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Transforming the First-Year Engineering Experience through Authentic Problem-Solving: Taking a Models and Modeling Perspective

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Abstract

A models and modeling perspective led to Model-Eliciting Activities (MEAs), authentic mathematical modeling problems, being introduced into a first-year engineering program in 2002. A design research perspective then led to iterative improvements in the design of these activities, strategies for their implementation, and strategies for assessing student work to promote effective learning across multiple learning objectives. This paper describes two different research threads that have lead to significant transformation of the first-year engineering experience. The first thread relates to problem formulation. The second thread relates to the dimensions along which instructors evaluate students' open-ended problem solutions.

Keywords: Model-Eliciting Activities; authentic mathemcatical modeling; problem formulation; assessment

1. Introduction

First-year engineering students need to engage in significant engineering problem solving or design experiences (National Research Council, 2005). Such experiences should provide students with a means of engaging in activities that reflect the nature of engineering practice while clearly supporting analytical skills development and professional skills development, such as communication and teaming. To address this need, Model-Eliciting Activities (MEAs) were introduced in 2002 into a very large, required first-year engineering course that is part of a first-year engineering program (Zawojewski, Diefes-Dux, & Bowman, 2008). MEAs are

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user-driven, open-ended, team-oriented, authentic mathematical modeling activities that are designed according to six research-proven guiding principles based on the models and modeling theoretical perspective of learning (Diefes-Dux, Hjalmarson, Miller, & Lesh, 2008). Through design-based research methods, the design of these problems, strategies for their implementation, and strategies for assessing student work have iteratively been improved to ensure effective learning across a wide variety of learning objectives. This paper describes two different threads of the research that has been conducted around the use of MEAs in the first-year engineering program that have lead to significant transformation of the first-year engineering experience. The first thread relates to problem formulation. The second aspect relates to the dimensions along which instructors evaluate students' open-ended problem solutions.

2. Models and Modeling Perspective

The models-and-modeling perspective assumes that solving concrete, situated problems is easier than abstract, decontextualized problems because, in the later case, one must make sense of the representation used to describe the situation (Lesh & Doerr, 2003). As such, this perspective acknowledges that the conventional approach to teaching in which information is "passed on" to students does not enable all students to learn (Lesh & Zawojewski, 2007). In fact, some students better demonstrate their understandings when alternative learning approaches are employed. This perspective also acknowledges that students bring prior knowledge and relevant ideas to new problem-solving situations, and that their knowledge and ideas can become increasingly sophisticated during a problem-solving episode. The long-term view of this perspective is that students' conceptual systems evolve over time.

Taking a models and modeling perspective in engineering education means that instructors believe that students can solve significant modeling activities. So such activities are not only appropriate for first-year engineering students, they are necessary for the continuous development of higher-level thinking skills. To effectively implement this perspective, instructional design must be seen as a broader endeavor than conventional teaching of content and use of textbook problems. It must encompass the design of the educational environment - the activities themselves, the implementation strategy, and the assessment strategy. It also encompasses the continuous gathering and analyzing of classroom-based data for the purpose of planning subsequent instruction (Zawojewski, Diefes-Dux, & Bowman, 2008).

2.1. Model-Eliciting Activities

Model-eliciting activities (MEAs) – the problems, their implementation, and the assessment of students' solutions - are an instructional system manifestation of the models and modeling perspective. The problems are user-driven and open-ended; they are authentic. They are model-eliciting in that they require students to mathematize (e.g., quantify, organize, dimensionalize) information in context (Lesh, Hoover, Hole, Kelly, & Post, 2000). They are thought-revealing in that they provide students and instructors a window on students' thinking during solution development. Six principles guide the design of MEAs. These principles, originally developed by mathematics education researchers for middle school classrooms (Lesh, et. al. 2000), have been adapted for engineering courses (Diefes-Dux, Hjalmarson, Miller, & Lesh, 2008). These principles are described below.

The *Model Construction* principle requires that the activity be designed to engage students in the mathematical model development for a user with a need. In engineering, a mathematical model is most often thought of as a single or series of equations that relate independent and dependent variables. A mathematical model, as used here, is a *system* used to describe another system, to make sense of a system, to explain a system, or to make predictions about a system. So, the models students develop for MEAs are procedures for solving a problem.

The *Reality* principles requires that the problem be posed in an authentic engineering situation. The authenticity of the problem must be carefully constructed so that students can initially make sense of the problem. However, the problem should also extend their knowledge and experience. The situation should also be authentic in the sense that realistic assumptions can be used by the students to assess the quality of their solutions.

The *Generalizability* principle requires that the model students create be sharable, re-usable, and modifiable. The implication is that the model developed by the students must be useful to the user, not just the students working on the model. Further, the model must be designed to anticipate the potential conditions under which it will be used. A shareable model is one that a user can implement and achieve the same results as someone else. A reusable model conveys for whom the model was created, the need it addresses, and the limitations of its use. This enables users to determine when it is appropriate to use the model as-is. A modifiable model contains justifications for the design decisions that went into creating the model. Such justifications enable others to change the model to meet their needs.

The *Self-Evaluation* principle encourages students to put themselves in a position to evaluate their own work. The criteria for success are conveyed through the activity by providing a specific user with a clearly stated need. The students need to attend to those criteria in order to produce a good solution.

The *Model Documentation* principle requires that students document their model. This principle allows students and instructors a window on the students' ways of thinking as the model develops. That is, a MEA is not only model-eliciting it is also thought-revealing (Lesh, et. al, 2000). The design of the documentation process should create opportunities for students to iteratively reflect on the development of their model. The design of the documentation process should also reveal to instructors (1) the quantities students are thinking about, (2) the relationships students believe are important (3) the kind of rules students believe govern operations on the quantities and quantitative relationships (Lesh & Doerr, 2003).

The *Effective Prototype* principle encourages a MEA designer to consider whether or not the student generated models for a particular MEA will provide useful prototypes, or metaphors, for interpreting other situations in the future. What is desired is that long after students produce solutions to a MEA, they will be able to draw on their experience to solve other, structurally similar problems.

2.2. Sample MEA

The Just-in-Time Manufacturing MEA (JITM MEA, Appendix A), as implemented in a first-year engineering course in 2011-12, will serve as an example of a MEA and a reference point for the discussion of research-based transformations to the first-year engineering experience. In this MEA, the Reality principle is addressed through the development of a situation in which D. Dalton Technologies (DDT), operates in a JIT manufacturing mode and requires a shipping service to move materials between two subsidiary companies in a timely fashion. DDT is unsatisfied with their current shipping service and needs the first-year engineering teams to develop a procedure to rank a number of alternative shipping companies using a historical data set (summarized in Table 1). The *Model Construction* principle is addressed by requiring students to use their knowledge of mathematics and statistics to develop a procedure (mathematical model) to rank shipping companies in order of most likely to least likely able to meet a DDT's delivery timing needs. When solving this MEA, students must find a way to balance findings with regards to central tendency, variation, and distribution of the data in the context of the problem to develop a procedure to rank the companies. The data set is constructed purposefully to produce tensions in students' thinking about the problem and push them towards exploring these three characteristics of the data.

The inclusion of the historical data set enables students to evaluate the criteria for success; thus the *Self-Assessment* principle is addressed. Students must communicate their solution in a memo format to DDT's CEO; the memo format guides students towards a generalizable solution. So both the problem and the implementation strategy address the *Documentation* and *Generalizability* principles. The act of using descriptive statistics to make decisions is something engineers do in practice. So it is anticipated that this problem will serve as an *Effective Prototype* in students' future education and work.

Table 1. Number of hours late for shipping runs from Lincoln, NE to Noblesville, IN (sample from complete data set)

Sample Data:	**IHE**	**DS**	**SC**	**UE**	**BF**	**DFC**	**NPS**	**FSP**
Team Draft 1 *(IHE, DS, SC,*	0	1.00	0	1.11	2.53	0.04	2.39	0.91
UE only, N = 255 for each)	1.31	0	7.39	0.90	1.57	0.09	6.21	2.50
Team Draft 2 & Team Final	0	10.49	1.81	0	3.57	0	5.14	0.79
(All shipping companies,	0	0.70	9.00	1.11	5.36	1.42	0.53	1.00
N = 255 for each)	1.73	0.71	4.22	0.84	2.24	1.80	13.97	1.13
	1.92	0.42	0.32	3.31	1.56	1.09	0	1.00
	…	…	…	…	…	…	…	…
Statistics for Data:								
Mean (hr)	1.49	1.51	1.49	1.52	1.54	1.52	1.60	1.60
Standard Deviation (hr)	2.54	2.19	2.25	2.56	1.34	1.55	1.61	1.74
Minimum (hr)	0	0	0	0	0	0	0	0
Maximum (hr)	16.4	10.5	13.0	26.0	9.3	16.2	14.0	14.0
Median (hr)	0.74	0.62	0.65	0.95	1.13	1.13	1.06	1.12
Counts:								
0 hr	100	36	79	14	14	17	1	16
< 2 hr	193	199	196	203	193	197	198	206
> 8 hr	9	9	6	4	1	1	2	6

Note: IHE= Iron Horse Expeditors; DS = Delphi Shipping; SC = ShipCorp; UE = United Express; BF = Blue Freight; DFC = Direct Freight Company; NPS = National Package Service; FPS = Federal Parcel Service

3. Design Research Perspective

A design research perspective (Brown, 1992; Cobb, diSessa, Lehrer, & Schauble, 2003; Collins, 1992; Collins, 1999; Edelson, 2002; Kelly, 2004; Lesh, 2002) has guided the development of increasingly better approaches to developing and implementing MEAs in the first-year engineering course(s) over the last 10 years. The design research approach has allowed researchers to "trace the evolution of learning in complex, messy classrooms and schools, test and build theories of teaching and learning, and produce instructional tools that survive the challenges of everyday practice" (Shavelson, Phillips, & Towne, p. 25). Design research approach is familiar to engineers as it is consistent with engineering practices of testing and revising (and iteration more broadly). Through this approach, research is conducted to inform curricular improvements, the curricular improvements are made and further studied, and the cycle begins again as further improvements are made. Like engineering design, the focus of design research is product development for a particular purpose. This focus has enabled the design and analysis of MEA problems, pedagogies for student learning, pedagogies for instructor training, and assessment tools. Large, required first-year engineering courses are complex contexts with many affordances and constraints. This research perspective enables test and revise cycles within such design contexts.

4. Transforming the First-Year Engineering Experience

4.1. MEA implementation setting

MEAs have been implemented in the required first-year engineering courses at Purdue University since 2002 (Zawojewski, Diefes-Dux, & Bowman, 2008). From 2002-2009, this course was a single offering that served approximately 1500 students in the fall and 400 students in the spring. The focus of this course was on problem solving and computer tools (e.g., Excel and MATLAB). The learning objectives for this course evolved from a subset of those appearing in the right column of Table 2 (items 1-6) to the full set shown there, in part due to the introduction of MEAs into the course. After 2009, the requirement became a two course sequence – Ideas to Innovations I and II. The enrollment in academic year 2011-12 in Part I was approximately 1800 students in the fall and 200 students in the spring. The enrollment in Part II was approximately 200 students in the fall and 1650 students in the spring. The focus of Part I is on design thinking, while the focus of Part II is on problem solving, modeling, and computer tools. A number of learning objectives from the first course carry into the second course (Table 2). MEAs are implemented in both courses.

From 2002 to 2009, the implementation of MEAs was supported by graduate teaching assistants (GTAs). GTAs received training on the implementation of MEAs and the assessment of student work on MEAs (Diefes-Dux, Osburn, Capobianco, & Wood, 2008, Diefes-Dux, Zawojewski, Hjalmarson, & Cardella, 2012). Each GTA was responsible for assessing and evaluating the work of 15 or 16 teams of 3 to 4 students. Since 2009, both GTAs and undergraduate teaching assistants (UGTAs) have supported the implementation of MEAs. All TAs receive training similar to that implemented in earlier years. Each GTA is responsible for assessing and evaluating the work of 10 teams, while each UGTA is responsible for 5 teams.

Table 2. Learning objectives for the required first-year engineering course sequence at Purdue University (2011-12)

Ideas to Innovations I	Ideas to Innovations II
Successful completion of this course will enable the student to: 1. Examine and analyze career information from various resources to make informed decisions about which engineering discipline to pursue, 2. Explain the critical role of cross-cultural and multidisciplinary teamwork in nurturing diverse perspectives and the creation of innovative engineering solutions that meets the needs of diverse users, 3. Develop meta-cognitive skills in evaluating own teamwork and leadership abilities, recognizing how own behaviour impact the whole team, and make team process adjustments when necessary, 4. Explain critical and diverse use of modeling in engineering to understand problems, represent solutions, compare alternatives, make predications, etc, 5. Use multiple models, estimation, and logic to triangulate and evaluate information coming from various data sources, 6. Collect, analyze, and represent data to make informative explanations and persuasive arguments, 7. Implement iterative processes, rich information gathering, and multiple modes of modeling when solving complex design problems, 8. Use systematic methods to develop design solutions and compare design alternatives, and 9. Consider the interconnectedness among social, economic, environmental factors (in the context of sustainability or systems) when solving engineering problems.	Successful completion of this course will enable the student to: 1. Develop a logical problem solving process which includes sequential structures, conditional structures, and repetition structures for fundamental engineering problems, 2. Translate a written problem statement into a mathematical model, 3. Solve fundamental engineering problems using computer tools, 4. Perform basic file management tasks using an appropriate computer tool, 5. Work effectively and ethically as a member of a technical team, 6. Develop a work ethic appropriate for the engineering profession, 7. Employ design and problem processes in modeling, problem solving and design work, 8. Evaluate and provide feedback to improve solutions to engineering problems, 9. Reflect on personal and team performance to achieve continuous improvement, and 10. Demonstrate an ability to engage in continuing professional development.

4.2. MEA implementation sequence

MEAs are launched with a set of individual questions that the students answer prior to getting into their teams to solve the MEA. Each team reviews its team members' responses to the individual questions and comes to consensus on the answers before starting to solve the MEA. The team solution is created through an iterative process of model development, feedback, and improvement. For Team Draft 1, student teams are provided with a small or less complex set of data that they can use to explore their mathematical ideas during their initiate solution development. For the *JITM* MEA (Appendix A), the Team Draft 1 data set consists of historical data for four (of the ultimately eight) shipping companies (see Table 1). For Team Draft 2 and Team Final Response, teams revisit their procedure using either peer feedback or TA feedback and larger or more complex data sets. Feedback and new data sets are intended to prompt teams to rethink the decisions they made when constructing their mathematical models.

This paper will focus on one design/implementation strategy and one assessment strategy that has transformed the first-year engineering experience as a result of research-based findings. The design/implementation strategy is tied to the use of the individual questions asked at the start of a MEA. The assessment strategy is concerned with the *MEA Rubric* dimensions used to assess student team work as student teams progress from Team Draft 1 to Team Draft 2 to Team Final Response.

5. Problem Formulation

Engineers need to develop good problem formulation skills because good problem formulations directly relate to the quality of problem solutions. Early versions of MEAs provided an opportunity for student to engage in task-level problem identification and some problem-scoping through a series of questions concerning the context of a problem. These questions were answered in class by students individually prior to engaging in team solution development. The three questions were: Q1) "Who is the client?", Q2) "What does the client need?", and Q3) "Describe at least two issues that need to be considered when developing a solution for the client". These questions were viewed as reading comprehension questions; they served the purpose of sufficiently engaging each student in the problem so that each student had a greater opportunity to contribute to the team solution from the beginning of the team problem solving period. When these questions were not present, instructors notice that team members were not always ready to fully participate at the same time, likely due to different reading and processing rates.

We, the authors (one a lead on MEA implementation in the first-year engineering courses), were interested in learning about the nature of student responses to these questions and the degree to which the GTAs could successfully assess student responses. A qualitative analysis of Fall 2007 student responses to these individual questions across three MEAs was conducted (Salim & Diefes-Dux, 2009). Analysis of student work from Fall 2007 provided a base-line for understanding students' ability to answer these questions as no instruction was provided on problem formulation. Further, the GTAs were provided with only a verbal overview of answers to these questions during their training (Salim & Diefes-Dux, 2010). Results showed that students had difficulty identifying the client (defined as the direct-user) from among the various stakeholders in the problem description. Students most often identify the client/direct-user to be the supervisor or firm that wants the engineering work done. For the *JITM* MEA, this means that students would identify Devon Dalton or DDT as the client/direct-user rather than the DDT Logistics Manager. (Note: As a result of this analysis it was found that no direct-user was actually described in the Fall 2007 *JITM* MEA text. This was rectified as of the Fall 2008 implementation of this MEA. But similar failings of the students to identify the direct-user were found in student responses to the other MEAs implemented in Fall 2007.)

Students also had difficulty articulating the client's need (Salim & Diefes-Dux, 2012). Difficulties included either misidentification of the deliverable or insufficient detail concerning the function and function behavior of the deliverable and the constraints for designing the deliverable. For example, for the *JITM* MEA, a typical student response to Q2 that misidentified the deliverable states, "*The client needs us to rate 8 companies using the shipping data provided and see which company will meet it's timing needs best.*" Here the deliverable is the rating, rather than a procedure to rank the shipping companies. A typical response to Q2 that lacks sufficient detail states, "*The client needs a procedure that ranks several shipping companies to help them decide which shipping company they should choose to do buisness with*." This response lacks detail with regards to the order of the ranking and the data that will be used or available to develop the model.

Further, the solution development issues students identified were often not related to the task-at-hand but rather to big-picture issues like shipping costs, shipping damage, and bad weather (Salim & Diefes-Dux, 2012). These are issues for which the students have no data to draw on when developing their models. For example, for the *JITM* MEA, a typical student response to Q3 was, "*The size of DDT plays a role in what shipping company they choose. The cost of shipping also plays a role.*" Student also tended to restate the problem in response to Q3. For example, "*One issue is how reliable are the companies in not being late.*" Developing a model to measure the reliability is the essentially the task.

This analysis helped us identify the nature of student responses when no formal instruction on how to answer these questions was provided. The literature review conducted at the time raised our awareness of the opportunity to recast our thinking about their utility of these questions – we began think about the individual questions as being related to problem formulation rather than just reading comprehension. As such, it became clear that students do not have an inherent ability to formulate problems. Further, given that over the three different MEAs implemented in Fall 2007 students' responses to these questions improved only slightly (Salim & Diefes-Dux, n.d.), it was apparent that students will not make significant gains in this ability through practice alone, particularly practice that is accompanied by minimalist GTA training resulting in unreliable and invalid GTA assessment of students work (Salim & Diefes-Dux, 2010) with little or no written feedback to students on their work (Ghazali & Diefes-Dux, 2012). Such repurposing of these questions was going to take system-level changes. Formal instruction for both students and GTAs was going to be required.

This initial research-informed move to using the individual questions as a means of engaging students in problem formulation turned out to be a timely systemic move as it matched well with the growing emphasis on design thinking occurring in other aspects of the course (that would eventually lead to the development of the Part I course). This move allowed us to begin using language that the students were learning in the design space into the mathematical modeling space.

Formal instruction on problem identification for first-year engineering students and their GTAs was incorporated into the first-year course in Fall 2008. This formal instruction consisted of an interactive lecture in which a faculty member walks the students through answering the individual questions for a sample MEA. The *Sports Equipment* MEA (Zawojewski, Diefes-Dux, & Bowman, 2008) has been used most frequently for this purpose. GTAs received similar instruction during their training with MEAs. The students individually read the sample MEA and attempt to answer the individual questions prior to coming to this lecture. To answer Q1, the faculty member has the students list as many stakeholders as they can find in the problem text and consider how these stakeholders will interact with or benefit from a solution to the posed problem. Typically there are eight to ten different stakeholders with various levels of direct concern with the mathematical model that the teams have been asked to create. As an example, Table 3 lists the stakeholders for *JITM* MEA in terms of being non-users, indirect-users, and direct-users. The students are helped to understand the term *client* which is defined as the *direct-user* - the person or groups of people who will use the team's mathematical model in their work. From the list of stakeholders, the faculty member assists the students in identifying the client/direct-user.

To answer Q2, students are directed to identify the thing that the team has been asked to create; the *criteria for success*, which describe what this thing is for and how it should function; and the *constraints*, which describe how the problem is bounded. Typically the constraints are related to the types of data the model is designed to use. In the case of the *JITM* MEA, an exemplar response to Q2 would read, "The DDT Logistics Manager (*client/direct user*) needs a procedure (*thing/deliverable*) to rank shipping companies in order of best to least able to meet DDT's timing needs (*criteria for success*) given historical data for multiple shipping companies of time late for shipping runs between two specified locations, in this case Lincoln, NE and Noblesville, IN (*constraints*)."

Q3 was designed to focus students on the task at hand, developing a mathematical model to rank shipping companies using historical late arrival time data. To answer Q3, students are introduced to the notion of problem scope. To identify issues most related to the development of a solution for the client/direct-user, the students are asked to map the issues that they raise to the stakeholders list they develop for Q1. Issues that are most relevant to indirect or non-users are not likely to be immediate task-level development issues. In the case of the *JITM* MEA, issues of traffic jams and bad weather are not considered relevant to the immediate task because the students have no data regarding these issues with which to develop their models. Granted, these are issues in the larger context of the problem and their disregard may ultimately limit the utility of the student team created solutions.

Table 3. Stakeholders and their possible relation to the solution to the *JITM* MEA

User Type	Stakeholders and Possible Relation to Solution
Direct User	*DDT Logistics Manager* – the one who will use the ranking procedure on the job
Indirect Users	*D. Dalton Technologies (DDT)* – company that needs a ranking procedure to help select a new shipping company; loses money when a poor choice is made *Devon Dalton, CEO* – supervisor for the Applications Engineering Team, will oversee the development of the ranking procedure; under pressure to increase company profits *Bowman* – producer of transducers that use Ceramica's product located in Noblesville, IN; will receive product from Ceramica using the shipping company selected via the ranking procedure; workers directly impacted by late shipments if production needs to be delayed or shutdown *Ceramica* - manufacturer of piezoelectric ceramic materials located in Lincoln, Nebraska; will ship materials to Bowman using the shipping company selected via the ranking procedure *Workers for DDT (especially Bowman)* – use the materials shipped from Ceramica to make product; they may receive increased salaries or bonuses for higher productivity *Others with Similar Shipping Needs* – people and organizations that need to rank potential shipping companies for on-time delivery may want to use/modify the requested procedure; selling the ranking procedure could mean income to DDT
Non Users	*Shipping Companies* – companies that could be selected via the ranking procedure to ship product for DDT *Pathways Transit (PT)* – shipping company that DDT is no longer working with due to late arrival times; could get selected via use of the ranking procedure in the future if it achieves a better on-time shipping history *Applications Engineering Team* – the team hired to create a ranking procedure; a high-quality ranking procedure could mean continued employment *Devon Dalton's Assistant* – has access to the historical data; might be in communication with potential shipping companies *DDT customers* – want to get their DDT products soon after they place an order

Fall 2008 student responses to the individual questions and their GTAs' assessment of their responses were again analyzed (Salim & Diefes-Dux, 2010, Salim & Diefes-Dux, 2012). While GTAs improved in their evaluation and assessment of students' responses (Salim & Diefes-Dux, 2010, Ghazali & Diefes-Dux, 2012), improvement in students' ability to answer these questions was modest (Salim & Diefes-Dux, 2012). Students' continue to be confused about the terms client and direct user, they continue to under specify what the direct user needs, and their focus is still a mix of big-picture and task-level issues. Further refinement of the instructional system around problem formulation was clearly needed to address these research findings.

Further literature review helped us continue to understand our findings by bringing in ideas concerning expert-novice differences with problem formulation (e.g. Atman, Yasuhara, Adams, Barker, Turns, & Rhone, 2008; Cross, 2004), the Structure-Behavior-Function framework (e.g. Chan, Wu, & Chan, 2010), and the interplay between the two (e.g. Hmelo-Silver, & Pfeffer, 2004). This has helped us understand the likely trajectory of student learning and development of skills related to problem formulation. In essence, novices spend less time at problem formulation compared to experts and tend to provide less detail in their problem formulations.

In academic year 2011-12, more research-informed changes were made. The formal instruction and the individual questions were revised to differentiate two levels of problem formulation: big-picture problem scoping and task-level problem identification. The individual questions were expanded to include two big-picture problem scoping questions (Appendix A, Problem Formulation a & b) and three task-level questions, including a revised Q3 (Appendix A, Problem Identification c-e). This set of questions essentially formalizes the Fall 2008 faculty member led approach to answering the original Q1 to Q3 questions. Student must now (1) list the stakeholders they find in the problem and describe how each stakeholder is related to the deliverable and (2) consider issues that might arise for the stakeholders when their solution is implemented. The revised Q3 directs students to consider the immediate task and the data they are provided with the problem and consider what might be complex about solving the problem.

In addition to these changes, the individual questions were moved to a homework that is completed before teams meet to begin to create their MEA solution. This ensures that (most) students have read and thought about the problem before team dynamics take over and potentially marginalize some team member's contributions. The team consensus piece was also formalized so that teams must submit a single response to Problem Identification questions c and d before moving forward with team solution development. Further, student and GTA training was bolstered to incorporate training on the two levels of problem formulation.

6. Dimensions for Assessment of Team Solutions

From 2002 to 2006, the assessment strategy for evaluating student team solutions to MEAs evolved slowly as the implementation of MEAs in such a large course stabilized. During this period, there was a reliance on the Quality Assurance Guide (QAG) (Table 4) developed for secondary mathematics educators (Lesh & Clarke, 2000). This single-dimension guide focuses on the extent to which solutions address the client's need and are shareable, reusable, and modifiable. This guide was very difficult for GTAs to use because the QAG is not specific to particular MEAs. The GTAs were unclear on what specifically to look for in student work. They struggled to reliably assign a single score to student team work, and they were uncomfortable doing so.

A rubric that is valid, representing an authentic assessment of engineering work products, but also reliable in a large scale implementation with multiple TAs providing feedback and assessment was desired. Through the use of an engineering expert panel, aspects of solutions to open-ended problem that practicing engineers care about when assessing work products were identified and translated into a generic rubric (*MEA Rubric*) for use with any MEA (Diefes-Dux, Zawojewski, & Hjalmarson, 2010). A GTA panel helped refine this rubric for practical classroom use (Diefes-Dux, Zawojewski, & Hjalmarson, 2010). Through iterative cycles of classroom implementation and study of the use of the *MEA Rubric*, a four dimension model for assessing team solutions to MEAs emerged (Table 5). These dimensions operationalize the original QAG terminology and intent and provide a basis for instruction and feedback on mathematical modeling. For each MEA implemented in the first-year engineering courses, an *Instructors' MEA Assessment/Evaluation Package* (*I-MAP*) was then developed. An *I-MAP* is a MEA-specific guide for assessing and evaluating student work along the dimensions of the *MEA Rubric*. Each dimension of the *MEA Rubric* is described in Table 5 with reference to the essentials ideas (core elements of performance) from the *I-MAP* for the *JITM* MEA.

The research-informed evolution of the *MEA Rubric* and subsequent implementation of the rubric has impacted classroom instruction in a variety of ways. Research findings pertaining to each dimension of the rubric are summarized in the sections that follow. Changes in classroom instruction as result of these findings are also discussed.

Table 4. Quality Assurance Guide (Ways to evaluate and respond to students' work) (Lesh & Clarke, 2000, p. 145)

Performance Level	**How useful is the product?**	**What might the client say?**	**What questions should be asked?**
Requires Redirection	The product is on the wrong track. Working longer or harder won't work. The students may require some additional feedback from the teacher.	*"Start over. This won't work. Think about it differently. Use different ideas or procedures."*	To assess students' work, put yourself in the role of the client. To do this, it's necessary to be clear about answers to the following questions. 1. Who is the client? 2. What conceptual tool does the client need? 3. What does the client need to be able to do with the model? Then, the quality of students' work can be determined by focusing on the question – *How useful is the model for the purposes of the client?*
Requires Major Extensions or Refinements	The product is a good start toward meeting the client's needs, but a lot more work is needed to respond to all of the issues.	*"You're on the right track, but this still needs a lot more work before it'll be in a form that's useful."*	To assess usefulness, and to identify strengths and weaknesses of different results that students produce, it would be helpful to consider the following questions. 1. What information, relationships, and patterns does the model take into account? 2. Were appropriate ideas and procedures chosen for dealing with this information? 3. Were any technical errors made in using the preceding ideas and procedures?
Requires Only Minor Editing	The product is nearly ready to be used. It still needs a few small modifications, additions, or refinements.	*"Hmmm, this is close to what I need. You just need to add or change a few small things."*	But, the central question is – *Does the product meet the client's needs?*

6.1. Mathematical Model Complexity

Investigations into the mathematical models students develop consist of looking at students' accounting of the various information and data provided. These investigations reveal students' misconceptions and their depth of understanding of relationships between elements. This "thought-revealing" (Lesh, et.al, 2000) aspect of MEAs allows instructors to address students' deficiencies immediately or in subsequent course offerings.

Research on students' mathematical models in response to the *JITM* MEA consisted of identifying the statistical and mathematical measures used (Carnes, Cardella, & Diefes-Dux, 2010) in three iterations of solution development. This analysis revealed that some students use mean, and only mean, to rank the shipping companies. Student teams do this despite the fact that the mean late times of the shipping companies are only minutes apart, making differentiation between the ranks meaningless in practical terms. Further, many student teams failed to account for the distribution of the shipping company data. Preliminary findings from current research on GTA feedback reveal that these student teams fail to account for distribution despite feedback prompts from instructors to do so in a subsequent modeling iteration.

Table 5. *MEA Rubric* dimensions used in assessment of student work (Diefes-Dux, Zawojewski, Hjalmarson, & Cardella, 2012)

Dimension of *MEA Rubric*	**Core Elements of Performance (Adapted from the I-MAP and GTA Training)**
Mathematical Model Complexity: A mathematical model may be in the form of a procedure or explanation that accomplishes a task, makes a decision, or fills a need for a direct user. A high quality model fully addresses the complexity of the problem and contains no mathematical errors.	In the *JIT Manufacturing MEA*, patterns of late arrival are important. The procedure needs to look past measures of central tendency and variation to the actual distribution of the data; attention should be paid to the frequency of values, particularly minimum and maximum values. The mathematical model must take into account all types of data provided to generate results. If any shipping company's data, in entirety or parts, are not used in the model, a *reasonable* justification must be provided.
Generalizability	
Re-usability: The procedure can be reused in new but similar situations. Therefore, the direct user is identified, as well as the user's needs in terms of the deliverable, criteria for success, and constraints. An overarching description of the procedure is provided and assumptions and limitations for using the procedure are clarified.	The response indicates or provides: • Who the direct user is (DDT's Logistic Manager) • What the deliverable is (a procedure for ranking shipping companies) • Criteria for success (a ranking procedure to rank order companies from best to least able to meet DDT's timing needs) • Constraints • An overarching description (dependent on the model developed) • Assumptions and limitations for use (dependent on the model developed)
Modifiability: The procedure is easily modified for use in different situations. Therefore, the procedure contains acceptable rationales for critical steps in the procedure and clearly states assumptions associated with individual procedural steps.	When teams use any statistical measures, these must be justified by explaining what these measures tell the user. When developing intermediate rankings or weighting methods, these must be justified.
Share-ability: Based on the given description of the procedure, the user can apply the procedure and replicate results from the given data set. Therefore, all of the results from applying the procedure are provided to illustrate its use, and the procedure is easy for the user to understand (clear, complete, and economic).	• If the mathematical model is described in enough detail, then one should be able to apply it to the given data and generate results that match those reported in the team response. • Rankings and results are provided in the team description of the model. • Results are reported to an appropriate number of significant digits. • The description of the mathematical model should be free of distracting and unnecessary text.

It was surprising that student teams do not connect the *JITM* MEA to the regular classroom instruction. The *JITM* MEA is implemented either following or in parallel with traditional lectures and homework assignments on the topic of descriptive statistics. Through this topic, students learn to compute standard statistical measures (e.g., mean and standard deviation) and create histograms using Excel and MATLAB. Students also learn to compare and contrast various distributions. So, it appears that students have difficulty transferring this content knowledge to their solutions to the *JITM* MEA. This hesitancy of students' to use variation is noted in the literature review of students' development in understanding variation when comparing distributions by Ben-Zvi (2004).

We hypothesize that a number of things are happening that prevent students from moving past measures of central tendency when solving this problem. First, students appear to be reducing the MEA to a mathematics problem and dismissing the problem context. So these student teams do not attend to the insignificance of mere minutes of difference between shipping company late time means. Second, a number of students believe that mean is a measure of consistency, and, in fact, state this as their justification for using mean in their ranking procedures. These students believe they are already addressing an aspect of variability. Third, student teams that receive feedback that includes a prompt for distribution may believe they have sufficiently accounted for distribution through an accounting of standard deviation in their models. Finally, students may have difficulty finding ways to quantify histogram information in ways that work in their models.

In 2011-12, a number of approaches have been taken to help students engage in the context, understand mean and standard deviation, and consider ways of quantifying distribution. First, the new series of problem formulation questions are used to raise students' awareness of the problem context. In the case of *JITM* MEA, it is expected that students will explore the big ideas of just-in-time manufacturing and consider these ideas with respect to their impact on stakeholders. A new study of student teams' attention to the context during the development of their models, need to be conducted to learn whether this problem formulation step is sufficient to help students keep the context in mind.

Second, additional time is spent in a lecture activity. Faculty has students draw four different distributions with the same mean and sample size. During this activity, we found that students often cannot move past drawing normal distributions with different standard deviations all centered on the same mean. Many students do not consider skewed, bi-modal, uniform, or highly random distributions. The faculty discusses the students' drawings and those not appearing across the class, emphasizing the shapes of various potential distributions with the same mean. This activity is followed by an individual data generation step after Team Draft 2. Students are instructed to individually develop two data sets that test their team's model in ways that are different from the shipping company data provided in the MEA. Preliminary results from an analysis of this activity (conducted in Fall 2011) indicate that students failed to quantitatively describe their data sets, much less how their data sets were different from those provided or how their model would be further tested by their data sets (Diefes-Dux & Cardella, 2012). A refinement of the activity instructions is being implemented in Spring 2012 to better direct students towards describing their data sets quantitatively. Further research will investigate (1) how students respond to the revised activity and (2) which individual data sets teams retain in the testing of their model for the Team Final Response (they are asked to retain one from each team member) and their reasoning for selecting these data sets.

Third, the descriptive statistics topic has been extended to include the conversion of histograms into cumulative distribution plots to enable quantitative likelihood predictions. Investigations on this content addition will focus on whether and how student teams' include a measure a distribution in their mathematical models.

6.2. Share-ability

The *Share-ability* dimension of the *MEA Rubric* focuses on the presentation of quantitative results, overall readability of the documentation, and conciseness. It has been an ongoing struggle to get student teams to present quantitative results. Results, when available, are often presented to far too many significant figures and without units. Carnes, Diefes-Dux, and Cardella (2011) showed how this issue persists from Team Draft 1 to Team Final Response in an analysis of Spring 2009 student work on the *JITM* MEA.

Lecture material has been developed to discuss the relative importance of the *MEA Rubric* dimensions from the engineer's point of view. In essence, it is explained that a model is only as good as its ability to be used by others. Results are the evidence that a model actually works and that others can use to verify the model works. A high-quality model is compromised by a lack of evidence that it works. The need for quantitative results is re-iterated during peer review as something students should look for in the work of others. For first-year engineering instructors, the presentation of quantitative results must be continuously monitored so that it can be addressed in class or through homework instructions during students' iterative model development for any MEA.

6.3. Re-usability

Re-usability constitutes a bringing together of the task-level problem formulation with an overarching description of the mathematical model and listing of limitations and assumptions for use of the model (Table 5).

Carnes, Diefes-Dux, and Cardella (2011) showed that student teams in Spring 2009 improved in their supply of the necessary description of the problem and its solution following TA feedback. Improvements to the TA training with problem formulation coincided with improved *I-MAP* instructions on how to assess *Re-usability*. Via the *I-MAP* TAs are provided with an explicit list of items that should be included in student teams' solutions. TAs are trained to write feedback that confirms the presence of required items and lists missing items.

We were however concerned to find that peers were not providing equally effective feedback on this dimension (Carnes, Diefes-Dux, & Cardella, 2011). This indicates that students do not know what belongs in this section of their MEA solution documentation, despite the fact that these items are listed in the MEA homework instructions at every iteration point (see Appendix Team Draft 1 memo format).

As of 2011-2012, the dimensions of the *MEA Rubric* are mapped to the memo format presented in the MEA homework instructions (see Appendix Team Draft 1 memo format). It is hoped that this will clarify for students what is expected for each dimension or where each dimension is accounted for in their documentation. This mapping is then used in revised classroom instruction on peer review. This interactive lecture provides a strategy for reviewing another team's work, including what to look for in a complete opening paragraph to the memo (which maps to *Re-usability*). It is envisioned that reiterating what *Re-usability* entails, at a point in time after their first introduction to MEAs, will help students recall what this dimension entails.

6.4. Modifiability

Modifiability is addressed by providing rationales for design decisions. For a MEA solution, this means either rationalizing critical steps in a model for which choices are available or providing justification for hard-coded values embedded in a model. Carnes, Diefes-Dux, and Cardella (2011) showed that 15 out of 50 student teams in Spring 2009 did not provide adequate rationales on their *JITM* MEA Team Final Response. Current research shows that those that did attempt to provide rationales either restate a decision that was made or draw on personal experience.

In response to this finding, new lecture material and an activity was developed for 2011-12 to show students the basis of higher quality rationales. Students are exposed to the idea of evidence-based rationales. On a continuum of quality of rationales, students are shown that rationales based on work experience, problem context, external research, and science or math theory are superior to rationales based on personal experience. The students are then given a prototypical student team solution to a MEA they have recently solved and asked to (1) identify all of the rationales provided in the solution and identify where no rationales are provided but are needed, (2) identify the basis of the rationales, and (3) re-write three rationales at a higher level. Analysis of student work on this activity and their MEA solutions will reveal whether or not this strategy is effective in improving students' ability to rationalize their models.

7. Conclusion

A models and modeling perspective highlights the value of modeling activities for first-year engineering students. Successful execution and subsequent improvement of such activities requires a systems approach to the design of activities, their implementation, and assessment of student work. A design research perspective enables ongoing improvement to a system nested in a complex classroom setting through the collection and analysis of system elements, such as student work and TA assessments of student work. This paper shows that these perspectives have the power to transform a highly traditional first-year engineering course into a first-year engineering experience that provides students with opportunities to develop higher-order skills necessary for the practice of engineering. In particular, this paper highlights the use and study of MEAs to engage students in problem formulation, to improve their conceptual understanding of descriptive statistics, to encourage them to present quantitative results, and to enable them to provide evidence-based rationales for their design decisions.

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Appendix A. Just-in-Time Manufacturing MEA (Spring 2012 version)

Individual Activity

1. Individually read the company profile and CEO request below.

Company Profile – D. Dalton Technologies

The Bowman and Ceramica Divisions of D. Dalton Technologies develop advanced piezoceramics and custom-made ultrasonic transducers.

D. Dalton Technologies (DDT) was founded in 2000 to advance the ultrasound field using piezoelectric materials. DDT acquired Bowman Transducers, a company that is well known for producing innovative transducers, and Ceramica, a manufacturer of piezoelectric ceramic materials located in Lincoln, Nebraska. These companies were purchased in the summer of 2001 and have each been strengthened by the addition of high-tech equipment and an increase in the number of amply qualified engineers. DDT is the up-and-coming premier supplier of top-quality transducers in the United States.

Through the improved vision of D. Dalton Technologies, Ceramica is broadening its line of piezoelectric materials. Piezoelectric materials convert electrical signals into a mechanical response (as in a speaker) or mechanical signals into an electrical response (as in a microphone). Most piezoelectric materials are compounds of metals and oxides that require precise processing conditions to produce optimum properties. Presently, Ceramica's primary focus is on the expansion of the composite materials product line. Several applications are now under active development with current and potential Ceramica customers. Ceramica is developing a new line of materials that will withstand high temperatures and still retain their polarization. This is an example of one of the exciting new projects in the works for Ceramica.

Bowman, located in Noblesville, Indiana, is also benefiting from the direction and the investment of D. Dalton Technologies. Bowman has added additional transducer design professionals to its engineering staff. Transducers are devices that convert one form of energy into another. The diverse customers of Bowman want custom transducers for products such as sensors that monitor oil well drilling tips, medical instruments such as diagnostic imaging ultrasound, discs for accelerated bone healing and devices for intravascular procedures, and in-home electronic gadgets such as telephones and stereo equipment. Bowman takes extra care to create custom transducers that fit the needs of each of its clients.

D. Dalton Technologies, together with Ceramica and Bowman Transducers, is ready to design and manufacture transducers to fit your specific needs. D. Dalton Technologies understands that progress is made not only by taking advantage of the latest in technical innovations, but also adhering to the best of the "tried and true". Therefore, it is the goal of the company to provide clients with the highest quality customer service and products. Because of the dedication and insight of the president and founder, Devon Dalton, D. Dalton Technologies can honestly say, “Your ideas plus our commitment equals perfect solutions.”

Interoffice Memo

To: Applications Engineering Team
From: Devon Dalton, CEO
RE: Shipping Issues
Priority: [Urgent]

Our company operates a just-in-time manufacturing system. After several years of shipping with Pathways Transit (PT), it has come to my attention that PT has not been meeting our shipping needs. We are having problems with late arrival times. The fact that PT is not consistently arriving at the time they have promised is causing D. Dalton Technologies (DDT) production problems. This means that our Logistics Manager needs a method to identify a new shipping company.

I want to make use of your team's analytical expertise. DDT is small; therefore, we need your team to serve in an engineering project management function on this project. Your team's task is to design a procedure to rank potential shipping companies. My assistant has collected historical data on several potential companies for you. Eight shipping companies have been identified as able to transport materials directly from Ceramica to Bowman. As you know, arrival time of materials is a big issue for DDT. Since the piezoelectric materials are designed specifically for each custom order, it is imperative that the delivery of materials occur just-in-time for Bowman to begin the manufacturing process that uses all of the shipped materials. Because we operate with a small workforce and only one shift, minutes to a few hours can make a difference in our ability to complete devices for our custom applications by our contracted delivery date. This makes arrival time of materials of great importance. We have in excess of 250 data points for each shipping company. At this time, the data for only four companies is available. This data is stored in a file called jit_data_partial.txt. The four shipping companies are Iron Horse Expeditors (IHE), Delphi Shipping (DS), ShipCorp (SC), and United Express (UE). The data is in hours late for shipping runs from Lincoln, Nebraska to Noblesville, Indiana.

Your team should brainstorm different ways in which to analyze the shipping data. Then, your engineering team will use the sampling of data provided for the four shipping companies to develop a procedure to rank the shipping companies in order of most likely to least likely able to meet our timing needs.

In a memo to my attention, please include your team's procedure and the rank order of the shipping companies generated by applying your procedure to the sample data. Be sure to include additional quantitative results as appropriate to demonstrate the functionality of your procedure. Please be sure to include your team's reasoning for the each step, heuristic (i.e. rule), or consideration in your team's procedure.

Please send your complete memo to me by next week.

DD

2. ***Just-in-Time*** (JIT) is a management philosophy that originated in Japan and was put into practice in the 1970s. Its practice was developed and perfected by Toyota.

   Use and document (with proper citations) at least ***two*** external resources to learn ***three*** things about JIT that are relevant to this problem context.

   In the Context Setting box on the MEA 1 interface, list, ***in your own words***, the ***three*** things you learned and ***explain how each is relevant to this problem context***. In the same box, below the three things learned, list your citations using APA format. (For help with APA reference formats, see http://owl.english.purdue.edu/owl/resource/560/01/)

3. Individually, answer the following questions.

   Problem Formulation: Parts a and b ask you to take a big-picture view of the problem.

a. List as many stakeholders as you can think of who may be impacted by the deliverable your team has been asked to create. For each stakeholder, explain the relationship between the stakeholder, the problem, and the deliverable.

b. Your solution will be implemented in the context described here and potentially in other contexts. Describe issues (minimum five) that might arise for stakeholders when your generalizable solution is implemented.

   Here your team has only been asked to consider late shipping times in the development of your solution. What other issues may need to be considered when committing to a shipping company and attempting to operate in a just-in-time fashion.

   Problem Identification: Parts c to e ask you to take a task-level view of the problem.

c. Consider your list of stakeholders. Who is the direct user of the deliverable your team is being asked to create?

d. In a few sentences and in your own words, what does the direct user need? (Remember to describe the deliverable, its function, the criteria for success, and the constraints.)

e. Consider the immediate problem as described and the sample data provided. Describe at least two ideas you have for why this problem might be complex to solve.

<u>Team Draft 1</u>

1. Within your team, compare your answers to the individual questions. Your team must come to consensus on these two questions:

c. Who is the direct user of the deliverable your team is being asked to create?
d. In a few sentences and in your own words, what does the direct user need? (Remember to describe the deliverable, its function, the criteria for success, and the constraints.)

2. In your team, formulate a plan to use the historical data to develop a procedure to rank shipping companies in terms of most likely to meet DDT's timing needs to least likely to meet the timing needs.

   Use the following outline to help organize your team's response and ensure that your team has not forgotten necessary items.

CAUTION: The memo that your team submits should not contain outline formatting when it is complete. The outline below is just a content guide.

Items I A-C are typically all covered in the first paragraph and item II is typically in easy-to-follow numbered steps. Item III could be in a combination of paragraph and tabular form, depending on the nature and quantity of the results generated by your team's solution. (*NOTE: Your team cannot receive a grade higher than a D if you do not present results (Item III). Why? A supervisor and direct user would want to see results. Without results, your team has only attempted part of the task (provided the supervisor and direct user with a solution); your team would not have provided evidence that it actually works.*). Item IV includes any other requested information.

TO: Name, Title
FROM: Team #
RE: Subject

I. Introduction (***Re-usability***)
   A. In your own words, describe the problem. (~2-3 sentences) This should include your team's consensus on who the direct user is and what the direct user needs in terms of the deliverable, criteria for success, and constraints.
   B. Provide an overarching description of what the procedure is designed to do or find – be specific (~1- 2 sentences)
   C. State your assumptions about the conditions under which it is appropriate to use your procedure. Another way to think about this is to describe the limitations of your procedure.

II. List the steps of your procedure (***Mathematical Model***). Provide clear rationales for the critical steps, assumptions associated with individual procedural steps (***Modifiability***), and clarifying explanations (e.g. sample computations) for steps that may be more difficult for the direct user to understand or replicate (***Shareability***).

III. Present results of applying the procedure to the specified data in the form requested. (***Shareability***)

IV. Other requested information

Hint 1: Spelling and grammar are important (***Shareability***). Let Word check for some of these errors. Do realize that Word will not find all of your errors and it will identify some that are not really errors at all. Your team needs to proof-read carefully.

Hint 2: Be sure to give your team's reasoning for the each step, heuristic (i.e. rule), or consideration in your team's procedures. (***Modifiability***)