Proposal of Management Framework of Engineering Analysis Modeling Knowledge for Design Validation

Yutaka Nomaguchi*, Kousuke Nakashima† and Kikuo Fujita‡
Department of Mechanical Engineering, Osaka University

Abstract

Any engineering analysis model is indispensable to predict the behavior of a product for its rational design validation. In the modeling process of engineering analysis, an engineer idealizes physical phenomena and introduces assumptions, which depend on a various factors of design, such as the type of the product, the objectives of the engineering analysis or design time constraints as well as the physical features of the product. Therefore, the contents of the modeling dynamically changes through design process, which comprises iterations of hypothesis verification of multiple design alternatives. Because the knowledge of engineering analysis exists in the modeling process, it is important to capture and manage the process for enhancement of rationality and reusability of engineering analysis models. This research aims to propose a management framework of engineering analysis modeling knowledge for design validation process. This paper introduces an outline of a framework, in which EAMM (Engineering Analysis Modeling Matrix) is used to capture a snapshot of the modeling concepts, and IBIS (Issue-based Information System) is used to represent transition of the modeling concepts and the arguments behind it. A design process of a micro mixing mechanism demonstrates the potential and promise of a proposed framework..

Keywords: Knowledge management, design knowledge, modeling process, design process, engineering analysis model

1 Introduction

An analysis simulation has been widely adopted for validation of product design and system design accompanying the progress of computational engineering. Because a product's physical behavior consists of complicated multidisciplinary phenomena by nature, a designer makes various modeling idealizations, e.g., dimensional reduction, geometric symmetry, feature removal, domain alterations and so on, in order to build a practically useful analysis model for design validation. The modeling idealizations depend on a variety of design factors, such as the type of product, the objectives of the engineering analysis, physical features of the design and the design lead time [Doraiswamy et al., 1999]. Therefore, the contents of the modeling dynamically changes through design process, which comprises iterations of hypothesis verification of multiple design alternatives. This modeling process in which a designer makes some idealizations based on associated justification is the heart of all engineering analysis models [Grosse et al., 2005]. Therefore, capturing the modeling process is an important issue for reusing the models, and for performing verification and validation of the models. However, the modeling process usually remains in the realm of the designer's tacit knowledge. A framework to systematically capture the modeling knowledge of a working designer has not yet been established.

This research aims to develop such a framework for describing and managing the knowledge involved in engineering analysis modeling during design validation. First, Engineering Analysis Modeling Matrix (EAMM) [Nomaguchi et al., 2009] is adopted as a description format that can organize various concepts of engineering analysis modeling process, e.g., considerable physical phenomena, a way of simplification, mathematical representations, interpretation of calculation results, and so on. EAMM takes the form of a nine cell matrix by combining a pair of three-fold concepts, i.e., modeling levels and modeling aspects, seven scaphoid boxes called operation spaces, i.e., simplification, discretization, envisioning, analytic calculation, numeric calculation, continuation and interpretation, are arranged among the cells. Each concept of the modeling knowledge is described in a corresponding cell or box. A working designer can describe various elements of modeling knowledge in such a format. The association of the cells and boxes facilitates the organization of the modeling process and allows its overview to be used for modeling verification and validation. A sheet of EAMM corresponds to a snapshot of engineering analysis modeling. In order to manage multiple alternatives of modeling and to describe design rationale behind the determination of any modeling idealization, this research adopts a conventional argumentation model, gIBIS [Conklin and Begeman 1988], and formalizes the description patters of the engineering analysis modeling process.

This paper also demonstrates a descriptive example of a design process of a micro liquid mixer to show the framework's capability of modeling process description for design validation.

2 Engineering Analysis Modeling

2.1 Engineering Analysis for Design Validation

In general, a design process comprises the following four steps; *addressing a design alternative*, *validation* of the alternative from any perspective of requirements, *critique* of the alternative based on the validation, and *modification* of the alternative [Dym 1994]. Engineering analysis is one of methods of the validation to ensure that the product's physical features meet the requirements. If the requirements are not met, a designer should study the cause of it and modify the design alternative. Even if the requirements are satisfied, more accurate engineering analysis would be done for surer design validation. That is, engineering analysis strongly depends on the design rationale.

2.2 Concepts of Engineering Analysis Modeling

While the physical behavior of a product consists of complicated multidisciplinary phenomena by nature, a designer makes some idealizations in order to build an analysis model applicable for design validation. This means that an analysis model does not faithfully mirror the real behavior of a product, but gives just a quantitative representation of the physical phenomena on which a designer focuses. Therefore, it is important to explicitly describe and deliberate modeling concepts, e.g., which physical phenomenon should be considered and what simplification should be done, for appropriate modeling.

2.3 Knowledge Creation in Design Process

----
*e-mail: noma@mech.eng.osaka-u.ac.jp
†e-mail: nakashima@syd.mech.eng.osaka-u.ac.jp
‡e-mail: fujita@mech.eng.osaka-u.ac.jp

One further feature which we must not ignore is that a design process is a hypothesis verification process in which a designer should simultaneously explorer multiple alternatives. Because it is not clear what knowledge should be applied in advance of problem solving, knowledge should be acquired or created in design process. This process is characterized by reflection-in-action [Schön 1982] that is a knowledge creation process in which a designer hypothetically defines the problem, arrives at an alternative solution, understands the problem through verification of the solution, and revises the problem definition if needed.

The same process is found in engineering analysis modeling for design validation. The contents of the modeling dynamically changes accompanying a change of design. A designer explores multiple alternatives of the engineering analysis modeling. Although systematized knowledge of physical phenomena, e.g., solid mechanics and fluid mechanics, and systematized knowledge of computational modeling, e.g., finite element modeling, is needed in the engineering analysis modeling, modeling idealizations should be decided by the reflective hypothesis-verification process. Modeling knowledge is dynamically acquired through this modeling process.

2.4 Research Issues

Based on the above discussion, this research addresses the following three issues toward development of a management framework of engineering analysis modeling knowledge.

1. *An integrated framework for capturing both design process and engineering analysis modeling process:*

As noted in Subsection 2.1, engineering analysis strongly depends on the design rationale. Therefore, a knowledge management framework should capture both design process and engineering analysis modeling process in an integrated manner.

2. *Explicitly describing the modeling process concepts:*

As noted in Subsection 2.2, a designer determines various modeling concepts, such as the target objects of analysis, the phenomena to be considered, appropriate simplification, and so on, in engineering analysis modeling for design validation. All of these concepts constitute modeling knowledge. Therefore, a description framework for explicitly describing these concepts is required to capture modeling knowledge and to organize it.

3. *Handling multiple alternatives:*

As noted in Subsection 2.3, knowledge creation through hypothesis and verification is indispensable in engineering analysis modeling. A management framework should capture multiple alternatives of the engineering analysis modeling and argumentation among the alternatives, and enable a working designer to switch to an alternative for comparative study if needed.

2.5 Our Approaches

This research proposes a knowledge management framework that tackles the above three issues on management of engineering analysis modeling knowledge. Corresponding to the issue noted in 2.4.2, this research adopts EAMM, which is a knowledge description format that we have proposed [Nomaguchi, et al. 2009]. A sheet of EAMM describes a snapshot of engineering analysis modeling. Corresponding to the issue noted in 2.4.3, this research adopts gIBIS, which is a conventional argumentation model [Conklin and Begeman 1988]. gIBIS is used to organize multiple design alternatives and analysis modeling alternatives, each of which is described by EAMM, and to represent argumentation behind the determinations. Finally, corresponding to the issue noted in 2.4.1, this research formalizes the gIBIS description patters for the design process and the engineering analysis modeling process in order to represent both the design process and the engineering analysis modeling process in gIBIS format.

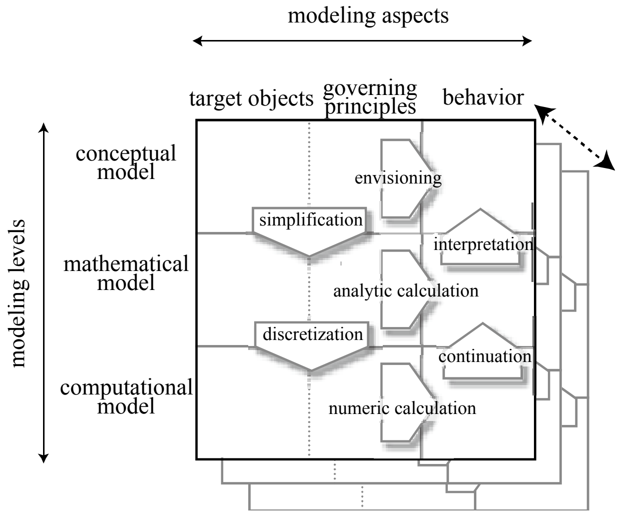

Figure 1. Engineering Analysis Modeling Matrix (EAMM)

3 Engineering Analysis Modeling Matrix

This section briefly introduces the contents of EAMM.

3.1 Overview

When an engineering analysis model is built, a designer determines target objects for which behavior is examined by engineering analysis, determines the target object phenomena under consideration, and simulates the behavior by calculation. Based on these empirical facts, this research defines the following three aspects of engineering analysis modeling, i.e., the *target object* consisting of a specific part and its product attributes relating to the analysis; the *governing principle*, that is, a physical phenomenon predicted to be dominant on the target objects; and the *behavior*, that is, the physical behavior of the product predicted under the determined target objects and the determined governing principles.

As noted in Subsection 2.1, a purpose of engineering analysis in design is to validate a designer's expectation for the physical behavior of a designed product by simulation with an analysis model. In fact, before building a mathematical model of engineering analysis, a designer qualitatively or conceptually understands the physical behavior of the designed product and predicts how well the design solution would achieve design requirements [Forbus, 1984]. An analytically solvable mathematical model or a ``back-of-the-envelope" analysis is effective especially at the early stages of the design process, in which exploring multiple design alternatives is more important than validating a design solution by an accurate computation [NASA, 1995]. When an analytical solution cannot be obtained, a computational model such as the finite element model is required. Therefore, this research defines the three levels of engineering analysis model as the conceptual model, the mathematical model and the computational model This classification of three modeling levels corresponds to the definition of modeling level given by the ASME *Guide for Verification and Validation in Computational Solid Mechanics* [ASME V&V 10-2006, 2006].

EAMM is a matrix of two axes, i.e., a horizontal axis of modeling aspects and a vertical axis of modeling levels. Figure 1 shows an overview of EAMM, which takes the form of a nine-cell matrix by combining the two modeling axes, each having three sub concepts. Seven scaphoid boxes called operation spaces are arranged among the cells. The shape of an operation space signifies the modeling process. Because target objects and governing principles are in general determined concurrently, no operation space is defined between a target object cell and a governing principle cell. Because each cell space and each operation space refers to a specific concept of the modeling process, a designer can concisely describe the contents of modeling knowledge in an appropriate space and obtain an overview of the modeling process by the associated description.

We propose that EAMM enables a working designer to explicitly describe and organize modeling processes in engineering analysis without depending on a specific modeling method or a specific product. Furthermore, we propose that multiple alternative models built in validating design alternatives can be managed by switching multiple sheets of EAMM.

3.2 Cell Spaces

The description of each cell space is defined as follows.

- *Conceptual model of target objects* is qualitative representation of real world entities and attributes is a conceptual model of target objects.
- *Mathematical model of target objects* is a simplified geometry model.
- *Computational model of target objects* is a discretized representation of time and space, which is continually represented in a mathematical model.
- *Conceptual Model of Governing Principles* is qualitative representation of considerable physical phenomena of target objects.
- *Mathematical Model of Governing Principles* is mathematical representation of principles of physical phenomena considered in the engineering analysis. It consists of governing equations of phenomena, which is usually given by partial differential equations or ordinary differential equations, boundary conditions and initial conditions.
- *Computational Model of Governing Principles* is discretized representation of differential equations that gives an approximated numerical solution of the equations. Its content is different depending on a discretization method, e.g., a computational model consists of difference equations in finite difference method.
- *Conceptual model of behavior* is qualitative representation of physical behavior of a designed product.
- *Mathematical model of behavior* is a continuous solution of a mathematical model of governing principles.
- *Computational model of behavior* is a discretized numerical solution of a computational model of governing principles.

3.3 Operation Spaces

Between the cell spaces in EAMM, seven pentagon-shaped spaces are introduced for description of engineering analysis modeling operation, i.e., simplification, discretization, envisioning, analytic calculation, numeric calculation, continuation, and interpretation.

- *Simplification* is an operation that reduces or omits nonessential objects of a real world in order to build an appropriate and solvable mathematical model. This is the heart of any engineering analysis modeling.
- *Discretization* is an operation that discretizes time and space of variables of target objects and governing principles in order to obtain a numerical solution of a mathematical model when it cannot be solved analytically.
- *Envisioning* is an operation of predicting the physical behavior of designed product qualitatively without using a mathematical model.

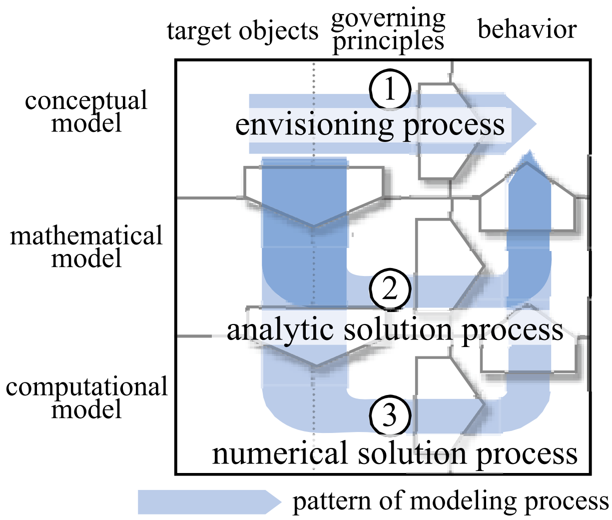

Figure 2. Patterns of modeling process

- *Analytic calculation* is an operation that solves differential equations analytically.
- *Numeric calculation* is an operation that obtains a numeric solution by solving discretized equations.
- *Continuation* is an operation that interpolates a solution of discretized equations, continual space attributes, and approximates a behavior of a mathematical model.
- *Interpretation* is an operation for confirming whether the solution of a mathematical model suits the prediction of physical behavior of the product.

3.4 Modeling Process Patterns

Sequence of filling in spaces of EAMM depends on the type of engineering analysis modeling process. This research discusses the following three primitive modeling process patterns, i.e., envisioning process, analytic solution process and numerical solution process. Note that an actual process of engineering analysis modeling consists of iterations of these primitive patterns.

- *Envisioning process*

Before the analysis modeling, a designer qualitatively but wholly predicts the possible behavior of the product. This process is performed only at a conceptual model as shown in Figure 2-(1).

- *Analytic solution process*

An analytically solvable mathematical model or a back-of-the-envelope analysis is effective especially in the early stages of design process. In this case, a designer describes a conceptual model, then builds a mathematical model, and finally validates the conceptual behavior based on an analytical solution of the mathematical model. This process pattern is shown in Figure 2-(2).

- *Numerical solution process*

In the case that a numerical solution is used, a designer describes a conceptual model, builds a mathematical model and a computational model, obtains a mathematical behavior by continuation of a computational behavior, and finally validates the conceptual behavior based on the mathematical behavior. This process pattern is shown in Figure 2-(3).

4 Design Process Representation

4.1 Transition of Engineering Analysis Model

The contents of the engineering analysis modeling process change accompanying the changes of design. While EAMM can describe a snapshot of engineering analysis modeling, it cannot

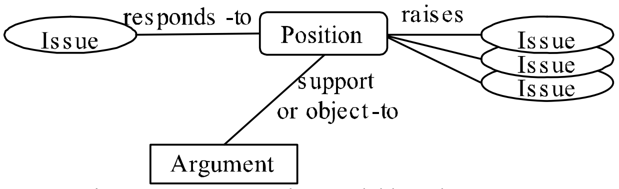

Figure 3. Argumentation model based on gIBIS

represent a transition of the modeling contents through design process. This transition process usually takes a form of a tree structure, which branch represents an existence of multiple alternatives. In order to represent the transition, this research adopts gIBIS, a conventional argumentation model which is often used to represent a tree structure including branches of multiple alternatives. gIBIS is a hypertext that comprises the three types of text node as shown in Figure 3. *Issue* is a node, which represents an issue addressed in argument. *Position* is a node that represents one of multiple alternative solutions to an issue. A position node has a *respond-to* link to an issue, to which a position gives a solution. A position node can be followed by an issue node, when a new issue is raised from a position. In this case, a *raise* link is arranged between a position node and an issue node. *Argument* is a node that represents an argument among multiple positions. If an argument supports a position, a *support* link is arranged between them. If an argument objects to a position, an *objected-to* link is arranged. Each node has an active or inactive status that indicates the node is currently adopted or not adopted.

Figure 4 shows an example of a transition of modeling contents and its IBIS representation. A description of EAMM changes from (1) to (2) as shown in the right side of Figure 4, when ``simplification 1” is modified to ``simplification 2.” This transition process is represented by gIBIS as shown in the center of Figure 4; the two alternative, ``simplification 1” and ``simplification 2,” are addressed to the issue ``what is simplification?” and the latter alternative is currently active.

4.2Design Operations for Engineering Analysis Modeling

In order to systematically describe the IBIS representation noted in Subsection 4.1, this research defines description patterns of a pair of an issue and an alternative position concerning both a design process and an engineering analysis modeling process. We call such a pattern a design operation [Nomaguchi et al. 2006]. Firstly, *addressing a design alternative* and *building an engineering analysis model for design validation* are defined as a top-level design operation, which correspond to the first two steps noted in Subsection 2.1. Some sub-level design operations are defined for each top-level design operation. Consequently, the IBIS representation takes a form of a hierarchical structure as shown in Figure 4. This section introduces the following 15 sub-level design operations of *building an engineering analysis model*, each of which corresponds to an act of describing the contents of a relevant EAMM space, while the detail of sub-level design operations of *addressing a design alternative* is explained in our prior paper [Nomaguchi et al. 2006].

1. Setting a purpose of analysis
2. Setting target objects
3. Setting physical phenomena considered
4. Setting envisioning results
5. Setting simplification
6. Setting geometry
7. Setting boundary elements
8. Setting boundary conditions
9. Setting initial conditions
10. Setting governing equations
11. Setting a discretization method
12. Setting a mesh size
13. Setting other discretization options
14. Setting calculation results
15. Setting an interpretation

4.3 Categories of Argument Description

Describing the content of an argument node and making a support or object-to link correspond to the *critique* step noted in Subsection 2.1. This paper defines some typical categories pattern of the argument in order to support a designer to systematically describe the contents of an argument node.

There are two top-level categories of an argument description, i.e., (1) comarison between multiple alternatives and (2) an intention of setting an alternative. The first category includes various perspectives of design validation which depend on the type of design. Concerning the latter category, this research introduces

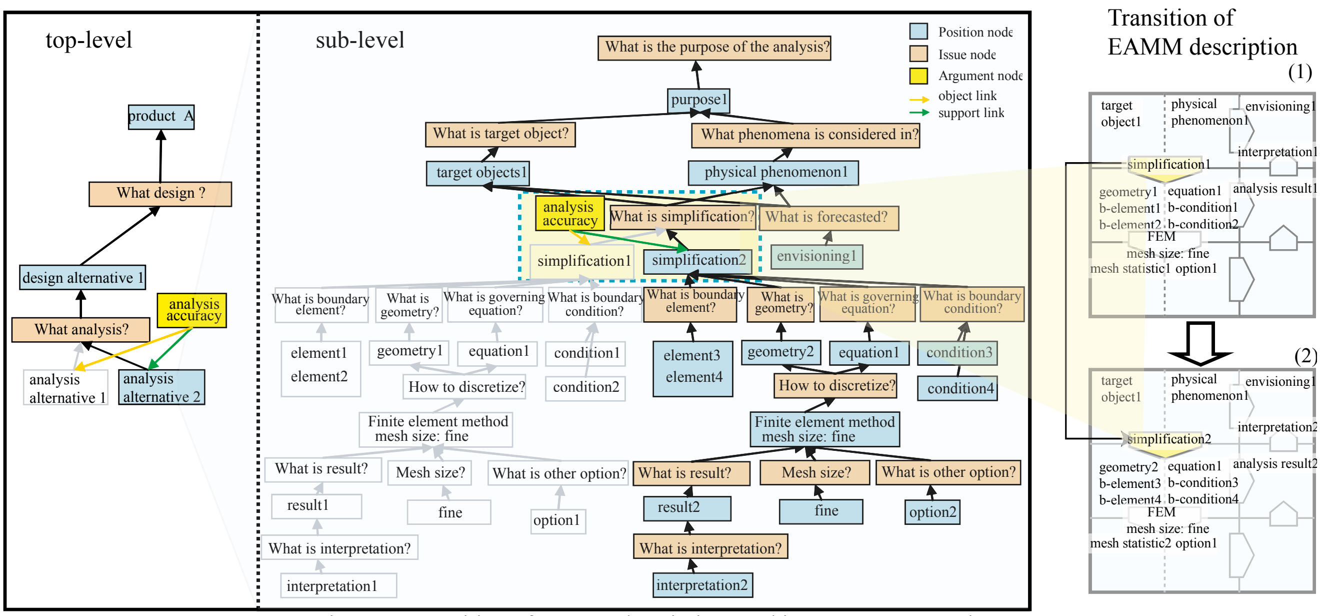

Figure 4. Transition of EAMM descriptions and its IBIS representation

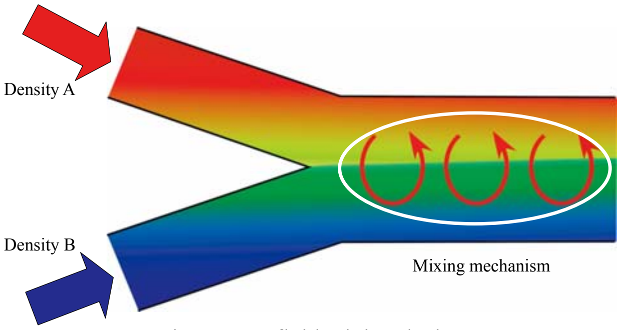

Figure 5. A fluid mixing device

the following two two-folds, i.e., (I) the analysis result validates the envisioning and (II) the analysis result does not validate the envisioning, and (A) modifying the design alternative and (B) modifying the analysis model alternative. By combining the two two-folds, the four sub-categories can be defined, that is, I-A, II-A, I-B and II-B. The sub category B is further categorized into the following five sub-sub categories, i.e., (a) changing accuracy, (b) decomposing an analysis target into sub parts, (c) changing a physical domain, (d) building a simple analysis model for exploration, and (e) revising an error of an analysis model.

5 Example of Design Process Description

5.1 Overview of Design Example

A design example which this paper uses is a design of a fluid mixing device working in a μTAS (Micro Total Analysis System) on a micro chip of 160 μm x 320 μm. A μTAS is an ultra-small chemical system that integrates minimized components such as a pump, a valve, and a sensor, and it is mainly used in a domain of medical research, environmental research and chemosynthesis [Kotera 2005]. A device shown in Figure 5 is designed to mix two kinds of fluid, each of which has the equal viscosity and the different density. A stirring effect by turbulent flow cannot be expected because Reynolds number of the fluid is very small in this scale. Therefore, any mixing mechanism is required in this device in order to meet the required mixing performance. However, it should work with small energy.

In a design process of the fluid mixing device, 12 design alternatives and 13 analysis modeling alternatives are addressed. The following paragraphs show its details in chronological order.

Firstly, a designer proposes three design alternatives of a mixing mechanism, i.e., using magnetic fluid and mixing it by variable magnetic field (design alt. 1), using a stirrer (design alt.2), and stirring by convection by heating a device’s wall (design alt. 3). The former two alternatives are tested by envisioning (modeling alt. 1 and 2), and a designer determines that they have less reliability than the design alt. 3. Concerning the design alt. 3, a simple analysis model is built to calculate Rayleigh number (analysis alt. 3). The calculation result shows that it is less than the critical Rayleigh number, and then convection will hardly occur.

In place of the unreliable three design alternatives, a designer proposes another design alternative, using an optical mixer (design alt. 4). Because a behavior of the optical mixer mechanism is complicated, a FEM system is required to validate the design alternative. A designer builds a trial simplified analysis model that focuses on the small area around the mixer (analysis alt. 5). Although this model assumes the fluid incompressibility, no flow and no diffusion, it takes much time to obtain a numeric solution. Therefore, a designer determines further simplifications, i.e., an optical mixer is idealized as a rotating cylinder which surface is idealized as no slip boundary (analysis alt. 4).

As a reference to validate the mixing performance of an optical mixer, a designer makes a design alternative which doesn’t have any mixer (design alt. 5). An analysis model for it (analysis alt. 6) is built under the same assumption as the analysis alternative 4. As another reference to validate the mixing performance of a rotating mixer, a designer makes a design alternative of an optical mixer which does not rotate (design alt. 6), and builds its analysis model (analysis alt. 7). Based on the comparison of calculate results of analysis alternative 4, 6 and 7, a designer confirms that an optical mixer has enough mixing performance.

A designer explorers design alternatives of the optimal number of an optical mixer located in the mixing device. A designer also examines the effect of rotation for each design alternative of the number of an optical mixer. Consequently, a designer examines six design alternatives (design alt. 7 to 12). For each, an analysis model is built (analysis alt. 8 to 13). Based on the comparison of the calculate results of these analysis model alternatives, a designer knows that the more the number of an optical mixer, the better mixing performance, but three optical mixers brings out better performance than four optical mixers, because a space within the mixing device is too narrow to arrange four optical mixers such that the fluid does hardly flow. Therefore, a designer adopts the design alternative of three rotating optical mixers (design alt. 9).

In order to verify the analysis model alterative 10, a designer built two another analysis models, each of which has finer mesh (analysis alt. 14, 16). Based on the comparison among the calculate results of these models, it is found that the analysis model alternative 10 has enough accuracy. Consequently, the design alternative 9 is validated.

5.2 Description of Design Process

Figure 6 shows a part of description of the design process explained in Subsection 5.1 using the proposed framework. Transition of design alternatives and analysis model alternatives are represented in the IBIS format. Purposes and design rationale can also be represented by argument nodes. A colored node means that its content is active.

It is shown that the design alternative 9 is finally adopted and it is because there are enough spaces for liquid flow between mixers. Rationales of analysis models that are built for validating design alternatives are also described. For example, the analysis model alternative 10, 14, 16 are built for validating the design alternative 9, and the accuracy of the first model is verified by the latter two models.

5.3 Discussion

As shown in Figure 6, the proposed framework can capture the knowledge of engineering analysis modeling for design validation. In order to enhance usability of the framework, its implementation remains as an open issue. Concerning this, we have been developing an integrated design support framework that dynamically manages multiple perspectives and multiple alternatives in design process, called DRIFT [Nomaguchi et al. 2006]. Our future works include integration of the framework proposed in this paper into DRIFT.

6 Conclusion

This paper introduces an outline of a framework for describing and managing the knowledge involved in engineering analysis modeling during design validation. The framework adopts EAMM as a description framework of the concepts of

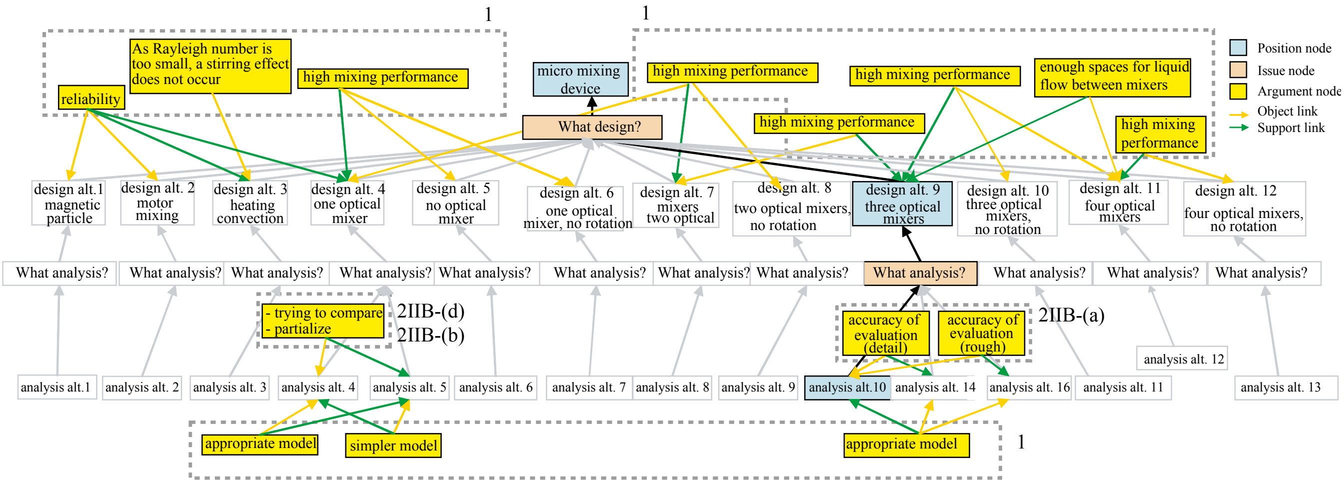

Figure 6. Argumentation model of design validation process in mixing device design

engineering analysis modeling. A conventional argumentation model, gIBIS is adopted in order to represent transition of the contents of engineering analysis modeling accompanying transition of design alternatives. This paper also demonstrates a description example of a design process of a fluid mixing device working in a µTAS, which shows the possibility of the framework.

References

ASME V&V 10-2006, 2006, *Guide for Verification and Validation in Computational Solid Mechanics, PTC 60 Committee on Verification and Validation in Computational Solid Mechanics*, the American Society of Mechanical Engineers

CONKLIN, J. AND BEGEMAN, M. L., 1988, gIBIS: A Hypertext Tool for Exploratory Policy Discussion, ACM Transactions on Office Information Systems, Vol. 6, No. 4, pp. 303–331.

DORAISWAMY, S., KRISHNAMURTY, S., AND GROSSE, I., 1999, Decision Making in Finite Element Analysis, *Proceedings of Design Engineering Technical Conferences (DETC99)*, CIE-9058

DYM, C., *Engineering Design: A Synthesis of View*, (1994), Cambridge University Press.

FORBUS, K. D., 1984, Qualitative Process Theory, *Artificial Intelligence*, Vol. 24, No. 1-3, pp. 85-168

GROSSE, I. R., MILTON-BENOIT, J. M., AND WILEDEN, J. C., 2005, Ontologies for Supporting Engineering Analysis Models, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 19, No. 1, pp. 1-18.

KOTERA, H., 2005, Surface and its Treatment of MEMS and µ TAS, *The Journal of the Surface Finishing Society of Japan*, Vol. 56, No. 10, pp. 572-579.

NOMAGUCHI, Y., TAGUCHI, T. AND FUJITA, K., 2009, Research on Knowledge Management Framework for Engineering Analysis Modeling, Transaction of the Japan Society of Mechanical Engineers, Series C, Vol. 75, No. 756, pp. 2181-2190. (in Japanese)

NASA, ED., 1995, *Systems Engineering Handbook*, NASA.

NOMAGUCHI, Y., TAGUCHI, T. AND FUJITA, K., 2006, Knowledge Model for Managing Product Variety and its Reflective Design Process, *Proceedings of the 2006 ASME Design Engineering Technical Conferences & Computers and Information in Engineering Conference, The American Society of Mechanical Engineers (ASME)*, DETC2006-99360

SCHÖN, D. A., 1982, *The Reflective Practitioner – How Professionals Think in Action*, Basic Books Inc.