	1264.4	183.5	204.6	31.4	52.1	2.55
x_{25}	816.8	1055.9	1086.6	119.7	218.6	50.3	53.6	2.49
x_{26}	906.8	863.0	1400.0	137.4	171.1	56.2	46.5	2.46
x_{27}	1138.9	1002.3	1216.9	102.2	195.7	29.4	56.6	2.50
x_{28}	853.0	849.5	1323.1	121.4	293.3	27.2	34.7	2.34
x_{29}	1047.1	907.8	1315.8	194.1	268.3	47.5	46.1	2.55
x_{30}	1127.4	954.4	1402.0	145.1	190.6	24.4	55.5	2.54

Across all sample x_1-x_{30}, c_1 values range from 801.8 to 1149.5. These values can be converted into integral values 1, 2, or 3 by equally splitting the range into three and number them from the lower end. If applying the rule to c_2-c_7, the corresponding integral values can be obtained. But for d_1, the rule is different because the classification of d1 depends on a key value 2.5, therefore, all values less than 2.5 is classified as 1 and values between 2.5 and 2.75 are as 2. Others are 3. From this conversion, the original table 2 can be changed to form a compatible two-dimensional decision table (not shown here), and from this decision table, the important degrees w and w^* can be calculated as shown in Table 3.

Table 3. Vehicle dynamics important degree of suspension parameters calculation results

Structure parameters	w	w^*
c_1	0	0
c_2	0	0
c_3	0	0
c_4	1/30	0.5
c_5	0	0
c_6	0	0
c_7	1/30	0.5

The computing process is illustrated in Eq. (3-4). w is an important rough set value, in order to identify the selectable parameters and discarded parameters, the w^* column of the Table 3 indicates c_1-c_3 and c_5-c_6 can be discarded design change parameters for the vehicle dynamic behavior such as the horizontal stability, while c_4 and c_7 are selectable parameters.

According to the result, we can select (c_7) and (c_4) as two change propagation paths for further design development in the execution layer.

6 Conclusions

Change propagation is especially problematic in CoPS. A new design change model(P-B-S design change model) for CoPS with effective analysis tools has been proposed. (1) It facilitates designers to assess the scope of each proposed change accurately; (2) Based on this model, the multi-disciplinary behavior matrix analysis is applied to search change propagation paths effectively; (3) By using the rough set based space reduction tool, the design process becomes more efficient; and (4) this method can be used in multi-disciplinary engineering design projects with some domain knowledge support.

In the future, this design change model may be extended to support change propagation risk assessment and change propagation prediction.

References

[1] GIFFIN M, DE WECK O, BOUNOVA G, et al. Change propagation analysis in complex technical systems[J]. *Journal of Mechanical Design*, 2009, 131(8): 081001.

[2] ECKERT C M, KELLER R, EARL C, et al. Supporting change processes in design: Complexity, prediction and reliability[J]. *Reliability Engineering & System Safety*, 2006, 91(12): 1521-1534.

[3] ECKERT C, CLARKSON P J, ZANKER W. Change and customisation in complex engineering domains[J]. *Research in engineering design*, 2004, 15(1): 1-21.

[4] CLARKSON P J, SIMONS C, ECKERT C. Predicting change propagation in complex design[J]. *Journal of Mechanical Design*, 2004, 126(5): 788-797.

[5] JARRATT T A W, ECKERT C M, CALDWELL N H M, et al. Engineering change: an overview and perspective on the literature[J]. *Research in engineering design*, 2011, 22(2): 103-124.

[6] CROSS N. *Engineering design methods: strategies for product design*[M]. John Wiley & Sons, 2008.

[7] HOBDAY M. Product complexity, innovation and industrial organisation[J]. *Research policy*, 1998, 26(6): 689-710.

[8] AHMAD N, WYNN D C, CLARKSON P J. Change impact on a product and its redesign process: a tool for knowledge capture and reuse[J]. *Research in Engineering Design*, 2013, 24(3): 219-244.

[9] SAEEMA A, YETHISH K. Engineering change during a product's lifecycle[J]. *Guidelines for a Decision Support Method Adapted to NPD Processes*, 2007.

[10]SHANKAR P, MORKOS B, SUMMERS J D. Reasons for change propagation: a case study in an automotive OEM[J]. *Research in Engineering Design*, 2012, 23(4): 291-303.

[11]NONSIRI S, COATANEA E, BAKHOUYA M, et al. Model-based approach for change propagation analysis in requirements[C]//*Systems Conference (SysCon), IEEE International*, 2013: 497-503.

[12]ROUIBAH K, CASKEY K R. Change management in concurrent engineering from a parameter perspective[J]. *Computers in Industry*, 2003, 50(1): 15-34.

[13]COHEN T, NAVATHE S B, FULTON R E. C-FAR, change favorable representation[J]. *Computer-aided design*, 2000, 32(5): 321-338.

[14]YANG F, DUAN G. Developing a parameter linkage-based method for searching change propagation paths[J]. *Research in Engineering Design*, 2012, 23(4): 353-372.

[15]KERNSCHMIDT K, VOGEL-HEUSER B. An interdisciplinary SysML based modeling approach for analyzing change influences in production plants to support the engineering[C]//*Automation Science and Engineering (CASE), IEEE International Conference on*, 2013: 1113-1118.

[16]GHONIEM M, FEKETE J D, CASTAGLIOLA P. A comparison of the readability of graphs using node-link and matrix-based representations[C]//*Information Visualization, INFOVIS 2004. IEEE Symposium on*, 2004: 17-24.

[17]JARRATT T, KELLER R, NAIR S, et al. *Visualization techniques for product change and product modelling in complex design*[M],Diagrammatic Representation and Inference. Springer Berlin Heidelberg, 2004: 388-391.

[18]DI BATTISTA G, EADES P, TAMASSIA R, et al. Algorithms for drawing graphs: an annotated bibliography[J]. *Computational Geometry*, 1994, 4(5): 235-282.

[19]LAMPING J, RAO R. Laying out and visualizing large trees using a hyperbolic space[C]//*Proceedings of the 7th annual ACM symposium on User interface software and technology. ACM*, 1994: 13-14.

[20]KELLER R, EGER T, ECKERT C M, et al. Visualising change propagation[C]//*DS 35*: *Proceedings ICED 05*, *the 15th International Conference on Engineering Design*, *Melbourne*, *Australia*, 2005:15-18.
[21]ZHANG H Z, HAN X, LI R, et al. A new conceptual design method to support rapid and effective mapping from product design specification to concept design[J]. *The International Journal of Advanced Manufacturing Technology*, 2016: 1-15.
[22]HEHENBERGER P. Perspectives on hierarchical modeling in mechatronic design[J]. *Advanced Engineering Informatics*, 2014, 28(3): 188-197.
[23]PAWLAK Z. Rough set theory and its applications to data analysis[J]. *Cybernetics & Systems*, 1998, 29(7): 661-688.
[24]FANG H, TAN J R, YIN G F, et al. Process auxiliary decision-making based on rough sets and regulation distance computing[J]. *Chinese Journal of Mechanical Engineering*, 2009, 22(4): 528-534.
[25]LIU D，HU P，LI T R， et al. An Approach for Attribute Weights Acquisition Based on Rough Sets Theory and Information Gain[C]// *International Conference on Intelligent Systems and Knowledge Engineering. Paris: Atlantis Press*，2007: 1296-1302.
[26]STEIN M. Large sample properties of simulations using Latin hypercube sampling[J]. *Technometrics*, 1987, 29(2): 143-151.

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