PRODUCT COMPLEXITY: A NEW MODELLING COURSE IN THE INDUSTRIAL DESIGN PROGRAM AT THE UNIVERSITY OF TWENTE

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ABSTRACT
Product complexity is a new subject in the new curriculum of the Industrial Design bachelor program at the University of Twente. The subject teaches students systematic methods to create engineering models that reproduce a product's behaviour. The idea is to minimize the complexity of product design by applying proper modelling techniques. Students make use of technical knowledge acquired during their careers to explain how artifacts work.

Keywords: Product, modelling, behaviour, complexity

1 INTRODUCTION

Designing requires strong modelling skills. Design processes can be seen as a continuous model-making progression that gradually specifies the characteristics of the product being designed and evaluates its expected behaviour [1]. To achieve this, two types of models are used: the ones describing the physical characteristics of the product (for example geometry, colours and texture) and the ones describing the technical functioning of the product (for example deformation, stresses, and energy consumption). A product's well-functioning depends on the quality and expressiveness of the models that are used to determine its behaviours.

Typically, Industrial Design (ID) and Engineering Design (ED) curriculums have courses focusing on teaching both types of model-making abilities. On one hand, some courses teach how to represent the geometry of products using different techniques that range from hand based sketching methods up to physical and virtual mock-ups. On the other hand, technical courses focus on modelling product behaviours by addressing physical principles (grouped by disciplines) using mathematical representations. Traditionally, such courses start by teaching the physical meaning of the principles in question, and continue by stating the related formulas. Later, after a large coverage of different formulas has been presented, students are asked to solve problems. The result is that problem solving abilities gets the emphasis, while model-making abilities remain crude. Furthermore, as technical courses tend to be grouped around disciplines, the ability of making interdisciplinary models is not taught.

In order to fill-in this missing model-making ability, a new subject has recently been designed and implemented in the bachelor program of Industrial Design at the University of Twente. In this paper the author aims at presenting the structure of this subject and sharing the learned experiences from teaching it. Product Complexity, as the subject is named, teaches students systematic approaches to develop quantitative behavioural models that explain products functioning principles. The subject also teaches how to integrate models from different disciples (for example, electro-magnetism with mechanics and ergonomics) and how to communicate them to peers. The course is grounded on widely accepted design theory and methodology literature.

This paper is further organized as follows. Section 2 introduces the contents of the subject by describing its rationales, the utilized modelling approach and the themes that are treated. Section 3 summarizes the most relevant implementation issues, namely, the objectives, the time structure, the place in the curriculum and, finally, the teaching methods utilized. Section 4 makes a brief evaluation and presents conclusions.

2 CONTENTS

Product complexity teaches a systematic approach to making behavioural models of an artifact's functioning. These models specify the different states an artifact transits when it is functioning as well as the relations guiding these transitions. Such models are instances of the principles of nature (e.g. heat transfer or Newton's law) applied to an artifact. By creating appropriate behavioural models of artifacts, designers can identify their complexity and determine approaches to deal with it, hence the name product complexity.

2.1 Rationales

This subject is based on the notion that behaviours, indistinctively of their domain, emerge in nature following a constant pattern [2]. This pattern, shown in Figure 1, states that if an object is exposed to an external energy input, it will undergo a change in state, and that this state transition is ruled by a principle of nature. In this sense, the laws of nature describe the emergence of behaviours as well as their related states and states transitions. When behaviour cannot be explained by any existing law of nature, research is required to model that behaviour.

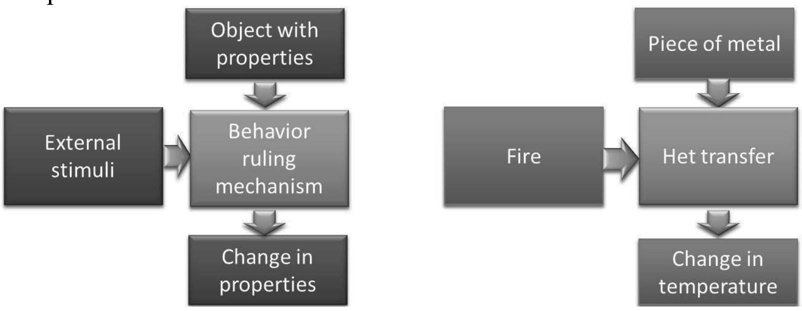

Figure 1. Behaviour emergence pattern

2.1.1 Design in the context of behaviours

In the context of design, synthesis consists of creating a new artifact model (the physical description) that achieves a wanted function by displaying a specific chain of specific behaviours. Therefore, an artifact's functioning depends on the behaviours it undergoes and the specific order in which these behaviours occur over time and space. Analysis consists of identifying the relevant behaviours, building up models as instances of ruling principles (the behavioural descriptions) and applying numerical or logical calculations to determine the change in states. Design is the recursive completion of synthesis and analysis processes that lead to an artifact model that fulfils a given functionality. Therefore, the degree of sophistication of a design process depends on the designer's awareness of existing behaviours as well as hers/his model making abilities.

2.1.2 Product Complexity

Based on the previous concepts, complexity is here defined as a property of a system that describes how all of its characteristics are connected and interrelated among each other. The more properties involved, and the more interrelations between the emergent behaviours, the more complex the system is. For example, the system in Figure 2(a) has a lower complexity than the system shown in Figure 2(b), as the number of behaviours and interconnections in the first case is lower than those in the second one. Therefore, understanding complexity is uncovering the connections, while managing complexity is dealing with all the connections and knowing how to proceed next.

2.2 Behavioural Modelling Method (BMM)

Based on the aforementioned concepts, a method has been developed to model an artifact functioning:

1. Identify the artifacts functions and components that will be the target of modelling.
2. Identify the behaviours coupled to those functions and components.
3. Develop a behavioural map of the artifact and identify its ruling principles.
4. Determine the properties (states) that can be used to assess the artifacts behaviour.
5. Instantiate the ruling principles for each (group of) components such that they describe both the previously determined states and their transitions.
6. Assemble all the behavioural models into one artifact overall model.

7. Solve the model by replacing the parameters by numerical values. Depending on the complexity of the obtained model, different mathematical techniques can be employed for this purpose (e.g., finite element method, numerical integration, linearization)
This method serves as backbone of the subject.

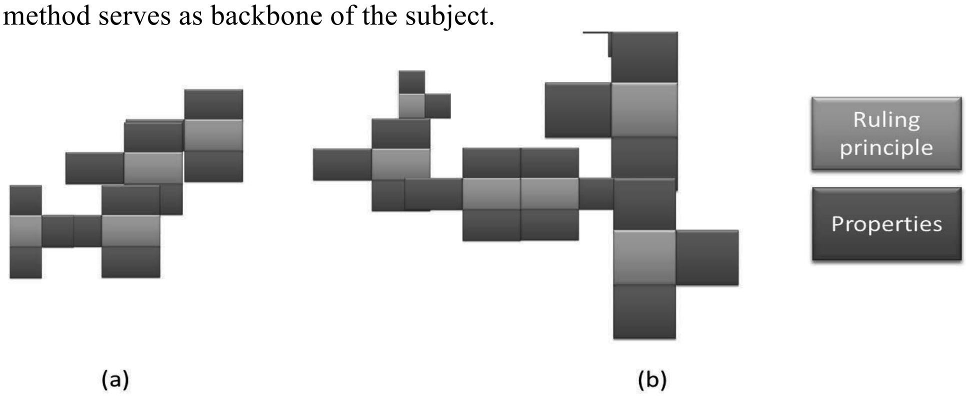

Figure 2. Product Complexity

2.3 Themes

2.3.1 Theme 1: Introduction to product complexity

This theme presents the rationales of the subject as presented in Section 2.1 and introduces two formal theories on design complexity, namely, complexity in Axiomatic Design Theory (ADT) based in [3] and Complexity of Multidisciplinary based on [4]. The basic idea of complexity in ADT is that without difficulty in understanding (or making, operating, etc.), a system is not complex. In this sense, complexity is the property of a system that makes it difficult to understand with the available knowledge about its constituents parts. On the other hand, complexity of multidisciplinary states that complexity can be studied from the view point of knowledge structure [4], identifying two types of complexity: complexity by design and intrinsic complexity of multi-disciplinarily. The former is attributed to the structure of the design problem, while the latter deals with behavioural characteristics.

2.3.2 Theme 2: Function Behaviour State/Structure (FBS)

This theme presents the FBS framework as a tool to interrelate an artifacts function with its physical properties. This covers steps 1 and 2 of the BMM. FBS models a design artifact by distinguishing the following levels of object representation: Function, Behaviour/State and Structure. The basis of the FBS model is that the transition from function to structure is performed via the synthesis of physical behaviours. Therefore, behaviours allow characterizing the implementation of a function. As many different views of the FBS model have been developed and researched, the course adopts the FBPSS model as presented by Zhang et al [5]. This model is based on the analysis and generalization of the Japanese ([6], [7]), European ([8]), American ([9]) and Australian ([1]) schools of design modelling. This theme also presents a method, based on the FBS framework, for building Mode of Deployment (MOD). According to Chandrasekaran's and Josephson's explanation [10], the MOD of a product (or device) *D* in some world *W*, represented as $M_{(D,\ W)}$, is the specification of all the ways in which causal interactions between *D* and the entities in *W* are instantiated. The mode of deployment is a concatenation of behaviours organized according to their discipline, and it accounts for step 3 in BMM.

2.3.3 Theme 3: Design Process Units (DPU)

This theme deals with the creation of analytical models to describe behaviours. The idea is that the behaviours identified making an FBS model are further characterized into parameterized models where the laws of nature are instantiated for that particular artifact. This theme is based on the design information classification as proposed by Webber [11], McMahon [12] and Schotborgh [13]. This classification states that there are three base types of information recurrently used during design processes, namely, design (or embodiment) information, scenario information and performance information. Embodiment regards information describing the object being designed, like its topology, material and geometry. Embodiment information is analogues to the physical properties in the behavioural emergence pattern stated in Section 2.1. Scenario is related to the set of entities describing the flow of energy, mass or information the embodiment is exposed to. Scenario is analogous to the energy entries as specified in Section 2.1. Performance determines how the embodiment behaves under a certain (group of) scenario, and can be both energy quantities or physical object properties. Performances are analogous to the state variables in the behavioural emergence pattern. The relation between these three types of information varies according to the design phase where they are applied. In the synthesis phase, embodiment information is specified such that it meets certain performance values for a given scenario. In an analysis, performances are quantified or qualified for an embodiment that is undergoing a given scenario by using analysis equations. The information triplet of embodiment, scenario and performances, together with its analysis relations, is defined as a DPU. Making DPUs covers steps 4 and 5 of BMM.

2.3.4 Theme 4: Model Implementation and Design (MID)

This theme deals with the implementation of DPUs as design process building blocks. The idea is to model design artifacts as webs of different DPUs representing knowledge at different levels of detail and for different components and assemblies. Either embodiment, scenario or performances serve as point of join among the artifacts constituents DPUS. By making DPU maps of an artifacts components, one can get an overview of the levels of multidisciplinary and interconnectedness between the different knowledge chunks. DPU maps can be used to determine product development strategies, knowledge fields interfaces and build up analysis models of the artifacts being designed. This theme is based on the frameworks described in [14] and [15]. Deriving design strategies is based on the work presented in [16]. When embodiment, scenario and performance parameters are known, but the analysis equations are unknown, an analysis model has to be assembled prior to starting a design process. When developing a simulation or analytic model is not possible because of time constraints or complexity of the principles, an experimental set-up can be used as analysis model. Theme 4 supports steps 6 and 7 of BMM.

3 IMPLEMENTATION

This section explains the objectives, teaching methods and structure of the subject as it has been implemented. The course development method is based on the book *"Leren (en) doceren in het hoger onderwijs"* (learning and teaching in higher education) [17]. The overall structure is presented in Figure 3, and consists of 5 blocks dealing with different topics.

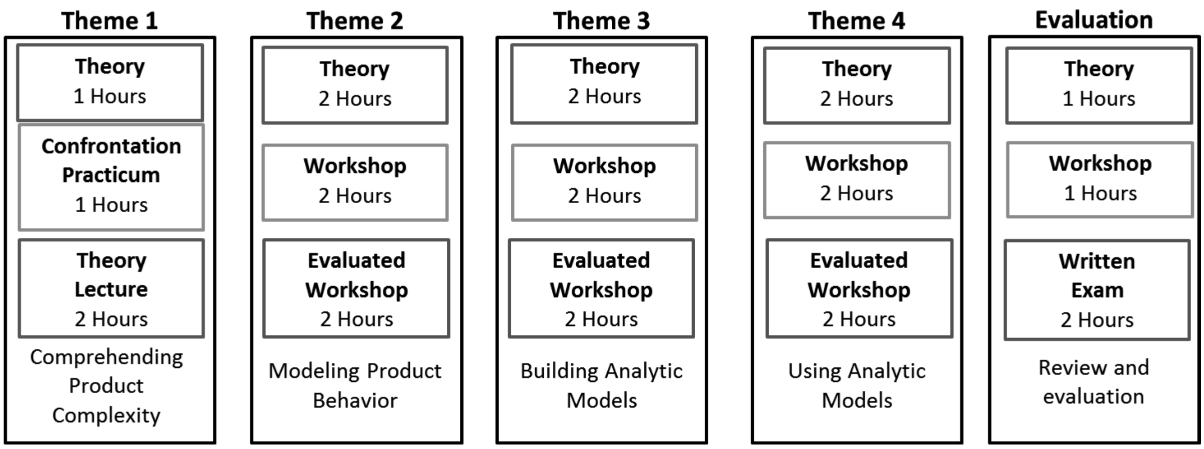

Figure 3. Product complexity structure and contact hours

3.1 Place in the Curriculum

The bachelor program of industrial design engineering covers a large diversity of technical courses. In these subjects students learn about different phenomena of physics as well as how to use mathematics to model them. Technical subjects include mechanic statics, mechanics of materials, mechanic dynamics, heat transfer, energy conversion and electronics. The program is organized in such a way that the knowledge gathered in technical subjects (as well as in non-technical subjects) is applied during the development of design project courses. Product complexity takes for granted that students manage all this knowledge. The subject Product Complexity has been placed in the second quarter of the third year of the bachelor program and has a total working load of 70 hours.

3.2 Objectives

The mission of this subject is teaching a systematic approach to making models of an artifacts functioning mechanisms. This mission has been translated into a number of objectives following Bloom's cognitive domain taxonomy. The objectives are:

O1. Describe the characteristics of product complexity: Build up the cognition ability of knowledge. It is appointed in block 1 and derives from the contents of theme 1.

O2. Determine which behaviours should be considered in modelling a product functioning: Build up the cognition ability of analysis. It is appointed in block 2 and is based on theme 2.

O3. Identify interdisciplinary aspects of the product: Build up the cognition ability of comprehending. It is appointed in block 2 and derives from theme 2.

O4. Build analytic models to quantify those behaviours: Build up the cognition ability of synthesis. It is appointed in block 3 and derives from theme 3.

O5. Implement analytic models to model product behaviour: Build up the cognition ability of analysis. It is appointed in block 3 and block 4. It derives from theme 3 and theme 4.

O6. Evaluate analytic models of product behaviour: Build up the cognition ability of evaluation. It is appointed in block 3 and block 4. It is based on theme 4.

O7. Communicate and inquire in a structured way design knowledge: Build up the cognition ability of knowledge. It is appointed in block 2 and block 3. It derives from theme 3 and theme 4.

Figure 4 shows the resulting model of a water boiler that was developed by a group of students. The model shows relevant physical principles and parameters (O1, O2), interconnection between different parameters (O3, O4, O5) and describes a design strategy (O6, O7).

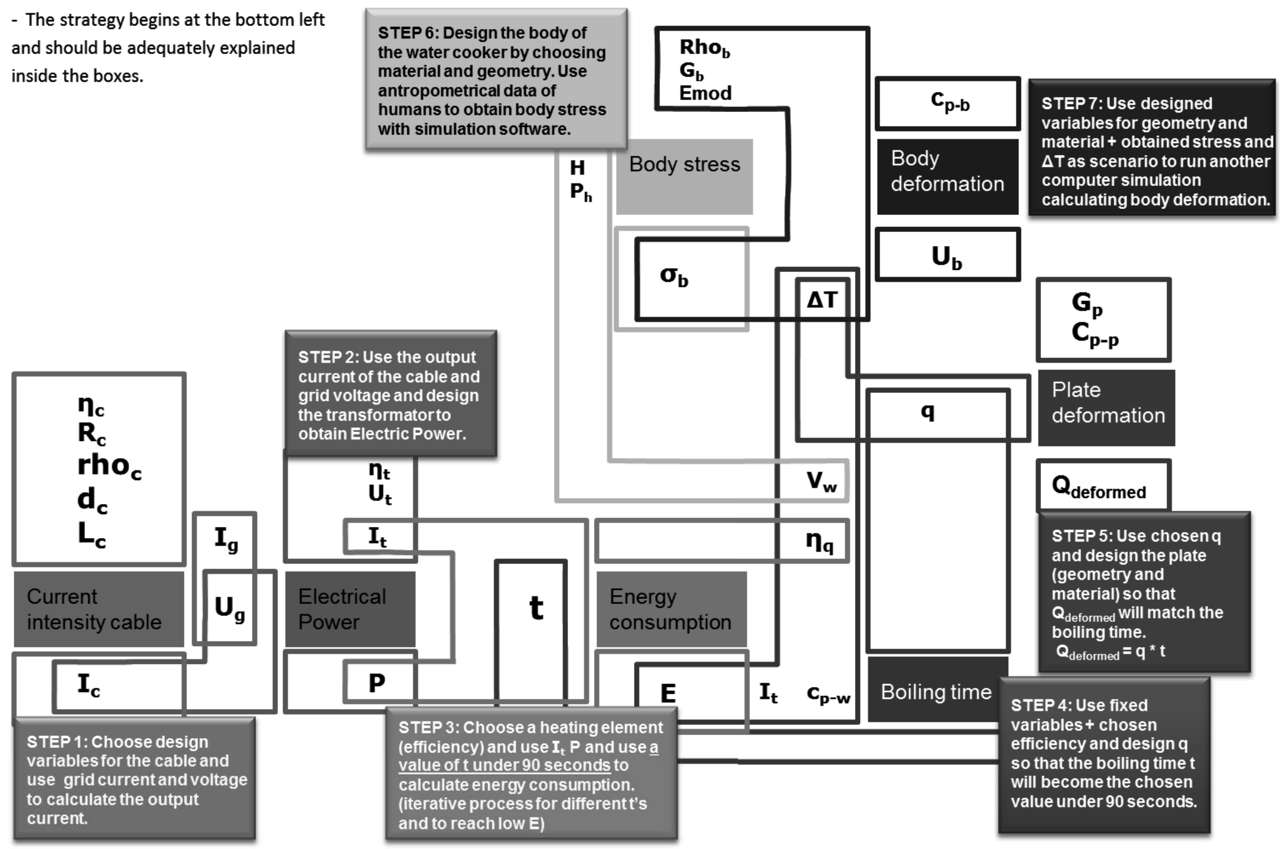

Figure 4. Example model of a water boiler

3.3 Teaching method

The implementation of this subject combines theory lectures and workshops to cover the learning objectives. The evaluation is based on both evaluated workshops and a written exam. Theory lectures have the goal of presenting theoretic background. Methods (e.g. how to make an MOD) are also presented with a worked out example. Workshop lectures have the goal of having students experiment with the learned methods and initiate discussions about the rationales of the taken decisions. All workshop lectures deal with the task of modelling one of the following artifacts: coffee machine, electric tooth brusher, water boiler, baby bottle and a hair drier. All artifacts have been provided by Philips Consumer Lifestyle and are physically available to all the students. The first workshop in block 1 confronts the students with the task of making a model prior to learning the BMM approach. In the last workshop in block 5 students get the chance to apply the learned method to the same artifact utilized in the confrontation workshop. The goal is to accentuate the awareness of the usefulness of the learned techniques. The evaluated workshops are used to keep students involved in the subject such that the learning of a past block method are clear at the moment another block starts. Finally, the written exam focuses on the theoretical aspects of the subject.

4 CONCLUSIONS

The subject has been taught for the first time between the months of November 2011 and February 2012. The student's educational council has distributed an evaluation form to all students to determine the degree of accomplishments of the objectives and grade the teaching and evaluation method. However, by the time this paper was written the results have not been computed. Despite of this, observations on the models produced by students indicate the subject was successful in teaching a systematic approach to making models of artifacts and manage design complexity by doing so.

REFERENCES

[1] Gero, J. S., and Kannengiesser, U., 2004, "The situated function-behaviour-structure framework," Design Studies, 25, pp. 373-391.

[2] M. Erve, v. d., 2008, "Explaining Auto-Emergence in Physics and Society," White paper.

[3] Suh, N. P., 2005, "Complexity in Engineering," Annals of CIRP, 54(2): 581-598.

[4] Tomiyama, T., 2006, "Dealing with Complexity in Design: A Knowledge Point of View," Design Methods for Practice, pp. 137-146.

[5] Zhang, W. J., Lin, Y., and Sinha, N., 2005, "On the Function-Behavior-Structure Model for Design," Canadian Design Engineering Network conference 2005.

[6] Umeda, Y., and Tomiyama, T., "FBS modeling: Modeling scheme of Function for Conceptual Design," Proc. Working Papers of the 9th Int. Workshop on Qualitative Reasoning About Physical Systems, pp. 271-278.

[7] Umeda, Y., and Tomiyama, T., 1997, "Functional Reasoning in Design," AI in Design, 12(2), pp. 41-48.

[8] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K. H., 2007, Engineering Design: A Systematic Approach, Springer.

[9] Chandrasekaran, B., Goel, A., and Iwasaki, Y., 1993, "Functional Representation as Design Rationale," IEEE Compute, 26, pp. 48-56.

[10] B. Chandrasekaran, J. R. J., 2000, " Function in device representation," Engineering with Computers, 16(3/4), pp. 162-177.

[11] C., W., "CPM/PDD – an extended theoretical approach to modelling products and product development processes," Proc. 2nd German-Israeli Symposium on Advances in Methods and Systems for Development of Products and Processes., Fraunhofer-IRB-Verlag, Stuttgart, pp. 159 - 179.

[12] McMahon, Ohsuga, and Brown, 1998, CAD/CAM principles, practice and manufacturing management, Addison-Wesley Longman Ltd.

[13] W.O. Schotborgh, E. C. M., F.J.A.M. van Houten, 2012., "A knowledge acquisition method to model parametric engineering design processes," International Journal of Computer Aided Engineering and Technology, 4(4).

[14] Jauregui-Becker J.M, Tragter H, and van Houten, F. J. A. M., 2009, "Structure and models of artifactual routine design problems for computational synthesis," CIRP Journal of Manufacturing Science and Technology, 1(3):120-125.

[15] Jauregui-Becker J. M., W. W. W., Van Houten F. J. A. M. , "Modeling the Structure and Complexity of Engineering Routine Design Problems," Proc. 21st CIRP Design Conference.

[16] Jauregui-Becker, J. M., Wits, W. W., and van Houten, F. J. A. M., "Reducing design complexity of multidisciplinary domain integrated products: a case study," Proc. 41st CIRP Conference on Manufacturing Systems, pp. 149-154.

[17] T. Kallenberg, L. G. v. d., A. Braak ter 2009, Leren (en) doceren in het hoger onderwijs, LEMMA, Den Haag.