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A systematic approach to coupling disposal of product family design (Part 2): case study

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Abstract

In this part of the work, we described the application of coupling disposal of product family design proposed in Part 1 on bridge crane. Firstly, axiomatic design theory was utilized as framework to analyse functional requirements and select suitable design parameters with “zigzagging” mode. Secondly, the trolley of bridge crane and its safety protection devices were considered as a real case to be analysed in detail. According to the relation between functional requirements and design parameters, axiomatic design matrix of bridge crane was built, and design structure matrix was constructed. Considering comprehensive correlation degree among design parameters including their functional relevance, connection relevance and physical relevance, we clustered and grouped design parameters into modules with less dependent degree in design structure matrix. Then coupling incidence matrix of product family design for the trolley is established, and it is discussed on the coupling inside modules and the coupling among design parameters with different modules. According to analysis on incidence influence degree, implementation sequence of modules is identified and corresponding decoupling method is proposed.

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Keywords: bridge crane; product family design; coupling analysis; decoupling; axiomatic design

1. Introduction

The bridge crane is a kind of important industrial production equipment, and widely used in industrial and mining enterprises, railway transportation and port *etc*. Its design process is complex and changes with work condition and loading characteristics. The bridge crane has many types, which is a typical customized product, and its variants are mainly determined by lifting capacity, operating speed, classification group, use conditions and so on. The change of each design factor can generate some new product variants, but they are often improved and modified based on existing machine types. The traditional design methods of bridge crane are generally suitable for small batch design modes with excessive reliance on experienced designers, and don’t quickly respond to the needs of individual customers at low cost.

Product development based on a suitable platform has been the main tool for reducing complexity without sacrificing innovation. A well-designed product platform has been proven an effective strategy for product development to economically and efficiently create product families that provide sufficient product variety and market coverage [1]. Product family design is a difficult task - it involves all of the complexities of product design compounded by the challenges of coordinating the design of multiple products. Successful development of a platform and deployment of a product family require input from multiple disciplines [2]. Since there exists the relationship between modules within a given product family, it may induce the coupling of product family design and increase the difficulty of product design. However, most investigations have not addressed the problem of coupling for product family design [3]. The existing researches on coupling analysis are oriented to single product, and are mainly for design iterative sequence to achieve functional requirements (FRs). Xiao and Cheng [4] presented a systematic approach to decoupling of product family design based on AD and coupling incidence matrix.

In this paper, the trolley of the bridge crane is used to discuss coupling association between design parameters (DPs)

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in product family, and corresponding decoupling method based on axiomatic design and coupling incidence matrix is proposed.

The rest of the article is organized as follows. Section 2 discusses disposal strategy of the coupling in product family design. In section 3, a method of analysing and disposing coupled design for product family on bridge crane is proposed. Finally, the conclusions are remarked in section 4.

2. Disposal strategy of the coupling for bridge crane design

The basic purposes of bridge crane are hoisting, traversing in longitudinal and latitudinal direction with a certain speed, and other functional requirements. Taking the basic type of 20t crane as an example, its classification group is A7, span L is 19.5m, lifting height H is 12m, lifting speed v is 18m/min, trolley traversing speed v_t is 48 m/min, and crane traveling speed v_t is 72m/min, respectively.

AD offers a judgment criterion for successful design and improves design activities [5]. In this paper, independence axiom in AD is utilized to analyse functional requirements of bridge crane that are classified into basic functional requirements, expectable functional requirements as well as adjunctive functional requirements. And then functional requirements are mapped into design parameters. According to the relationship between FR and DP, and sensitivity and differences among design parameters, platform parameters are identified. This will weaken the coupling of product family design from strategy level of product family plan.

In AD, decomposition is realized by zigzagging methodology between functional domain and physical domain, and hierarchies for FRs and DPs are created in their respective domain. For bridge crane design, functional requirement of the highest-level (FR_0) is determined, representing the main requirement of the hierarchy, with the mapping of the corresponding design parameter (DP_0):

FR_0: Hoist, traverse in longitudinal and latitudinal direction.

DP_0: Bridge crane with electric double-beam-trolley.

After FR_0 and corresponding DP_0 were determined, the decomposition of the next level was done by using the AD zigzagging method, as shown in Fig. 1.

Based on designer's experiences, the mapping between FRs and DPs can be described with the following equation.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{bmatrix} = \begin{bmatrix} 1 & & & & & \\ & 1 & & & & \\ & & 1 & & & \\ 1 & 1 & 1 & 1 & & \\ 1 & 1 & 1 & 1 & 1 & \\ 1 & 1 & 1 & 1 & & 1 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{bmatrix} \tag{1}$$

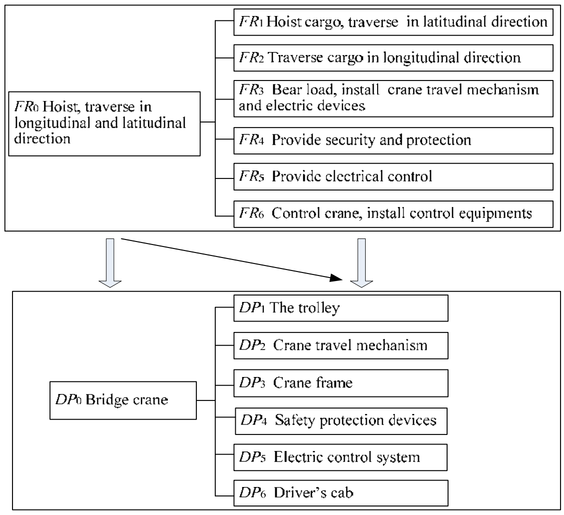

Fig. 1. Mapping and decomposition of functional requirements-design parameters of bridge crane.

From Eq.(1), we can see that there is no coupling among FRs and only exists unidirectional associations on the whole. This is a kind of decoupled design, and the independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence. FRs and DPs should be decomposed to the leaf-level until we create a hierarchy. Then, design parameters responding to basic functional requirements are identified, such as $FR_3 \rightarrow DP_3$. The basic structure of bridge frame is composed of double girder and end carriage. The section of girder and end carriage could be modified. The basic structure types of hoisting mechanism, trolley traverse mechanism and crane travel mechanism are lifting motor – brake - winder, trolley traverse motor - brake- trolley wheel group and crane travel motor - brake - crane wheel group, respectively. These basic structures are regarded as common parameters that satisfy basic functional requirements of bridge crane. Due to limited space and functional similarity, this paper only analyses the trolley and its safety protection devices.

For coupling analysis of product family, it is unnecessary to define the trolley and safety protection devices to the specific numerical values in the mapping process of FR-DP. These design parameters are not given with specification and type, as shown in table 1 and 2 such as motor, brake, reducer and so on. According to customer satisfaction, the FRs of bridge crane are divided into basic functional requirements, expectable functional requirements and adjunctive functional requirements. Each DP corresponds to one FR. DPs that reflect basic functional requirements for product family are defined as common parameters, and that reflect adjunctive functional requirements are defined as customization parameters. Then design matrix of the trolley based axiomatic design is established. Since design matrix can't capture the interactions among the design parameters in design process, it should be converted to design structure matrix (DSM), reference to literature [6]. DSM is a popular representative and analysis tool for system modeling, especially for purposes of decomposition and integration [7]. A DSM displays the relationships between components of a system in a compact, visual, and analytically advantageous format. DSM of the trolley is shown in Fig.2. In Fig. 2, DPs in first column with marked 'b' and 'a' are those corresponding to basic functional requirements and adjunctive functional requirements respectively, and other DPs are those corresponding to expectable functional requirements.

DSM of the trolley can be divided into two parts. One is common platform parameters, another is other DPs. Considering the functional relevance, connection relevance and physical relevance between design parameters, we cluster into coupling incidence matrix of product family for the trolley with high cohesion degree in a single module and low coupling degree among all the modules, as shown in Fig. 3.

Once lifting mode and lifting weight are given, fetching device DP_{118} can be identified, which is the most basic design parameter of the crane. Since the wire rope is determined by lifting weight and rope strands in pulley block, rope strand can be represented by the rope DP_{119}. The loadings of the trolley (including lifting weight and the trolley's weight) are fully borne by wheel groups, and trolley traversing speed is characterized by wheel. So both of the loading and traversing of the trolley speed may be represented by driving wheel group $DP_{128.}$

3. Method of analysing and disposing coupled design for product family

From Fig. 3, we may see that the coupling incidence matrix of the trolley is divided into five platform modules and eight independent customization modules (parameters). Meanwhile, it has eight incidence elements outside the cluster, i.e., A_1, A_2, B, C_1, C_2, C_3, D and E, where A_2 is an interaction between platform module and customization module, and the rest are interactions among platform modules. There is no intercoupling between modules in this case. Moreover, there exists the coupling association between design parameters inside the first module, and only unidirectional association between design parameters inside other modules. The detailed influence of these incidence elements is analysed as following.

Table 1. Functional requirements hierarch of the trolley.

FR$_1$ Hoist, traverse longitudinal and latitudinal direction			
FR$_{11}$ Hoist cargo	FR$_{12}$ Traverse in latitudinal direction	FR$_{13}$ Bear load, install mechanism of the trolley	FR$_{14}$ Provide security and protection
FR$_{111}$ provide lifting power FR$_{112}$ provide lifting torque and speed FR$_{113}$ provide brake power FR$_{114}$ provide brake torque and mode FR$_{115}$ slow down and increase torque FR$_{116}$ connect and transit torque FR$_{117}$ compensate install deviation of lifting mechanism FR$_{118}$ load handling FR$_{119}$ bear and lift cargoes FR$_{1110}$ pass around and save labour FR$_{1111}$ guide and brace FR$_{1112}$ wind FR$_{1113}$ receive rope	FR$_{121}$ provide traversing power FR$_{122}$ provide traversing torque and speed FR$_{123}$ provide brake power FR$_{124}$ provide brake torque and mode FR$_{125}$ slow down and increase torque FR$_{126}$ connect and transit torque FR$_{127}$ compensate install deviation FR$_{128}$ traverse actively FR$_{129}$ traverse passively FR$_{1210}$ guide wheel in horizontal direction	FR$_{131}$ provide install and support mode FR$_{132}$ ensure installation size FR$_{133}$ provide installation plane FR$_{134}$ provide support for cable line	FR$_{141}$ avoid overload FR$_{142}$ avoid lifting device rushing to the top FR$_{143}$ avoid the trolley rushing to the limitation FR$_{144}$ reduce the impact FR$_{145}$ prevent people falling FR$_{146}$ prevent rope disorder FR$_{147}$ remove obstacles of crane frame FR$_{148}$ prevent dust and rain, and protect the safety of personnel

Table 2. Design parameters hierarch of the trolley.

DP$_1$ The trolley			
DP$_{11}$ Hoisting mechanism	DP$_{12}$ Trolley traverse mechanism	DP$_{13}$ Trolley frame	DP$_{14}$ Safety protection devices
DP$_{111}$ motor drive type DP$_{112}$ motor parameters DP$_{113}$ brake device DP$_{114}$ brake parameters DP$_{115}$ reducer DP$_{116}$ coupling DP$_{117}$ compensation shaft DP$_{118}$ load handling device DP$_{119}$ wire rope DP$_{1110}$ hook assembly DP$_{1111}$ fixed pulley group DP$_{1112}$ drum type DP$_{1113}$ drum parameters	DP$_{121}$ motor drive type DP$_{122}$ motor parameters DP$_{123}$ brake device DP$_{124}$ brake parameters DP$_{125}$ reducer DP$_{126}$ coupling DP$_{127}$ compensation shaft DP$_{128}$ driving wheel group DP$_{129}$ driven wheel group DP$_{1210}$ horizontal wheel device	DP$_{131}$ trolley frame type DP$_{132}$ trolley frame DP$_{133}$ backing board DP$_{134}$ cable frame	DP$_{141}$ load lifting limiter DP$_{142}$ hoisting height limiter DP$_{143}$ over travel-limit switch DP$_{144}$ bumper DP$_{145}$ guard rail DP$_{146}$ rope guard DP$_{147}$ rows of baffle DP$_{148}$ cover

DP \ DP	111	112	113	114	115	116	117	118	119	1110	1111	1112	1113	121	122	123	124	125	126	127	128	129	1210	131	132	133	134	141	142	143	144	145	146	147	148
111^b	1																																		
112	1	1																																	
113^b			1																																
114		1	1	1	1																														
115	1	1			1								1																						
116		1		1	1	1							1																						
117		1					1																												
118^b								1																											
119^b								1	1	1																									
1110									1	1																									
1111									1	1	1																								
1112^b												1																							
1113									1			1	1																						
121^b														1																					
122														1	1						1														
123^b																1					1														
124															1	1	1	1			1	1													
125														1	1			1			1														
126															1		1	1	1																
127																		1	1	1					1										
128^b								1													1														
129																					1	1													
1210^a																							1												
131^b																								1											
132													1								1			1	1										
133																								1	1	1									
134																								1			1								
141^a									1																			1							
142^a																													1						
143^a																														1					
144^a																															1				
145																									1							1			
146^a																																	1		
147^a																																		1	
148^a																																			1

Fig. 2. DSM of the trolley

DP \ DP	118	119	1110	1111	1112	1113	111	112	113	115	114	116	117	128	129	121	122	123	125	124	126	127	131	132	133	134	145	141	142	143	144	1210	146	147	148
118^b	1																																		
119^b	1	1	1																																
1110		1	1																																
1111		1	1	1																															
1112^b					1																														
1113		①			1	1																													
111^b		↑					1																												
112		A_1					1	1																											
113^b									1																										
115				C_1	→	①	1	1		1																									
114								1	1	1	1																								
116				C_2	→	①		1		1	1	1																							
117								1					1																						
128^b	①	←	B											1																					
129														1	1																				
121^b																1																			
122														1		1	1																		
123^b														1				1																	
125														1		1	1		1																
124														1	1		1	1	1	1															
126																	1		1	1	1														
127																			1		1	1		①	←	E									
131^b																							1												
132				C_3	→	①						D	→	①									1	1											
133																							1	1	1										
134		A_2																					1			1									
145		↓																						1			1								
141^a		①																										1							
142^a																													1						
143^a																														1					
144^a																															1				
1210^a																																1			
146^a																																	1		
147^a																																		1	
148^a																																			1

Fig. 3. Coupling incidence matrix of product family for the trolley.

The incidence parameters DP_{118}, DP_{119}, DP_{1113}, DP_{128} and DP_{132} in different modules are considered as controllable factors in parameter design and experimental design techniques are firstly utilized to analyse their influence on the design objectives, in order to correspondingly control and adjust their deviation. Especially for DP_{118}, it influences several design parameters in other modules. The goal of experimental design is to ensure that the size and weight of the trolley is respectively small and light [8]. According to visual analysis of the results of experimental design, it is shown that the impact of DP_{1113} (the drum) on two design objectives is biggest, DP_{132} (trolley frame) take second place and DP_{118}'s is smallest.

The rope DP_{119} is coupled with hook assembly DP_{1110}. The comprehensive correlation degree among design parameters inside module 1 is shown in Fig. 4.

By analysing the functional relevance, connection relevance and physical relevance between design parameters, the comprehensive correlation degree among design parameters can be calculated according to the importance degree of each relevance criterion [9,10]. Suppose there are n design parameters in coupling incidence matrix of product family, the comprehensive correlation degree between DP_i and DP_j is $r(i, j)$, and then the interaction matrix **R** of design parameters can be constructed, as following.

$$\mathbf{R} = \begin{array}{c} \\ \end{array}\begin{array}{cccc} DP_1 & DP_2 & \cdots & DP_n \end{array} \\ \mathbf{R}=\begin{bmatrix} r(1,1) & r(1,2) & \cdots & r(1,n) \\ r(2,1) & r(2,2) & \cdots & r(2,n) \\ \vdots & \vdots & & \vdots \\ r(n,1) & r(n,2) & \cdots & r(n,n) \end{bmatrix}\begin{matrix} DP_1 \\ DP_2 \\ \vdots \\ DP_n \end{matrix} \quad (2)$$

	DP_{118}	DP_{119}	DP_{1110}	DP_{1111}
DP_{118}	1			
DP_{119}	0.15	1	0.2	
DP_{1110}		0.5	1	
DP_{1111}		0.4	0.75	1

Fig. 4. Comprehensive correlation degree among DPs in module 1.

DP_{119} is mainly dependent on lifting capacity and rope strands, while DP_{1110} is mainly dependent on rope strands, classification group and the diameter of the rope. The weight of hook assembly DP_{1110} conversely has influence on pulling force of the rope, but the effect is little. So to match the rope, the primary thing is to select the wire rope, and then design hook assembly.

The incidence element A_1 between module 1 and module 2, which represents the effect of DP_{119} on DP_{113}, can be denoted as $DP_{119}{\rightarrow}DP_{113}$. The following incidence elements are also expressed in this way. The association relationship between module 1 and module 2 and coupling incidence path are respectively shown in Fig. 5 and Fig. 6, respectively. The type and size of the wire rope decide the specification of the drum. The diameter of the drum is related to crane classification group (a given basic parameter) and the diameter of the rope, and the length of the drum is determined by the diameter of the rope and rope capacity. The ways to weaken coupling are 1) controlling the deviation of the rope to reduce the influence on the drum, and 2) improving the adaptability of the drum to the rope. The diameter and length of the drum can be adjusted according to the actual situation. For example, if the diameter of the rope d is 20mm, the diameter of drum should be

$D>e\times d=22.4\times20=448$mm

where e is the rope-diameter ratio. According to classification group of crane (A7), e is equal to 22.4.

In fact the value of D is taken as 500m due to considering transmission ratio of the reducer and the diameter of the drum. So the drum has the ability to change within a certain range.

The incidence element B ($DP_{118}{\rightarrow}DP_{128}$) between module 1 and module 4. DP_{118} represents lifting weight. DP_{128} is dependent on lifting weight and deadweight of crane. The wheel is designed and calculated according to the maximum lifting weight, thus the impact of DP_{118} on DP_{128} ($DP_{118}{\rightarrow}DP_{128}$) is small, which is weak coupling and the influence can be ignored.

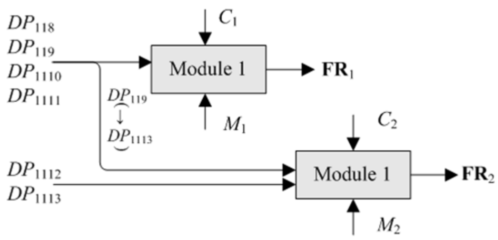

Fig. 5. Association relationship between module1 and module 2.

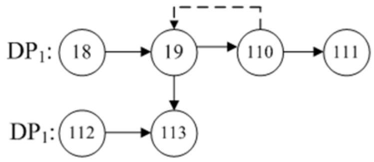

Fig. 6. Coupling incidence path between module1 and module 2.

The incidence element A_2 ($DP_{119}{\rightarrow}DP_{141}$) between module 1 and customization module (parameter). The hoisting height limiter is determined by the tension of the rope. The suitable limiter is chosen to match corresponding rope, or the capacity of limiter is adjusted to adapt to the rope within a certain specification.

The incidence element C_1 ($DP_{1113}{\rightarrow}DP_{115}$) and C_2 ($DP_{1113}{\rightarrow}DP_{116}$) between module 2 and module 3. If the diameter of the drum is modified, its speed and torque will change, which may cause the change of transmission ratio of the gear reducer and the brake. Moreover, the coupling located between drum and reducer is also adjusted. One effective decoupling method is to integrate the design parameters. For example, the permanent magnet motor with low speed and high torque that installs inside the drum is taken as prime mover. Another method is to match reasonably the drum and reducer, since the brake DP_{114} influenced by the reducer and the coupling DP_{116} itself has greater adaptability.

The incidence element C_3 ($DP_{1113}{\rightarrow}DP_{132}$) between module 2 and module 5. The length of the drum affects the width of trolley frame that have an impact on track centre of the trolley. The approaches to weaken coupling are 1) to control variation range of the drum so as to reduce its impact on trolley frame, and 2) to integrate design parameters and use the permanent magnet motor with low speed and high torque according to processing method of incidence parameter C_1 to shorten the overall length of hoisting mechanism. The width of trolley frame shouldn't be too small due to the limitation of itself structure and track centre of the trolley, so it is insensitive to the change of the length of the drum.

The incidence element D and E between module 4 and module 5. There is an interaction (coupling) between these two modules ($DP_{128}{\rightarrow}DP_{132}$ and $DP_{132}{\rightarrow}DP_{127}$). DP_{128} represents the load of the trolley and DP_{142} represents bearing capacity of trolley frame. The change of the width of trolley frame may result in the modification of the length of the compensation shaft DP_{27} on trolley traverse mechanism. Furthermore, the effect of $DP_{128}{\rightarrow}DP_{132}$ is greater than that of $DP_{132}{\rightarrow}DP_{127}$. So, module 4 is prior to module 5 in product family design. Here, the approaches to weaken coupling are 1) to control variation range of the load to reduce its impact on section size of trolley frame; 2) to improve the adaptability of trolley frame to the change of the load within a certain range; 3) to use higher strength material in trolley frame to decrease the sensitivity to the load; and 4) to take advantage of the nonlinear characteristics of compensation shaft to trolley frame, since there exists the inconsistency of their variation between the length of compensation shaft and the width of trolley frame. The former is to adapt track centre and compensation effect, and the latter is to meet the needs of structure arrangement and track centre.

4. Conclusions

For the development of series products, the design coupling of single product, of course, should be analysed, but for product family design it is more important to consider global planning problem. In design of product family, axiomatic design theory is utilized as framework to analyse functional requirements, and design parameters are selected by “zigzagging” mode. The basic FRs must be well satisfied and corresponding DPs shared by product variants within a given product family are determined. According to the relationship between functional requirements and design parameters, as well as the sensitivity and differences among design parameters, platform parameters can be identified. This will weaken the coupling from strategic level of product family plan.

For the coupled problem of product family design for bridge crane, this paper analyses association relationship between design parameters based AD and coupling incidence matrix. We cluster DPs of the trolley into modules with high cohesion degree in a single module and low coupling degree among all the modules. Then the interface among modules can be identified, and incidence parameters are considered as controllable factors as well as experimental design techniques are utilized to analyse the influence of incidence parameters on design objectives. The coupling inside modules and the coupling between design parameters in different modules are discussed. According to different coupling modes, corresponding decoupling methods are presented. In this case study, traditional design needs richer experience. Through applying the proposed method, it is more reasonable for the design of the trolley, and can weaken the coupling and reduce design time. The methodology is also applicable to the design of other product family that can be modularized with interactions between modules..

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