Compound Problem Solving: Workplace Lessons for Engineering Education

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Abstract

For practitioners and researchers who incorporate real-world problems into their teaching, it is essential to understand real-world problem solving and the nature of problems for better design of the instruction. Several models exist that address the categorization of problems. David Jonassen's design theory of problem solving describes eleven different problem-types mapped on a four-dimensional scale. Real world problems are more likely to be compound problems meaning they contain a variety of different problem types. This paper describes the findings of two studies, (a) a single-case study of a steel engineer and (b) a multi-case study comparing the findings to 90 problem-solving narratives of other engineers. Both studies are located in an US-American context. Results confirm that real-world problems are intertwined problems (compound problems) and that transitions from one problem type to another within a compound problem are a unique class of problems themselves. These 'transition problems' have properties, which are not represented in other problem types, and therefore extend the design theory.

I. Introduction

For years, reports have validated the importance of problem solving in the workplace. For instance the SCANS Report "What Work Requires of Schools" [1], states that problem solving is an essential thinking skill for workers. Engineers, physicians, managers, etc. are hired, retained, and rewarded for their abilities to solve workplace problems. For engineering education, this means a challenge to integrate workplace real-world problems into the curriculum and staying abreast with new challenges and changing roles of engineers in the workplace.

If education programs are to fulfill these challenges, a better understanding of the nature of workplace problem solving is necessary. This holds especially true for instructional and educational strategies that heavily utilize problems, like 'problem-based learning' (PBL) or case-based teaching. Understanding problems and problem solving is essential in order to better design problems, better design support structures for students engaging in PBL, and research the effectiveness on students' performance and conceptual development. Several models exist that address the categorization of problems. One of the most comprehensive is David Jonassen's design theory of problem solving in which he describes eleven different problem-types mapped on a four-dimensional scale [2,3]. Although, these problem types are helpful to classify problems, real world problems, as acknowledged by Jonassen, are more likely to be "meta-problems" or compound problems containing a variety of different problem types. While there is a growing body of literature on researching differences in solving the variety of different problem types [4], little research provides understanding of compound problems or the interaction of problem types within compound problems. This paper tries to provide some insights on this gap in the literature.

II. Theoretical Foundation

Problem-based learning (PBL) modules or courses have been implemented in numerous engineering programs, including biomedical engineering [5], chemical engineering [6], software engineering [7], design processes [8], aerospace engineering [9], and construction engineering [10]. Although PBL represents a very influential pedagogical innovation, little research is done on how workplace-problems are structured, so many PBL programs cannot adequately design problems when designing curriculum and instruction. In his framework on designing problems in PBL curriculum, Hung [11,12] points out that it is crucial for the impact of the PBL enterprise to align systematically - throughout the design process - the nature of the problem, the nature of the skills involved, the content material, the goals to achieve, and the strategies to be employed. In addition to the design of PBL curriculum, programs, which employ PBL, face a continuous challenge to maintain their base of problems authentic and informed by the every-day practice of practitioners. This entails –together with a systematic process of identifying attributes of work place problems – the challenge to understand the underlying mechanism and cognitive and socio-cognitive processes, which are at work when people solve problems.

A. Conceptualizations of problem solving

Educators historically have assumed that a general (and generic) problem solving model is sufficient and the problem solving skills acquired through working on simple and well-defined problems would easily transfer into more complex and ill-defined problem solving tasks [13]. Not surprisingly, most instructional materials like textbooks utilize well-structured problems, because they were considered to sufficiently prepare learners for more ill-structured and complex problem solving tasks.

These assumptions were challenged by a wide variety of researchers (see for example [14]), arguing that problems vary by nature, context, constraints, and problem solver characteristics [15,16,17]. That is, learning to solve story problems in schools does not enable graduates to solve complex and ill-structured workplace problems. Different kinds of problems engage and require different cognitive processes [3].

One of the recent and more influential classifications is the design theory or meta-theory of problem solving by David Jonassen [2,3], in which problems are mapped on multiple dimensions providing a taxonomy of problems with classes of attributes.

Jonassen [2] proposed a classification of problems on a continuum between ill-structured and well-structured problems. For well-structured problems, the parameters of problems are specified in the problem statement; they possess knowable, correct solutions that are determined by preferred solution paths; and they apply a limited number of regular rules and principles that are organized in a predictive and prescriptive arrangement [2]. The kind of problems most often encountered in engineering education programs (except for capstone and assorted design experiences) is the story (word) problem, which is well structured. When learning to solve story problems in engineering, students learn to translate relationships about unknowns into equations, solve the equations to find the value of the unknowns, and check the values found to see if they satisfy the original problem [18]. This linear process implies that solving problems is a procedure to be memorized, practiced, and habituated and that emphasizes answer getting over meaning making [19].

B. Workplace Problems

However, nearly every workplace problem is ill-structured. Ill-structured problems have vaguely defined or unclear goals and unstated constraints; they possess multiple solutions and solution paths or no consensual agreement on the appropriate solution; they involve multiple criteria for evaluating solutions; they possess no explicit means for determining appropriate actions or relationships between concepts, rules, and principles to be used; and they require learners to make judgments and express personal opinions or beliefs about the problem and defend them [2].

By designing problems in any problem solving or problem-based learning environment and in problem solving in jobs, the dichotomy of ill structured and well structured proved not to be sufficient to capture the essential attributes of problem solving [3]. Several additional proposed dimensions of problems exist. Mayer and Wittrock [20] referred to ill- and well-defined and routine-non-routine problems, whereas Smith [21] introduced the problem solver by distinguishing between determining factors of the problem and determining factors of the person solving the problem.

A more comprehensive list of problem dimensions was introduced in the second paper by Jonassen [3] distinguishing between ill and well structured, complex and simple, situated and abstract, and static and dynamic categories for problems. These four dimensions let to his design theory specifying attributes of 11 problem variations ranging from logic problems over troubleshooting and design to dilemma problems, to name a few. See figure 1 for an illustration mapping the different problem types on the four different dimensions).

Jonassen clarifies that the individual types of problems are archetypes, rarely occur pure, and the distinction rather serves an analytical purpose. ‘Real-world’ problems consist of a combination of many problem variations, rendering them to be compound or “meta-problems” [3, p.81].

C. Purpose of the study

This purpose of this paper is to examine compound-problems and to answer fundamental questions on the nature of workplace problem solving.

The more concrete research questions are as following:
1. How do different problem variations interplay within so called compound problems?
2. When engaged in a compound problem, how does a problem solver switch between the different problems and from one problem-solving mode required by one problem type into another mode required by another problem type?
3. Is the design theory by Jonassen [2,3] sufficient to describe compound problems or does the theory need to be extended?

To operationalize this research, the following steps will be taken: First, to investigate the problem solving processes of an engineer in two jobs, a design and a troubleshooting job. Second, to build a model of the workplace problem solving. Third, to compare and contrast the single case study with other previously documented cases of problem solving by engineers.

III. Methodological Framework

As a methodological framework, the author employed a "modified analytic induction" [23] process, a qualitative research methodology that uses a systematic set of procedures to develop an inductively derived grounded theory [24]. Modified analytic induction provided a methodology for identifying themes and categories within engineering stories told by practicing engineers. In the analytical induction approach, data built the basis for further descriptions and interpretations, but as the term induction indicates, the methodology did not employ an a-theoretical empiricism, but rather was informed by prior research. This research methodology seemed very appropriate for answering fundamental research questions about the nature of workplace problem solving.

This paper draws from two studies. The first study was conducted as a single case study with an engineer in the international steel (tube and pipe) business. In the second study, results of the single case study were utilized to generate a rubric to code 90 interviews with engineers on solving their everyday job problems to compare and contrast research findings.

IV. Study 1: Single Case Study

The research in the first study focused primarily on the particular types of problems encountered and processes of problem solving employed by an engineer during the design and troubleshooting in the context of steel mills for the production of tubes and pipes.

A. Participant

The research participant in the first study was a 65-year-old male engineer who holds a B.Sc. in Electrical and Mechanical Engineering. After working as an electrical engineer on radar systems in the 1960s, he switched in the 1970s to the steel industry and continues to work as an independent general contractor and consultant. His clients range from small steel mill installations to large multi-national corporations producing tubes and pipes as their core business. He is considered an expert in turnkey solutions for new steel mills, re-designing and extending existing steel mills, and trouble-shooting systems that have severe performance problems.

B. Data Sources

For the single case study, the following data sources were utilized:
a. Design drawings, specification with documents, contract information
b. Ten formal interviews and numerous informal interviews
c. Informal observations during design and troubleshooting sessions

C. Data collection

The data of the single case study were collected over the period of a year and drew from two related but different projects. In the first project, the installation of a large steel mill was nearly complete, though fine-tuning, troubleshooting, and assessment questions were in the foreground. The second project started within the second month of the year and was focused on early-stage constraints, design issues, and goals.

During the first meetings the researcher asked the engineer to describe in as much detail as possible what he knows about the two projects, including goals, constraints, foreseeable problems, and possible solutions. In the remainder of the interviews, the engineer was asked to explain and walk the researcher through different steps of the problem and to describe changes in his knowledge about the problem, solution strategies and solutions. The formal interviews were held irregularly with the time between interviews ranging from three weeks to two months; the interviews were two to three hours in length.

During the time of the observations, the engineer was drawing, reviewing drawings, making estimates, performing calculations, contacting vendors and his clients, and inspecting equipment. During the observation periods, the engineer was prompted to describe the processes and engage in meta-cognitive reasoning, especially in building decision and constraint trees [24]. The data collection in this phase also included his drawings and estimates; these were later annotated. There were three observation periods totaling approximately 5 hours.

D. Data analysis

For the qualitative analysis of all the available data, the interviews were transcribed. The graphical material was annotated and connected with the interview transcripts if pertinent for the interview topics. The observation notes were sorted and initial connections to the other forms of data were documented. To make sense of the data, all the material was first read to develop initial coding schemes until emerging categories were saturated [25], meaning no new dimensions appeared from the data. Based on the coding scheme, the data were then analyzed and coded in-depth. The coding rubric was designed to establish different problem attributes, the emergence of different problems within problems, and the change over time in conceptualizing the problem, determining the solution strategies, and evaluating the solution.

The different problems occurring were treated as multiple cases, in which a modified analytic induction process took place. Bertaux noted the importance of several cases "which together help the investigator understand what is called the object" [26, p.9]. In this study, the objects were the three-fold research questions as laid out above. By utilizing a multi-case look at the different problems, several problems and problem solving strategies were compared and contrasted with one another, as well as with the existing conceptualizations of Jonassen [2,3].

With its modified analytical induction, the multi-case lenses within a single case study design was expected to produce additional insights into the three research questions and “bracketing” [23] prior conceptualizations for the moment. Strauss and Corbin defined this approach as "a qualitative research method that uses a systematic set of procedures to develop an inductively derived grounded theory about a phenomenon" [25, p.24]. The five processes of modified analytic induction (mentioned above) reflect the systematic set of procedures within the grounded theory paradigm.

Collecting and coding the material constituted step one of the constant comparative analysis. Codes are abbreviations or symbols applied to a segment of words to facilitate sorting and clustering word segments relating to a particular topic or question [23]. Using the guiding questions, the author developed categories of information (open coding). In the open coding phase, the author examined the textual and visual information (transcripts and drawings) for salient categories of information supported by the text. Further, the theories were interconnected (axial coding), a story was built that connects the categories (selective coding), and a discursive set of theoretical propositions (with a single category as the central phenomenon in the center) was created to fulfill the last three steps of the comparative analysis (adapted from [25]).

In the process of analysis, a qualitative research tool, Qualrus from Ideaworks, was utilized. It allowed coding of texts and multimedia materials (including the drawings) and provided a variety of tools in the development of theory out of data, including a concept-mapping tool.

E. Results and Discussion

The findings of the first study can be structured into two areas: (1) problem solving processes and (2) reflections and extensions of the design theory of problem solving.

1) Problem solving processes: The two projects could be broadly categorized as a design and troubleshooting problem in the process of setting up a steel mill and adjusting the steel mill configurations for different needs. However, several aspects emerged that put the preliminary categorization of the design problem in question, as can be seen by the following example description: The engineer installed a new production line that should produce 200 steel tubes in 20 cycles at 10 minutes/cycle. On the one hand, the design problem in this particular case is very

well structured – all specifics of the current state (need, existing production capacity) and the goal state (specifics of the solution) are known. The process of solving the problem on the other hand looks very different: there are multiple tools, processes, considerations, and decisions to find the most cost-effective and efficient solution. In summary, the problem is very well-structured, the process of solving it, is very ill-structured.

Looking into the process of solving the problem, other differentiations have to be taken into consideration. The solving of this design problem contains several complex and ill-structured decision processes (weighing of options and forecasting the impact of decisions on a wide variety of variables). The process also contains procedural and well-structured components, like the measuring of values and the installation of components. In the design theory, this problem would have been conceptualized as ill structured and complex. The differentiation between the well-structured problem statement (specifications), the ill-structured process of finding an acceptable solution, and the well-structured but complex procedural steps to change specifications or measure the current state of the problem, questions this classification. The study confirmed previous conceptualizations that the project, even categorized as a design problem, contained many different other problem variations required to solve the problem in its entirety [27,28].

Another example from the troubleshooting-problem at a steel mill (the second project) will further demonstrate this point. In this project, a steel mill has a complex performance problem. There is a five second delay, when one cycle ends and the next can start. With thousands of cycles per year, the economic implications of this problem are considerable for the company. The current state is unclear, the goal state is very clear (the machine should run again under similar specifications as before without the 5 second delay); the process is ill-structured (since the current state is not clear, it is not clear what the error is and therefore not clear what solution path to take). The analysis of the error is at the core of this particular problem. If we look deeper into the process of trouble-shooting, we find that it is again a mix between well-structured and ill-structured problems. The process of getting data is very well-structured (well-described procedures of measuring malfunctions), the interpretation of the data and the decisions about which direction to go from the findings is very ill-structured. The actual solving of the problem is again very well-structured (well-defined procedures of how to change parts, or change actual specific settings).

The question of classification seems at first purely academic. There are however huge implications in teaching students problem solving skills, designing and developing problems, and providing support during problem solving activities. The project sheds light on problem solving in the context of an expert engineer. Expert problem solving is often conceptualized as seeing the bigger picture [29,30,31] and rather conceptually than procedurally understanding a problem [32,33,34]. This study challenges the strong separation between conceptual and procedural knowledge in describing problem solving, as similarly argued by Barnett [35]. In the present study, the research participant is able to work with the well-structured components of the problem, has the experience and the skills to put preliminary findings in context, and is able to decide in an ill-structured situation where to go next. In summary, he seems to be able to switch seamlessly between the well-structured and ill-structured, between the simple and complex components of the problem and is able to match his skills to the particular problem solving process in front of him, confirming earlier conceptualizations by Dicks, Garzotto, Hedberg, and Zeng [36].

2. Extensions of design theory of problem solving: As seen in the findings described above, the design theory doesn't make a distinction between the process and the solution. It subsumes the process under the structuredness. The research conducted here would suggest that there is a need to make a distinction between the structure of the problem and the structure of the process of solving the problem. The example descriptions above show that problem solving of so called ill-structured problems becomes more complex, because it seems to be necessary to take internal transitions within a problem (from well-structured to ill-structured) into account.

The research findings of the first study suggest to break down each problem type, separating a) the process to identify the actual state, b) the nature of the actual state, c) the process to identify the goal state, d) the nature of the goal state, e) the process of problem solving, f) the determination of success, and g) the measurement of success. The dimensions to classify problems as introduced by Jonassen [3], structuredness, complex/simple, static/dynamic, context (inter) dependent, need then applied to the different parts of the broken-down problem.

V. Study 2: Comparing results with stories of engineeers

The second study compared the findings of the first to already collected and analyzed stories of 90 engineers discussing their problem solving strategies. The library can be found at the homepage of the Center for the Study of Problem Solving, School of Information Science and Learning Technologies, University of Missouri-Columbia (http://csps.missouri.edu). Details on the creation of the library and an initial analysis of the contained data can be found elsewhere [37]. The main goal of the second study was to test the findings of the first study across a larger population of cases.

A. Process

Findings from the first study were utilized to generate a rubric that was applied to 90 interviews conducted with engineers on problem solving in a variety of different engineering fields. The rubric consisted of elements that were found from the single-case study, mainly the intertwindness of different problem types (meaning the co-occurrence of multiple problem types within a single compound problem), the intra-problem transitions in the process of problem solving, and the shift to new and un-foreseen problems within a larger problem.

Data were analyzed by primarily qualitative methods, similarly as the single-case study and content and constant comparison analyses of results of study 1 to the data sources of study 2.

B. Findings and Discussions of Study 2:

As depicted in figure 2, the large majority of problems are intertwined with one or more problems. It is interesting to note, that the majority of intertwined problem types are different from the problem in which they are embedded (label number ending with 1). In this category, the author classified for example an emerging decision problem within a design problem, a text-book problem that occurred during a troubleshooting problem etc. In the remaining intertwined problems, the same problem type occurred. Additionally, figure 2 can be interpreted that when multiple problems are intertwined it is more likely that the problems are different in nature.

It is noteworthy, that problems categorized as intertwined and different (for example under label 21) are by no means close to comparison. The author tried to further classify and would have ended up with eighty different combinations of different problem types, taking especially the goal, process, and structure of the problem into consideration. The findings would indicate that during the process of problem solving, new compound problem variations emerge which seem to have unique features and attributes that are hard to compare to each other.

Figure 3 provides insight into one dimension on which one can map different compound problems: the transition between different problem solving modes during one problem-solving activity. Surprisingly, only in a small number of problems, in this sample of 90 interviews contained a back-and-forth switch between one problem and another. Surprisingly, the number of big deliberate switches between different problems was rather large.

This number together with the qualitative data it is derived from, would also indicate that within bigger problems there are smaller discrete problems occurring that follow in sequence.

An emerging finding was the label 3 (transition is the problem) in which the transition from one problem to the other within the compound problem is described as the crucial problem. Classical literature on complex and ill-structured problem solving (especially designing) indicates that problem solving means decomposing the complete problem into sub-problems of solvable size (see [38,39,40]). Although this study does corroborate the overall description of the problem solving process as mentioned above, the findings especially represented by figure 3 would indicate that through the necessary decomposition process, through the diverse nature of the sub-problems, and through the overall assembly of the decomposed problems into a whole, a new class of problems emerge, the transition problems. Further research is necessary to shed light on the transition problems and how to adequately address them in the design and utilization of problems in education.

VII. Limitations of the study and further research need

There are numerous limitations to the study. The single-case study was in the field of steel engineering. It needs to be further investigated, whether design and trouble-shooting problems in steel engineering are comparable to other engineering fields. The engineer in the single-case study was particularly articulate about his thinking processes and in reflecting on the constraints of his work. If further research wants to utilize the methodologies of this study to different case studies, other elicitation methods need to be considered and compared, if the research participants are less able to share their reasoning processes.

For the author, this study is only a small first step in understanding the complexity of the problem solving enterprise. Transition problems need to be further researched in order to understand the process of problem solving and to extent further the notion of expertise in problem solving.

Additionally, the extension on the design theory or meta-theory of problem solving has still to find its way into the design of problem-solving oriented instruction, particularly into creation of PBL curriculum.

VII. Conclusions

There are several conclusions that can be drawn from the data. Work-place problems are hard to compare, especially since most problems seem to be unique compound problems. Seamless transitions between different problem types and the shift into different problem solving modes within a particular compound problem seem to be an important skill set. Additionally, transition problems that occur when moving from one problem solving mode into another during a problem solving process are problems that are underresearched and need further extensions. There are numerous implications for research in problem solving, instructional strategies that deal with complex and ill-structured problem solving in a variety of different fields, and PBL curriculum-wide initiatives.

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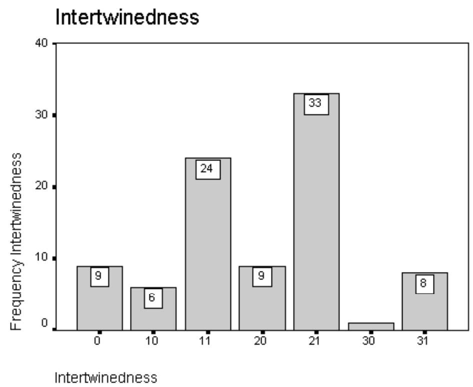
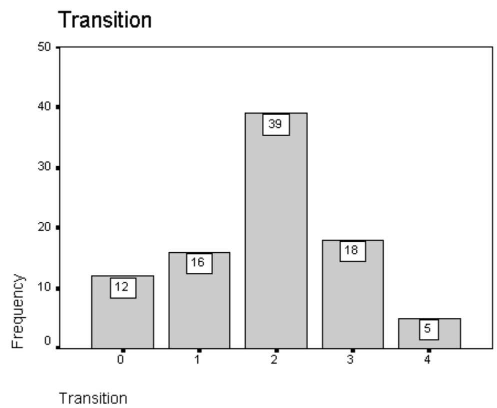
Figure 1: Problem types mapped on 5 dimensions, based on Jonassen [3].



Legend:

0	No intertwined problems
10	1 problem intertwined, same problem type
11	1 problem intertwined, different problem type
20	2 problems intertwined, same problem type
21	2 problems intertwined, different problem type
30	3 problems intertwined, same problem type
31	More than 2 problem intertwined, different problem type

Figure 2: Frequency of intertwined problems



Legend:

0	No transition
1	Constant back and forth
2	Big deliberate transitions (different mode and different problem)
3	Transition is problem
4	Unclassifiable

Figure 3: Frequency of types of transitions