# Examining Student Learning of Engineering Estimation from METTLE

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**Abstract:** Engineering estimation is the determination of any physical quantity up to a specified level of accuracy. It is an important activity done before and during engineering design. Therefore, engineers need to be able to make estimates, but research suggests that even graduating students are unable to make good estimates. This is because they are not trained in estimation as part of their curriculum. We designed a technology-enhanced learning environment (TELE) based on progressively higher order modelling to train students in engineering estimation. We evaluated the TELE to explore what students learn from it. We found that students learned the various reasoning processes involved in performing estimation, recognized the role of evaluation in estimation and the need for practical considerations in estimation. These results have implications for redesign of our TELE to improve student learning of estimation.

**Keywords:** engineering estimation, technology-enhanced learning environments, modelling

## 1. Introduction

Consider this problem: *"You are participating in an electric car race in which you are required to design an electric car of weight 7 kg with wheel diameters of 4" that can accelerate at 1 m/s$^2$ and traverse a track of 10 m without burning out. Estimate the electrical power needed to achieve this performance and the specifications of the motor you will need."* Engineers often make estimates of, and judgements regarding physical quantities such as this during the design process, in order to establish the feasibility of a design or narrow down the set of design choices. While such estimates are necessary in system design (Linder, 1999; Shakerin, 2006; Dunn-Rankin, 2001) they are hard to make because they involve "mastering the complexity" (Mahajan, 2014) of the system by identifying physical quantities that can be safely neglected. Such estimation is typically used to make a decision that allows one to proceed in the design process when faced with lack of information, resources or strategies.

Research into the differences between practicing engineers and graduating students reveals that there is a marked difference between the performance of the two groups on the quality of estimates for quantities like drag force and energy (Linder, 1999). This indicates that students have very little intuition for these quantities. This is not surprising because as Ferguson observed (Ferguson, 1977) "*The real "problem" of engineering education is the implicit acceptance of the notion that high-status analytic courses are superior to those that encourage the student to develop an intuitive "feel" for the incalculable complexity of engineering practice in the real world."* Linder differentiates the characteristics of the learning activities of engineering curricula and rough estimation, and demonstrates that the learning that happens in current engineering curricula do not prepare students for rough estimation activities. This is because these learning activities are primarily well-structured in nature while rough estimation is ill-structured. The ability to solve well-structured problems does not transfer to the ill-structured problems (Jonassen, 1997). Therefore, it is important for instruction to be tailored to developing students' estimation skill explicitly. A literature survey to identify teaching-learning strategies for engineering estimation showed that while there are some guidelines and activities to teach estimation (Mahajan, 2014; Linder, 1999; Shakerin, 2006; Dunn-Rankin, 2001), there is a lack of evidence-based teaching-learning strategies for engineering estimation.

Research suggests that engineering problems are solved by a combination of model-based reasoning and the use of external representations (Nersessian, 2009; Aurigemma et al, 2013). In particular, the use of external representations helps experts detail out their mental models during the estimation process (Kothiyal et al, 2016). Thus estimation is an instance of model-based reasoning

(MBR). In this paper, we present our solution to support the learning of engineering estimation, a technology-enhanced learning environment (TELE) called Modelling-based Estimation Learning Environment (METTLE). In METTLE, students solve estimation problems by following the phases of the MBR estimation process. We describe our design of METTLE and its evaluation with the research goal of exploring what and how students learned about engineering estimation after interacting with METTLE. We conducted a lab study wherein students interacted with METTLE and we interviewed them in order to explore their understanding of what estimation means and how it is done. The results give us insight into how to refine METTLE to better support students' learning of estimation.

## 2. Related Work

Estimation is a type of ill-structured problem (ISP) (Jonassen, 1997) and so, we draw from literature on teaching-learning of ISP solving in order to design a TELE for estimation. Jonassen proposes an instructional strategy for learning ISP solving, with affordances and scaffolds for each step of PS depending on the cognitive requirements of the step. Several researchers have empirically evaluated the role of various affordances and scaffolds on ISP solving skill. For example, the use of concept mapping in the learning of problem solving has been investigated extensively (Stoyanov & Kommers, 2006; Hwang et al, 2014; Wu & Wang, 2012) in TELEs and found to be effective for learning. Similarly, the role and nature of question prompts (Ge & Land, 2004) as a scaffold in the learning of ISP solving in a TELE and from a teacher has been studied and found to improve learning significantly.

As estimation is a type of engineering problem, we also consider research-based teaching-learning strategies for engineering problem solving (Woods et al, 1997; Kalnins et al, 2014; Shekar, 2014; Zheng, 2013). The majority of these strategies are based on using problem-based learning (PBL) and project-based learning (PjBL) in engineering classrooms (De Graaf, 2003; Perrenet, 2000). The salient feature of these pedagogies is a problem or project as a means of organizing student learning of concepts and skills, with emphasis on the learning process, self-directed learning and collaboration (De Graaf, 2003). Among these strategies, there have been variations in which students receive instruction in improving specific problem-solving skills along with, or prior to, attempting the problems (Woods et al, 1997; Pimmel, 2001). This is necessary because PBL/PjBL assumes that students possess or will develop in the process of solving, the necessary problem solving skills, and this may not always be true (Woods et al, 1997). What is needed is to identify target skills and give opportunities to students to practice the skills and receive feedback until they have achieved mastery (Woods et al, 1997). Use of question prompts while students solve engineering problems has been found to improve students' problem solving skills (Zheng, 2013). Another strategy (Wankat & Oreovicz, 2015) focusses on developing students' problem solving method by using a seven step problem solving strategy to design instruction. Students learn problem solving by systematically applying the strategy on different types/levels of problems in order to become aware of their problem solving process.

Several authors have recognized the importance of estimation for engineers and the need for developing the estimation skill explicitly among student engineers (Mahajan, 2014; Linder, 1999, Shakerin, 2006; Dunn-Rankin, 2001). They have presented guidelines for activities that can support the learning of rough estimation. Linder recommends teaching conceptual knowledge of estimation, increasing the number of rough estimation activities done by students and including learning activities that have characteristics similar to those of rough estimation activities such as engineering analysis, sketching, building, explaining and diagnosing, where students have to select relevant information and balance different types of information. Mahajan uses a five-step approach in his course titled "The Art of Approximation in Science and Engineering" with the steps a) describe an estimation tool like divide and conquer b) illustrate its application with an example from a particular domain, c) repeat with examples from different domains d) provide practice in the usage of a tool in practice problems and e) present more practice problems without clues as to which tools to use so that students learn to select which tools to apply. In addition, Dunn-Rankin suggests that whenever possible numerical values be tied to everyday physical objects and activities. This helps students develop an intuition for reasonable values for physical quantities. Shakerin recommends that students be encouraged to practice estimation and be made aware of its importance through short exercises with everyday objects and activities.

Literature on teaching-learning of engineering and general ISP solving offers us research-based guidelines on what types of scaffolds and affordances might support the learning of an ill-structured problem such as engineering estimation; for example, the use of question prompts. However the specific activities, scaffolds and their sequencing in an effective LE for estimation is not clear from this literature. On the other hand, within literature on engineering estimation, there are several heuristics and strategies that instructors have used, but they have not been substantiated by empirical evidence. In this work, we bridge this gap by designing and empirically evaluating a TELE for engineering estimation. In the next section, we describe the theoretical basis of the design of the TELE.

## 3. Theoretical Basis of METTLE

### *3.1 Progressively Higher Order Modelling-Based Estimation*

By studying experts solving estimation problems, we found that (Kothiyal et al, 2016) experts begin the estimation process using their preliminary mental models of the given problem and detail them until the model is sufficiently rich enough for the estimation purposes (Figure 1). This first model is based on understanding how the system functions (functional model) and the detailed qualitative and quantitative models are developed by mentally simulating the initial mental model. Further, we found that experts periodically evaluate the utility of their models for estimation and revise them if they do not meet this criteria. Hence it is desirable to guide novices through a similar process where they begin with their own mental models, build, evaluate and revise them to create richer and more useful models by interacting with appropriate affordances and scaffolds in the TELE. For these reasons, we chose progressively higher order modelling as the pedagogical foundation of METTLE. Research has shown this pedagogy to be an effective strategy to improve students' inquiry and learning (Sun & Looi, 2012; Mulder et al, 2011). We call this MBR learning design as *"Progressively Higher Order Modeling with Evaluation and Reflection"* (ProHOMER). There are five tasks in ProHOMER namely, functional, qualitative and quantitative modeling, calculate and evaluate. The three modeling tasks each have sub-tasks of create a model, evaluate the model and reflect on the modeling activity. In the calculate phase, students choose and evaluate the reasonableness of values, and calculate the estimate. In the evaluation task, students evaluate whether their estimate is reasonable by two standards. Finally students reflect on the entire estimation process.

In order to develop engineering estimation skill, TELE must provide affordances for and scaffold the creation of all three models, namely, functional, qualitative and quantitative models for estimation (Sun & Looi, 2012; Mulder et al, 2011). Therefore, the TELE must trigger and support students' mental simulation processes. Literature suggests that students have difficulty in doing mental simulation (Hegarty et al, 2003) and tend to proceed directly to building equations (Wankat & Oreovicz, 2015). Hence we propose the affordance of a fully manipulable simulation of the problem system (Lindgren & Schwartz, 2009). Such simulations have also been used in a number of modeling TELEs (Govaerts et al, 2013; Swaak & De Jong, 2001) to improve students' modeling abilities.

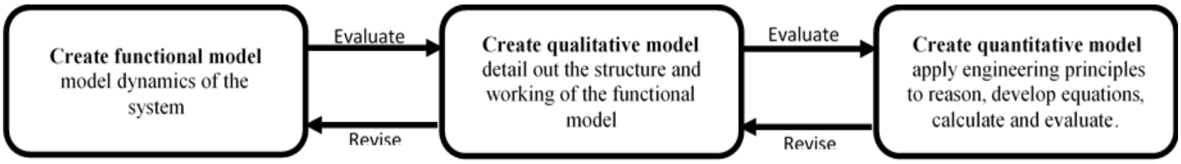


Figure 1. Phases of the Estimation Process - reproduced from (Kothiyal et al, 2016)

### *3.2 Scaffolding Modelling-Based Estimation*

In order to learn estimation, students need to actively engage in deliberate practice of the MBR estimation process (Ericsson, 2008). Their interaction with TELE has to be carefully designed such that the TELE scaffolds their doing and learning process. There are several frameworks which define the types of scaffolds needed for complex, ill-structured tasks in TELEs (Basu et al, 2015; Quintana et al, 2004; Kim & Hannafin, 2011). Further, students need scaffolds to learn the MBR estimation process and for evaluation and reflection.

Research has shown that external representations such as concept maps (Hwang et al, 2014) knowledge maps (Lee et al, 2005), dual maps (Wu & Wang, 2012), conceptual organizers, process maps, argument maps and causal maps (Quintana et al, 2004; Slotta & Linn, 2009) are effective in order to learn ill-structured problem solving and scientific inquiry. These representations facilitate process management, model building and sense-making. In order for students to manage and learn the three phased MBR estimation process, we propose a visual representation of the process, which simultaneously shows the overall structure of the estimation process and the details of each task and sub-task, in order to give students a “forest and trees” view of the process.

The role of evaluation and reflection on the solving of ISPs such as engineering estimation has been discussed extensively in literature (Jonassen, 1997). In addition, students must learn to think about certain aspects specific to estimation problems such as whether the estimate is reasonable by various standards, which parameters can be safely ignored and how to choose numerical values while doing calculations without compromising on accuracy (Mahajan, 2014). Research has shown that students must be scaffolded in order to articulate and reflect on their inquiry (Quintana et al, 2004) and problem solving (Kim & Hannafin, 2011). Elaboration question prompts have been successfully used in ill-structured problem solving to get students to elaborate and explain their thinking (Ge & Land, 2004). Therefore, we introduce a sub-task in each modelling task wherein students evaluate their models for their utility to give the desired estimate and plan the next modelling tasks, as we had also observed with experts. We use question prompts in order to get students to think about their models and estimated values, the specific aspects of estimation problems and the MBR estimation process.

## 4. Design of METTLE

In METTLE students solve estimation problems by doing the five tasks of the ProHOMER learning design. The current version of METTLE has the following problem which students solve using the ProHOMER pedagogy: *“You are participating in an electric car race in which you are required to design an electric car of weight 7kg with wheel diameters of 4” that can accelerate at 1m/s^2 and traverse a track of 10m without burning out. Estimate the electrical power needed to achieve these specifications.”* Students have the option of doing the tasks in any sequence they wish and they may iterate and redo tasks until they are satisfied that they have passed the evaluation check for their numerical value and obtained a good estimate. Once the student selects a task, he/she has to do all the sub-tasks of that task before proceeding to the next task. After solving a problem, they reflect on their estimation process. There are affordances available for creating the models and question prompts for evaluation, planning and reflection. In addition, METTLE has general purpose tools for information, drawing and taking notes, simulating the system, mapping the estimation process and a calculator, which are always available to the student. The key features are described below.

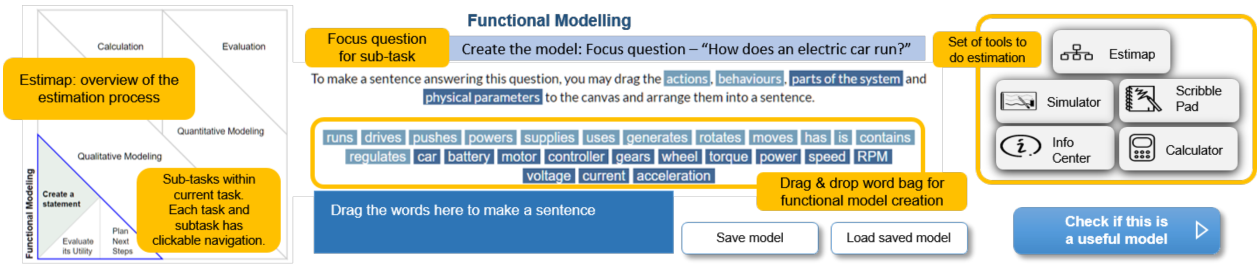

Figure 2. Estimap depicting the progressively higher order modelling tasks and a modelling sub-task

1. Estimap: This is a clickable map (Figure 2) depicting the five tasks of the ProHOMER design. The student can click on any task to see its sub-tasks and begin doing the task. The Estimap is the central process management feature from where the student chooses tasks and thus his/her solution path.
2. Modelling tasks and sub-tasks: Each modelling sub-task (Figure 2) has a focus question and a modelling affordance. For example, the focus question for “Create the functional model” is, *“How does an electric car run?”* The modeling affordance for this task is a drag-and-drop word bag from where the student can select words to create a sentence answering the focusing question, thus

creating the functional model. The modelling affordance for qualitative modeling is a causal map creator and for quantitative modelling it is a drag-and-drop equation builder. The evaluation and planning sub-tasks have a series of question prompts that students have to answer. For example, the question prompt for "Evaluate the functional model" is *"Does the model describe how power is generated and used in this system? Explain."*
3. Calculation task: In this task, the student selects numerical values for parameters in their equation and calculates the power estimate. Students are prompted to think about the "reasonableness" of the numerical values and justify them.
4. Evaluation task: In this task, the student evaluates whether their final estimate is of the right order-of-magnitude and comparable to other known values by answering a series of question prompts such as, *"What order of magnitude of power do you expect is needed to run a car? Is the power you determined of the expected order of magnitude? If not, what could be the reason?"* The students use the prompts to self-assess their estimate and are not provided any feedback by METTLE currently.
5. Simulator: This consists of a variable manipulation simulation (Fig 3) showing the problem system (a in Fig 3), the parameters affecting power in the system (c in Fig 3) and graphs showing the variation of power with each of these parameters (d in Fig 3). The parameters are presented to the student one-by-one in order to constrain their exploration productively (b of Fig 3).

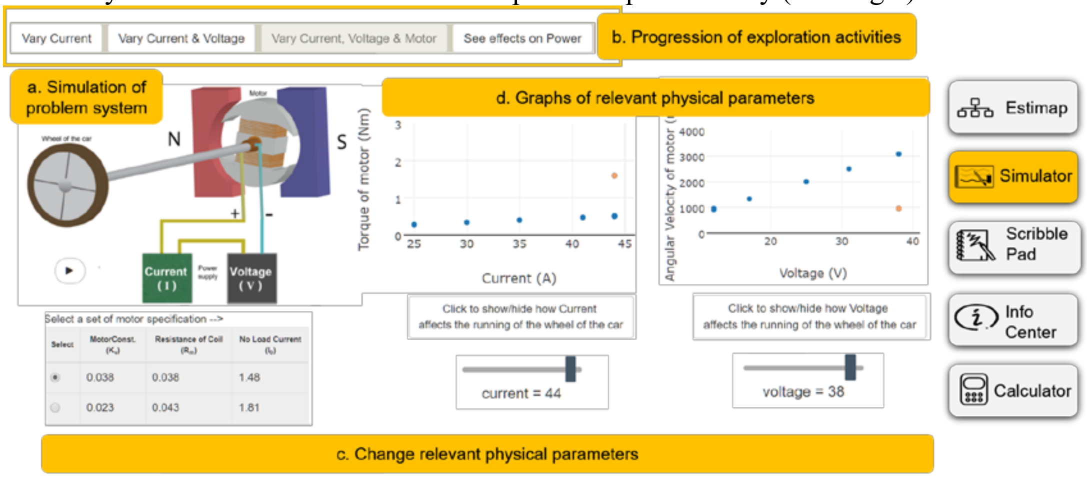

Figure 3. Simulator

6. Scratch Pad: In this space students can take notes and draw while they read or use the simulator.
7. Info Center: This space has reference material including documents/webpages/videos for the student to familiarize themselves with the problem system.
8. Reflection activity: In this activity, the student answers a set of question asking them to reflect on their own problem solving process, the tasks which they did and the sequence in which they did them. An example question is, *"Why did I need to do all these steps (of estimation)?"*

## 5. Research Method

For this evaluation of METTLE our goals are (1) to explore what students learned about engineering estimation and (2) to understand how the features in METTLE enabled this learning. This exploration is necessary in order to identify the additional features and learning activities necessary in METTLE to improve student learning of estimation. Specifically, this study answers the research question, "What and how do students learn about engineering estimation after interaction with METTLE?"

### *5.1 Research design and participants*

As the purpose of this study is exploration, we collected qualitative data in order to examine the nature of the learning. We performed a lab study and participants were eleven students (one female) from second year undergraduate engineering programs, eight from Mechanical Engineering and one each from Aerospace Engineering, Chemical Engineering and Engineering Physics. They were selected by purposive sampling in order to cover a range of backgrounds - departments and engineering curricula –

in order to increase the likelihood of observing diverse aspects of learning. Further, we had a selection criteria that they had all participated in some non-curricular technical activities such as engineering design competitions. The reason was that we had earlier found that solving estimation problems requires a fluidity with application of engineering concepts (Kothiyal & Murthy, 2015) which develops with technical experience and we did not want lack of this fluidity to be a barrier in the development of the estimation skill. The average age of students was 20 years and they were familiar with the use of computers through other courses and labs in their curriculum. One participants' data was not used as the audio recording was of poor quality and could not be transcribed.

### *5.2 Data Sources*

We collected multimodal data including (i) individual student semi-structured interviews after their interaction with METTLE (audio-taped and transcribed) (ii) Screen recording of students' interaction METTLE using the screen capture software CamStudio (http://camstudio.org/) (iii) Student generated artefacts during their interaction with METTLE (iv) Video recording of the student while they worked in METTLE. We answered our research question by analysing student interviews and using the screen recording, student artefacts and video to understand and elaborate on participants' interview responses.

### *5.3 Procedure*

The overall procedure for the research study consisted of the following steps:

- Initial briefing: We briefed participants about the study and its objectives and their consent was obtained for recording their audio, video and computer screen.
- Pre-test: Students solved an estimation problem on paper, independently and without any researcher guidance. However they were allowed to use the Internet to search for resources/information/concepts that they needed. They were allowed as much time as they needed to solve the question.
- Interaction with METTLE: Students interacted with METTLE and solved one estimation problem. During this interaction they were not allowed to use the Internet; however they were free to ask the researcher any questions regarding how to use METTLE or how to solve the problem in METTLE.
- Individual semi-structured interview: After the interaction, we interviewed students using a stimulated recall protocol wherein their screen capture was played back to them and we asked them to describe what they did at each point in the solving process and reasons for their actions. In addition, we asked them questions about the nature of estimation and the estimation process.

### *5.4 Data Analysis*

We employed thematic analysis (Braun & Clarke, 2006) in order to analyze our data and answer the research question. Thematic analysis is an appropriate method for this research question because our goal is to explore the range of estimation learning experiences existing within our data and the features of METTLE which enabled these experiences. The thematic analysis was done by the first author of this paper, a trained researcher in qualitative methods in Educational Technology. Following the methods of inductive thematic analysis we first transcribed the interviews and familiarized ourselves with the data. At this stage, in order to get a better understanding of student responses and their context, especially when they referred to their actions or created artefacts in METTLE, we studied the relevant screen capture, video or artefacts and added these annotations to the transcripts. Then we generated initial codes across the entire data set and collated related codes into categories and themes. Next we reviewed the themes against the raw data for consistency and generated an analysis map. Finally we refined our themes by examining their details and created clear descriptions of them.

## 6. Results

We found three themes in students' learning of estimation, elaborated below: (i) estimation is an MBR process (ii) evaluation is necessary for estimation (iii) estimation requires many practical considerations

1) Estimation is a model-based reasoning process

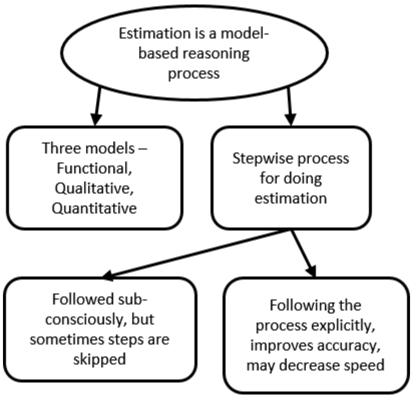

Figure 4. Map of theme 1

Almost all students understood that estimation is a MBR process with three modelling phases of functional modelling (understanding the system), qualitative modelling (identifying the relationships between parameters) and quantitative modelling (forming an equation) that must be done stepwise as described here by S4, *"You first build up a functional model, that you think of, you only imagine right, imagine the moving parts, like what goes where, what happens when, what pushes what and all sorts of things. You kind of think of an imaginary model, you try to think of an animation, and then you try to get to the various relationships between the quantities, the, qualitative modelling shows exactly that, then the quantitative modelling, there you actually start writing down the equations and tinkering around with them,"*

Further students realized that they typically follow this process only sub-consciously, and so tend to skip steps as mentioned by S2, *"…the sequence I would say, actually, I always try to follow the sequence in some or the other way, like I generally try to follow the sequence, I might usually miss the qualitative part, but after understanding the requirements, I generally jump to the mathematical part."* Also, students recognized that following the process explicitly would improve accuracy in case of unfamiliar problems, but decrease speed in the case of familiar problems as explained in this quote from S3, *"…but if there is something, which I think I don't know much about that, then, now, I think I should prefer this way, where I would make a model and everything, but, otherwise, if I know the system well, then, I think I will go with that, because, I think that is much, like that would save time for me."*

Students reported that the ProHOMER structure presented in METTLE, via the Estimap, helped them recognize that estimation is an MBR process as described by S1, "*So, I went through this* [pointing to Estimap] *so I knew that evaluation needs to be the last and so ...functional modelling was something which I found to be the best part to start with because you need to know how a car runs. Before solving a problem I should know that. After that the qualitative and then the quantitative and the calculation and evaluation.*"

2) Evaluation is necessary for estimation

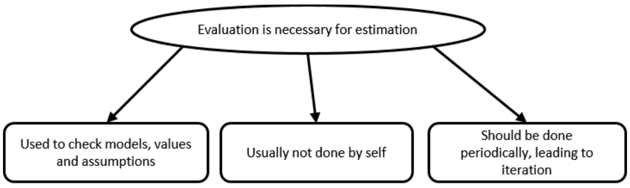

Figure 5. Map of Theme 2

Students recognized that evaluating the models, parameters and values, checking whether obtained estimates are reasonable and realistic and verifying their intuition, assumptions and approximations is necessary in order to obtain better estimates as exemplified in this quote from S5, *"I think just that the evaluation part was very critical, because, if that is not there, we might not be able to identify where we have gone wrong at all, and that helps you go through the cycles faster,"* Further they also observed that when estimating on their own they usually do not evaluate as S7 mentioned, *"Okay, yeah, most of the times when we solve the question, we get an answer, we don't think that way, that can it be that much or no? But yeah, maybe after solving this, after writing this answer, we would go back and think that, no it can't be that much and maybe we should do it again."*

Students recognized that the evaluation questions at specific points in the ProHOMER pedagogy, provided by METTLE were critical in getting them to evaluate and subsequently make revisions in their solution if necessary. This is exemplified by this quote from S1, *"I wouldn't have evaluated it at any step or something like that. So that's where the evaluation part helped me out. It helped me... it stopped me at the crucial places and made me decide like what I have done is right or not.*" However, while students learned the need to evaluate periodically and the questions they must ask themselves while evaluating, their responses show that their numerical evaluations were often inaccurate, perhaps because of their limited knowledge and experience. For instance, students often were unable to evaluate whether a particular value was of the right order of magnitude or not.

3) Estimation requires many practical considerations

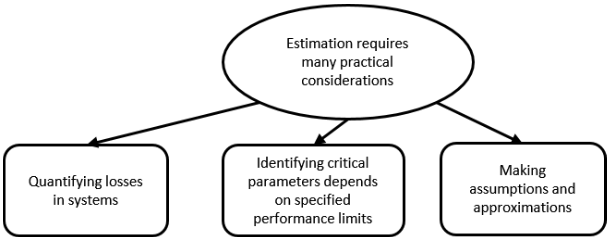


Figure 6. Map of Theme 3

Students recognized that doing estimation requires thinking of several practical aspects of engineering problems. One of these is quantifying losses, which they have difficulty understanding, as S7 describes: *"I didn't even know that there were two different things, we are considering the losses, I didn't know that... that should be made clear that there are losses considered and by what factor is the difference between the input and output power."* Students observed these differences in the simulator, however they were unable to quantify them suitably as seen in their choices of values during calculation.

Students observed that in order to decide which parameters are critical, they need to understand the limits of system performance when it is actually working. As S2 says, *"So, it depends on what is critical, in the system where I want to put it, so, if I were to say, the current in the system at certain time, should not exceed the maximum current value, then I cannot go with average value, I need to know that at all times the current is below the Imax, it should not be that current is below the Imax, so, it becomes, a system constraint, that in the system which I want to put it, I cannot have something, like an average is below the constraint, but instantaneous can cross it, so, I think my system will decide how I would use it."* Making such judgements requires experience with similar systems and students often struggle with this as was seen in their choices of values while calculating estimates.

Finally students understood the need to make assumptions and approximations because estimation does not require precision, but speed. However the assumptions and approximations should be reasonable in that they do not cause large errors in the estimate. Students, however, are unable to make these judgements and may end up making inappropriate assumptions for the wrong reasons (such as ignoring air drag when it cannot be), as S5 says, "*Umm, because I think that the order of those terms is complex. Like when we were trying to study for them, I think the coefficient of drag that you have to calculate, that depends on a lot of things, and to calculate that I need lots of data, so, I left them out.*" The evaluation questions in METTLE alerted them to these considerations, however METTLE did not help them make better judgements as seen from their responses to the evaluation questions.

## 7. Discussion and Conclusion

The goals of this evaluation of METTLE were to explore what and how students' learned after interacting with METTLE. In order to answer our research question, we did thematic analysis of the transcripts of student interviews annotated with their created artefacts, and on and off screen actions during problem solving with METTLE. We identified three themes in students learning namely, (i) estimation is a MBR process (ii) evaluation is necessary for estimation and (iii) estimation requires many practical considerations. The analysis also gave insights into how students learned these aspects from interacting with METTLE. Students described the role of the "Estimap" in making the MBR process explicit and this is consistent with the benefits of external representations for process management documented in scientific inquiry (Quintana et al, 2004) and problem solving (Hwang et al, 2014). Also, students were not inclined to apply all the steps of this MBR process for problems that they perceived to be straightforward. Despite the focus questions of the modeling and evaluation sub-tasks, we found that if they were familiar with the problem, students skip the initial steps and jump to equation building, as reported in literature (Wankat & Oreovicz, 2015). This shows that additional scaffolds are necessary in METTLE in order to trigger students' cognitive mechanism of mental simulation to ensure that they begin with functional modelling regardless of their familiarity with the problem.

Students explained that the periodic evaluation questions in METTLE helped them in learning to periodically evaluate their models and values, and the specific structure of the evaluation question guided them regarding what to consider while evaluating their models. For example the question, *"Does your equation relate power to the speed of the car?"* highlighted to students that they should think of the speed of the car as one of the parameters. This result is in agreement with research into the role of question prompts (Ge & Land, 2004) in ISP solving. However, the evaluation questions for numerical values were insufficient for students to learn how to select numerical values. This is because this requires extensive experience and intuition of similar objects and values (Mahajan, 2014). For instance, many students were not able to evaluate what the power required by the electric car would be compared with the power required by a vacuum cleaner because they were unfamiliar with the power of the latter. As recommended in literature, we propose to add activities and additional scaffolds in order to develop students' skill in choosing and evaluating numerical values, (Linder, 1999; Mahajan, 2014).

Finally, students recognized that estimation requires them to think about many practical aspects, again due to the questions in the evaluation and plan sub-tasks of each modelling phase. But it appears that these questions were insufficient for them to learn how to reason about these practical aspects. This was evident from student generated artefacts in METTLE; students were unable to quantify the losses in the system, justify appropriately why some factors like friction and air drag can be ignored or decide which parameters are critical and which are not. This is because such reasoning is based on experience with similar systems and operating conditions, and the current version of METTLE does not have any guidance on how to think about these aspects nor do students have any exposure to such problems in their engineering curriculum (Mahajan, 2014). We will add scaffolds and activities in METTLE to train students in reasoning about the practical aspects of estimation.

Together these results offer some guidelines to teachers who want to teach estimation in the classroom. Students learn estimation by learning to apply the three-phased MBR process which begins with functional modelling by mental simulation. Mental simulation is a cognitive tool which can enable students to visualize the working of the entire system and how different parameters "flow" inside the system. Teachers can scaffold their mental simulation by providing appropriate question prompts to students which guide them to visualize the layout of the system, think about how it works, what is the mechanism that drives it, what are the aspects that you can control and so on. Further teachers should intermittently prompt students to evaluate their models and values. In order to develop students' sense of numerical values, teachers must make them do several small activities of comparing values of commonly used physical parameters such as power, force, etc. Finally, doing several such engineering problems will improve students' ability to reason about the practical aspects of engineering problems.

In future work, we will employ these results regarding what and how students learned in order to understand the cognitive mechanisms that support this student learning. We will do deeper process analyses of student actions during the pretest and interactions with METTLE in order to identify the cognitive mechanisms which enable students to use the external representation of "Estimap" in order to understand the MBR estimation process. Further, process analysis will also show us how students approach ill-structured problems and thus, where and what scaffolds can modify this process in order to become more productive. For instance, we can identify where scaffolds are needed in order to trigger students to do mental simulation rather than equation building.

The sample size of this study is small, which is a limitation. However the larger goal of this evaluation is a rich and in-depth characterization of how students learn about estimation in METTLE, and how this learning mechanism can be made more productive. The current results, which are a part of the larger evaluation, reveal the nature of learning that happened in METTLE. Coupled with the deeper process analyses of student interactions, we will develop an account of students' cognitive mechanisms as they learn in METTLE, along with what and where additional activities and scaffolds are needed in order to make learning more effective.

## References

Aurigemma, J., Chandrasekharan, S., & Nersessian, N. J. (2013). Turning Experiments into Objects : The Cognitive Processes Involved in the Design of a Lab-on-a-Chip Device. *J. Engg Edu., 102*(1), 117–140.

Basu, S., Sengupta, P., & Biswas, G. (2015). A Scaffolding Framework to Support Learning of Emergent Phenomena Using Multi-Agent-Based Simulation Environments. *Res. Sci. Edu.*, *45*(2), 293–324.

Braun, V., & Clarke, V. (1996). Using thematic analysis in psychology. *Qual. Res. Psych., 3*(2), 77–101.

De Graaf, E., & Kolmos, A. (2003). Characteristics of problem-based learning. *International Journal of Engineering Education*, *19*(5), 657-662.

Dunn-Rankin, D. (2001). Evaluating Design Alternatives – The Role of Simple Engineering Analysis and Estimation. *2001 ASEE Annual Conference & Exposition*.

Ericsson, K. A. (2008). Deliberate practice and acquisition of expert performance: A general overview. *Academic Emergency Medicine, 15*(11), 988–994.

Ferguson, E. S. (1977). The mind's eye: Nonverbal thought in technology. *Science*.

Ge, X., & Land, S. M. (2004). A Conceptual Framework for Scaffolding Ill-Structured Problem-Solving Processes Using Question Prompts and Peer Interactions. *Edu. Tech. Res. Devt., 52*(2), 5–22.

Govaerts, S., Cao, Y., Vozniuk, A., Holzer, A., Zutin, D. G., Ruiz, E. S. C., ... & Tsourlidaki, E. (2013). Towards an online lab portal for inquiry-based stem learning at school. In *Intl. Conf. Web-Based Learning (pp. 244-253)*. Springer Berlin Heidelberg.

Hegarty, M., Kriz, S., & Cate, C. (2003). The roles of mental animations and external animations in understanding mechanical systems. *Cognition and Instruction, 21*(4), 325–360.

Hwang, G., Kuo, F., Chen, N., & Ho, H. (2014). Effects of an integrated concept mapping and web-based problem- solving approach on students' learning achievements, perceptions and cognitive loads. *Computers & Education, 71*, 77–86.

Jonassen, D. H. (1997). Instructional Design Models for Well-Structured and Ill-Structured Problem-Solving Learning Outcomes. *Educational Technology Research and Development, 45*(1), 65–94.

Kalnins, S. N., Valtere, S., Gusca, J., Valters, K., Kass, K., & Blumberga, D. (2014). Cooperative problem-based learning approach in environmental engineering studies. *Agronomy Research, 12*(2), 663–672.

Kim, M. C., & Hannafin, M. J. (2011). Scaffolding problem solving in technology-enhanced learning environments (TELEs): Bridging research and theory with practice. *Comp. & Edu, 56*(2), 403-417.

Kothiyal, A., & Murthy, S. (2015). Exploring Student Difficulties in Divide and Conquer Skill with a Mapping Tool. In *Workshop on Technology Enhanced Learning of Thinking Skills (TELoTS) at the 23rd International Conference on Computers in Education (ICCE 2015),* Hangzhou, China.

Kothiyal, A., Murthy, S., & Chandrasekharan, S. (2016) "Hearts Pump and Hearts Beat": Engineering Estimation as a form of model-based reasoning. *The 12th International Conference of the Learning Sciences (ICLS 2016), vol. 1,* pp. 242-249.

Lee, Y., Baylor, A. L., & Nelson, D. W. (2005). Supporting problem-solving performance through the construction of knowledge maps. *Journal of Interactive Learning Research, 16*(2), 117.

Linder, B. M. (1999). Understanding Estimation and its Relation to Engineering Education. MIT.

Lindgren, R., & Schwartz, D. L. (2009). Spatial Learning and Computer Simulations in Science. *International Journal of Science Education, 31*(3), 419–438.

Mahajan, S. (2014). The art of insight in science and engineering : Mastering complexity. The MIT Press.

Mulder, Y. G., Lazonder, A. W., & Jong, T. De. (2011). Comparing two types of model progression in an inquiry learning environment with modelling facilities. *Learning and Instruction, 21*, 614–624.

Nersessian, N. J. (2009). How Do Engineering Scientists Think ? Model-Based Simulation in Biomedical Engineering Research Laboratories. *Topics in Cognitive Science, 1*, 730–757.

Perrenet, J. C., Bouhuijs, P. A. J., & Smits, J. G. M. M. (2000). The suitability of problem-based learning for engineering education: theory and practice. *Teaching in higher education, 5*(3), 345-358.

Pimmel, R. (2001). Cooperative learning instructional activities in a capstone design course. *Journal of Engineering Education, 90*(3), 413-421.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., ... & Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. The Journal of the Learning Sciences, 13(3), 337-386.

Shakerin, S. (2006). The Art of Estimation. *International Journal of Engneering Education, 22*(2), 273–278.

Shekar, A. (2014). Project based Learning in Engineering Design Education : Sharing Best Practices. *121st ASEE Annual Conference and Exposition.*

Slotta, J. D., & Linn, M. C. (2009). WISE science: Web-based inquiry in the classroom. Teachers College Press.

Stoyanov, S., & Kommers, P. (2006). WWW-intensive concept mapping for metacognition in solving ill-structured problems. *Intl. J. Continuing Engineering Education and Life-Long Learning, 16*(3/4), 297.

Sun, D., & Looi, C. K. (2012). Designing for model progression to facilitate students' science learning. *Proceedings of the 20th International Conference on Computers in Education (ICCE 2012),* 674–681.

Swaak, J., & De Jong, T. (2001). Discovery simulations and the assessment of intuitive knowledge. *Journal of Computer Assisted Learning, 17*(3), 284–294.

Wankat, P. C., & Oreovicz, F. S. (2015). Problem solving and creativity. In *Teaching Engineering* (pp. 66–88). Purdue University Press.

Woods, D. R., et. al (1997). Developing Problem Solving Skills : The McMaster Problem Solving Program. *Journal of Engineering Education, (April)*, 75–91.

Wu, B., & Wang, M. (2012). Integrating problem solving and knowledge construction through dual-mapping. *KM&EL, 4,* 248-57.

Zheng, W. (2013). Correlation Analysis of Scaffolding Creative Problem Solving Through Question Prompts with Process and Outcomes of Project-Based Service Learning. *In 120th ASEE Annual Conference & Exposition.*