A TYPOLOGY OF ENGINEERING DESIGNS IN PROBLEM-BASED PROJECTS

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ABSTRACT

The *problem-based project* is a widely applied method for creating learning experiences that closely resemble engineering practice. Problem-based projects support active learning, experience with design and implementation, and integrated learning experiences. These three learning principles are all key standards in CDIO. In problem-based projects, teams of engineering students develop solutions to problems (often across disciplines and in cooperation with an industrial partner, e.g. a manufacturer, a public utility, or a software developer). A good solution meets design requirements and solves the project's problem. However, beyond these two characteristics, the nature of (good) engineering solutions is under-explored. The purpose of this study is to contribute to the understanding of the nature of engineering solutions in problem-based projects across engineering disciplines. The study's findings include a set of general characteristics of great engineering solutions and a typology of three solution archetypes. The study labels these archetypes as 1) the adapted solution, 2) the "either/or"-solution, and 3) the multiple-elements solution. For each archetype, the paper specifies the corresponding class of problems that the archetype can logically address. In addition, the paper delineates (1) how each archetype relates to a project's analysis and (2) how each archetype is evaluated, implemented and operated. The typology aids both students and project supervisors in conducting reports with a coherent flow beginning with a problem, continuing with analysis and solution design, and finally ending with implementation.

KEYWORDS

Problem-based project, project-based learning, engineering design, design typology, standards: 2, 3, 5, 7, 8, 11

INTRODUCTION

Active learning, experience with design and implementation, and integrated learning experiences are key standards in CDIO. One of the most widely applied method for implementing these standards in educational practice is the *problem-based project.* Synonyms for problem-based project are capstone design course, challenge-based learning, and innovation projects. With few exceptions, traditional final projects in engineering education programs are also problem-based projects. Within the CDIO Initiative, many applications of Design-Implement Experiences are often pedagogically conducted as problem-based projects.

In a problem-based project, a student team solves a problem. A problem in engineering is usually constituted by either an improvement potential with an existing entity (e.g. an app with a too long launch speed) or that someone has a need for a currently non-existing entity (e.g. a manufacturer needs a robot). In problem-based projects, a student team develops an engineering design that constitutes the solution to the problem. For example, developing the app so the launch speed is faster or designing the robot that the manufacturer needs.

In many engineering education programs, students cooperate with an industrial partner, for example a manufacturer, a power plant, or a software developer. The project's problem usually resides with the industrial partner.

Engineering designs take many shapes. Civil engineers design buildings and bridges, manufacturing engineers design production and logistics systems, software engineers design programs and algorithms, and chemical engineers design chemical processes and products. The list exemplifies how engineering solutions are different across disciplines. Engineering solutions do also exhibit similarities. Two examples: (1) a solution meets design requirements and (2) a solution solves the project's problem. However, beyond these two examples, the nature of (good) engineering designs is under-explored. The purpose of this study is to contribute to the understanding of the nature of engineering solutions in problem-based projects *across disciplines.* Specifically, the study has two research questions (RQs):

RQ1: What are the characteristics of engineering solutions in problem-based projects?

RQ2: Which engineering solution archetypes do students develop in problem-based projects?

Through interviews with educators across engineering disciplines, the study first identifies the general characteristics, similarities, and differences of engineering solutions across disciplines. Second, the study uses these characteristics, similarities, and differences to create a *typology* of engineering solution archetypes.

In an earlier study, this paper's first author examined what external examiners considered the key challenges and success criteria for great projects. The discussion with the external examiners kept coming back to the one key challenge of ensuring coherence between project elements. Students must ensure a coherent flow between the structural elements of a project (problem, analysis, solution design, test, and implementation). Students struggle with the fit between (1) problem and analysis, (2) problem and solution, (3) analysis and solution, and (4) solution and the methods for assessing feasibility and planning implementation and operation. The solution is part of three of these struggles.

A typology of engineering solution archetypes creates awareness. If a student team knows which solution archetype they develop, they are better equipped to make decisions that ensure a coherent flow throughout the project. For example, whether their archetype can logically address the project's problem and how the results of their analysis should be applied in the team's solution design.

Understanding engineering solutions in problem-based projects is especially useful for cross-disciplinary projects that do not provide students with discipline-specific standards and methods. Applications of CDIO's Design-Implement Experience often integrate several disciplines in solving one problem, so the typology would provide a guideline currently not existing.

The remainder of this study is organized as follows: First, the literature review examines the characteristics of solutions in problem-based projects described in extant research. Second, the paper describes the study's methodology. Third, the paper presents findings including the typology of engineering solution archetypes. Fourth, the paper discusses implications, and provides conclusions.

LITERATURE REVIEW

The objective of this review of relevant literature is identifying the characteristics of engineering solutions in problem-based projects in engineering education. The study searched for relevant sources in Web of Science (Core collection) using the following search string:

> (TS=("engineering education" AND "problem-based" AND project AND (solution OR design))) *AND* **LANGUAGE**: (English) *AND* **DOCUMENT TYPE: (Article)**

The search results show that solutions are not dealt with across disciplines on an abstract level, but rather tangibly and discipline-specific. Recent examples are Gadhamshetty *et al.* (2017), who examine project-based learning in renewable energy technology, Dulekgurgen *et al.* (2016), who examine design projects in environmental engineering, and Santos-Martin *et al.* (2012), who present the experiences of problem-based projects about electrical components in wind turbine technology.

A few studies in the sample deal indirectly with characteristics of solutions in problem-based project in engineering education. Holgaard *et al.* (2017) have designed a five-step problem formulation sequence. As part of the five steps, Holgaard and her coauthors mention a number of characteristics of a good solution:

1. The problem formulation process defines a "solution space" that sets limits to what can constitute a solution to the problem
2. The problem (if formulated correctly) will "direct the problem solving process"
3. The problem formulation must include success criteria and demands from the solution

In further steps beyond the problem statement, Holgaard *et al.* (2017) state that student teams should "use relevant theoretical perspectives and models" to ensure that solutions meet the demands.

A search in the CDIO Knowledge Library using "problem-based" as search string returns 18 hits. Edström and Kolmos (2012) examine the differences between CDIO and PBL. While their study is comprehensive, it does not provide an explicit set of characteristics for solutions in either CDIO or PBL. Malherio *et al.* (2015) describe solution building as the most critical phase in engineering and that engineers must not simply find the right solution, but also build it. Malheiro and colleagues describe solution design within CDIO as 1) idea generation, 2) idea selection and substantiation, and 3) prototype development. The study does, however, not provide explicit descriptions about the nature of a solution. The present paper adresses this gap in engineering education literature.

METHODOLOGY

Given the scarcity of explicit characteristics of engineering solutions in extant literature, the study applies an inductive, interview-based research design.

To facilitate a base for interview discussions, the study develops an interview guide consisting of issues related to (1) project work in general and (2) engineering solutions in particular. The first part of the interviews concerned general issues such as when and how educations apply problem-based projects as pedagogical method. Examples of question are:

1. "How do you use project work in the education that you work with?"
2. "Could you characterize a typical project process that your students go through during a semester?"
3. "How do students apply theory, methods, and models in a project?"

These are general questions that contribute to a broad understanding of how educations use project work as a learning methodology. The second part of the interviews concern engineering solutions. Topics for discussion were among others what constitutes a solution, how students develop solutions, how solutions match with problems and analyses, and how students evaluate, implement and operate solutions. Examples of questions are:

1. "What do consider an analysis?"
2. "How does a solution fit with the analysis
3. "How are decisions made in the design process?"

The total set of issues is based on the two authors' prior experience with project course design, supervision, coordination, development. However, during interview rounds, the interview guide was developed further to reflect the totality of knowledge gained throughout the entire study.

Sample of interviewees

Interviewees were 20-25 education directors and experienced instructors from three Danish universities (Technical University of Denmark, University of Southern Denmark, and Aalborg University). Although all interviewees were employed by Danish universities, several interviewees were non-Danish nationals with experience from non-Danish engineering education. In addition, the sample included external examiners from industry.

Study procedure and protocol

The study first interviewed one set of educators within mechanical and manufacturing engineering. In the second round, the set of interviewees was expanded to include educators from other engineering disciplines (construction, chemical engineering, business engineering, and software engineering).

During both interview rounds, the study inductively identified characteristics, similarities and differences of engineering solutions across engineering disciplines.

Using the identified set of similarities and differences, the study developed a typology of engineering solution archetypes. The focus was on archetypes relevant for educational practice and not general engineering practice, where academic requirements do not apply.

Using interview data, the two authors developed a set of engineering solution characteristics and a set of engineering solution archetypes. Much interview data was discipline specific. For

example, many interviewees provided examples of specific projects form their field. The role of the two authors was to condense the data and extract more abstract, cross-disciplinary answers to the study's two RQs.

The analytical reasoning of the typology development

Within manufacturing engineering, projects often concern improving an existing entity (usually a process of some kind) by (1) selecting a problem, (2) identifying causes, and (3) designing a set of policies, tools, procedures, etc. that address each cause. The solution is therefore a set of differing elements. When interviewing mechanical engineering lecturers, projects often concern developing a new entity (e.g. a new engine or machine component). In such a project, students (1) analysis the user need, (2) specify the design requirements, (3) analyze the subsystems or functions of the entity, (4) identify possible technologies for each subsystem, (5) design a solution by picking one technology for each subsystem). The project's solution is not a set of elements as in the prior example, but one logically constructed entity adapted to a set of design requirement. When discussing these results with civil engineering educators, their answers resembled the answers by the mechanical engineering lecturers, but with one critical difference. A solution often consists of not one, but two or more conceptual solutions that each meet design requirements to a varying degree and at a varying cost. The team, their industrial partner, and occasionally a construction client must choose one of the developed solutions, which the student team later specifies in detail. When discussing these solutions with lecturers from software, electric, and chemical engineering, the typology appeared complete. See the description of each archetype in the paper's findings section.

FINDINGS

This section addresses the study's two RQs. First, the section presents the general characteristics of engineering solutions in problem-based projects in engineering education. Second, the section presents the study's typology of engineering solutions.

General characteristics of engineering solutions in problem-based projects

The study has found that regardless of engineering discipline (e.g. chemical engineering or mechanical engineering) engineering projects are not concerned with conducting traditional research that answers unanswered questions about the world, but with developing solutions to problems. If a project designs a house, develops an algorithm, or constructs a liquid separation process, then the house drawings, the finished algorithm, and the constructed liquid separation process each constitute the project's solution. To draw the house, develop the algorithm and construct the separation process <u>is</u> to design a solution.

The following three subsections describe the study's results. The three subsections concern 1) the requirements of an engineering solution, 2) the basic nature of a solution, and 3) the relationship between the solution, on the one hand, and the project's problem and analysis, on the other hand.

Requirements for an engineering solution

The study has found the following general requirements for a good engineering solution:

1. The solution is based on the results of the project's analysis
2. The solution meets the requirements of the industrial partner
3. The solution is implementable both technically, practically, and economically with the industrial partner
4. The solution meets the university's requirements of a good solution
5. The solution will credibly solve the problem of the project

In addition to these requirements, there are a set of "nice-to-have" desirable characteristics, that the solution is beautiful, exciting, and perhaps a bit surprising.

The nature of an engineering solution

In a problem-based project, the study has found that an engineering solution is a *decision hierarchy*. Although the practice of conducting a project often is an iterative and complex process, the *formal* process of designing a solution means making a number of decisions in a logical sequence. Together, the total set of decisions forms a design decision hierarchy. In the decision hierarchy, some decisions are superior to others. Figure 1 illustrates a decision hierarchy.
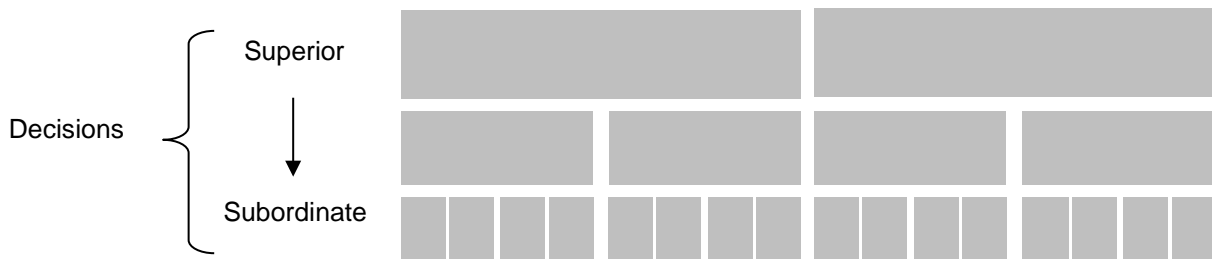

Figure 1. The solution is a decision hierarchy

The superior decisions, which concern overall issues, are taken early in the project period. These decisions limit the decision space for the subordinate decisions that concern issues of higher detail.

For example, if building a house, the first decisions by the architect concern the outer dimensions of the house. These dimensions limit the decisions concerning ground plan and staircases. These decisions are superior to decisions concerning the interior design of the kitchen, living room, bathrooms, etc. The most subordinate decisions in decision hierarchy concern the most detailed decisions. In a house, these decisions concern e.g. power outlets, ceiling material, bathtub design, etc.

The relationship between the project's analysis and the solution

Projects, where the problem is an improvement potential in an *existing* entity, conduct an analysis of the root causes of the project's problem. The solution then either eliminates the root causes or reduce their impact on the problem, and thus solves the problem. For projects, were the problem concerns designing a *new* entity, the analysis does not find root causes, but

instead identifies all relevant design requirements for the solution. The project team then designs a solution that meets these design requirements.

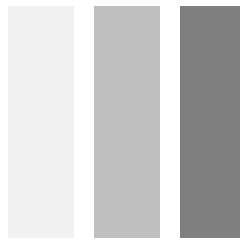### Typology of engineering solution archetypes

When examining solutions across disciplines in problem-based projects in engineering education, the study has identified three solution archetypes. These archetypes are labelled 1) the adapted solution, 2) the "either/or"-solution, and 3) the multiple-elements solution. Figure 2 illustrates the three archetypes and provides an example.
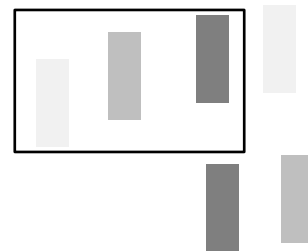
The adapted solution	The "either/or" solution	The multiple-element solution

The adapted solution — Example: An app developed through an iterative process that adapts to all requirements from the industrial partner.

The "either/or" solution — Example: A suspension bridge, a cable-stayed bridge, and a tunnel are three alternative connections between an island and the mainland. The industrial partner (often a construction client) must choose "either-or"

The multiple-element solution — Example: The study has selected three out six potential elements. Together, these three selected elements constitute the solution to a problem (see a specific example in paragraph below)

Figure 2. The typology of solution archetypes

Figure 2 shows the study's typology, which consists of three archetypes. The adapted solution is constituted by a single, comprehensive entity. A single, comprehensive entity could be a bridge, a machine, or an app. The "either/or" solution first develops two or more single entities that (each) function as a solution, but with varying degrees of effectiveness, cost, and ease of implementation. The multiple-elements solution consists of several solution elements that each address a cause for the projects problem. Example: A project deals with a high failure rate from a production process. The project has analyzed the root causes and identified a set of three elements that together vastly reduce the amount of failures. The set of elements are (1) clearer assembly instructions, (2) a stricter component control procedure, and (3) a higher frequency of production equipment maintenance.

The following three subsections describe the three archetypes in more detail.

The adapted solution

The adapted solution emerges from a design process, where the student team first identifies the design requirements and then develops a solution that fits with the requirements. The design process can be either sequential or iterative where the student team identifies and specifies design requirements not only prior to but also during the solution design process. These requirements are often technical (e.g. a product must endure 24h use), legal (e.g. a filling machine in the pharmaceutical industry must provide documentation for each batch), and derived directly from users or customers (e.g. a building must be heated with a heat pump). The adapted solution is often applied in software development and development of mechanical products. In software development, the success criteria of an app relate to how well the app meets the design requirements (often from future users of the app).

This solution fits well if the project's problem concerns the development of a new entity. The adapted solution is evaluated by how well the solution meets design requirements, costs and ease of implementation. The solution is usually implemented in one piece rather than bit-by-bit.

The "either/or" solution

In some fields, a solution is not one single entity that is adapted to a set of (often emerging) design requirements, but rather a *set* of several single entities. Figure 2 provides an example from civil engineering. The student team develops three different solutions and the construction client will then select "either/or".

In addition to designing two or more solutions, the "either/or" solution includes a subsequent analysis of how well each alternative solution meets the design requirements, and also often how much the solution costs to implement and the ease of implementation.

As with the adapted solution, the "either/or" solution fits well if the project's problem concerns the development of a new entity. The "either/or" solution is evaluated by how well the solution that is selected meets design requirements. In addition, costs and ease of implementation are often included in the selection. The selected solution is usually implemented as one unit rather that piece-by-piece.

The multiple elements solution

A multiple-elements engineering solution consists of a selected set of elements that together comprise the solution to the problem. The basis for designing a multiple-elements solution is not an identified and specified set of design requirements, but instead an analysis of the root causes of the project's problem. Beginning with the project's problem (e.g. many failures in a production process), the analysis works its way through a set of cause-and-effect trajectories. These trajectories lead to the root causes of the problem (root causes could be unclear assembly instruction and defective components). A student team often designs several solution elements that differ in effectiveness, cost and ease of implementation. The project then selects a group of elements for further study and finally implementation.

The multiple-elements solution differs from the two previous archetypes in several ways: 1) what the multiple-elements solution will be is unknown prior to the root cause analysis, 2) the solution often consists of elements that are intuitively unrelated, and 3) the solution is evaluated, implemented and operated on an element-by-element basis rather than as one comprehensive unit.

The implementation of the solution must consider interdependencies among solution elements when selecting solutions elements for the final solution. Furthermore, the student team should consider whether solution elements should be implemented all at once, element by element, or in "waves".

CONCLUSION AND DISCUSSION

The study has identified the general characteristics of engineering solution and developed a typology of three engineering solution archetypes. These archetypes are labelled 1) the adapted solution, 2) the "either/or"-solution, and 3) the multiple-elements solution. Figure 2 illustrates the three archetypes and provides examples.

The typology vis-à-vis extant research in the CDIO initiative

Within the CDIO Initiative, Carmard et al. (2013) and Malmquist et al. (2015) present two project frameworks labelled Innovative Conceptual Engineering Design (ICED) and Challenge-based Learning, respectively. ICED focuses on core engineering skills, Challenge-based learning focuses on societal challenges, and both concepts are very ambitious with respect to the magnitude of the problems that projects solve ranging from technical challenges (e.g. spacesuits and habitats for Mars missions) to sustaining life on earth (e.g. providing energy from fusion and improving urban infrastructure). While ICED primarily develops what the present labels the adapted solution, the Challenge-based framework frameworks integrate all three archetypes, but appears to focus mostly on the multiple-elements archetype that solves root causes to problems.

Value of typology for educational practice

For students and educators, the typology promotes awareness. If a student team knows their project's problem, they can better identify the solution archetype that fits with their problem. When knowing the archetype, students will better understand:

1. The relationships between the solution and the project's analysis on the one hand, and the solution and the implementation on the other hand
2. How to evaluate the feasibility and the nature of solution implementation and operation

Study limitations and future research

The study is built on educator interviews only. A future study could test whether examining 100 actual projects across engineering disciplines would lead to the same three archetypes. Such a study would have to control for possible bias (the risk of identifying what the researchers already know, i.e. the archetypes in the current study).

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