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DESIGN ORCHESTRATION COMPOSER - A MODEL BASE ENABLING HOLISTIC MANAGEMENT OF PRODUCT, DESIGN PROCESS, AND ORGANIZATION

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ABSTRACT

As the industries develop, product enlarges its scale and increases its complexity. To defeat past products, more functions and mechanisms have been installed. It requires more and more people involved, disciplines needed, which have to orchestrate toward the achivement of a better product. However, due to complexity of design, management of the design process and the organization becomes huge challenge. Considerable time and efforts are required for the better management. Failures of management appear as delays, over-budgets, inferior functionalities or defects. Literally, scale and complexity of a product are exceeding the limit that mankind can manually deal with.
The aim of this study is to establish the model base that enables model based management of product, design process, and organization. The major function of the model base application is realized by the domain specific calculations and analyses. By considering the domain specific rationales, it is possible to describe detailed relationships and give insightful translation of the analysed results.
The case study on a solar boat design project demonstrates the use of the model base and its applications.

Keywords: project management, design management, complexity, multiple domain matrix, model based management

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1 INTRODUCTION

As industries develop, their products increase in size and complexity. To defeat the past products, more functions and mechanisms have been installed. It requires more and more people involved, disciplines needed, which have to orchestrate toward the same goal, to design a better product. Therefore, the key to success is how to manage design for better orchestration.

Before products were so large-scaled and complex, managers could have a holistic view of a product and its entire design project. They understood which part was connected to another, who was responsible for which part, and who needed to cooperate with whom. In these simpler situations, managers could manage the design process and the organisation quite well.

Now, conditions are changing. With the increase in scale and complexity, managing the design process and the organisation has become a major challenge. Effective management requires considerable time and effort. Delays, inflated budgets, inferior functionalities, and defects are regarded as administrative failures. Literally, management of large-scaled and complex product design no longer can be performed manually. Therefore, a considerable part of the success of state-of-the-art design projects is based on how well a design team can manage complexity (Lindemann et al., 2009).

The aim of this study is to establish the model base that enables model-based management of product, design process, and organisation. The use of a computational model will help managers analyse strengths and weaknesses, and to explorer possible corrective measures.

2 RELATED WORKS

2.1 Previous studies on the management of design

Several studies have discussed the application of MDM, DMM, and DSM to the management of designs and processes. Eckert et al. (2006) and Clarkson et al. (2001) proposed a method for predicting the potential propagation of effects that are triggered by changing a design parameter. Lindemann et al. (2009) explored MDMs to understand complex systems from a structural viewpoint.

Additionally, DSM, MDM, and other complementary methods have been studied to create design processes with high manageability. Eppinger et al. (1994) suggested the use of DSM to create product development processes with a lower likelihood of iterations. The method suggests sequences of design tasks based on the analysis of precedence among tasks. Since tasks and their input-output relations need to be defined, it is not possible to take change of task descriptions into account.

As for a comparison between product (or process) structure and the organisational structure of human resources, Sosa et al. (2004) presented a diagnosis of the misalignment between product and organisational structure. Kreimeyer et al. (2007) presented the application of MDM to the composition of a multi-functional team.

2.2 Position presented in this paper

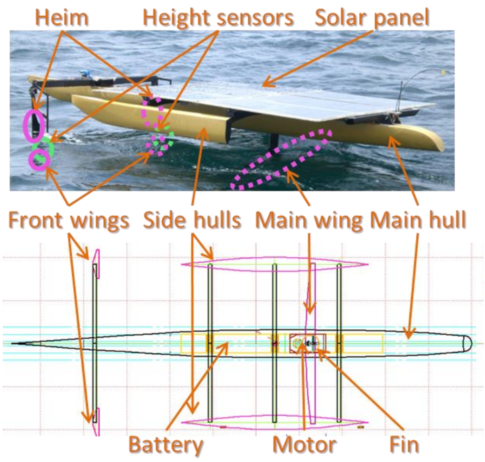
Although several previous studies have made use of MDM, DMM, and DSM for successful design management, it should be noted that each method is applicable to its specific domains. Therefore, to enjoy the advantages of each method, design teams must create individual models for analyses. However, acquisition of such models requires much time and effort. If a single maintainable model base that bridges several different domains could contribute to multiple aspects of design management, it would accelerate the use of the various methods in the industry. Thus, this paper proposes a structure of a model base for enabling holistic management of design.

Most previous studies on coordination of the design process describe the dependencies among tasks and calculate the coupling and sequencing of tasks. Likewise, dependencies among the elements of a product are described for structural analyses of a product. In contrast, this study, for example, discusses how the design process should be structured in relation to the product, which is an objective of the process, and the organisation implementing design. As a result, the design process can be viewed from both a product and organisational points of view, and vice versa. This model is useful for the management of design activities as a whole by integrating viewpoints on product, design process, and organisation. For example, if the weaknesses of an organisation are detected, it is possible to consider countermeasures in the design process (e.g. design review planning). Though the domains of organisation and process are different, they are interlinked logically; therefore, it is possible to enhance inter-domain analysis.

3 CASE STUDY

3.1 Case introduction

To demonstrate the proposed method, evaluate its feasibility, and examine the validity of results, a case study of a solar boat design project was executed. This project was managed by graduate students at the University of Tokyo as part of a course offered by the Department of Systems Innovation. Figure 1 illustrates the solar boat developed in the project. The matrix in Figure 1 provides QFD data for the design of the solar boat. Details of QFD are explained in section 4.2.



Design Parameters

Function Metrics	dp1	dp2	dp3	dp4	dp5	dp6	dp7	dp8	dp9	dp10	dp11	dp12	dp13	dp
fn1	1	3	1	1	1	1	1	1	1	1	1	1		
fn2	1	1	1	1	1	1	3	3	1	1	1	1		
fn3		1	1	1	1		1	3	1	1	3	1	3	1
fn4		1	1	1	1		1	3	1	1	3	1	3	1
fn5	3	1	1					1	1		1	1		
fn6	3	1	1	3	1	1		1	1		1	1		
fn7	1	1		1	1		1	1		1	1			3
fn8	1	1		1	1		1	1		1	1			3
fn9	1	1		1	1		1	1		1	1			1
fn10	1	1		1	1		1	1		1	1			1
fn11	3			3			1	1	1	1	1	1		
fn12	3						1	1	1	1	1	1		

DOC Design Orchestration Composer

Figure 1. Picture and QFD data of solar boat applied for case study

3.2 Prototype software

The proposed model and applied methods were incorporated into the Design Orchestration Composer (DOC) software, an object-oriented MDM-based design support system. This system provides structural analyses of a product and organisation to facilitate model-based assistance for the management of design activities. The case study was performed with the use of this software.

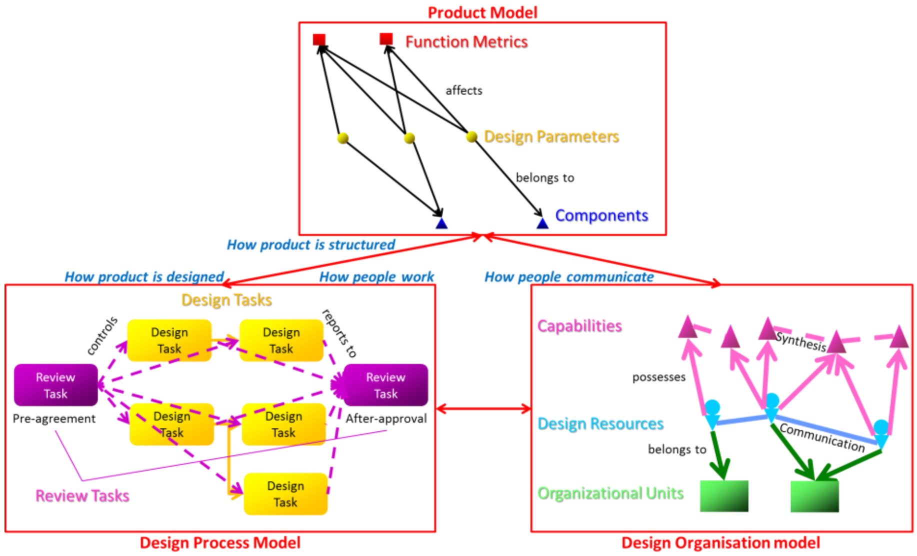


Figure 2. Overview of the integrated model for product, design process and organisation

4 STRUCTURE OF THE MODEL BASE

4.1 Model overview

To enable model-based management of design, it is essential to link the product, design process, and organisational information by considering the relationships among them. Figure 2 shows an overview of the proposed integrated model of a product, its design process, and the organisation. As shown in Figure 2, the structure of a product influences the structure of design process. It implies that the structural analysis of a product model can yield the structure of the design process model. Likewise, product structure influences the organisational structure. It implies that the structural analysis of a product model can yield the structure of the organisation model as well. Further, how people work together in the design process is affected by how they communicate within an organisation, and vice versa. The integrated model of product, process, and organisation provides managers of design activities with an arena to explore possible structures, strengths, and weaknesses of design processes and organisations. Details of the product, design process, and organisation model are described below.

4.2 Product model

The following three element domains represent product information.

Design parameters: These are the product elements that are designed directly. Several design parameters are dealt with as preconditioned (fixed). To mitigate the risk of propagating the effect of change before a design project is begun, it is agreed that these parameters will not be changed. The determination of preconditions is affected by the design principles of each project.

The design parameters of the solar boat are the length of the main wing, stiffness of the side hulls, capacity of the battery, etc. (a total of 23 parameters).

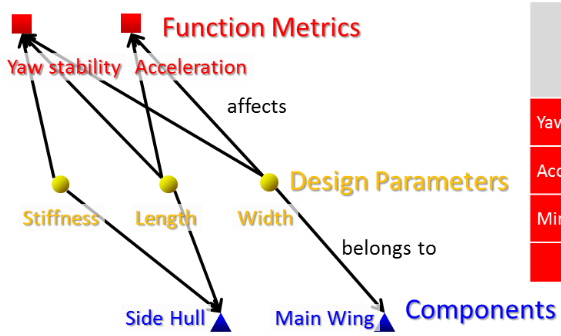
Components: These are the physical elements that constitute a product. Every design parameter belongs to one component, and each component has at least one design parameter. A component physically constrains how the design process is coordinated.

The components of the solar boat are the main wing, side hulls, battery, etc. (a total of 10 components).

Function metrics: These are the observable metrics used to evaluate the functionality of a product. They cannot be designed directly; rather, they are realized through the determination of design parameters. Each functional metric is assigned a relative importance for each project.

The function metrics of the solar boat are acceleration, yaw stability, maximum travel distance, etc. (a total of 12 function metrics).

As explained above, each element contains information by which it is characterized. In addition, these three types of elements are related to each other. An overview of a product model is shown in Figure 3.



	Importance	Side hull		Main wing		...
		Stiffness	Length	Width	Length	Stiffness	...
Yaw Stability	4	1 ↑	3 ↑↓		3 ↓	3 ↓	...
Acceleration	3	3 ↓	3 ↑↓	3 ↑			
Min. Radius	2	3 ↓		1 ↑		1 ↑	
⋮	⋮	⋮					⋱

Sensitivity 3 ↑ Characteristics

Figure 3. Grammar and matrix description of product model

As shown in Figure 3, the determination of design parameters affects function metrics. To detail these relationships, four types of information (described below) are attributed to each relationship.

Sensitivity: This information is the extent to which change in design parameter affects a function metric. It is preferable to have several levels of sensitivity. In this paper, two levels are defined: (3) *strong enough* to change the corresponding function metric and (1) *not strong enough* to change the corresponding function metric.

Characteristics: This information is the tendency of a function metric to react to change in a design parameter. There are four types of characteristics: (1) the larger, the better, (2) the smaller, the better, (3) the closer, the better and (4) unknown.

Operational risk: The risk of undesirable effects on other function metrics that may be caused by a change in the corresponding design parameter. In general, the determination of a design parameter affects several function metrics. Characteristics, however, may differ from one another. Therefore, when a design parameter is changed to improve a function metric, other function metrics may be affected negatively.

This is defined as risk. A risk has three levels: no risk, high risk, and low risk. Risk is calculated by taking into account the characteristics and the importance of a function metric.

Operational preference: The decision regarding whether a design parameter should be determined specifically to improve a corresponding function metric. This has three levels—preferred, not preferred, and controversial. Operation preference is calculated using a structural analysis of the relationships among design parameters and function metrics.

4.3 Design process model

The following two element domains represent design process information.

Design tasks: These are activities to determine one or more design parameters. As a physical constraint, a design task cannot bridge several components. Design tasks are set in a sequence that then constitutes a design process. By referring to the part of a product model that each task is responsible for, tasks are related through their coordination among design parameters.

In the case study, design tasks were deduced by analysing the product model (explained later, see section 5.1). The resultant design process comprised 14 design tasks.

Review tasks: These are the activities of discussing and determining how the relationships among design parameters are managed. There are two types of design review: formation of a pre-agreement and confirmation of after-approval.

In the case study, review tasks were deduced by analysing the relationships between design tasks and organisational structure (see section 5.4).

Since a review task is intended to manage the relationships among design parameters, it is linked to the design tasks that determine these parameters. The relationships among review tasks and design tasks are shown in Figure 4.

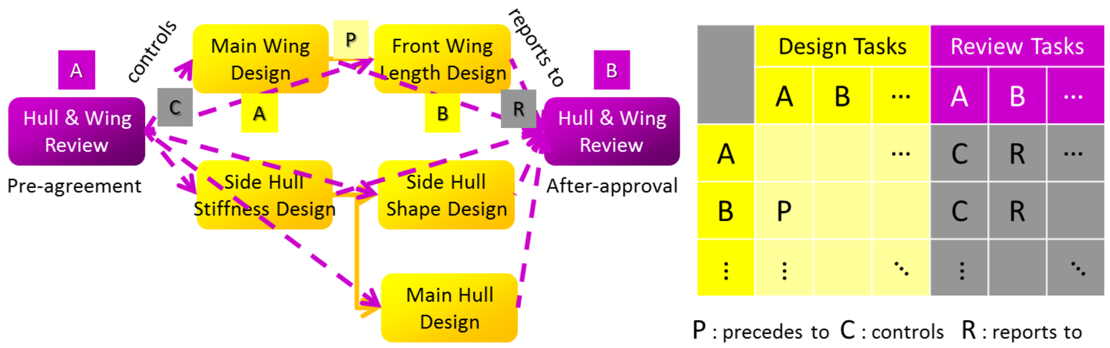


Figure 4. Grammar and matrix description of design process model

4.4 Organisation model

The following three element domains represent organisation information.

Capabilities: These are abilities to implement design. Capabilities of an organisational unit are expressed as the collective capabilities of design resources belonging to the unit. The company demonstrates its strategy through coordination of capabilities.

The capabilities involved in the solar boat design project are fluid dynamics, strength of materials, mechanism, vibration, and material science.

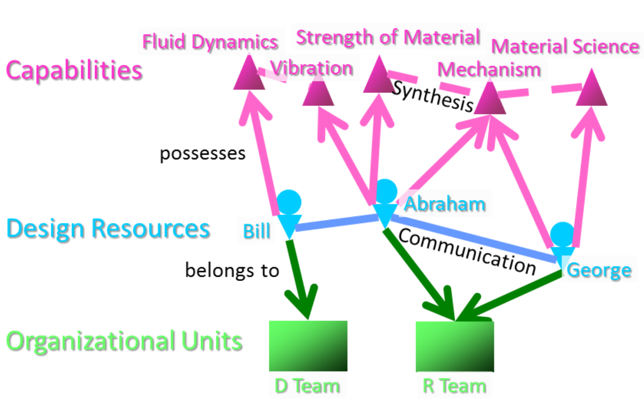
Design resources: These are those who implement design. Each design resource belongs to one or several organisational units. Communication among design resources within an organisational unit enables coordination of capabilities.

The design resources of the solar boat design project were Bill, Barack, John, Abraham, and George.

Organisational units: These are places where design resources are gathered according to certain objectives. An organisational unit is a place to coordinate and foster capabilities.

These three element domains are interrelated. Relationships within the three domains in an organisation model are illustrated in Figure 5.

The organisational units of the solar boat design project are: the D team (located in Tokyo) and the R team (located in a suburb of Tokyo.



Fluid dynamics	3			···
Vibration		3		
Strength of material		1		
Mechanism		3	3	
⋮	⋮			⋱
	Bill	Abraham	George	···
D team	X			···
R team		X	X	
⋮	⋮			⋱

Figure 5. Grammar and matrix description of organisation model

4.5 Model integration part

To integrate product, design process, and organisation models, elements of the models must have relationships with each other. Figure 6 shows how these models are integrated.

To integrate product and design process models, design parameters and design tasks must be connected. These relationships mean that 'a design task is responsible for the determination of a design parameter'. As for integration of a design process model and an organisation model, design tasks are connected with capabilities and design resources. These relationships mean 'a design task requires a capability' and 'a design task is implemented by a design resource', respectively. Likewise, integration of product and organisation models is achieved by integration of design parameters and capabilities (i.e. 'determination of a design parameter is realized by a capability').

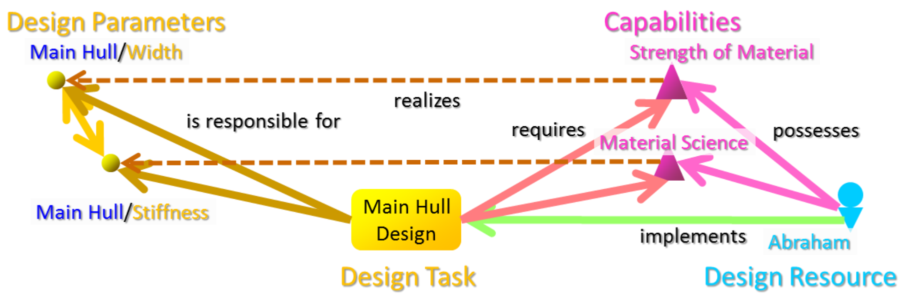


Figure 6. Grammar to bridge product, process, and organisation models

5 MODEL-BASED MANAGEMENT

Integrated model of product, process and organisation enables model-based management of design in several cases. This paper discusses parts of various uses of the integrated model.

5.1 Design process structuring

To better manage product design, well-considered preliminary structuring of the design process is essential. A design process should be structured so that it can be managed easily (Oizumi et al., 2011, and Oizumi and Aoyama, 2012b).

Design activities can be seen as a series of activities to improve function metrics so that required levels are achieved. Though several design parameters may contribute to the improvement of a function metric, they should be determined according to rational of designers. In this paper, the rational order applied to the determination of design parameters is referred to as prioritisation. Prioritisation among design parameters is deduced from the relationships between function metrics and design parameters from the viewpoints of sensitivity, operational risk, and preconditions.

To form a highly manageable design process, it is important to have a holistic view regarding prioritisation of design parameters. As a prioritisation is given in each viewpoint by each function metric, by combining prioritisations in multiple viewpoints by multiple function metrics, loops of prioritisation among design parameters are then found. That is, 'a' is prior to 'b' from one viewpoint; 'b' is prior to 'c' from a different viewpoint; and ‘c’ is prior to ‘a’ from yet another viewpoint. For these sets of design parameters, determining which one to begin with can be a subject of controversy. Therefore, design parameters need to be determined concurrently. Thus, it is possible to divide product design into design tasks and establish a sequence by analysing prioritisation among the design parameters. The DSM of design parameters is used for this analysis (Figure 7). Each cell contains a set of prioritisations from the design parameter of the column to that of the row. The value shown in each cell is the sum of the importance values from prioritisations. The DSM-partitioning technique (Eppinger et al., 1994) can identify the sets of design parameters that should be considered concurrently, and determine their sequence. Partitioning is applied regardless of components. Thus, these sets are divided into subsets according to components, which are candidates of design tasks.

Figure 8 provides screen shots from the case study. As shown in Figure 8, design tasks and their sequences were calculated with the proposed method. For example, design of the front wing began with determination of stiffness and length; width was determined later.

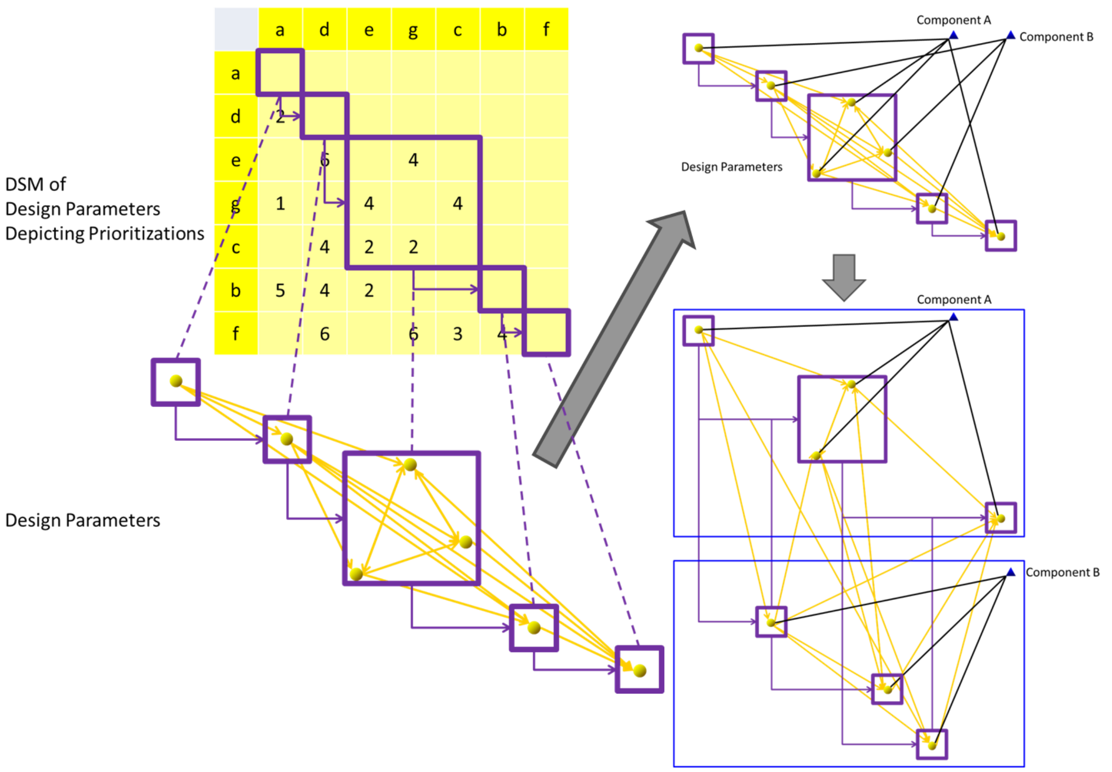


Figure 7. Structuring the design process by partitioning and component-based division

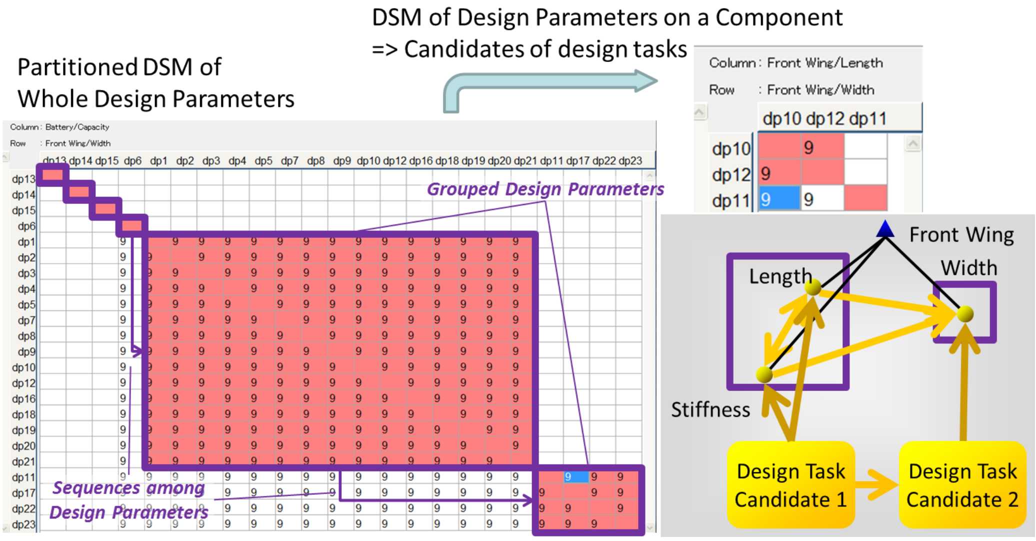


Figure 8. Resultant partial design process in the case of the solar boat

5.2 Organisational structure design

Organisational structure design is a fundamental method for strategically enhancing innovation and the competitiveness of an organisation. An organisation should be structured so that competencies are displayed. Design resources should be aligned in such a way that needed communications and synthesis of capabilities will occur. In this paper, a computational method that will deduce organisational structure logically is presented (Oizumi and Aoyama, 2012a).

If a company wants to synthesise specific capabilities, design resources that possess those capabilities must be in communication with each other. Placing design resources in the same unit is a good strategy for facilitating communication. Therefore, it is possible to suggest how design resources should be allocated to an organisational unit on the basis of a product model, as shown in Figure 9.

The DSM of design resources is used for this analysis (Figure 9). Each cell contains a set of communication needs between the design resources of the column and that of the row. The value shown in each cell can take several values of these communication needs (e.g. importance, number of reasons). Clique detection was used in the algorithm to group design resources. Because the DSM of design resources tends to be quite dense, it is preferable to apply an algorithm that strictly limits the size and number of groups. For this purpose, therefore, clique detection seems to be appropriate.

Because the case study comprised only five design resources, structuring did not have a huge effect on team competitiveness. However, it successfully identified important persons for their communication.

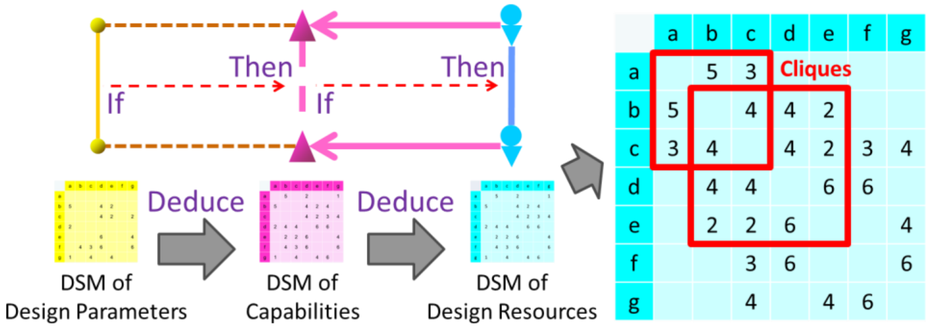


Figure 9. Organisational structure design

5.3 Assignment of implementers to design process

The manageability of a design process depends not only on its task structure but also on implementation of those tasks by design resources. Thus, the proper assignment of the implementers should be considered.

This paper introduces model-based assistance for the assignment of design resources to design tasks. The manageability of the design process is affected by how well implementers of tasks understand other tasks related to their own. By modelling understanding among design tasks in view of capability possession, it is possible to discuss the proper assignment of implementers on the model base.

The MDM that consists of design tasks, capabilities, and design resources is employed for this analysis. Figure 10 shows the quantification of understanding and manageability evaluation of the design process in view of understanding among design tasks.

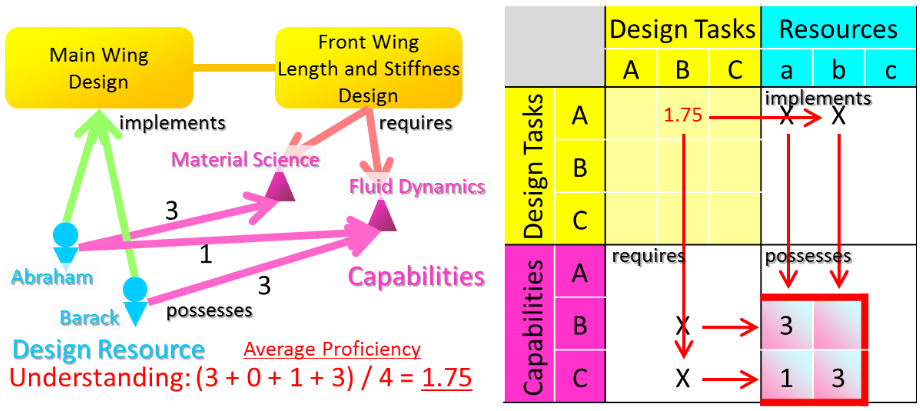


Figure 10. Assignment of implementers by means of MDM

5.4 Establishment of management activities

The management scheme of a design process namely affects manageability of the design process and its competitiveness. Therefore, activities of managing the design process needs to be considered so that the process is managed well while maintaining competencies of the organisation. This paper proposes model-based assistance for the establishment of management activities (Oizumi and Aoyama, 2012b).

Upon establishment of management activities, companies need to determine management styles for each part of the design process appropriately and strategically. Rigid management may impede the exploration of design solution space and result in a less competitive product. If a given task is fairly common, however, rigid management may be better. On the other hand, for those parts of a product that are strongly connected with market advantages, the exploration of a solution is essential to its success. Thus, two types of management styles are discussed in this paper: formation of pre-agreement, and integration and after-approval.

Formation of pre-agreement: If design principles are aligned to coordinate dependencies among design parameters before design tasks are initiated, the risk of contradictions, and thus rework, can be diminished. The design principle is set before the design solution space is explored. Therefore, the achievement of higher quality is not emphasised. This style is preferred for cases in which dependencies are less important and those who implement each task belong to different units that are not related closely.

Integration and after-approval: If designers engage in frequent discussions and cooperate to find better answers, high quality can be expected on this part. In this style of management, however, concrete design principles are not agreed upon beforehand; thus, there is a certain risk of rework or delay. This style of management is preferred for cases in which dependencies are important and in cases in which those who implement tasks are in the same unit, or in different but close units.

Column : Sensor Approval

Row : Side Hull Stiffness Design

	dt1	dt2	dt3	dt4	dt5	dt6	dt7	dt8	dt9	dt10	dt11	dt12	dt13	dt14
dt1	92	44		122	34	156	200	122	34	90	40	64	48	128
dt2	22			22		22	44	22		11		22		22
dt3				34	17	34	49	32	15	32	30	17	15	34
dt4	126	44	62	113	93	256	372	235	72	200	144	100	48	190
dt5	62		49	146		196	275	172	69	148	138	76	39	205
dt6	136	44	66	240	132	158	400	256	84	218	168	104	78	242
dt7	164	66	80	320	212	406	438	443	114	281	228	197	75	396
dt8	104	44	64	230	142	288	478	129	72	194	144	132	54	288
dt9	38		15	48	27	54	87	42		74	84	12	24	24
dt10	122	22	49	186	95	[illegible]	305	177	108	88	206	90	63	174
dt11	96		30	120	78	[illegible]	[illegible]	108	108	186	108	48	48	96
dt12	48	22	34	99	83	142	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	188
dt13	52		45	114	42	138	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	114
dt14	140	44	66	242	176	334	418	273	108	267	216	167	108	215

Important coordination

	Same Unit	Different Unit (close)	Different Unit (far)
More Important Coordination	Integration & After-Approval	Integration & After-Approval	Controversial
	Design Review	Task Force & Design Review	Controversial
Less Important Coordination	Controversial	Controversial	Pre-Agreement
	Controversial	Controversial	Design Review

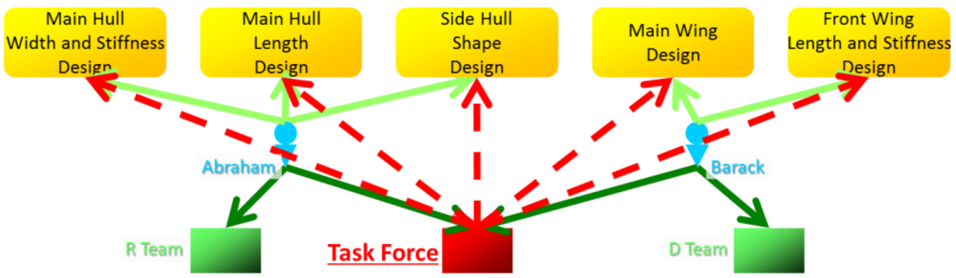


Figure 11. Establishment of a task force

The DSM of design tasks is used for this analysis (Figure 11). Each cell contains a set of coordination between the design parameters of the column task and those of the row task. The value shown in each cell is the sum of importance values associated with coordination. The colour of a cell shows whether those tasks are implemented in a unit (green) or in different units (white). Suggested management activities can be visualised under the rule shown in the table in Figure 11.

In the case study, five design tasks (shown in Figure 11) were underway concurrently with establishment of the task force attended by Abraham and Barack.

6 DISCUSSION AND CONCLUSION

The strength of the proposed model comes from the integration of the product, design process, and organisation models. It enables quasi-simultaneous consideration of multiple aspects of product design. For example, the structure of the design process is discussed in view of the product and the resources implementing design of it. As a result, it is possible to discuss manageability of the design process from both product and organisational viewpoints. This implies that structuring of the design process is not calculated by any single aspect that could impede other aspects of design.

Furthermore, it is possible to discuss complementary measures within a mixture of several domains. For example, though the design process is difficult to manage in view of product structure, it can be complemented by the proper assignment of design resources.

To sum up, the integrated model facilitates holistic management of design. The major function of model-based application is realised by domain-specific calculations and analyses. While Lindemann et al. (2009) generalised the deduction of indirect dependencies and structural analyses, the proposed method employs domain-specific ways of deducing links and analyses. Thus, it is possible to describe detailed relationships and offer an insightful translation of the analysed results.

To verify the usefulness of the model and the proposed methods, an academic-industrial cooperative research project was conducted. In this project, the proposed model base and model-based management support methods were applied to a large-scale product. Subsequently, the usefulness of the model base and its applications were verified to a large extent. The next step would be to improve feasibility. An environment for maintaining models across generations (as in PLM), which can generate and change models while design is going on, would reduce exhaustive time and effort spent on the creation of models. Actually, most data sources of the proposed model came from existing data maintained by the company. Thus, the proposed model base seems to be maintained easily.

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