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DESIGN PROCESS PLANNING FROM A VIEWPOINT OF PROGRESSIVE NATURE OF KNOWLEDGE ACQUISITION

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ABSTRACT

Design process planning has become more important toward competitiveness in a market under the various challenges of product development. This trend demands not only relative or qualitative but also quantitative planning scheme. This paper firstly reviews state of the art of design process planing and shortcomings of conventional approaches, and investigates the characteristics of design process through a case analysis of student formula project. Progressive nature of knowledge acquisition that is performed by respective designers and task consistency among designers and teams that is promoted through meeting are focused as key characteristics of design process dynamics. Following this insight, this paper proposes a system of axioms and theories for distinctively defining the meaning of tasks, knowledge, design quality, meeting and overall shape of design process, outlines the perspective of the design process planning methodology based on the formal model, and demonstrates its application to the student formula project.

Keywords: Design process planning, Design knowledge, Design structure matrix

1 INTRODUCTION

A recent manufacturer faces various challenges of product development, such as increasingly complicated systems, sophisticated components, diversifying product variety, and shortening lead time. A manufacture must define appropriate tasks which compose design process and appropriately allocate designers, time and budget to them. However, upper streams of design process are something indistinct. Accomplishment of each task cannot be discriminated by a threshold. Design quality is not clearly measurable. A significant characteristic of upper streams is that it inevitably includes iterations [1]. Another essential feature is that knowledge takes a crucial role in such process. A designer does not only apply already-systematized knowledge to a product such as knowledge about physics, but also progressively acquires concrete knowledge on the whole and parts of a product with exploring what and how to apply general knowledge to it [2]. Although its performance depends on each designer's skill, collaboration mechanism of designers, etc., such acquisition is accomplished gradually along the progress of design process. This paper calls this 'progressive nature of knowledge acquisition.' Since design is not optimizing but satisfying problem, progress of knowledge acquisition must be cut off at the delivery time. It is recognized that the objective of design process planning is to maximize the possibility of higher acquisition of concrete knowledge under such a viewpoint.

When considering the extend of knowledge acquisition, that is, design quality, it depends on how much prerequisite knowledge a designer has, how experienced a designer is in an assigned task, and so forth. A design process manager should schedule a superior designer, who has good ability of knowledge acquisition, to a critical task for achieving the above objective. As today's scale of product development is not one of any simple tool, it is usual that product development is executed by collaboration of multiple designers, or sometimes, collaboration of multiple teams since the amount of knowledge acquisition is divided and assigned to a swarm of designers and teams. In other words, a design process is divided into some tasks, each designer or team takes charge of a part of them, and they are coordinated toward better collaboration. A designer or a team is required to communicate with each other in order to acquire design knowledge and to secure consistency among divided tasks. While such communication is indispensable, too much communication often makes a whole of design process inefficient. Thus, strongly-related tasks should be assigned to a single designer or a single team for relaxing communication cost, because communication within a smaller swarm is more efficient than one between a bigger swarm across different terms.

This paper challenges to understand and formulate the above dynamics of design process for developing a sophisticated design process planning methodology. Under the ill-defined features of the aforementioned design knowledge acquisition, this research adopts an axiomatic approach and develops a system of theorems as a basis for establishing design process model. The perspectives for a design process planning methodology based on the axioms and theorems are outlined for demonstrating their promise.

2 STATE OF THE ART OF DESIGN PROCESS PLANNING

This section briefly surveys design process planning approaches and methods that have been proposed, and discusses open issues of design process planning.

The first step of design process planning is to identify and describe tasks and their iterations. There are several methods for such phases of process planning. For example, IDEF0 [3] is the most conventional approach. It is designed to model the decisions, actions, and activities of an organization or system by input and output of information. DSM (Design Structure Matrix) is also widely recognized as a method for modeling iterations of design process [4]. DSM represents a dependency among tasks by a matrix. Some algorithms of clustering that groups related tasks together and of partitioning that permutes tasks so as to reduce iterations are proposed under the DSM scheme. IDEF0 and DSM provide at-a-glance description of design process and such descriptions are effective for understanding and arranging the structure of iterations, while they do not support a manager to evaluate a quantitative feature of design process such as design lead time and associated design quality.

When quantitatively estimating achieved design quality and lead time of whole design process, uncertainty of these features could be a bottleneck because the quantitative features of design process depends on intangible factors, such as the skill of an individual designer, collaboration mechanism of designers and so on. A good design manager can achieve design process planning by empirical understanding of intangible factors of design process. However, as the numbers of participating designers and the scale of design process are increased, it obviously becomes more difficult that even any good manager generates superior and appropriate design process plan without any evaluation of its qualitative aspects. To rationally support large-scale design process planning, any methodology for evaluating quantitative features is indispensable as theory or procedure. Some methodologies for quantitative evaluation of design process have been proposed in recent years and they introduce any mathematic model for describing occurrence of task iterations somehow.

Chao *et al.* proposed Design Task QFD that represents relationships between risk factors of design and tasks and supports estimation of magnitude of risk of each task [5–7]. Ostergaard *et al.* proposed a methodology that evaluates efficiency of collaboration in design process by using analogy of electric circuit [8]. This methodology models risk factors of collaboration as resistance of electric circuit so as to estimate efficiency of collaboration quantitatively. Yang *et al.* proposed a methodology of risk estimation based on gain analysis of decision network [9].

Simulation based approaches are also available to estimate uncertainty. A rework simulation [10,11] is typical of them. In this simulation, rework probability is defined for each iteration between tasks that is represented by DSM. Monte Carlo method is adopted for estimating duration of design process. A research group of Clarkson have been developing Singposting methodology that is a Markov chain based simulation methodology [12–15]. Singposting method defines a task as a state transition that changes values of design parameters. Design process is defined as a chain of state transitions. Transition probability is defined for each state transition so as to estimate duration, cost and design quality of whole design process, and their ranges.

Although many researchers have tackled, we have not yet had a definitive model of the design process, especially that is effective for its upper streams, because of difficulty in modeling the aforementioned intangible factors. This research stands for the hypothesis that the progressive nature of knowledge acquisition is a key to establishing a design process model as mentioned in Introduction, and ventures to adopt an axiomatic approach for formulating the design process for excluding vague factors as much as possible with this reason. Even though such a mathematical approach has some shortcomings in the aspects of describing detail characteristics, it is expected to be robust against the intangible factors and to be self-consistent within the axiomatic system.

In the following, the next section analyzes a student formula project to reveal some essential

Dimensions	
Overall L×W×H	2600×1375×1075 mm
Wheelbase	1680 mm
Tread [Front]	1200 mm
Tread [Rear]	1200 mm
Weight [with 68kgf driver]	236kgf [304kgf]

Suspension Parameters [Front & Rear]	
Suspension Type	Double wishbone
Tire size	Racing clicks 20.0x7.5-13
Wheels	13in, 5.5J , Offset +45, Hole 4, PCD 100
Minimum ground	80 mm
Powertrain	
Engine	Model 609cc KAWASAKI KVF-650 CVT
Compression ratio	10.4 : 1
Induction	NA
Fuel type	High-octane gasoline
Max power RPM	More than 30.3PS/4000
Max torque RPM	More than 6.5kgf-m/3500
Fuel system [manf’r]	FI

Figure 1. Formula car of OFRAC

factors of the design process under the viewpoint of progressive nature and others. Succeeding sections defines and deduces axioms and theorems, and proposes design process planning methodology.

3 A CASE ANALYSIS OF STUDENT FORMULA PROJECT

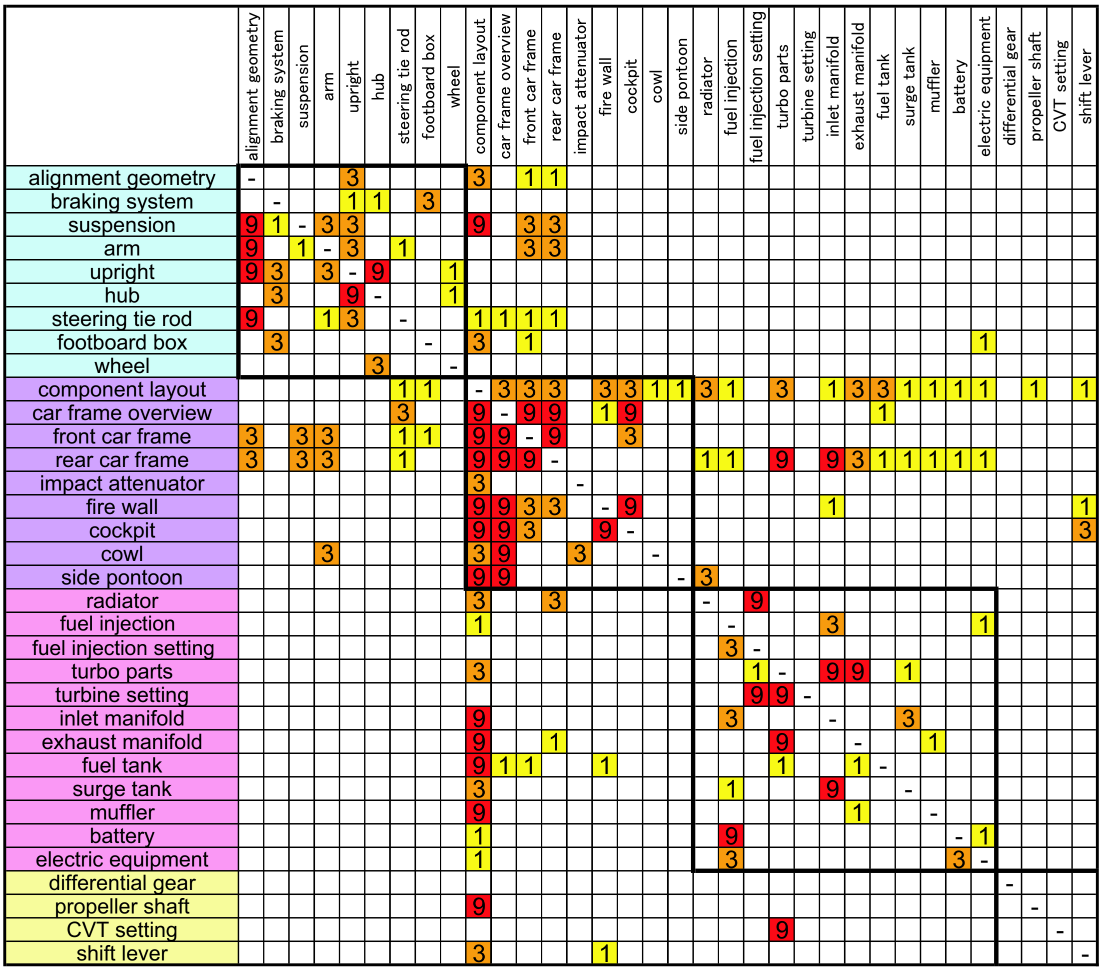
3.1 Formula Project and its Task Structure

The Student Formula SAE Competition of Japan [16] was started in 2003 for providing an opportunity for students to develop their engineering skills. OFRAC (Osaka university Formula RAcing Club) is the team of Osaka University that is challenging this competition since its beginning. While student formula project is not in real circumstances of manufacturing firms, it is small-sized but as highly creative and collaborative as an engineering design project. It contains all phases from conceptual design to manufacturing design. In addition, all kinds of information are open and easily accessible for the university members. With these reasons, the OFRAC design project is used as a case for investigating the natures of design process.

Figure 1 shows a formula car manufactured by OFRAC project in 2006 and its major specifications. About twenty undergraduate and graduate engineering students of Osaka University participate in the project, and they design, manufacture, and assemble almost all of components except for some parts such as major components of its powertrain, which are provided by a vehicle manufacturer. The members have changed every year because of student graduation and entrance. They have tackled some new engineering challenges every year while inheriting the design and results of the previous year. This means that some members are novices and others are experts, the performance of knowledge acquisition is diverse among them, consistency among their knowledge acquisition must be secured through several types of team meetings toward creativity and challenges.

The case analysis was executed by intensive interviews with the OFRAC members. Figure 2 shows DSM of this project, which was described based on the collected task information and progress reports. Because an architecture of a formula car is not so variable, a task of this project corresponds to a component, such as a braking system or a car frame. Each task contains conceptual design phase, detailed design phase and manufacturing phase. In general, a design project sometimes has to begin with identifying the tasks. While task identification should be a part of an integrated planning methodology, this paper focuses on scheduling and resource allocation of identified tasks.

In the matrix, a dependency of a task is represented with four numbers, 0, 1, 3, and 9, according to the degree of interactions between specific tasks. The larger the degree is, the stronger the dependency is. This matrix shows that the project is devided into 34 tasks, and that these tasks are allocated to four teams. As shown in the matrix, there are various types of interactions, that is, some are within a term, and others are across different terms. Further, more interactions are allocated within each term in order to efficiently and effectively share and exchange knowledge acquisition.



	alignment geometry	braking system	suspension	arm	upright	hub	steering tie rod	footboard box	wheel	component layout	car frame overview	front car frame	rear car frame	impact attenuator	fire wall	cockpit	cowl	side pontoon	radiator	fuel injection	fuel injection setting	turbo parts	turbine setting	inlet manifold	exhaust manifold	fuel tank	surge tank	muffler	battery	electric equipment	differential gear	propeller shaft	CVT setting	shift lever
alignment geometry	-				3					3		1	1																					
braking system		-			1	1		3																										
suspension	9	1	-	3	3					9		3	3																					
arm	9		1	-	3		1					3	3																					
upright	9	3		3	-	9			1																									
hub		3			9	-			1																									
steering tie rod	9			1	3		-			1	1	1	1																					
footboard box		3						-		3		1																		1				
wheel						3			-																									
component layout							1	1		-	3	3	3		3	3	1	1	3	1		3		1	3	3	1	1	1	1		1		1
car frame overview							3			9	-	9	9		1	9										1								
front car frame	3		3	3			1	1		9	9	-	9			3																		
rear car frame	3		3	3			1			9	9	9	-						1	1		9		9	3	1	1	1	1	1				
impact attenuator										3				-																				
fire wall										9	9	3	3		-	9								1										1
cockpit										9	9	3			9	-																		3
cowl				3						3	9			3			-																	
side pontoon										9	9							-	3															
radiator										3			3						-		9													
fuel injection										1										-				3						1				
fuel injection setting																				3	-													
turbo parts										3											1	-		9	9		1							
turbine setting																					9	9	-											
inlet manifold										9										3				-			3							
exhaust manifold										9			1									9			-			1						
fuel tank										9	1	1			1							1			1	-								
surge tank										3										1				9			-							
muffler										9															1			-						
battery										1										9									-	1				
electric equipment										1										3									3	-				
differential gear																															-			
propeller shaft										9																						-		
CVT setting																						9											-	
shift lever										3				1																				-

Figure 2. Design Structure Matrix of the formula car project

3.2 Progressiveness in Knowledge Acquisition

As Schön suggested, a designer does not only apply already-systematized knowledge to a product such as knowledge about physics, but also progressively acquires concrete knowledge about what and how to apply general knowledge to a product through reflection-in-action [2].

This progressive nature of knowledge acquisition can be found in the following example of formula car design. Design quality of a car frame is measured by rigidity to some collision modes, and light weight. Therefore, a designer who is in charge of a car frame can acquire knowledge required for this task from a textbook of strength of material and fracture mechanics. He/she can acquire a more detailed analysis by means of a structural CAE analysis. However, it is necessary to acquire knowledge to apply it in order to understand design quality of a car frame at more advanced level. For instance, an OFRAC member has understood that the rigidity of the frame connection part is more important than the rigidity of the frame material in evaluating the rigidity of the frame, and that the rigidity of connection between a front arm and a bellcrank is the most important. This means that a designer should consider modulus in torsion of the connected part when he/she builds an quantitative model of the frame rigidity. These have been understood through actually producing the formula car. It is difficult to obtain this kind of knowledge without design practice. Although the performance of such acquisition depends on designer's skill, collaboration mechanism of designers, etc., it is observed that every project member shows such progress.

3.3 Mapping Knowledge Progressiveness to Achievement Levels

Any quantitative standard of progress in knowledge acquisition is necessary in order to discuss knowledge acquisition process mathematically. Sakamoto and Fujita propose the following ten-degree standard for quantifying design achievement level [17].

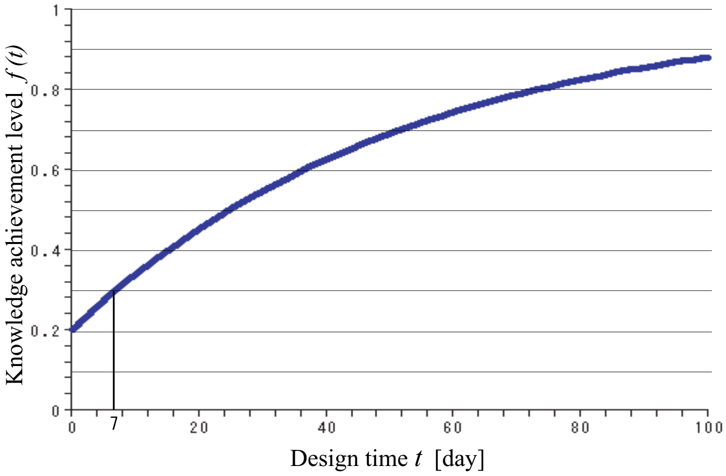


Figure 3. Growth curve of inlet manifold design

Level 0.0 : Relating knowledge of a task is unknown. This corresponds to the initial condition of totally new design.
Level 0.1 : A designer can refer to a product of past generations or other companies that has a good track record in a market. This corresponds to the initial condition of similar design.
Level 0.2 : A designer knows a qualitative model to evaluate design quality.
Level 0.3 : A designer knows a single quantitative model to evaluate design quality. But the designer stays in qualitative understanding of conditions for applying the model.
Level 0.4 : A designer knows a single quantitative model to evaluate design quality. The designer also knows quantitative conditions for applying the model.
Level 0.5 : A designer knows plural quantitative models to evaluate design quality. The designer also knows their conditions quantitatively.
Level 0.6 : A designer knows a single-objective optimization model of design quality. But the designer stays in qualitative understanding of conditions for applying the model.
Level 0.7 : A designer knows a single-objective optimization model of design quality. The designer also knows its conditions quantitatively.
Level 0.8 : A designer knows a multi-objective optimization model of design quality of a product. But the designer stays in qualitative understanding of conditions for applying the model.
Level 0.9 : A designer knows a multi-objective optimization model of design quality. The designer also knows its conditions quantitatively.
Level 1.0 : A designer knows a complete multi-objective optimization model of design quality of a product. This is the limiting highest level.

Sakamoto and Fujita discuss a method for estimating the achievement level of optimal design of an electronic product [17]. For such a purpose, they introduce the following exponential growth curve model which represents the achievement level progresses toward the highest level under the above system of quantification.

$$f(t) = 1 - (1 - f_0)\ e^{mt} \tag{1}$$

where, t means design time, $f(t)$ means the achievement level of knowledge at time t, f_0 means initial knowledge level and m means an ability of knowledge acquisition. f_0 and m usually depends on each designer and the type of each task.

This research applies this model for analyzing the formula car design project. That is, Figure 3 shows a growth curve of inlet manifold design task. According to an interview to a designer who takes charge in this task, he only knew a qualitative model of a inlet manifold at the beginning of design. This corresponds to level 0.2. After seven work days, he learned a quantitative model to evaluate an inlet manifold although he has not yet learned its conditions. This corresponds to level

0.3. His ability of knowledge acquisition m can be solved by $f(0) = f_0 = 0.2$ and $f(7) = 0.3$, then $m = 0.019$. A task's necessary duration to reach at a target achievement level can be estimated by using the above growth curve. When a target level of inlet manifold design is 0.4, Figure 3 indicates that it will take about 15 work days. If a manager wants to leverage this task's achievement level, he/she has to ask a designer to work more harder, or another designer, whose f_0 and m is larger than this designer's, should take charge of this task.

3.4 Task Consistency and Knowledge Revision in Collaboration

It is already stated that a designer acquires knowledge through design progress from one at a fundamental level to one at an advanced level for a specific task. In collaboration, however, such progress of knowledge acquisition is performed under the assumed result of associated tasks, i.e., expectation of task consistency secureness. In other words, achievement level of knowledge acquisition may reduce when assumption on task consistency is not secured as a result of design progress.

Such a situation can be also explained with the example of the student formula project. The task of the car frame design deeply depends on the other tasks, such as cockpit design, as shown in Figure 2. A designer should frequently communicate with each other in order to rationally carry out depending tasks. However, a designer cannot always acquire the latest information of the other tasks at any time. A designer should carry out the task by setting some assumptions about the part concerning the other tasks. For instance, when the rigidity of the frame is evaluated, the designer needs information of cockpit position. Then, the designer of the car frame contacts the designer of the cockpit, and calculates the frame rigidity based on information obtained. On the other hand, the designer of the cockpit makes an effort to improve the cockpit design quality, such as visibility range of a driver, and may revise the position of the cockpit for that. The information of cockpit position will only be assumed at that time. As for the frame rigidity calculated based on old information, when the information of cockpit position has been revised, the rigidity calculation should be also revised. That is, the assumed knowledge becomes false at this occasion. The achievement level of knowledge concerning the car frame design temporarily falls, and therefore, the designer should design again and improve the achievement level of knowledge. However, it can be thought that the consistency between the car frame and the cockpit was improved by this revision. Both design quality of each task and consistency level of depending tasks are related to the whole design quality of a product.

This research expands Eq. (1) as follows in order to model the achievement level reduction of task i by collaborating task j at time T;

$$f'_i(T) = f_i(T) - \Delta Q_{ij}(T) \tag{2}$$

where, f_i and f'_i is task i's achievement level before collaboration and one after collaboration, respectively. This research assumes that consistency level between tasks, A_{ij}, is a monotonic increasing function of collaboration time that can be modeled by Eq. (1), and that ΔQ is inversely proportional to the consistency level. This rsearch uses the following equation to represent ΔQ;

$$\Delta Q_{ij} = \alpha\, r_{ij}\, \left(1 - A_{ij}(t)\right) \cdot \Delta f_i(t) \tag{3}$$

where, $\Delta f_i(t)$ is increment of achievement level of task i from the previous collaboration, r_{ij} is task i's dependency level to task j. Because ΔQ would vary by various intangible factors that is not considered here, the above equation contains α as a tuning parameter. Based on the case analysis of OFRAC, this research determines $\alpha = 0.05$ as the worst case of achievement reduction.

3.5 Prerequisites of Formal Model of Design Process

The above case analysis of OFRAC project illustrates the progressive nature of knowledge acquisition and consistency securance. It brings us the following observations;

- Design quality of a task corresponds to level of knowledge which an assigned designer acquires by executing a task.
- Consistency between tasks corresponds to level of knowledge which designers assigned to the tasks have acquired through communication.
- Communication within a team is more effective than communication among plural teams.
- The fewer tasks concerned with communication, the more effective communication is.

These extracted facts can be the standpoint for formulating and developing the system of axioms and theorems, which are explored in the next section. As stated in Section 2, these axioms and theorems strongly depend on human factors, such as characters, private life influence, relationships between designers, motivation, and so on. This research limits the minimum set of intangible factors of design process planning, and it is expected to be robust against the intantible factors and to be self-consistent within the axiomatic system.

4 AXIOMATIC MODEL OF DESIGN PROCESS

4.1 Definitions

Firstly, the following terms are defined in order to discuss an axiomatic theory.

4.1.1 Design

This research focuses on engineering design that includes product definition, conceptual design, and the other detail design phases toward development of a product. In design process, a designer gradually concretizes objectives of design during concretizing design quality.

4.1.2 Knowledge

As the question of what is knowledge has been a main issue of philosophy and its answer has been difficult, there are a lot of aspects of defining knowledge. This research does not discuss this issue deeply, but adopts the following simple definition.

Knowledge is a set of justified true belief that a designer believes true so far.

Although its performance in justifying believes depends on designer's skill, collaboration mechanism of designers, etc., such knowledge acquisition is accomplished gradually along the progress of design process. Thus, this research states that design process is knowledge acquisition process.

4.1.3 Achievement level of knowledge

This research introduces achievement level of knowledge that means amount and quality of knowledge. Its detail has already introduced in Subsection 3.3. A designer can acquire knowledge at an advanced level through design activities and learning based on knowledge at a fundamental level that he/she has already acquired. On the other hand, achievement level of knowledge reduces when acquired knowledge that a designer believed true turns out to be false.

4.1.4 Task

This research defines each task as a part of design process. As a scale of a recent product development has become larger, required amount of knowledge has become massive. It is usual that a product development is done by collaboration of multiple designers, or sometimes, collaboration of multiple teams in order to reduce amount of knowledge required by a designer or a team. In this collaboration, a designer takes charge of a certain part of design process.

4.1.5 Design quality

Design quality is defined as a degree of the whole of specific characters and performances that shows whether the designed product matches its requirements. Each task will bear a part of design quality. For instance, design of a car frame is one of tasks of formula car design. Required performances are rigidity to some collision modes, and light weight. Thus, design quality of a car frame is acquired by promoting both two performances.

4.1.6 Task dependency, task consistency

Most tasks are usually defined as a design process corresponding to a part of a product. Since each part of a product depends on other part(s), each task also depends on other task(s). Therefore, a designer has to carry out a task while taking care of consistency with other task(s). This research defines task dependency as a degree of dependency of two tasks that can be measured by how much knowledge of the other task is required to carry out a task. In addition, task consistency is defined as a degree of consistency between tasks.

4.1.7 Meeting

Meeting is defined as a part of design process whereby a designer confirms consistency of his/her knowledge with the other task(s). A designer can know that his/her knowledge is true or false by meeting with the other designer.

Based on these definition, some axioms and theorems are introduced in the following subsections.

4.2 Axiom on Design Quality

Design quality of a product can be measured by its specific characters or its performance indexes, after it is manufactured and launched to the market, or sometimes at the end of life. In reality, it is impossible to precisely prospect the design quality that will be finally accomplished at planning of design process. However, any prospection is indispensable to qualitatively evaluate a planned design process. Thus, it is assumed that adequate design quality of a task can be obtained if achievement level of knowledge on the task reaches an adequate level. The following axiom is introduced;

Axiom 1. Correspondence of knowledge and design quality : Design quality of a task at a certain moment can be measured by achievement level of knowledge on the task that has been acquired by that time.

According to the definition of knowledge, design quality measured by this axiom may be inconsistent with the other task's quality. Therefore, total design quality of a product should be discussed by design quality of each task and consistency among tasks.

4.3 Axioms and Theorems on Knowledge Acquisition

By definition, a designer acquires knowledge through design process. The following axioms are introduced;

Axiom 2. Knowledge acquisition : The achievement level of knowledge about design process is monotonically increasing function of working hours spent for the design process.

A diligent designer may work for his/her task besides working hours. However, such devoted working hours will not be included in planned working hours in this research. A quantitative model that this research aims is for a design manager to evaluate a design process plan by considering designer's skill and communication mechanisms. In this objective, devoted working hours is out of focus of the planning. Even if devoted working hours is not considered, such a designer can be evaluated in the point that design quality can be efficiently improved by little working hours.

Axiom 2 and the definition of task deduces the following theorem.

Theorem 1. Knowledge acquisition about task : The achievement level of knowledge about a task is a monotonically increasing function of working hours if there is no uncertain factor of the other tasks.

Axiom 1 and theorem 1 deduce the following theorem.

Theorem 2. Promotion of design quality : Design quality about a task is monotonically increasing function of working hours if there is no uncertain factor of the other tasks.

By definition, a task depends on each other. A designer cannot actually acquire knowledge of the other task without meeting with a designer who takes charge in the other task. However, he/she can assume it in order to carry out his/her task temporarily.

Axiom 3. Assuming knowledge : A designer can assume knowledge of the other task when he/she cannot acquire it at that moment.

Assumed knowledge may turn out to be false by revision of knowledge in the meeting. Axiom 2 and Axiom 3 deduce the following theorems;

Theorem 3. Knowledge revision : Achievement level of knowledge of a task may fall by knowledge revision in the meeting.

Theorem 4. Design quality revision : Design quality of a task may fall by knowledge revision in the meeting.

4.4 Axioms and Theorems on Task Consistency

It is difficult for a design manager to estimate task consistency no less than design quality. This research measures task consistency level by the achievement level of knowledge as well as design quality.

Axiom 4. Correspondence of knowledge and task consistency : Task consistency between the tasks at a certain moment can be measured by achievement level of knowledge that have been acquired by that time.

Knowledge concerning consistency between tasks is acquired by the meeting between the concerned tasks. Axiom 2 and 4 deduce the following theorem;

Theorem 5. Knowledge acquisition about task consistency : The achievement level of knowledge about task consistency is monotonically increasing function of working hours spent for meeting between the concerned tasks.

By definition, consistency level between depending tasks concerns possibility of knowledge revision of the task. The following axiom is introduced;

Axiom 5. Relationship between consistency level and knowledge revision : The higher is the consistency level, the lesser is reduction of achievement level of knowledge of the task in a future meeting.

Theorem 4, 5 and axiom 5 deduce the following theorem;

Theorem 6. Design quality revision and meeting time : The more is the meeting time concerning a task, the lesser is reduction of design quality of the task in a future meeting.

4.5 Axioms and Theorems on Meeting

In order to introduce axioms about meeting, this research introduces two dichotomies of meeting types. One is meeting with fewer versus many tasks, and the other is meeting within a team versus between different teams. These dichotomies define the following four types of the meeting; (a) meeting concerning a part of a team, (b) meeting concerning a whole of a team, (c) meeting concerning a part of plural teams and (d) meeting concerning all teams. A meeting (a) corresponds to a daily consultation in a team. A meeting (b) corresponds to a regular meeting in the team. A meeting (c) corresponds to irregular meeting and consultation between different teams. A meeting (d) corresponds to a design review in which all the project members participate. Based on these dichotomies, the following two axioms are introduced;

Axiom 6. Knowledge acquisition in a meeting (1) : Knowledge acquisition in a meeting in a team is more effective than that in a meeting between different teams.

Axiom 7. Knowledge acquisition in a meeting (2) : Knowledge acquisition in a meeting concerning fewer tasks is more effective than that in a meeting concerning many tasks.

These two axioms and theorem 5 deduce the following theorem;

Theorem 7. Task consistency and meeting (1) : Task consistency increases much more by a meeting within a team than a meeting between teams.

Theorem 8. Task consistency and meeting (2) : Task consistency increases much more by a meeting concerning fewer tasks than a meeting concerning many tasks.

These two theorems and theorem 6 deduce the following theorems;

Theorem 9. Design quality revision and meeting (1) : Reduction of design quality of a task in a future meeting becomes lesser when the depending tasks are carried out in the same team.

Theorem 10. Design quality revision and meeting (2) : Reduction of design quality of a task in a future meeting becomes lesser when a meeting is carried out with the fewer concerning tasks than the many tasks.

5 PERSPECTIVE FOR DESIGN PROCESS PLANNING METHODOLOGY

5.1 Three Phases of Design Process Planning

This research develops a design process planning method and its associated planning tool based on the formulated definitions, axioms and theorems in the last result. The design process planning method should consist of the following three phases:

(i) Task identification · · · to divide a design process into a set of tasks, and to categorize them a set of clusters. The result is taken as a form of the optimized DSM table.
(ii) Task scheduling · · · to assign designers to either task(s) and schedule communication timing and method. The result is taken as a form of the Gantt chart, and some potential alternatives are generated.
(iii) Quantitative evaluation · · · to select the best plan by estimating design duration, design quality, etc. of a product achieved in respective alternatives.

Among these three phases, although the first one may be similar to any DSM based planning method, dependency degrees between tasks is given as either of four degrees, 0, 1, 3 and 9, according to strength of task relationships in order to manage task dependency more precisely against the axioms and theorems developed in Subsection 4.5. That is, a set of tasks that are strongly related each other are allocated within a cluster, in order to minimize amount of communication by assigning a task cluster to a single designer or a single team. In the second phase, the different levels of designer's skill, task difficulty, etc. must be taken into consideration under the axioms and theorems developed in Subsection 4.3 While the third one requires any mathematical models on design quality, task consistency, etc., they should be formulated under the system of axioms and theorems developed in Subsections 4.3, 4.4 and 4.5 and growth curve model, which numerically represents designer's skill, achievement level, task consistency level, etc., stated in Subsection 3.3. Dynamical simulation of transition of achievement level of knowledge acquisition is implemented based on such models for quantitatively evaluating alternatives.

5.2 Outline of Planning Methodology and Prototype Tool

Figure 4 shows an overview of this design process planning methodology that is composed of the above three phases. In the figure, a rectangle node and an arrow between nodes represent a procedure of design process planning. A text in bold characters represents input information for each procedure. A round corner rectangle with broken line shows procedures supported by a quantitative model based on the proposed axiomatic theory. When tentatively generated alternatives don't meet the requirements, the procedure must be backtracked to any early phases. Thus, the overall flow includes some backward chains. A prototype system is implemented in Java programming language (jdk 1.4.1) on Windows XP.

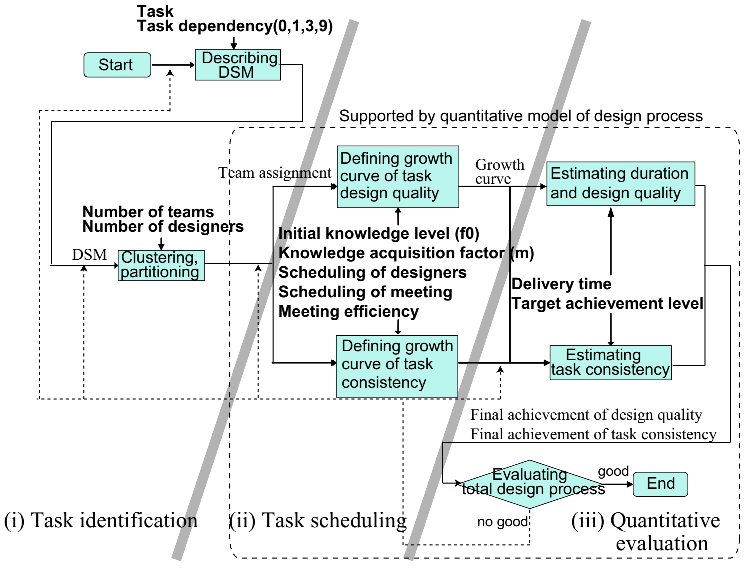
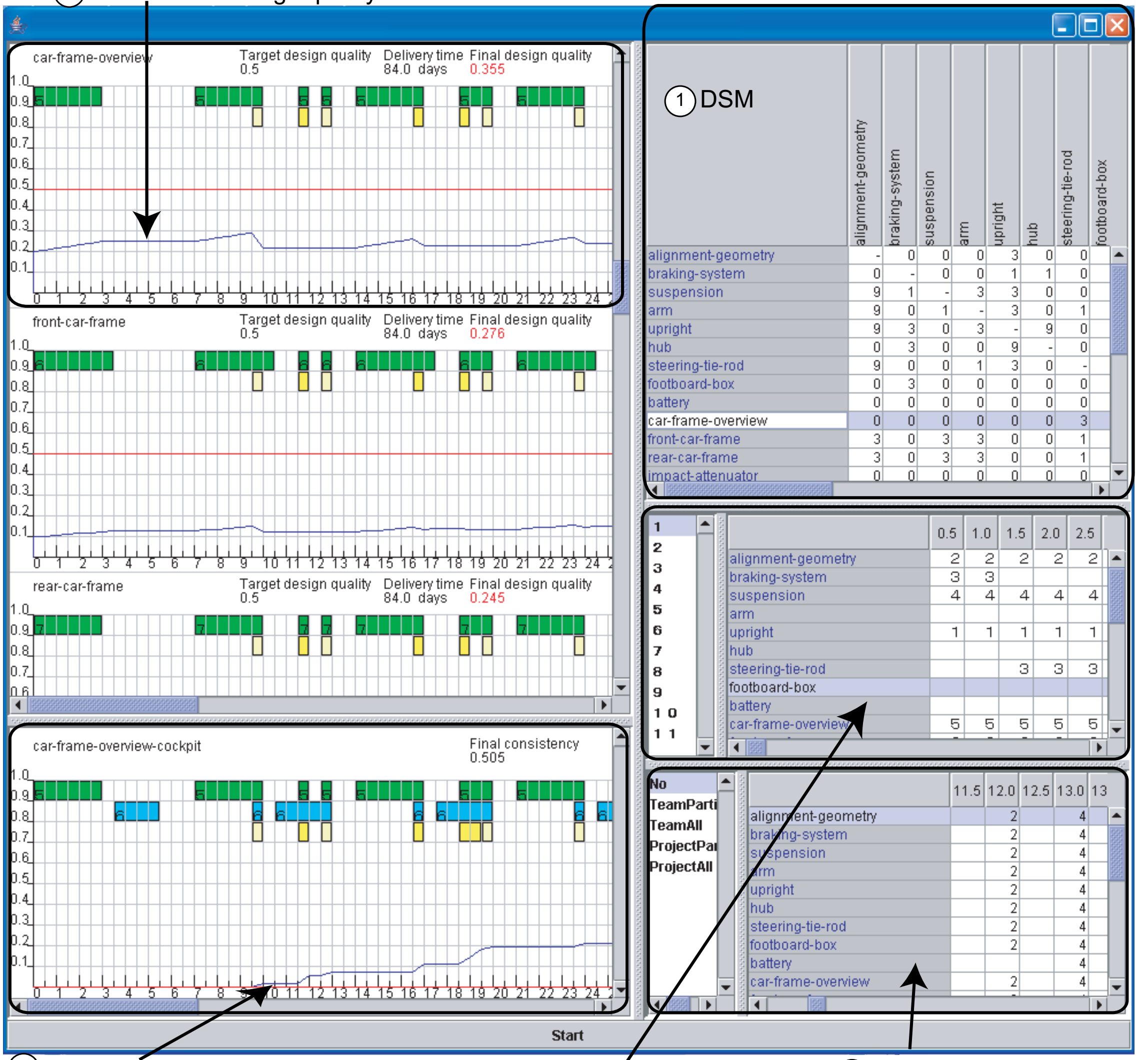


Figure 4. Overview of design process planning methodology

5.3 A Case Study of Design Process Planning

Figure 5 shows a snapshot of planning a formula car design project on the prototype system. At the first phase, tasks and task dependencies of this project are inputted to DSM table (Figure 5-①). In this case, the clustering algorithm suggests a task assignment plan for four teams. At the second phase, a task schedule of 11 designers and meeting schedule among the four teams are planned by a manager in Gantt charts (Figure 5-② and ③). A manager also inputs delivery time of this

④ Estimation : design quality of car frame



① DSM

	alignment-geometry	braking-system	suspension	arm	upright	hub	steering-tie-rod	footboard-box
alignment-geometry	-	0	0	0	3	0	0	
braking-system	0	-	0	0	1	1	0	
suspension	9	1	-	3	3	0	0	
arm	9	0	1	-	3	0	1	
upright	9	3	0	3	-	9	0	
hub	0	3	0	0	9	-	0	
steering-tie-rod	9	0	0	1	3	0	-	
footboard-box	0	3	0	0	0	0	0	
battery	0	0	0	0	0	0	0	
car-frame-overview	0	0	0	0	0	0	3	
front-car-frame	3	0	3	3	0	0	1	
rear-car-frame	3	0	3	3	0	0	1	
impact-attenuator	0	0	0	0	0	0	0	

1
2
3
4
5
6
7
8
9
1 0
1 1

	0.5	1.0	1.5	2.0	2.5
alignment-geometry	2	2	2	2	2
braking-system	3	3			
suspension	4	4	4	4	4
arm					
upright	1	1	1	1	1
hub					
steering-tie-rod			3	3	3
footboard-box					
battery					
car-frame-overview	5	5	5	5	5

No
TeamParti
TeamAll
ProjectPar
ProjectAll

	11.5	12.0	12.5	13.0	13
alignment-geometry		2		4	
braking-system		2		4	
suspension		2		4	
arm		2		4	
upright		2		4	
hub		2		4	
steering-tie-rod		2		4	
footboard-box		2		4	
battery				4	
car-frame-overview		2		4	

⑤ Estimation : consistency between car frame and cockpit

② Scheduling of designers

③ Scheduling of meeting

Figure 5. A snapshot of planning a formula car design project

project and target achievement level of each task. Based on these planning data, the system estimates design quality of each task that will be achieved in the delivery time, and consistency level between tasks. Figure 5-④ shows that target achievement level of design quality of 'car frame overview' is 0.5. However, it is also shown that the final achievement level in delivery time (84 days) is only 0.355. This is because meeting time between car frame and cockpit is so short (Figure 5-⑤) that knowledge of car frame design is frequently revised. Augmenting meeting time between these tasks is an alternative plan in order to leverage car frame design quality.

6 CONCLUSIONS

This paper formulated the system of axioms and theorems as a foundations toward developing a design process planning methodology that can be evaluate quantitative factors such as design quality, required resources, associated risks. While the focus on the progressive nature and consistency securance of knowledge acquisition is expected to be a novel view toward a new planning scheme, many research issues, such as building the detail of a mathematical model, validation of fundamental model, procedure, etc., remains as future works.

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