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EVALUATING RELATIVE INSTRUCTIONAL EFFECTIVENESS AND EFFICIENCIES OF DESIGN ACTIVITIES FOR PRODUCT PLATFORM PLANNING

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ABSTRACT

Product Platform Planning is markedly different from the traditional product development process and a relatively new development in engineering design. To present the basic principles of this new and different engineering design topic as well as current research on planning and architecting families of products, in our previous study, we developed an online resource. The tool includes a set of three cases, a tutorial, and a glossary in a multimedia format hosted on the Internet. The cases are based on a family of product power tools. They present information in the form of function diagrams, assembly diagrams, customer needs and market-segment data. In addition, they have been designed to provide different product platform assignments at an increasing level of complexity.

This paper presents two preliminary quantitative methods to evaluate the instructional effectiveness and efficiencies of the learning tool. Also, a model linking the two methods is proposed. The proposed model is defined in terms of two nodes: service delivery node and learning node. The learning node involves analyzing the effectiveness of the tool, which is based on the students' design concepts for the case assignments. The service delivery node involves analyzing the efficiency of the tool, which is based on the case studies and three output variables—assignment appropriateness, clarity, and effectiveness—and a single input variable—assignment technical complexity. The performance of both nodes is measured using Data Envelopment Analysis (DEA). The measurement experiment was conducted with five undergraduate students at Virginia Polytechnic Institute and State University who participated in a summer National Science Foundation Research Experience for Undergraduate (REU) program focused on product platform planning.

A major outcome of this research is an improved understanding of relative instructional effectiveness and efficiencies of the learning activities for product platform planning. Also, a model to relate these two analyses quantitatively is developed. Furthermore, it contributes in terms of developing a relative measurement of instructional efficiencies of design activities with the simultaneous considerations of their desired outputs and input variables.

INTRODUCTION

Product platforming provides product diversity through shared resources at a reduced price by sharing components, interfaces, knowledge, production processes, etc [1]. Products that are "derived" using components or modules from the platform constitute a product family. Product platform planning (or product family planning) calls for the simultaneous, planned development of a set of related products [2].

Product platform planning is different from the conventional product development process in that it involves the planned design and development of a few different products at the same time. Being a currently developing methodology, it is rarely a part of the engineering curriculum. Considering its relevance in today's industry, it is important that it is incorporated in the education system. Platform planning involves management of design, and involves management concepts such as market research, customer needs, product management, etc. These concepts are new to an engineering student and have to be presented in a manner that allows for greater understanding and learning. On the other hand, a

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management student, or product manager in industry may not be familiar with engineering fundamentals and will have to be given a suitable introduction.

As all this calls for the integration of platform planning into the engineering and business curriculum, we have developed an online learning tool in our previous work [3]. In the tool, problem based learning is enabled through a set of three case studies based on a popular family of power tools. Specific activities guide learners through a platform planning process. In addition to product platforming, the cases promote learning concepts of function-based family design, component sharing, modularity, customer needs-driven approach, market analysis, decision-making, etc.

Five senior engineering students have used the three case assignments of the learning tool during their summer research experience at the SMART (Systems Modeling and Realization Technologies) laboratory at Virginia Polytechnic Institute and State University [4]. All the students were sponsored by the National Science Foundation's Research Experience for Undergraduate (REU) Program for product platform planning [5].

The objective of this paper is to report on the instructional effectiveness and efficiency of the learning tool. A simple model with two nodes—service delivery and learning—that depicts the desired support process of the tool and links the effectiveness and the efficiency analyses is developed. Some initial insights about the effectiveness of the case studies are generated based on the students' design responses to the assignments as the output variables and the students' perceptions on the efficiency of the tool as the input variables. The effectiveness analysis is carried on at the learning node. The efficiency analysis is conducted at the service delivery node. As this node has a single input, assignment technical complexity, the output of the node is the same as the input of the learning node. For the efficiency evaluation, commonly used methods in the literature do not take into account differences in inputs characteristics, such as technical complexity and scoping, which impact the tool performance and the suitability of making cross-tool use comparison. As addressing this issue and facilitating cross-tool use comparison, Data Envelopment Analysis (DEA), a linear programming-based performance evaluation methodology, is employed by the proposed model. DEA can simultaneously consider tool use instances on outcome dimensions, as well as differences in key input characteristics. This paper demonstrates how DEA can be adopted as our assessment method using the case assignments.
Section 2 presents a literature review of some of the important topics in design concepts evaluation approaches. In addition, a brief review of relevant DEA literature and background information on the learning tool are provided in this section. Section 3 includes information about the survey method used to collect data for the DEA model and the design concepts assessment approach for the effectiveness analysis. As the DEA model specifications are presented in Section 4, its results are discussed in Section 5. Finally, conclusions and future work are provided.

LITERATURE REVIEW AND BACKGROUND ON THE LEARNING TOOL

1. Design concept evaluation approaches as student learning assessment

A design concept generation approach was proposed by Linsey et al [6] as an evaluation to students' learning outcome. In particular, the effectiveness of functional modeling during conceptual design via its impact on student designer performance was investigated in their study. The study includes three outputs of a design activity: quantity of ideas, technical feasibility, and novelty. On the other hand, Kenneth et al [7] used a survey method to measure student perceptions about their professional growth and correlated them with perceived course emphasis on learning outcomes for design skills, teamwork skills, and communication skills. The survey contains seven contracts, which are teamwork, information gathering, problem definition, idea generation, evaluation and decision making, implementation, and communication. Another student designer learning assessment is proposed by Safoutin et al [8]. In their study, a design attribute framework for course planning and learning assessment is introduced. Their intention was to transform the Accreditation Board of Engineering and Technology (ABET) learning outcomes into a standard and generalized assessment tool. The framework includes two dimensions of a given learning outcome: individual components of the outcome and nature of student understanding of each component. The individual components of the outcome are presented in terms of a set of design activities such as need recognition, problem definition, establish design objectives, etc. The nature of understanding of each design component is presented by using selected seven cognitive and affective categories of Bloom's taxonomy of educational objectives.

These studies and other related works have encouraged us to evaluate the students' design outcomes for the case assignments as a means of assessing the instructional effectiveness of our learning tool. The literature was also found supportive about setting up a positive correlation between the users' design performances in meeting the requirements of the case assignments and the instructional effectiveness of the tutorial. This information is integrated in our performance measurement of the tool as the learning node. The learning node represents the ultimate objective of our learning tool: to produce a positive change in the users' knowledge about product family and platform planning [9]. Students utilize the tool with their perceived quality (e.g., assignment clarity and effectiveness) and in turn show a change in knowledge, attitudes, behavior, etc. Users' behavior in this work is measured by evaluating their design outcomes as an indication of the learning level. However, most of the relative design outcome measurement techniques focus on assessing a single design outcome. As building on the existing measures, appropriate product platform and family principles, such as function and component commonalities across product families and differential specifications [10], were included in our evaluation system for the users' design outcomes. More details about the selection of such measures are presented in the following sections.

Designing an experiment for an idea generation method is as important as a performance measurement system. Shah et al [11] define two types of variables to design an experiment for an idea generation method for conceptual design. The first type—experiment variables—is defined as the variables whose effect on idea generation needs to be studied explicitly during the experiment. The second type—nuisance variables—is variables that are not of specific interest to the experimenter but that can still influence idea generation. As an example, various characteristics of designers influence the idea generation process, such as personality, motivation levels, and mood, etc. The effect of these nuisance variables needs to be blocked or controlled during the experiment in order to observe the effect of the experiment variables.

Additionally, Shah et al [12] identify three classes of variables as being important for characterizing the method: design problem, human factors, and the environment. It is observed that most studies focusing on evaluating idea generation methods consider human and environment variables as nuisance variables. The method variables depend on the specific idea generation method and can be identified from the procedure of each idea generation method. In addition, the variables that characterize the nature of design problems need to be studied in the experiment. Widely used problem variables in the literature are complexity, degree of innovation needed, and decomposability. In terms of human factors, it is recommended to choose "equivalent" sets of designers in as many respects as possible, such as their backgrounds or technical skills. Lastly, environment variables such as time constraint (deadlines), the location, ambient temperature, lighting, seating, etc. need to be controlled by maintaining an equivalent or an identical combination for all the groups involved in an experiment.

Our work employs a direct method involving a set of experimental variables. Possible nuisance variables are assumed to be equivalent for all the student designers and not changing through out the experiment. For example, student designers' background, characteristics, capacity, and all the other environmental factors are assumed to be identical. Since the focus of this work is to develop preliminary quantitative methods to evaluate the effectiveness and efficiency of the on-line tool, this assumption about the students is left unjustified here. For future studies, the reliability and the validity of the developed assessment technique in this work should be tested using larger user groups whose characteristics are scientifically identified.

2. Data Envelopment Analysis (DEA)

Our learning tool calls for the delivery of both effective and efficient instructional service to its users. Therefore, measuring only effectiveness and disregarding efficiency may be an incomplete (yet still valid) approach to performance assessment. Obviously, in an instructional adequacy concept, the actions of teaching and learning are desired to be effective, i.e. demonstration of desired learning behaviors such as good grade and good design. But it is also reasonable to assume that efficiency, i.e. appropriate material content, clarity in teaching material presentation, information accessibility, etc., possesses importance and thus needs to be measured. For the efficiency analysis, data envelopment analysis (DEA) method is used in this work.

DEA is a mathematical method based on the principles of linear programming theory and application. It enables one to assess how efficiently a firm, organization, agency, or such other unit uses the resources available (inputs) to generate a set of outputs relative to other units in the data set [13, 14]. Within the context of DEA, such units are called Decision Making Units (DMU). A DMU is said to be efficient if the ratio of its weighted outputs to its weighted inputs is larger than to the similar ratio for every other DMU in the sample [14]. The weights used are DMU-specific and during the application of DEA they are chosen by each DMU to maximize its own efficiency rating. The selection of the weights is only subject to limitations that they should be positive (or in certain instances non-negative) and they cannot result in an efficiency score larger than 100% or 1 in a zero to one scale [15, 16]. The weights for the inputs and outputs do not need to be identified by the researcher and instead they are determined by the DEA model in the best interest of DMUs [16]. The major advantage of DEA is that each input and output can be measured in its natural physical units. DEA can be performed to assess the relative efficiency of DMUs in a group within a single period or in sequence of periods [17].. As opposed to such traditional usages of DEA, the network models represent production and consumption processes as separate nodes [9]. A network model allows an allocation of resources between customer oriented and traditional production. Soteriu and Zenios [18] modeled a performance measurement system of the production process of branches of a bank in three nodes that capture the components of the service-profit chain and benchmark: operational strategies and service delivery systems, service delivery concepts, and customer satisfaction. Athanassopoulos [19] presented an optimization framework that includes capabilities, service quality and performance of a firm in a two-stage DEA model. In the literature, there are two major approaches to two-stage DEA models [9]. One approach is to run each model separately and then correlate the results. In the second approach, the projected values or performance targets from the first stage are carried over as inputs to the following node, next stage. In this study we used the former approach. Two DEA models are run over two nodes: learning node and service delivery node. More detailed information about the nodes and the performance measurement technique is provided later in this paper.

To be able to perform DEA, the researcher needs to choose homogeneous DMUs that use a variety of identical inputs to produce a variety of identical outputs. Calculated efficiencies are relative to the best performing DMU (or DMUs if there is more than one best performing DMU). The best performing DMU is given an efficiency score of 100 percent or 1, and the efficiencies of other DMUs vary, between 0 and 100 percent or 0 and 1, relative to this best performance [13]. However, it should be understood that DEA is a relative efficiency calculation tool as efficient frontier is not absolute but determined by the data set under investigation. For the accuracy of the model, it is important that variables that most impact the DMUs are included. However, if too many variables are included, a DEA model loses discriminatory power. That is, all or most units become efficient due to their unique levels of inputs and outputs. The recommended maximum number of input and output variables is equal to one-half the number of DMUs in any given category or analysis [20].

DEA has been widely applied to a multitude of problems in a variety of domains [21]. To the best of the authors' knowledge, DEA has not been used as an evaluation tool either for student learning or instructional performance of a teaching tool. As this research is the first of its kind, other application areas related to this research have been explored. Particularly, DEA applications in diverse nonprofit settings, such as social services and education institutes, were investigated, since such organizations include model data in similar forms to this research's. Some examples are service quality with respect to service timeliness and appropriateness, and customer satisfaction [21-24]. Performance variables in those applications helped us identify the variables in this study as well as their implementation in DEA. Currently, several DEA software packages exist to allow managers and researchers to implement DEA models without directly solving a linear program for each DMU [25, 26]. For this work, the Microsoft Excel-based DEA Solver program developed by Cooper et al [21] was used.

3. Background on the learning tool

The entire learning tool was developed in our previous work to present the basic principles of product platform and family planning as well as current research on planning and architecting families of products [3]. The aim of the online learning tool is to educate users on platform planning using problem-based learning. In order for the cases to be effective, two things need to happen. One, users will have to gain the basic principles as well as some details on platform planning before they can solve the cases successfully. Second, the cases themselves will need to be based on the knowledge of platform planning gained from the diverse literature that is prevalent today, in addition to being unified and coherent. In order to achieve these twin goals, there was need for a methodology to guide this effort. This methodology forms the direct basis for the tutorial section in the online learning tool. The methodology used in this effort places a greater emphasis on the earlier stages of platform planning compared to current literature. This is because the reason behind platform planning is to offer customers the variety that they need while at the same time ensuring market success of the products sold. This can be achieved only when greater attention is paid to the customer and the competition. Platform planning is as much a management tool as it is an engineering method. As our methodology is presented in a greater detail in our previous publication [3], it is introduced briefly here. The methodology consists of three major phases. The first phase involves understanding the customer, the market and competitors, and the firms own products and platforms. Next phase engages planning details including strategy, products, features and specifications for the planned family. The last phase involves actually developing architecture, or deciding on specification of platform and variant elements.

The tool has been designed to provide users with easily accessible information. The content has been organized to allow for simple, uncomplicated reading to allow for maximum learning. Pictures, diagrams, explanations and helpful links have been placed wherever needed. The website has been given six major sections in the form of index tabs: Introduction, Tutorial, Design Concepts, Glossary, Case Studies and Links. Sections with more than one major topic of content have a sub-menu as shown on the left side panel. Sequential links in the form of arrows are located to the left and right of the heading of a given topic. The sub-menu allows for easy access to any part of a given section, as opposed to a strictly sequential access. The website was created using Macromedia DreamWeaver in HTML (Hyper Text Markup Language). Some information has been linked to the main website in the form of Adobe's Portable Document Format (PDF). This allows for the presentation of data including graphs, tables and pictures to display as it was designed, irrespective of the browser used.

The Introduction section gives users an introduction to the field of platform planning, the online learning tool, and a link to a page giving details about the people behind the website. The Tutorial section expands on the Methodology introduced above by giving examples of some of the concepts. It functions as a resource to people using the case studies. As a standalone (used without the case studies), it functions as a source of knowledge about Platform Planning. Links from sections of the cases are directed to relevant portions of the Tutorial section. The Design Concepts section consists of topics not directly related to platform planning but are related to it, and would be helpful to users. Concepts explained are architecture, function based design, Pugh method and House of Quality. The Glossary section contains terms in two major topic areas: platform planning and function-based design. The terms in function-based design are further partitioned into flow definitions and function definitions. The Links section of the website has links to resources like platform planning efforts at participating universities and other universities, links to tutorial, etc.

For the case study section, three cases were developed. These cases are based on platform planning for a set of power tools. The first two are based on Black and Decker's cordless tools and the third based on a hypothetical firm, Essel tools. The cases have been designed to have an increasing level of complexity, from easy through to refined.

The first case deals with "bottom-up" design of a platform. The function model and assembly model of a Black and Decker Versapack drill are presented to the user. The assembly diagram consists of component names which are linked to their corresponding pictures. This gives users an idea of size and shape. Background on the Versapack family of tools is provided. Also, helpful links are provided. Links to relevant sections of the tutorial are provided. Information and pictures about grinders are given. The student is asked to design a cordless grinder with shared components from the drill. Specifically, the user is first asked to draw a common function diagram from which common sub-functions can be selected.

Case 2 teaches the concept of a vertical scaling strategy using Black and Decker's circular saw. The user is first familiarized with circular saw usage and features with corresponding pictures, description, and an exploded view diagram. Architecture concepts are then explained. A market segmentation grid for B&D products, as well as the proposed saw, is presented. It provides a table giving specifications for the proposed new family of cordless saws. A function model of the existing saw is given. The user is then asked to develop modules for the platform as well as variant products.

Case 3 portrays an ideal top-down approach to family planning. The user is exposed to customer needs and market based approach to product design and management. In addition, the user is expected to use his or her decision-making skills. The case is based on the grinder platform of a fictitious tool company. Detailed information on grinders has been presented in order to make users thoroughly familiar with the types, usage and parts of a grinder. An exploded view of a diagram is presented. Subsequently, the market presence of the tool maker (Essel tools) is presented on a market segmentation grid. Customer requirements data is presented in the form of a table of means and standard deviations corresponding to different market segments and performance levels. The assignment section asks users to study the competition by actually studying online websites like Amazon to get details on prices and features. The users then need to decide which segment the company will enter first. Product specifications are provided by the users who then identify modules and draw a power tower and a family map. Again, helpful links are provided in the Resources section.

THE QUESTIONNAIRE DESIGN AND THE STUDENT DESIGN CONCEPTS ASSESSMENT APPROACH

As this study is an initial attempt in developing a quantitative performance assessment technique for the on-line tool with a very low number of user participants, only two major nodes are included in the technique: learning node and service delivery node. As mentioned before, the learning node represents the ultimate objective of the tool: to produce a good learning experience in the users. At this node, users receive the learning support from the online tool with their perceived quality (assignment appropriateness, clarity, etc.) and in turn present a change in knowledge and behavior which in our case is measured as the quality of their design outcomes. For our online-tool, the service delivery node is about how efficient the tool is in creating teaching service to the users, regardless of the complexity of the learning material. Therefore, as assignment complexity is selected as an input for this node, its outputs are identified as the service attributes perceived by the users (assignment appropriateness, clarity, etc.). In regards to the relationship between the two nodes, the outputs of the service delivery node become the inputs of the learning node. As this relationship is detailed in the fourth section, this section presents what methods are used to collect the relevant data for the DEA models. In this study, we designed and conducted a survey questionnaire to collect data to identify the outputs of the service delivery node (which are the inputs of the learning node as well). The outputs of the learning node are described based on how well the students' design outcomes meet with our design solution expectations.

During the REU program, five engineering students spent one month at Bucknell University and then another month at Virginia Tech. Before coming to Virginia Tech, the students were already exposed to some product platform and family concepts by dissecting different families of disposable cameras and refrigerators at Bucknell University. As a small part of the program at Virginia Tech, the students were assigned to study the learning tool. Since the students have very similar education background and have experienced very identical environment (e.g., same activities in the summer program), they were expected to be quite similar, ideally the same, in utilizing the product platform and family knowledge they studied. This study assumes that potential differences in human learning and learning capacity, and the presence of reinforcement (nuisance variables) do not contribute to the differences in the students' performance significantly [11]. It is assumed that the students are equally capable of learning and utilizing the tutorial material. Therefore, the differences in their performance are solely attributed to the way the learning tool is designed. Additionally, only demonstrated immediate learning behaviors (the students' performance in design outcomes and their perceptions about the assignments) are focused in our analysis. Displaying the learned behaviors for different design problems outside the case studies' or presenting desired learning behaviors in different forms than submitted design solutions for the assignments are not included in this study [27].

During their first week of the program at Virginia Tech, the students studied all the material except the case studies in the tutorial at their own pace. Next, they were assigned one case study per week in the following three weeks. The students worked and turned in case assignment 1 and 2, individually. They worked on case assignment 3 as a team and turned in a single design solution to the assignment. The students were

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given two and three days to complete the first two assignments, respectively. A week was given for the last case study. Solutions to all the case assignments were submitted electronically. As part of the same summer program but besides using the learning tool, the students dissected a family of coffee maker and recorded the dissected product data in the design repository at University of Missouri-Rolla (UMR) [28].

After completing each case assignment, the students were asked about their experience with the case assignment via online questionnaires. For the first two cases, a web-link to the questionnaire was provided to them through e-mail. Since the last case assignment requires the students to use external resources more than the tutorial materials, evaluation of its effectiveness and efficiency was not included in this study. No questionnaire was prepared for this case study, instead, the students were asked to send one informal report about their experience as a team with this assignment. In this paper, only the instructional effectiveness and efficiency of the first two case studies are included. Further information about the questionnaire for case assignment 1 and 2, and the analysis of the student responses to them are presented in the following section. A discussion about the assessment of the students' design outcomes follows next.

1. Questionnaire design and response analysis

A single questionnaire was prepared and used to collect the students' perceptions about the first two case studies. The captured data is subsequently used by the DEA model developed in the next sections. With respect to the questionnaire construction, commonly known survey design and planning principles (i.e. construct identification, composing questions, and creating item scales) were applied [29, 30]. However, due to limitations in time and low number of tool users, constructing a pilot testing of the survey instrument was not possible for this study to refine the questionnaire. In the questionnaire construction, the overall purpose was to build the final questionnaire with the respondents in mind, for their ease and highest comprehension. The questionnaire includes 11 categorical and 3 open-ended questions.

The questionnaire is designed to obtain the users' perceptions about the two case studies on three major issues: assignment appropriateness, clarity, and technical effectiveness. The assignment appropriateness factor aims to reveal whether a case assignment truly asks the user to apply and demonstrate what he/she has studied throughout the learning tool. It focuses on the alignment between the case contents and the tutorial topics. The assignment clarity targets to find out how good the case studies are in communicating with the users. Besides technical and language correctness, it investigates whether the users come across any conceptual difficulty in identifying the solution approaches to the assignment. In the assignment technical effectiveness construct, information accessibility, helpfulness, and meeting the users' immediate learning expectations are included. Additionally, the questionnaires include a separate section (3 open-ended questions) for the users to report any other issues have not been asked. In this section, also the frequencies of using external resources and asking for the graduate student's help are asked. It is believed that the answers to these questions serve as a simple double check mechanism in interpreting the users' responses to the three major constructs. For example, we expect to observe a high frequency in asking for the graduate student's help when the assignment clarity is low.

With respect to selecting survey scale, there is a lot of discussion in the literature. Some researchers believe that even numbered scales better discriminate between satisfied and unsatisfied customers, positive and negative reactions or perceptions, because there is not a neutral option [31-33]. On the other hand, some studies show that respondents generally choose a positive response in the absence of a neutral midpoint option. All of our constructs have even number scales (six points) without a midpoint. It is believed that this scale guarantees a higher percentage of "Excellent" scores from respondents who otherwise, will tend to give a "Very good" score. At the same time, it provides an option of "Very good" for respondents who are satisfied but not "delighted", instead of rating "Good". In contrast, the major disadvantage of this scale is that for some respondents differentiating among 6 different ratings may be difficult. For example, some respondents might have difficulty to distinguish between a rating 2 and 3, or 4 and 5.

Only, four out of five students responded to the questionnaires for both case studies for a response rate of 80 %. Inter-consistency (Cronbach's alpha) for each factor in questionnaire was computed. Cronbach's alpha is defined as the average of the correlation coefficient of each item grouped in the same factor. Generally, an alpha value of 0.70 or greater is an acceptable level of reliability (the consistency measurement) [34]. SPSS software (statistics program) was used to calculate the inter-consistency values [35]. To strengthen the correlation of items pertaining to the same construct, suggested item deletions by SPSS were carried on. The computation shows significant increases in the internal consistency of the assignment effectiveness construct (from 0.54 to 0.86), when Question 8 is omitted for the first case study. Therefore, Question 3 was not included in the further analysis of the first case study.

For the second case study, the reliabilities of the appropriateness (0.7) and clarity (0.84) constructs are already higher than 0.7. All the items of these constructs were kept. For the assignment effectiveness construct, Question 8 and 9 were dropped to improve the inter-consistency from 0.54 to 0.75.

Additionally, the response distributions for the constructs of the both cases are looked at. For Case 1, the average responses to all the three constructs of the questionnaire stretch from the second half of the score of "Fair" (3.7) to "Excellent" (6). The range stretches from score 4 "Good" to 5.8, the second half of the rating range between "Very Good" and "Excellent" for Case 2. Based on the response distributions, it is observed that the students graded Case 1's technical effectiveness higher than its other constructs. This construct has not only the highest mean value among the three, but also has a relatively narrow distribution at higher scores, between 4.7 (~Very Good) and 6 (Excellent). The students have scored the assignment clarity of Case 1 in the largest range from 3.7 (~Fair) to 5.3 (Very Good). Therefore, it has the lowest but still positive ($\geq$4.5) mean value among the three constructs of Case 1. Based on these observations, it can be said that the assignment clarity of Case 1 was the most problematic one for the students, as the assignment effectiveness was the most satisfactory attribute. Similarly, the assignment effectiveness of Case 2 has received the highest average score from the students. In contrast to the first case, the assignment clarity and the assignment appropriateness were scored the second and the third on average, respectively.

In sum, it can be said that the assignment clarity needs design improvement first among the Case 1 constructs. For Case 2, we might try to improve the assignment appropriateness first. However, this statistics data does not provide us any sort of cross case comparisons for design improvements, since it does not account for the differences between the constructs. For example, it does not provide any information whether the presented distribution ranges and average scores are actually acceptable for a relatively low versus high assignment complexities. Therefore, it is not right to refer improvements for the constructs of Case 1 based on Case2 or vice-versa, when such information is excluded in the analysis.

2. **Design concept evaluation approach**

For both case assignments, the students' designs are scored based on whether they included or not some pre-determined design properties in their designs. For example, for Case 1, the students might be scored based on whether they included store and supply electric energy functions for a battery system in their functional structure of the cordless grinder. If the selected functions for the cordless tools (cordless drill and grinder) are included, 100 % is given for this section of the assignment.

For Case 1, all the students have chosen to represent and submit functional and assembly lists of their designs separately. Therefore, their designs were first scored for their functional and assembly appropriateness separately and then an average score was calculated for each student.

Four components and their corresponding functions are identified for scoring the students' functional structures for Case 1. A score over 100% is given to a design solution based on whether it includes (1) a battery system (store and supply e.e. functions) for the two cordless tools, (2) a shield system (protect/shield function) for the grinder, (3) a handle (for changing torque with importing human hand) for the all tools, and (4) a second handle (secure position and import human hand functions) for the grinder.

None of the students included functions representing the shielding system or the second handle of the cordless grinder while modifying the provided functional structure for the drill with the cord. On the other hand, they all included a battery system function into their design of the cordless grinder. Student 2, 3, and 5 realized that the body of grinder should be designed in a way to import human hand to change torque. Student 4 attributed this function to the drills only. Student 1 did not label this function for any of the tools.

For the assembly list part of the cordless grinder in Case 1, the expected solution is determined as the tool body, the second handle, and the shield system of the grinder with the cord and the battery system of the cordless drill. The students received higher scores for this part of the assignment. As all the students included the tool body of the grinder in their design, all but one added the second handle and the battery system to the assembly list of the cordless grinder. On the other hand, only Student 1 and 5 included the shield system in their design. In sum, the students were able to identify the obvious feature, battery system, both in the functional and component levels. However, features like shielding system and the second handle which are not contained by the cordless drill were mostly absent at the functional level, but generally included in the component level. Overall, Student 5 has received the highest average score (75%), while Student 3 has received the lowest average score (37.50%). While both Student 1 and 2 have the average score of 62.50%, Student 4's average score is 56.50%.

For Case 2, each student has submitted a modularity matrix for a circular saw family. The expected solution includes four subsystems matching with the provided market segment features: battery system, motor and transmission system, blade system, and bevel system. The mid-level product and the metal cutter are expected to include a similar blade system with the current product. Additionally, the battery and the motor and transmission systems of all the products in the family are expected to show high similarities: the same components within the family if it is possible. As the low-end saw and the metal cutter do not need a bevel system, it should be included in the rest. Students' solutions were scored based on how much of these criteria were integrated in their solutions. Student 3 has received the highest score (95.8 %), while Student 4 got the lowest score (62.5 %). Student 3 matched appropriate function groups with the components for all the subsystem but the blade. The major missing part in the design of Student 4 is the shaft system. Student 1, 2, and 5 have received the following overall scores, 91.7%, 70.8%, and 79.2, respectively.

As said before, these scores of the students can provide us clues on the instructional effectiveness of the tutorial. In such an approach, as high student scores can be attributed to high instructional effectiveness of the tutorial, low student scores can be attributed to its ineffectiveness. Based on the above discussion, all the students received higher scores for Case 2. However, a cross case comparison in terms of the instructional effectiveness can not be generated, unless the differences in the students' perceptions are included in the analysis.

This section has discussed the students' perceptions about the cases studies and how the students' design outcomes for the case assignments are scored. The former helped us identify the variables for the service delivery node. In addition to some

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clues about the effectiveness of the tutorial, the latter provided us the variables for the learning node.

Next section provides detail information about the process of the variable selection for the efficiency analysis and the selected DEA model.

DEA MODEL SPECIFICATION

We made the decision to build the model by utilizing the results from the questionnaires and the assessment of the students' design outcomes. Although these variables help conduct a preliminary evaluation of relative instructional efficiency of the two case studies, the data set employed does not capture all potential case assignment characteristics (input variables) that could impact students' design scores or other performance outcomes (such as displaying the knowledge in other design activities). In addition, a more comprehensive efficiency assessment requires application of subjective and objective usability tests including more than four tool users. As a result, the presented model and its results are limited in many ways. On the other hand, the reader should keep in mind that this work is intended to be an initiative for DEA application in evaluating relative instructional efficiency of the online tool in a quantitative manner. Best to the authors' knowledge, such an application is the first of its kind in this field. As the next section includes how the model variables were selected for the model, Section 4.2 introduces the implemented model and its results.

1. The model variables and their relations

The first step in modeling instructional performance of the case studies using DEA was to identify actual input and output variables of interest for the two nodes. The two nodes are combined to represent the support provided by the on-line tool. Figure 1 depicts the stage-by-stage relationships of the two nodes.

The conceptual model shown in Figure 1 depicts the two different nodes of the support provided by our tool, which are sequentially related. This clearly calls for the evaluation of performance in a stage-by-stage approach. As mentioned in the background section, many techniques exist in the literature to apply stage-by-stage concepts in DEA. This study will run a DEA model for each node, and then correlate the results. In this way, we will be able to integrate the results of the concept evaluation into the instructional efficiency assessment for a comprehensive performance measurement.

For the DEA model, assignment technical complexity is defined as the only input of the service node. Students' perceptions about the case studies in terms of their clarity, appropriateness, and effectiveness are defined as the outputs of the same node. These variables are also the inputs of the service delivery node. The design outcome scores calculated in the previous sections are the only type of outputs of the service delivery node.

The assignment technical complexity is determined according to the concepts (teaching objectives) included in the case studies presented in Section II. We developed the three case studies based on an increasing complexity level according to what product platform planning tools the users need to use. Users need to be able to utilize functional structure diagram in solving the first case study. Thus, the complexity level of this case study is the lowest, one. In the second case study, users need to build their own functional structures and use a technique, for example modularity matrix, to find the most appropriate components for the functions. Therefore, the complexity level for Case 1 is two. In addition to the platform planning techniques used in Case 1 and Case 2, users are required to come up with a product launch strategy for the third case study whose complexity level is three. However, in the actual DEA model, the numerical value of the technical complexity has to be entered in a positive correlation with the outputs (see the second section in the literature review). Therefore, in the actual model, the complexity indices of the first and the second case study are entered as 2 and 1, respectively. Finally, a decision making unit (DMU) is defined as a single problem solving instance in the model. Since the eight problem solving instances from only four students can be used for this analysis, the total number of DMUs in the model is eight. Defining problem solving instances as DMUs provides us the flexibility in conducting analyses from different perspectives such as from the case study and student perspectives as presented later.

The CCR (initially proposed by Charnes, Cooper and Rhodes in 1978) was used for the efficiency analysis. Our major intention in the design of the tutorial is to have the case studies clear, appropriate and technically effective as much as possible to promote better learning. Therefore, an output oriented approach, CCR-O, was selected for both nodes in Figure 1. Consequently, our model attempts to maximize outputs (clarity, appropriateness, and effectiveness) without

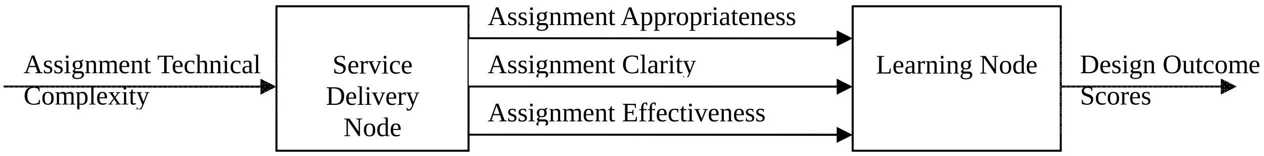

Figure 1: Concept model of the support process provided by the on-line tool

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requiring more of any of the observed input variables (technical complexity level) at the first node. Similarly, learning based design outcome performance is desired to be maximized at the given levels of the inputs (clarity, appropriateness, and effectiveness). Selected CCR model assumes the constant returns to scale of activities. That is, if an activity (x, y) is feasible, then, for every positive scalar t, the activity (tx, ty) is also feasible. The general CCR linear programming formulation used for this model is presented below:

$$
\begin{aligned}
&\text{Max } \theta \\
&\text{Subject to} \\
&\sum_{j=1}^{N} \lambda_j y_{js} \geq \theta y_{j_o s} \quad \forall \text{ s} = 1 \text{ to m} \\
&\sum_{j=1}^{N} \lambda_j x_{jr} \leq x_{j_o s} \quad \forall \text{ r} = 1 \text{ to n} \\
&\theta \geq 0, \lambda \geq 0
\end{aligned}
$$

Where

j:- 1……N represents DMUs from 1 to N (8 for our case) with ‘j’ being any DMU,

jo represents a specific DMU,

x_{jr} is input “r” for “jth” DMU,

y_{js} is output “s” for “jth” DMU,

θ is efficiency score, and

λ is intensity or contribution.

The next section presents the model results and our findings to improve the tutorial design based on these results.

2. DEA model results

Table 1 presents the actual model data as well as DEA results from the CCR-O model for the service delivery node. Given these data, one might tempt to draw a statistical regression line fitted to them. A regression line, as normally determined in statistics, goes through the “middle” of these data points and so the points above it can be defined as excellent and the point below it are defined as inferior or unsatisfactory. One can measure the degree of excellence or inferiority of these data points by magnitude of the deviation from the thus fitted line. On the other hand, the frontier line designates the performances of the best DMUs and measures the efficiency of other DMUs by deviations from them. There thus exists a fundamental difference between statistical approaches via regression analysis and DEA. DEA identifies points on the frontier line for future examination or to serve as a “benchmark” to use in seeking improvements. The statistical approach, on the other hand, averages these points along with the other observations as a basis for suggesting where improvements might be sought [21].

In Table 1, the data is presented by the case studies. First four highlighted DMUs belong to Case 1, as the last four are for Case 2. DMU 6, 7, and 8 were found to be efficient by our model. As shown in Table 1, all the efficient instances occur in the second case assignment. In other words, except the first student, all the students’ second case study problem solving instances are found to be efficient. Student 1 happens to have both the most and the least inefficient problem solving instances (DMU 1 & 5) within the five inefficient DMUs. Inefficiencies of the other DMUs, the problem solving instances of Student 2, 3, and 4 for the first case study, are computed as very similar due to their identical input and similar outputs.

There is no slack in the input side (all the CCR-O projections are identical with the actual input data). However, some output CCR-O projections are found to be higher than the highest possible survey scale, 6 (Excellent). The reason why this case has occurred is that the constraints associated with the survey scale (1 (very poor) as a lower bound and 6 (excellent) as a higher bound) are not included in the model. To obtain the projection values between the boundaries, one might want to modify some other existing models proposed for incontrollable variable cases in the literature, such as bounded variable model [36] or categorical models [37, 38], for this output oriented approach with controllable variables and the constant returns to scale assumption. However, such a modified model will provide the same efficient and inefficient DMUs and the peer relationships [21]. In our case, the value under CCR-O projection in Table 1 provides information on where added output is needed. As this is the desired outcome of this study, it sufficiently provides us a relative evaluation of the case studies and insights on opportunities for improvement.

In sum, Case 1 does not have any efficient DMUs while the percentage of efficient DMUs within the second case is 75%. Also, the average efficiency score of the DMUs within Case 1 is 0.52 as Case 2 has an average of 0.97 efficiency score. As discussed above, all the peers of the problem solving instances of Case 1 are within the second case study. Given these, Case 2 is dominantly, almost twice, more efficient than Case 1 from the instructional perspective. Correlating this result with the material contents of the two case studies, it can be said that it is instructionally more efficient to include the concepts of categorizing customer and market needs along with product architecture concepts (functional and component models) for product family planning examples. Additionally, the way these concepts are presented in the second case study seems more intuitive and cognitively appropriate for the students. The DEA model suggests improvements in all three outputs of Case 1. Therefore, the assignment appropriateness, clarity and effectiveness of the second case study should be studied more closely to improve the same elements in Case 1. Since the DEA model has included the differences in the inputs of the DMUs, the design remedies presented above are now based on fair comparisons.

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Table 1: CCR-O model results for identified 8 DMUs (case assignment solving instances) for the service delivery node

DMU	DEA Efficiency Score	Peer	Technical Complexity (Input)		Assignment Appropriateness (Output)		Assignment Clarity (Output)		Assignment Effectiveness (Output)	
			Actual	CCR-O Projection	Actual	CCR-O Projection	Actual	CCR-O Projection	Actual	CCR-O Projection
1	0.48	6&8	2	2	5.0	10.41	3.7	10.61	4.75	9.89
2	0.54	6,7&8	2	2	5.5	10.12	5.7	10.42	5.5	10.12
3	0.52	7&8	2	2	4.5	8.21	4.0	10	6.0	10.95
4	0.51	6&8	2	2	5.5	10.58	5.0	10.88	5	9.62
5	0.90	6&8	1	1	4.5	5.1	4.0	5.15	4.7	5.2
6	1	-	1	1	5.5	5.5	5.75	5.75	4.7	4.7
7	1	-	1	1	4.0	4.0	5.0	5.0	6.0	6.0
8	1	-	1	1	5.0	5.0	5.0	5.0	5.3	5.3

Additionally, Table 1 presents an interesting case for DMU 5. The model compares a problem solving instance of Case 2, DMU 5, with the two efficient Case 2 instances, DMU 6&8. In this case, the inefficiency of DMU 5 can be attributed to the student, Student1, who processed it. Following on the same analyzing approach, next the DEA results are analyzed by student body. As the decision makers for redesigning the tutorial, we gain more about how Student 1 has actually interacted with the case study, if we compare his interaction processes with the ways of Student 2 and 3. This will help us understand better why Student 1 has scored the appropriateness, clarity and effectiveness of the case studies the way he did in Table 1. The model also refers Student 2, 3 and 4 to itself. This urges us to pay attention the differences in these students' interactions with the two case studies to understand why the two case studies have worked differently for the same student. For example, say Student 2 has needed external sources in the first case study more frequently than he did for the second case study. Finding this out, we will know better why Student 2 has scored the second case study lower for the effectiveness output. Finally, Student 2, 3, and 4 are also referred to each others for the first case study, since the efficiencies of the corresponding DMUs are scored very similarly due to their similarities in the inputs and the outputs.

Similarly, Table 2 presents the actual output data and the efficiency scores and peers from the DEA model for the learning node. Since the inputs of this node are the same with the outputs of the previous node, they are not shown again in the table.

In Table 2, the data is presented by the case studies. The first four highlighted DMUs belong to Case 1 and the last four for Case 2. DMU 5 and 7 were found to be efficient by the model. Both DMUs belong to Case 2. Thus, the percentage of efficient DMUs within Case 2 is 50%, while it is zero for Case 1. These efficient instances represent the design outcome scores of Student 1 and Student 3 for Case 2. As DMU 6 (Student 2's design solution for Case 2) was found to be the least inefficient, whereas DMU 3 (Student 3's design solution for Case 1) is the most inefficient DMU. Overall, the average efficiency score for the DMUs within Case 1 is 0.58 as Case 2 has an average of 0.85. Given these, although Case 2 requires incorporation of more complex techniques than Case 1, it has supported the students to learn product family and platform planning topics better.

Table 2: CCR-O model results for identified 8 DMUs for the learning node

DMU	Actual Design Performance Score (Output)	CCR-O Projection for the output	DEA Efficiency Score	Peer
1	62.5	84.82	0.74	5
2	62.5	107.31	0.58	5
3	37.5	91.7	0.41	5
4	56.5	97.55	0.57	5
5	91.7	91.7	1	-
6	70.8	91.7	0.77	5
7	95.8	95.8	1	-
8	62.5	102.13	0.61	5

Figure 2 depicts how the efficiency scores for both nodes are distributed. Overall, DMU 7 (a Case 2 DMU) shows the perfect efficiency, whereas DMU 3 (a Case 1 DMU) shows the worst efficiency combination. As all the efficiency scores of the rest of the Case 2 DMUs are higher than 0.90 for the service delivery node, the two DMUs of Case 2 have learning node efficiency scores lower than 0.80. Although Case 1 DMUs have similar service delivery node efficiency scores, their scores for the learning node spread from ~0.4 to ~0.74. As can be seen,

Figure 2 helps us diagnose relatively how much improvement in each node is required. For example, to place DMU 5 at the perfect efficiency spot, where both efficiency scores are one, it is adequate to improve its efficiency for the service delivery node only. From the DEA results for the service delivery node in Table 1, it is identified that DMU 6

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and 8 (peers) can actually present the appropriate strategies for DMU 5 to achieve such an improvement.

In addition, the correlation between the efficiency scores of the two nodes is computed as 0.62. As this depicts a positive relationship between the two nodes, it shows that the similarity between the two efficiency scores of each DMU is about 62%. Therefore, one can expect to improve the user's learning with a 62% chance, through an improvement in the service delivery node, such as improving the assignment clarity. Below,

Figure 3 shows how efficiency scores change across the eight DMUs. As it can be seen clearly, the highest deviation between the two efficiency scores is observed for DMU 8, secondly for DMU 1, and thirdly for DMU 6. Removing DMU 1 and DMU 8 from the analysis will increase the correlation between the nodes up to 87%. Such a significant improvement in the correlation shows that it is worth figuring out the reasons of the discrimination in the efficiency scores of DMU 1 (Student 1 and Case 1) and DMU 8 (Student 4 and Case 2).

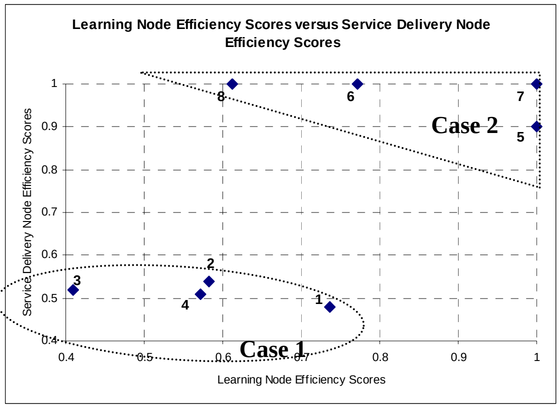

Figure 2: Learning node efficiency scores versus service delivery node efficiency scores

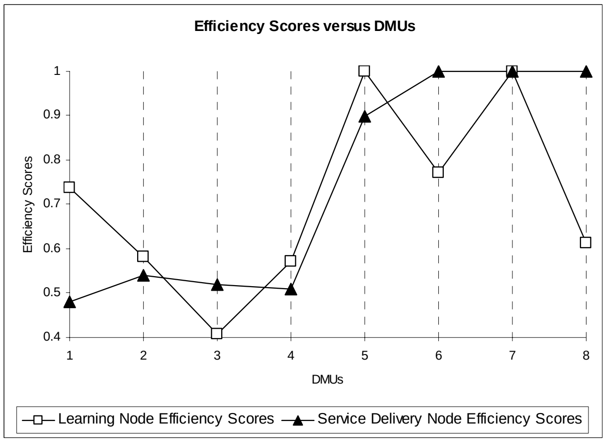

Figure 3: Efficiency scores across the DMUs

In sum, it has been shown that the implemented instructional assessment technique for the online tool for introducing product platform and family planning concepts is not only able to identify the tool performances across multiple dimensions, but also able to help decision-makers with potential improvement strategies.

CONCLUSIONS AND FUTURE RESEARCH

Providing quantitative ways for evaluating the instructional effectiveness and efficiency of our previously developed online tool for introducing product platform and family planning concepts, this study achieved its objectives. Particularly, it helped us gain improved understanding of relative appropriateness, clarity, and effectiveness of the two design activities for product platform planning besides their impacts on the students' learning. Also future improvements in the design of these activities were identified using generated peer relationships by the DEA model. The work has contributed in terms of developing a relative measurement of instructional efficiencies of design activities with the simultaneous considerations of their anticipated outputs and input variables. In other words, the proposed evaluation method eliminates assigning weights to be attached to each input and output, as in the usual index number approaches.

In this study, expected support provided by the tool is described in terms of two related nodes: service delivery and learning nodes. DEA was used to compute the performance of the each node separately. Developing the CCR-O models, output oriented model assuming constant returns to scale, relative efficiency of the two case studies were evaluated based on the two nodes. In the model, a single decision making unit (DMU) was defined as a single problem solving instance by a student. Case study assignment difficulty was chosen as the single input for the first node, service delivery node, while assignment appropriateness, clarity, and effectiveness were determined as the three outputs of this node. As these variables are also inputs for the proceeding node, learning node, the output values were obtained by conducting questionnaires focusing on five engineering students' experiences with the two case assignments. The second node, learning node, has a single type of output, evaluated design outcomes.

In our analysis, the DMUs were grouped by the two cases. Overall, the model showed that Case 2 is more efficient than Case 1 based on the students experiences with the case assignments and their design outcomes. In other words, the teaching objectives included in Case 2 have promoted instructionally more efficient results. The model suggests improvements in the three outputs of Case 1 at similar amounts at the first node. Additionally, identifying the 62% positive correlated relation between the two nodes, it is found that any improvement in the service delivery node is high likely to promote a good amount of improvement in the users' learning. Also, decision-makers should match any improvement in the learning nodes with DMU 5. In sum, as

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discussed throughout this paper, our model helped us identifying the sources and amounts of inefficiency for the two case studies across multiple dimensions. It also identified the benchmark members of the efficient set used to effect these evaluations and identify these sources of inefficiency.

However, it should be kept in mind that this is a preliminary study in which the process of identifying the characteristics of the production frontiers and more reliable inputs and outputs still requires more work. Therefore, for future work, different DEA models and methods need to be developed to compare results. Additionally, expert knowledge on the problem needs should be utilized in a systematic way before arriving at a definitive conclusion. Comprehensiveness of selected inputs and outputs and the assumptions of the analysis should be scoped carefully. Also, input and output data should be collected from a larger sample size to increase the statistic reliability of the experiment.

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