Proceedings of the TMCE 2010, April 12–16, 2010, Ancona, Italy, Edited by I. Horváth, F. Mandorli and Z. Rusák
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A FRAMEWORK OF DESCRIBING AND MANAGING ENGINEERING ANALYSIS MODELING KNOWLEDGE FOR DESIGN VALIDATION

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ABSTRACT

Engineering design is validated by engineering analysis. In the process for predicting the physical behavior of the design, the design components, physical mechanisms, etc. are idealized as models, the contents of which depend on a various factors such as the type of product, the validation objectives, and the design lead time as well as the design's physical features. It is important to examine such modeling knowledge to enhance the rationality and reusability of engineering analysis. This paper proposes a concise and comprehensive format for describing the knowledge of engineering analysis, called Engineering Analysis Modeling Matrix (EAMM). EAMM is a matrix of two axes, i.e., a modeling aspect axis and a modeling level axis. The former axis consists of target objects, governing principles and behavior, and the latter axis consists of conceptual, mathematical and computational approaches. EAMM takes the form of a nine cell matrix by combining the two modeling axes, each having the three sub concepts. Seven scaphoid boxes called operation spaces are arranged among the cell spaces. When a designer describes various elements of modeling knowledge in such a format, the association of the cells and boxes enables the designer to organize the modeling process and obtain its overview. The design of a water heater is used as an example to demonstrate the capability of EAMM for description and management of engineering analysis modeling knowledge.

KEYWORDS

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

1. INTRODUCTION

An appropriate engineering analysis model is indispensable in engineering design to allow rational evaluation and optimization. A designer idealizes the design's physical features, e.g., dimensional reduction, geometric symmetry, feature removal, domain alterations and so on, for modeling a product's physical behavior which by nature consists of complicated multidisciplinary phenomena. 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 [1]. This modeling process in which a designer makes some idealizations based on associated justification is the heart of all engineering analysis models [2]. 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. This paper discusses elemental concepts which constitute engineering analysis modeling knowledge, e.g., relevant physical phenomena, simplification methods, mathematical representations, the interpretation of calculated results and so on. Next, we propose the Engineering Analysis Modeling Matrix (EAMM), which organizes the modeling knowledge concepts in a matrix format. 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.

This paper also demonstrates a descriptive example of a modeling process in a water heater system design to verify the EAMM's capability of modeling process description.

2. ENGINEERING ANALYSIS MODELING

2.1. Engineering Analysis for Design Validation

One purpose of engineering analysis in design is to validate a designer's expectation for the physical behavior of a designed product; such validation is done through simulation using an analysis model. 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 deliberate modeling idealization, e.g., which physical phenomenon should be considered and what simplification should be done, for appropriate modeling.

2.2. Knowledge Creation in Design Process

One further feature which we must not ignore is that design is an open-ended problem in which a designer should simultaneously explorer problems and solutions. 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 [3] that is a knowledge creation process in which a designer hypothetically defines the problem, arrives at a 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. 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 engineering analysis modeling, modeling idealizations should be decided by a reflective hypothesis-verification process. Modeling knowledge is dynamically acquired through this modeling process.

2.3. Issues on Management Framework of Engineering Analysis Modeling Knowledge

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

- *A format for explicitly describing the modeling process:*

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 format for explicitly describing these concepts is required to capture modeling knowledge and to organize it.

- *Handling the hypothesis and verification process:*

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 process among the alternatives, and enable a working designer to switch to an alternative for comparative study if needed.

3. RELATED WORKS

This section outlines the various approaches taken by researchers in the past and present concerning engineering analysis modeling knowledge, and clarifies the approach of this research.

In general, prior researches into the development of a knowledge management framework can be categorized roughly into two approaches; those based on a computer-based framework that aims for automatic or semi-automatic problem solving, and those designed to help working engineers represent and organize knowledge with reflection-in-action. With regard to the management of engineering analysis modeling knowledge, the first approach includes various knowledge-based systems, e.g., automatic or semi-automatic modeling systems [4] [5] and object-oriented database systems for analysis models and modeling knowledge [6][7]. These systems suggest possible modeling solutions for given problems, acting like an engineering analysis expert by employing a number of heuristic rules or case examples stored in a knowledge base. The contents of the knowledge base are used for reasoning or retrieval by a computer only, but are not intended to be read and understood by a human.

In contrast to this approach, recent work has focused on knowledge representation that is readable by both computers and humans. For example, the ontology of engineering analysis modeling is useful to explicitly define modeling concepts, such as the aim of the analysis, accuracy requirements, and simplification methods, as well as the relationships among the concepts [8][2]. The PTC (Performance Test Code) 60 committee on verification and validation in computational solid mechanics of the American Society of Mechanical Engineers has recently defined terminology of modeling knowledge in order to build a framework for the evaluation of modeling reliability and a systematic method of verification and validation of analysis modeling [9]. These works provide an important foundation for a framework of knowledge management. However, these works assume that a knowledge engineer captures modeling knowledge after the modeling process is finished. Thus, these approaches do not focus on a concise representation format by which a working engineer can acquire an overview of modeling knowledge and organize it.

The approach for a knowledge organization framework has been seen in the so-called DFX (Design for X) methodologies [10]. A DFX is a systematic methodology for designing products and processes from a particular viewpoint (denoted by X), e.g., cost-effective, high-quality downstream operations through manufacture process including fabrication, assembly and testing. Most DFX methodologies adopt a conceptual network or a matrix format that gives a designer an overview of the described knowledge. For example, FMEA (Failure Mode and Effects Analysis) is a method for analysis of potential failure modes within a system [11]. In FMEA, the failure mode, its severity, and/or its effect on the system, can be organized in a matrix format, allowing the designer to determine the nature of the fatal failure. The usefulness of DFX methodology lies in its concise and comprehensive representation framework to formulate various concepts of engineering design.

This research is motivated by the fact that a DFX methodology encourages systematic documentation and deliberation of the design process because it offers a concise and comprehensive knowledge description framework. Such a framework for engineering analysis modeling will help engineers document and deliberate analysis modeling process, and consequently reuse modeling knowledge.

4. MODELING OF ENGINEERING ANALYSIS MODELING

Toward a format for explicitly describing and organizing engineering analysis modeling knowledge, this section discusses fundamental concepts of modeling knowledge.

4.1. Aspects of Engineering Analysis Modeling

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.

4.2. Levels of engineering analysis modeling

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 [12]. 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 [13]. 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.

The *conceptual model* is a model of a designer's qualitative understandings and predictions of physical behavior of the product that exist prior to building a mathematical model. A conceptual model is described by a natural language or a simple sketch.

The *mathematical model* is mathematical representation of physical phenomena. A physical phenomenon can be generally described by ordinary or partial differential equations representing time and space of target objects based on physical theories such as mechanics and electromagnetics. These representations constitute a mathematical model of engineering analysis.

The *computational model* is a discretized form of the mathematical model. In many cases, an analytical solution of a differential equation cannot be obtained. Therefore, a computational model is built by discretizing time and space and employing numerical methods to solve the relevant differential equations in place of an analytical solution.

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* [1].

4.3. Engineering Analysis Modeling Matrix

Based on the above discussion, this research proposes EAMM as a descriptive modeling format. 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 a nine-cell matrix by combining the tow modeling axes, each having three sub concepts. Seven scaphoid boxes called operation spaces are arranged among the cells. The shape of an operation

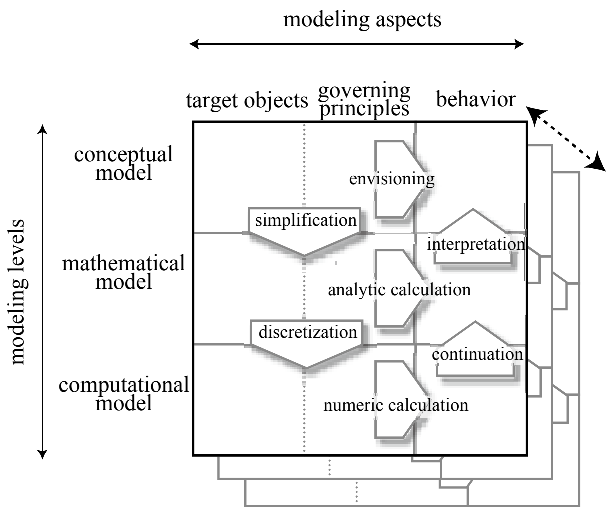


Figure 1 Engineering Analysis Modeling Matrix (EAMM)

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.

For the issues noted in Subsection 2.3, this research proposes 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, this research proposes that multiple models built in validating design alternatives can be managed by switching multiple sheets of EAMM.

5. CELLS OF ENGINEERING ANALYSIS MODELING MATRIX

This section explains the meaning of each cell space of EAMM by illustrating a simple analysis model.

5.1. Conceptual Model of Target Objects

Qualitative representation of an entity and its attributes comprise a conceptual model of target objects. This is described by a simple sketch or a natural language, e.g., ``the little boss exists on the flat plane,'' ``the metal components are interacting with the flexible drive belt'' and so on.

5.2. Mathematical Model of Target Objects

For a mathematical representation of target objects, a simplified geometry is used. For instance, in structural analysis and vibration analysis, a comparatively thin plate is modeled as a shell, and a cylinder shape part is modeled as beam. A geometry model simplified like this is a mathematical model of target objects.

5.3. Computational Model of Target Objects

A computational model of target objects is a discretized representation of time and space, which is continually represented in a mathematical model. For instance, space is represented by many grid points in the finite difference method [14], or by many finite elements in finite element method[15].

5.4. Conceptual Model of Governing Principles

A conceptual model of governing principles is a qualitative representation of dominant physical phenomena of target objects. For instance, a thermal expansion phenomenon is represented as follows; ``Almost all metallic materials and composite materials expand or shrink when temperature changes. The expansion or the shrinkage is proportional to the amount of the temperature change." Fourier's law, a governing principle of heat conduction, is represented as follows; ``The amount of heat that flows in the section at a certain point per each unit time is proportional to the temperature gradient at that point."

5.5. Mathematical Model of Governing Principles

A mathematical model of governing principles is a mathematical representation of the principles of physical phenomena. It consists of governing equations of phenomena, which usually take the form of partial or ordinary differential equations with associated boundary values and initial conditions.

For instance, a one dimensional mathematical model of Fourier's law is represented as $q(x,t) = -\lambda \partial u / \partial x$, where $q(x,t)$ is the amount of heat that flows in the section at the position *x* and the time *t*, and $\partial u / \partial x$ is the temperature gradient. The one dimensional heat equation is derived from this as follows; $\partial u / \partial t = \lambda \partial^2 u / \partial x^2$ [16].

A mathematical model of heat conduction can be built by applying initial conditions and boundary conditions to this equation, e.g., the Dirichlet boundary condition [17].

5.6. Computational Model of Governing Principles

A computational model of governing principles is a discretized representation of differential equations that gives an approximated numerical solution of the equations. Its content is different depending on the discretization method, e.g., a difference equation is used in a finite difference method.

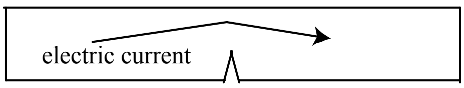
An example of a computational model of a heat conduction phenomenon is shown here. A mathematical model of heat conduction can be approximated by the average rate of temperature change over a minute displacement *h* as follows; $\partial u / \partial x = (u(x+h) - u(x)) / h$. Furthermore, by temporal discretization such as $t_k = t_{k-1} + \Delta t$, (*k=1, 2, 3…*), the following difference equation is derived; $(u_j^{k+1} - u_j^k) / \Delta t = \lambda (u_{j+1}^k - 2u_j^k + u_{j-1}^k) / h^2$ [16].

5.7. Conceptual Model of Behavior

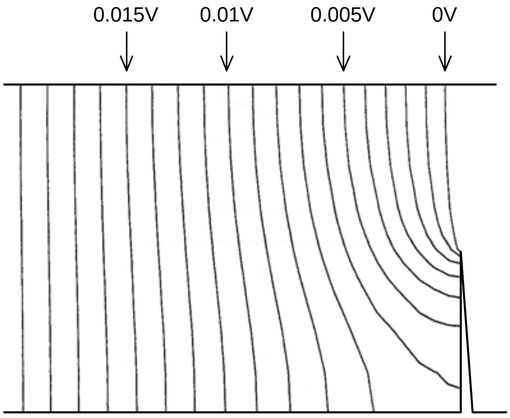
A conceptual model of behavior is a qualitative representation of the physical behavior of a designed product. Figure 2 shows an example of a stationary electric current model in a thin plate with a crack [18]. Before the analysis, a designer qualitatively predicts the behavior of the electric current as shown in Figure 2-(a), that is, “The electric current flows in the plate bypassing the crack. The more it approaches the crack edge, the more the current density increases.” A designer's qualitative prediction like this is a conceptual model of behavior. The prediction is validated by calculation results of a mathematical model, and revised if needed.

5.8. Mathematical Model of Behavior

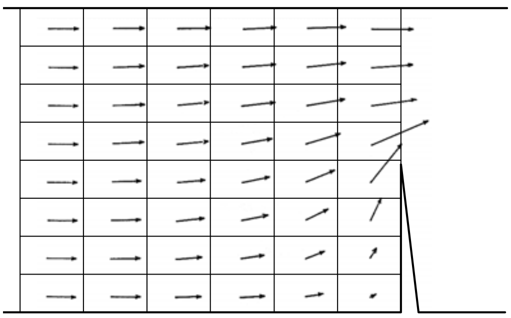
A mathematical model of behavior is a continuous solution of a mathematical model of governing principles. In the example of electric current analysis, a voltage value distribution chart given by an isoelectric line shown in Figure 2-(b) is an example of a mathematical model of behavior. In cases for which an analytical solution of the mathematical



(a) Conceptual behavior model



(b) Mathematical behavior model



(c) Computational behavior model

Figure 2 Behavior models of electric current

model cannot be calculated, a designer should calculate a discretized numerical solution instead and perform post-processing in order to get an approximated continuous solution.

5.9. Computational Model of Behavior

A computational model of behavior is a discretized numerical solution of a computational model of governing principles. The vector distribution of the current density obtained for the divided elements shown in Figure 2-(c) is an example of a computational model of behavior of the electric current analysis.

6. FORMALIZATION OF MODELING OPERATIONS

Between the cells making up EAMM, seven scaphoid boxes are arranged for description of engineering analysis modeling operations, i.e., simplification, discretization, envisioning, analytic calculation, numeric calculation, continuation, and interpretation. This section explains the definition of each operation space, and relationships between the operations and the cells.

6.1. Simplification

Target objects and governing principles should be appropriately simplified according to required accuracy of the analysis or constraints of computing time. 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. Simplification operations for target objects include dimensional reduction, geometric symmetry, feature removal, and domain alternations [19]. Simplification operations for governing principles include omission of minute effects, limiting of the area, focusing, insulation, using a lumped element description, linearization, making a small range variable a constant, and so on [20].

In EAMM, a simplification operation corresponds to the act of filling in mathematical model cells based on a description of conceptual model cells. A space for explanation of simplification is located between conceptual model cells and mathematical model cells of target objects and governing principles as shown in Figure 1.

6.2. Discretization

Discretization is an operation that discretizes the time and space variation of variables associated with target objects and governing principles in order to obtain a numerical solution of the mathematical model when it cannot be solved analytically. Discretization operations include determination of meshing pattern, meshing resolution, time discretization and so on [20].

In EAMM, a discretization operation corresponds to the act of filling in computational model cells based on description of mathematical model cells. A space for explanation of discretization is located between mathematical model cells and computational model cells of target objects and governing principles as shown in Figure 1.

6.3. Envisioning

Before the analysis modeling, a designer qualitatively but completely predicts the possible behavior of the product. Researchers of qualitative reasoning call this act envisioning [12]. This research adopts this name for an operation of predicting the physical behavior of designed product qualitatively without using a mathematical model.

In EAMM, an envisioning operation corresponds to the act of filling in a behavior cell of a conceptual model based on the description of a target object cell and a governing principle cell of a conceptual model. A space for explanation of envisioning is located between a behavior cell and a governing principle cell of a conceptual model as shown in Figure 1.

6.4. Analytic Calculation

Analytic calculation is an operation that solves differential equations analytically. In EAMM, this operation corresponds to the act of filling in a behavior cell of a mathematical model based on the description of a target object cell and a governing principle cell of a mathematical model. A space for explanation of analytic calculation is located between a behavior cell and a governing principle cell of a mathematical model as shown in Figure 1.

6.5. Numeric Calculation

Numeric calculation is an operation that obtains a numeric solution by solving discretized equations. In EAMM, this operation corresponds to the act of filling in a behavior cell of a computational model based on the description of a target object cell and a governing principle cell of a computational model. A space for explanation of the numeric calculation is located between a behavior cell and a governing principle cell of the computational model as shown in Figure 1.

6.6. Continuation

The behavior of a computational model is represented by the solution of discretized equations. This is interpolated to form continual space attributes, and approximates the behavior of a mathematical model. This research names this operation continuation. In general, a CAE system performs the continuation operation by post-processing. Its result usually takes the form of a contour figure.

In EAMM, this operation corresponds to the act of filling in a behavior cell of a mathematical model based on description of a behavior cell of a computational model. A space for continuation contents is located between a behavior cell of a computational model and a behavior cell of a computational model as shown in Figure 1.

6.7. Interpretation

A designer validates the prediction of physical behavior of the product by the solution of a mathematical model. This research calls this act interpretation. When the analysis solution is not as predicted, a designer determines that the design is not validated and it should be revised, or that the analysis model is wrong and it should be rebuilt. This determination is very important knowledge in engineering analysis modeling for design validation. By filling in spaces of EAMM, a designer can describe this knowledge and associating it with the other modeling knowledge contents.

In EAMM, this operation corresponds to the act of filling in a behavior cell of a conceptual model based on the description of a behavior cell of a mathematical model. A space for explanation of interpretation, in which the designer's determination is described, is located between a cell of mathematical behavior and a cell of conceptual behavior as shown in Figure 1.

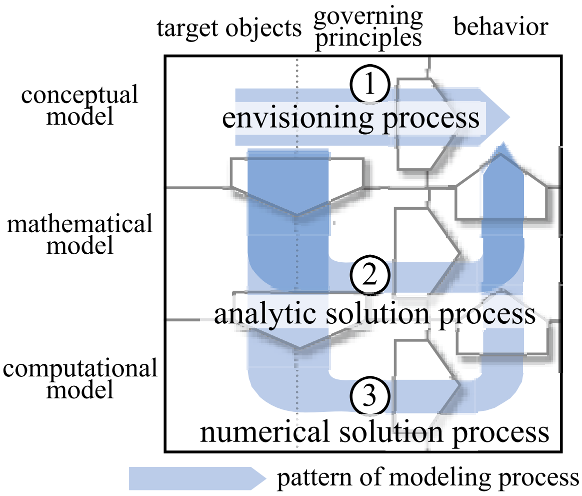


Figure 3 Patterns of modeling process

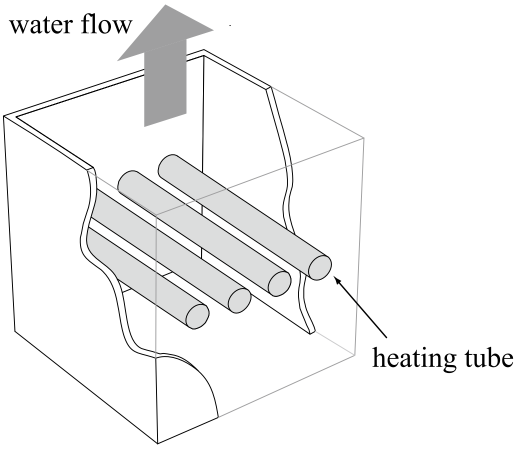


Figure 4 Schematic view of water heater

7. MODELING PROCESS PATTERNS

A sequence of description in the EAMM format depends on the type of engineering analysis modeling process. This research defines the following three primitive modeling process patterns as shown in Figure 3, i.e., envisioning process, analytic solution process and numerical solution process. Note that an actual process of engineering analysis modeling consists of recursive 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 the level of a conceptual model as shown in Figure 3-(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 3-(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 the mathematical behavior by continuation of the computational behavior, and finally validates the conceptual behavior based on the mathematical behavior. This process pattern is shown in Figure 3-(3).

8. DESCRIPTION EXAMPLE OF EAMM

This section verifies the ability of the EAMM format by a descriptive example of engineering analysis modeling.

8.1. Overview of Heater Design

This section supposes a design process of a water heater system, which includes design validation by using analysis simulation and hypothesis verification through multiple design alternatives and multiple modeling alternatives, in order to focus on the features of engineering analysis modeling noted in Subsection 2.1 and Subsection 2.2.

Figure 4 shows a schematic view of a water heater. The water that flows from the lower inlet to the upper outlet is heated by the heating tubes arranged vertically for the water flow. It is required that the average water temperature at the outlet is higher than 320 K when the average water temperature at the inlet is 293 K and temperature of the tube surface is 350 K.

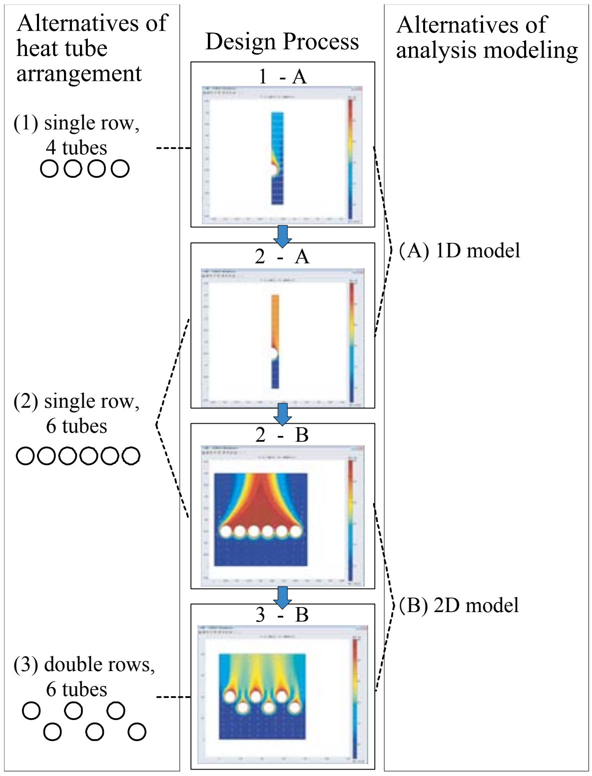


Figure 5 Alternatives and process of the water heater design

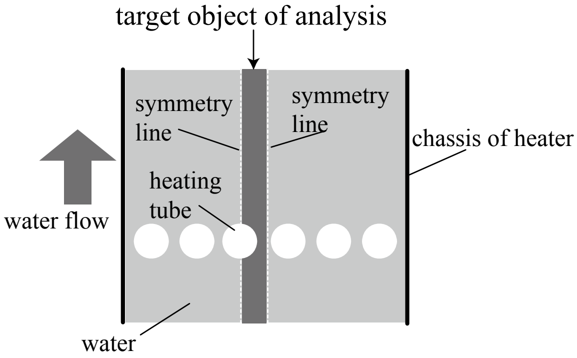


Figure 6 1D Model considering symmetry of heating tube arrangement

In the design process, three alternatives of the heating tube arrangement and two alternatives of analysis modeling simplification are proposed as shown in Figure 5. The design process proceeds as follows;

1. First, a designer expects that four or more heating tubes will raise the average outlet water temperature to 320K or more.
2. For validation of the alternatives of the heating tube number, a designer assumes that key features of the flowing water, i.e., temperature and flow velocity, have symmetry with respect to the heating tube, that is, they do not change in the heating tube's axial direction. A simple one-dimensional model in which the target objects' geometry is represented by a narrow rectangle that includes half a section of a heating tube is built as shown in Figure 6.
3. A designer validates the alternative of four heating tubes (1-A) and the alternative of six heating tubes (2-B) by the analysis model of Figure 6. It is confirmed that the six-tube alternative meets the requirement while the four-tube alternative does not.
4. In order to validate the design alternatives more accurately, a two-dimensional model is built by canceling the simplification of the heating tube symmetry. See 2-B in Figure 5.
5. The two-dimensional analysis of the six-tube alternative reveals that the heat transmission is not enough and it will not raise the outlet temperature to 320K. The cause of the unexpected results is that the space between heating tubes is too narrow and the heated water stays around the heating tube, then the heat gradient around the heating tube decreases. This phenomenon cannot be predicted by the 1D model built in the step 2, because the 1D model cannot simulate the water flow at the narrow space between tubes.
6. A designer proposes the double-row arrangement of the heating tubes in order to broaden the space between tubes (see 3-B in Figure 5). The two-dimensional model analysis validates that this design alternative will raise the outlet temperature to 320K or more.

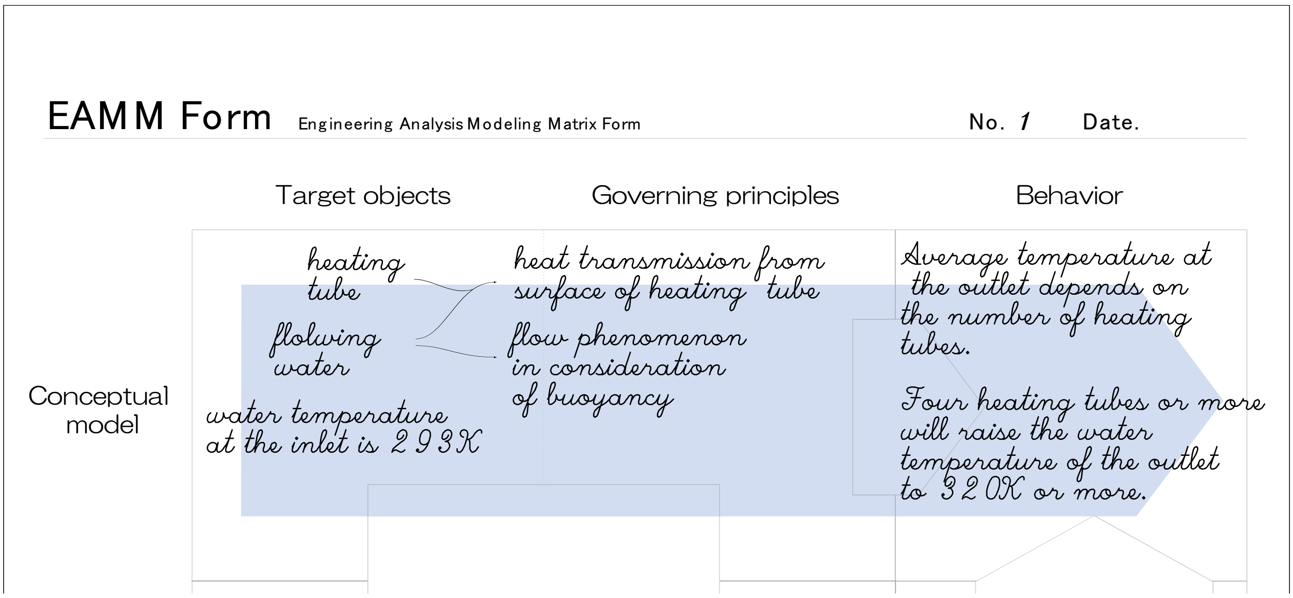


Figure 7 Description of conceptual model of a water heater analysis

8.2. Analysis Modeling Description on EAMM

This subsection describes the engineering analysis modeling in the water heater design using the EAMM format.

Envisioning

First, a designer qualitatively predicts the possible behaviors of the water heater in the envisioning process. This process is described in conceptual model cells of EAMM as shown in Figure 7. The target objects of the analysis include heating tubes and flowing water. The governing principles are ``heat transmission from the surface of the heating tube'' and ``flow phenomenon in consideration of buoyancy.'' By considering these concepts, a designer predicts the physical behavior of the water heater, i.e., ``the average temperature at the outlet depends on the number of heating tubes'' and `` four heating tubes or more will raise the water temperature of the outlet to 320K or more.''

Design Validation by 1D Model Considering Heating Tube Symmetry

A mathematical model is built based on the

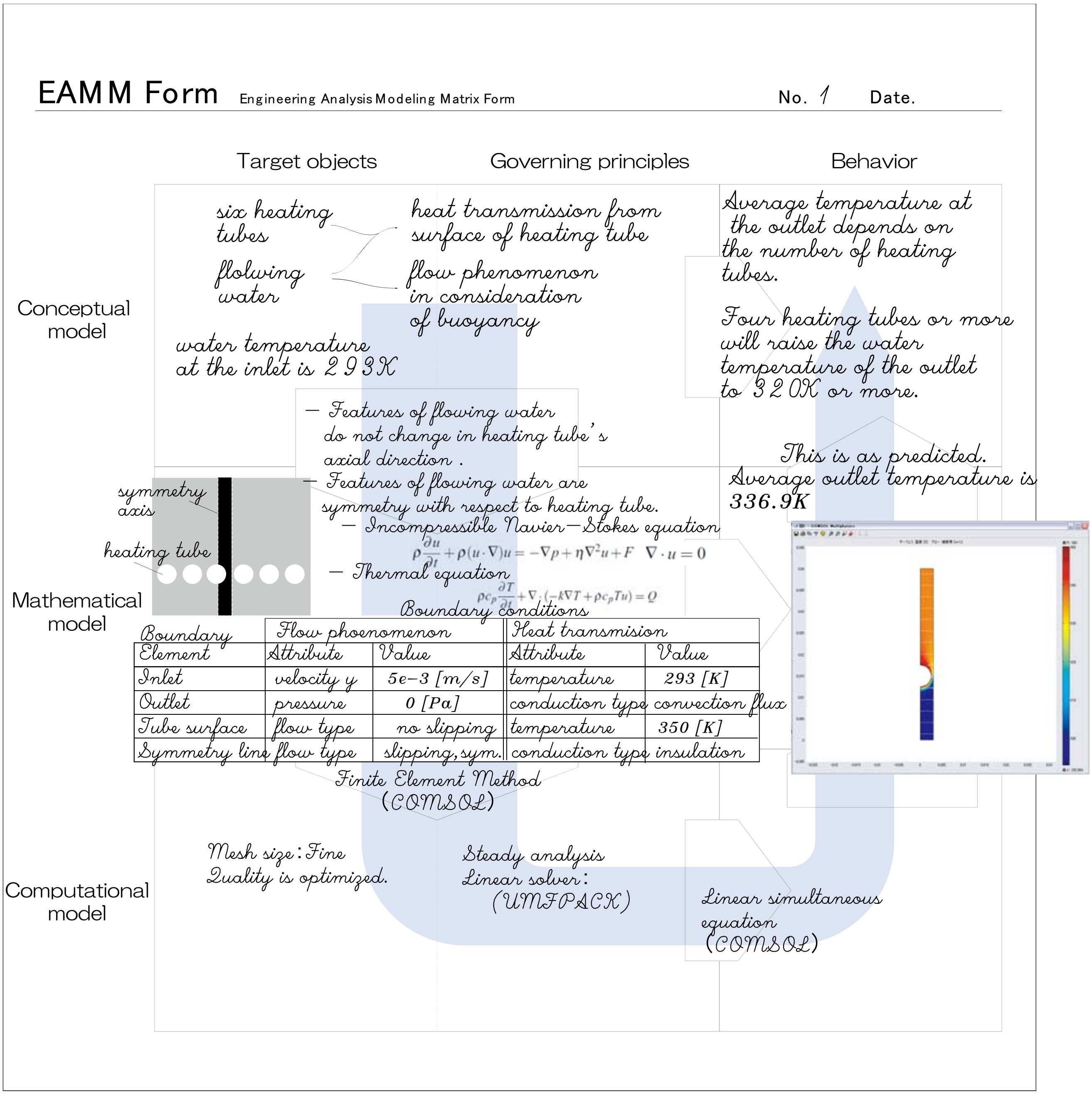


Figure 8 Modeling process of analyzing a water heater by considering symmetry of heating tube arrangement

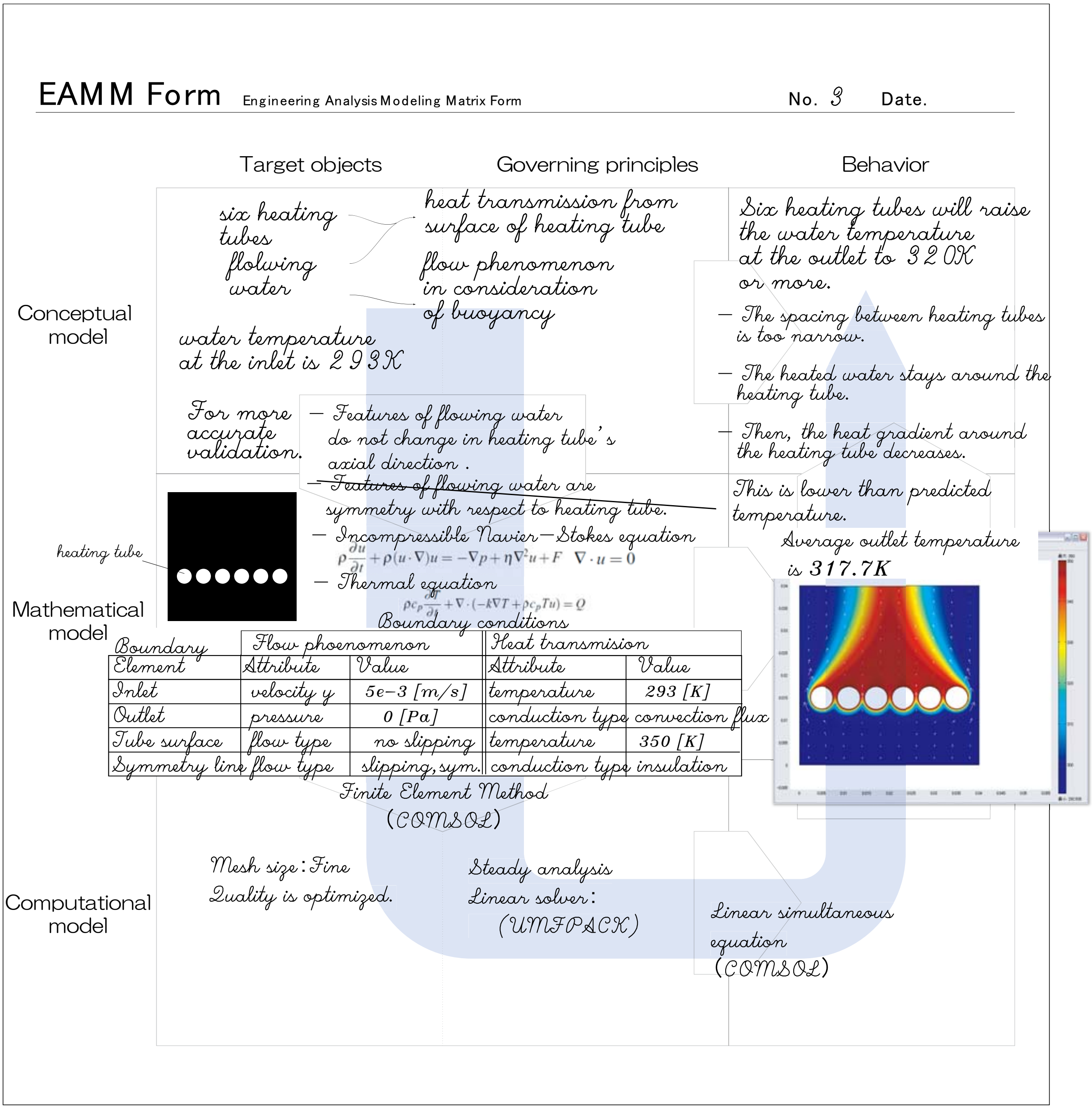


Figure 9 2D Modeling process of analyzing a water heater

description of the conceptual model cells.

Figure 8 shows the description of the modeling process considering heating tube symmetry for validation of the six-tube alternative (2-A of Figure 5). The simplification of this model, i.e., ``features of flowing water do not change in heating tube's axial direction'' and ``a feature of flowing water is symmetry with respect to the heating tube,'' is described in the simplification space. By considering this simplification, the geometry of target objects, governing equations, boundary conditions and initial conditions are described in mathematical model cells. Further, modeling contents of the computational model, i.e., ``a software package, named COMSOL Multiphysics (COMSOL Multiphysics is a trademark of COMSOL AB.), is used for finite element analysis of coupled physics,'' ``fine mesh size'', and so on, are described in computational model cells.

A numeric solution is a set of values allocated in each discretized element. The analysis software performs post-processing for the discrete solution, and generates the contour figure that is attached to the mathematical behavior cell. A designer interprets this result and validates whether or not the average outlet temperature is as predicted. In Figure 8, a designer writes ``this is as predicted" in the interpretation space.

Design Validation by 2D Model

Figure 9 shows the description of a two-dimensional modeling process for validation of the six-tube alternative (2-B of Figure 5). In the simplification space, a designer describes the intention of this analysis ``for more accurate validation" and canceling the simplification in consideration of symmetry of heating tube arrangement. In the interpretation space, the designer describes that ``this is lower than predicted temperature" and ``the space between heating tubes is too narrow, the heated water stays around the heating tube, then the heat gradient around the heating tube decreases."

Finally, Figure 10 shows the description of two-dimensional modeling process for validation of the double-row six-tube alternative (3-B of Figure 5). It is described that six tubes are arranged in two rows in the target object cells. In the interpretation space, a designer describes that the simulated temperature is

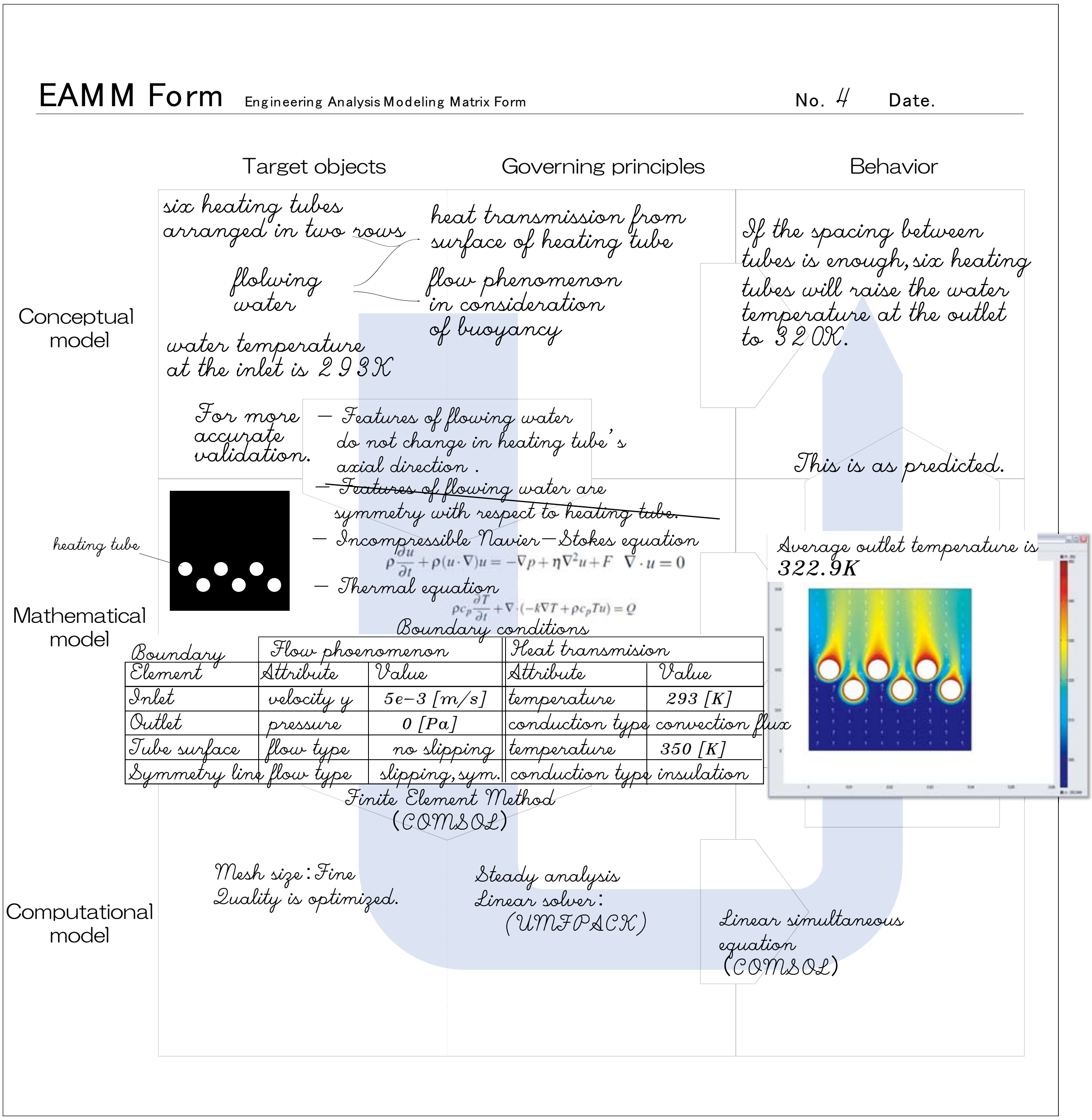


Figure 10 2D Modeling process of analyzing alternative solution of heating tube arrangement

as predicted.

9. CONCLUSION

This paper proposes a knowledge description format named EAMM as a framework for describing and managing engineering analysis modeling knowledge that can be used by a working designer. The example of Subsection 8.2 shows that a designer can concisely describe any information of an engineering analysis modeling process in the EAMM format, and obtain an overview of the process. The proposed framework is useful to enable a working designer to make unclear concepts explicit like a DFX method.

The amount and the granularity of the knowledge description in the EAMM format depend on the designer's thinking. In order to reduce such dependency so that the knowledge description will be more certain, our future work includes refinement of description patterns and vocabulary of engineering analysis modeling process.

A sophisticated computer-based framework is also required in order to manage multiple analysis models in larger-scaled design processes. We have been developing such a sophisticated design support framework, named DRIFT (Design Rationale Integration Framework with Three layers) [21][22]. Complicated modeling processes can be managed by DRIFT with a digitalized EAMM format. This is also included in our planned future work.

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