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Investigating the Benefits of Group Model Building Using System Dynamics for Engineers Without Borders Students

Mr. Jeffrey Paul Walters, University of Colorado Boulder

PhD Candidate in Civil Systems Engineering Mortenson Fellow in Engineering for Developing Communities University of Colorado Boulder

Kaitlin Litchfield, University of Colorado, Boulder

Kaitlin Litchfield received her undergraduate degree in Civil Engineering at the University of New Hampshire and recently completed her PhD at the University of Colorado Boulder in the Civil, Environmental and Architectural Engineering Department within the Mortenson Center for Engineering in Developing Communities. Her research interest is in recruiting, educating, and retaining engineers capable of meeting global development challenges, and her current work is focused on understanding engineers involved specifically with Engineers Without Borders-USA.

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ABSTRACT

More than ever, future engineering students will need improved tools to more holistically understand the complexities inherent in planning, implementing, and managing, healthy and sustainable development projects. Programs such as Engineers without Borders (EWB) have always had the objective of teaching systems thinking skills to address the complex systemic community issues inherent in international infrastructure development; however, methodologies used to foster systems thinking have historically remained implicit, and have primarily focused on reductionist approaches to project assessment, design, and evaluation. Group Model Building (GMB) using System Dynamics modeling has been successfully used for years in multiple fields to foster and grow understanding on a complex topic using the combined insight from multiple stakeholders to build informative qualitative diagrams and quantitative simulations. However, this tool has not been used in the context of engineering education, specifically focused on sustainable community development. This study proposes GMB as a tool for EWB students interested in community development engineering to more aptly grapple with the complex issues they will invariably face in their projects abroad and in their careers. The aims of this study were to introduce GMB to a group of EWB students and to explore how the exercise improved their understanding of systemic interaction of factors that influence the sustainability of their projects. This paper discusses the process used to introduce GMB to the students and their reactions throughout and after the process. Based on the students' growth in understanding of the factors and complexities in their project, we believe that this research provides valuable evidence and support for the future use of GMB as a tool for applying systems thinking in international infrastructure development projects.

INTRODUCTION

Leaders in both engineering education and industry agree that engineers must increasingly develop skills in systems thinking to be effective. In education, the emphasis on systems thinking can be witnessed from leaders like ABET with their student learning outcomes a-k: for example, outcome h, "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context." [1] For decades, the National Academy of Engineering (NAE) has also highlighted the importance of systems thinking among engineers, emphasizing the accelerating pace of technological advancement, global connectedness, and reliance on technology and infrastructure,[2–4] all of which stress the need for engineers to be able "to address large-scale systems problems."[2] In industry, employers have also emphasized the importance of systems thinking. For example, "managing complexity in a systems environment" is a desirable "transferable skill" of engineering graduates by employers.[5] Working with other disciplines both within and beyond engineering is an increasing necessity for successful engineering,[6] and this necessity is particularly critical for addressing issues of sustainable development .[7]

Despite agreement about the need for systems thinking among engineers, the field lacks a consensus about how to teach systems thinking. Systems thinking can be a challenge to teach and an even greater challenge to assess,[8] due, in part, to a vague definition of the term[10]. Shuman et al.[8] review a list of courses and university programs that have each attempted unique ways to achieve systems thinking through the fulfillment of ABET outcomes h (see above) and j ("a knowledge of contemporary issues"[1]). Although part of ABET's intention with the a-k outcomes was to provide schools with autonomy to make program-specific decisions to achieve the outcomes, the lack of direction allows for subjective interpretation and can lead to unintentional neglect for directly improving systems thinking. In some cases, programs have opted for systems thinking to be integrated throughout the curricula rather than be taught in specific courses;[9] however, this approach makes assessment of its effectiveness challenging,[8,9] and this approach ignores the importance of context when teaching systems thinking.[14]

To address the need for effective methods for teaching engineers systems thinking, this paper explores the use of a tool previously applied in other disciplines to aid systems thinking among a team of engineering students. In this paper, we first describe this tool—which uses group model building (GMB) to build system dynamics (SD) models—and we then describe our application of the tool with a team of Engineers Without Borders (EWB) students. We then share how this tool was used in a group workshop and its results, including comparisons of individual and group models, a synthesis of learning during the workshop, and responses to follow-up questions to demonstrate its potential for teaching and improving students' systems thinking. Specifically, we show that these EWB students gained greater understanding of the complexities in their project and of the opportunities for future actions to improve the sustainability of their project.

BACKGROUND

This section describes SD modeling and GMB as a way to teach systems thinking. We then conclude with the research questions that guided this study.

SD Modeling

SD modeling allows for tangible systems thinking to take place through the building of models that help the modeler(s) gain knowledge and understanding on potentially non-intuitive systemic outcomes of a particular problem.[10] A SD modeling exercise can take both qualitative and quantitative forms, where qualitative modeling (diagramming) typically precedes, and then facilitates, quantitative modeling (simulating);[11] however, qualitative system dynamic modeling often stands by itself as a useful way to teach systems thinking when the goal is to foster productive conversation about how system structure might influence behavior.[12] Additionally, qualitative system dynamics modeling is often most appropriate when model variables cannot be accurately quantified, as is often the case for exploratory modeling, similar to what was done in this study.

The general goal of qualitative SD modeling is to develop a causal loop diagram (CLD) which describes the causal structure hypothesized to drive the dynamic behavior of a system. This dynamic behavior is hypothesized to emerge through the formation of feedback loops. An example feedback loop could be: an increase in population causes an increase in people being born, which causes an increase in population, and so on (see Figure 1). CLDs are created by systematically identifying the polarity of relationships between pairs of factors in a SD model. Polarity designates the influence over time of one factor on the other as either positive or negative. For example, a positive (+) polarity signifies an increase in one variable will cause an increase in the other variable (such as increased in birthrate will cause an increase in population) and negative (-) polarity signifies an increase in one variable will cause a decrease in the other variable (such as an increase in people dying will cause a decrease in population). Once connections and polarities are drawn between factors, feedback loops, or circular chains of influence, can be identified. Discussion around the significance of feedback loops can then provide key insight into the dynamic drivers for a particular behavior, where the overall CLD process presents a way to visually demonstrate where certain strategic actions might have the greatest overall impact.[13]

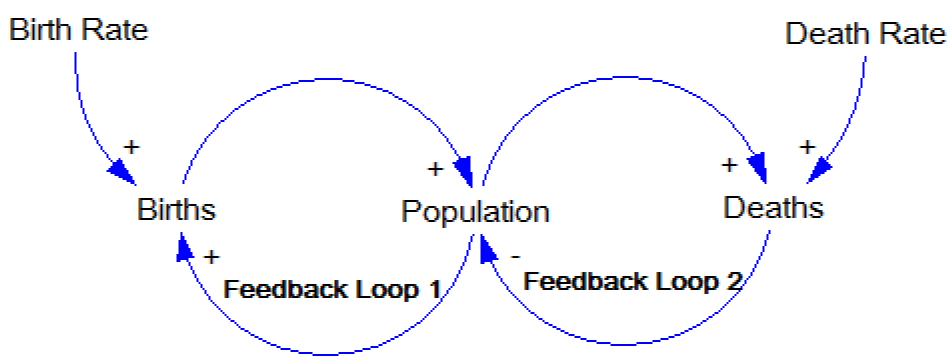

Figure 1. Example CLD for population dynamics

Because SD modeling attempts to organize systems diagrams that mimic the complexities of the real word, SD modeling is typically better applied in a group setting.[14] Therefore, an understanding of group model building (GMB) is an important consideration for teaching systems thinking through SD modeling.

Group Model Building

Everyone uses mental models to cognitively represent reality; however, these mental models generally exist as individual implicit frameworks[15]. GMB enables participants to make these implicit frameworks explicit through a process of diagramming and simulating SD models in a group setting.[16,17] Of the many benefits of GMB, the two most significant are how the GMB process enables workshop participants to (1) formalize and align their mental models within a group to learn how certain factors cause a complex behavior[14,16,18,19,20] and (2) provide a platform with which to discuss a complex problems using a unified method that better facilitates group consensus on possible strategies and future actions.[21-25]

GMB workshops can vary widely in frequency and duration. Some may require as little as two 3-hour sessions to build a model, while others may require multiple day-long sessions over a year's time to reach the same result[14]. The goals of a GMB workshop are highly dependent on the participants' desires. As mentioned previously, these goals typically culminate in the development of a SD model from which important insights can inform some sort of strategic action.[16] The quality of these insights is largely a function of the quality of the group facilitator and the knowledge and expertise of the participants.[16,26] Although GMB literature is rich with recommendations for facilitating a GMB workshop, no formal method exists.[14,16,27] An abbreviated example GMB workshop agenda based on these recommendations lists the following steps[14]:

Step 1: Introduce workshops participants to SD modeling language (arrows, polarity, etc.)
Step 2: Brainstorm problem variables
Step 3: Identify variable interaction and polarity
Step 4: Identify feedback loops to promote conversation on model implications
Step 5: Debrief overall model outcomes and potential strategic action(s)

Research Questions

The literature on engineering education clearly presents a need for tools and skills to foster systems thinking. We believe GMB may provide a useful tool to teach these systems skills; however, to our knowledge this tool has not yet been applied in the engineering education context. Therefore, we present a study which explores the benefits of GMB with EWB students involved with a rural water project in Peru. Specifically, this research asks the questions:

(1) What do project team members identify as the factors that contribute to the long-term functionality of their water project both individually and as a group?
(2) What do students learn by drawing connections between these factors?
(3) How does the GMB exercise influence the way they understand their project?

RESEARCH CONTEXT

In order to answer these research questions, we chose to facilitate a GMB workshop with a team of engineering students working on an Engineers Without Borders (EWB) project at the

University of Colorado, Boulder (CU). This team had been working together for four years in the small village of Llacamate, Peru, and had just finished installing a gravity-fed water system that piped water a substantial distance from a protected spring-source to the village. The current Llacamate team had nine students: four males and five females. Since the project was completed, the team had been working on a monitoring and evaluation plan to make sure certain that targets on water quality, quantity and reliability were met, and that the overall long-term functionality of the water system was secured. Collectively, these students spent significant time on this project either in Llacamate, including three trips to the field sight, or at CU planning, designing, fund-raising, and reporting. Based on their intimate experience with the project, we considered the nine team members experts who held detailed understanding of their projects' context that could be used in a GMB workshop. In order that the reader might better understand the context-specific models that resulted from the GMB workshop, we present a brief overview of the Llacamate water project.

The town of Llacamate has a population of about 200 people and is located in northwest Peru in the "altiplano" of the Andes about 50km from the Pacific Ocean coast, and 90km southwest of the regional major city Trujillo.[28] Because the town is the furthest town within the municipal seat of Chao, community members have significant issues with transportation, and they do not receive municipal support for secondary education facilities, sewage, and electricity.[29] A poor community, Llacamate has an economy based on agriculture, and it cultivates primarily beans, feed corn and sweet corn which they sell in markets (provided they find transportation) for about $5-$7 a trip. The completed EWB water project is now solely managed by the community water committee and funded by community members who pay a monthly service fee that helps with operation and maintenance costs.

RESEARCH METHOD

The GMB workshop conducted in this study was broken into two 2.5 hour sessions that took place on two separate days. Data was collected both before the first workshop session and after the final session to explore the students' growth in understanding the complexities of their EWB project. Individual pre-workshop models, recordings and observations from the modeling workshop, a final group CLD, and results from a follow-up survey, provided the data used in this study. Each of these data collection methods are explained below.

Model Comparisons

Prior to the first GMB workshop session, students were asked to trace out a diagram that they thought best demonstrated the systemic interaction of factors that influenced the long-term functionality of the gravity-fed water system in Llacamate. The intentions of this exercise were to (1) cause students to think about the project prior to the workshop and (2) provide evidence for how each individual student envisioned the projects' complexity prior to the modeling workshop. These models would later be compared with the group model. Six of the nine participants came to the first GMB exercise with their individual model. Each student's model was then redrawn electronically in Ventana Systems Inc. VENSIM[30] for ease of comparison. To preserve the contextual richness of each student's diagram, the spatial relationship between factors was kept consistent when drawing the electronic diagram.

Comparisons between students' pre-workshop models and the group's model used a complexity metric based on the number of factors listed, number of influences between factors, and number of feedback loops indicated explicitly.[31]

GMB Workshop

The GMB workshop was divided into two sessions in order to respect participants' time and to make use of modeling software between sessions. The objective for session 1 was to identify project factors and their influences to create a CLD. The objective for session 2 was to look at feedback loops and discuss their potential implications for the long-term functionality of the project. The two authors played the roles of facilitator and recorder. The facilitator ran the workshop by leading participants through the various modeling steps. The recorder took notes of key observations from the sessions.

Session 1 began with an introduction of session goals and a description of the principles of qualitative SD modeling (factors, influences, polarity and feedback loops). The session continued by asking students to brainstorm the factors they thought would influence the long-term functionality of the Llacamate gravity-fed water system. Each factor was listed on a white board, and factors were then aggregated into ten groups to simplify the diagram. A definition for each factor was agreed upon by the group before moving on to the discussion of influences. In total, students spent one hour brainstorming factors and agreeing on a definition for each factor. Each of the ten aggregated factors was then written on a blank whiteboard with ample space in preparation for diagramming. The diagramming process entailed focusing on each individual factor and considering its influence on every other factor. If an important connection existed, as determined by the group, an arrow and its associated polarity (+ or -) was drawn between the factors. Figure 2 displays an example in which case Factor A was determined to have a positive polarity on Factor B, a negative polarity on Factors D and E, and no influence on Factor C. In this example, the process would then be repeated for Factors B, C, D and E until all potential influences were considered. The diagramming process took about 1.5 hours. The final outcome of session 1 was a complete CLD displaying the systemic influence between factors.

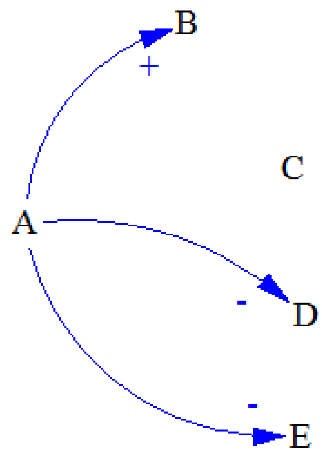

Figure 2. A visual example of the diagramming process, starting with Factor A

In the time between the first and second workshop session, the CLD model from session 1 was rebuilt in VENSIM for clarity. Using the software's loop identification tool, feedback loops within the CLD were identified to facilitate discussion about factors' influence on the water system functionality. The resulting CLD from session 1 had 1178 feedback loops. In order to focus future discussion, we developed a more manageable list of 50 feedback loops to present to the students in session 2 of the workshop.

Session 2 of the workshop began with review of session1, and a presentation of the final group model drawn in VENSIM. The goal for the session—to gain knowledge about project complexity by discussing the emergent feedback loops—was then described to the group. At the beginning of the session, each participant was given a printed list of 50 feedback loops from the final group model, displayed as Factor A→Factor B→Factor C…etc., to denote a circular causality (feedback) between Factor A on B on C and back on A. Students were then encouraged to discuss whether or not individual feedback loops made sense in light of the Llacamate project. This exercise allowed for detailed and context-specific narratives to emerge based on each student's experience with the project.

Post-workshop Survey

The intention for the follow-up survey was to gain individual students' opinions on the GMB workshop. Questions were guided in part by research done on evaluating the impact of systems thinking and GMB by Richmond,[10] Cavaleri and Sterman,[20] and Huz et al.,[32] who all measured shifts in systems thinking based on GMB participants' perceptions, and observed changes in participants' actions. In order to avoid response biases, survey questions were kept broad and open-ended, focusing solely on thoughts and opinions. Many of the questions were intentionally similar, focusing on the effectiveness of the workshop. The final question focused on the transferability of GMB to other EWB project by asking the students how the workshop might be useful for the team's future project in Huacapongo, Peru. The five questions included in the follow-up survey were:

- *Were the two group model building workshops useful? Why or Why not?*
- *How have these workshops influenced the way that you look at the Llacamate project, if at all?*
- *How did these workshops help you think differently about the long-term sustainability of the project, if at all?*
- *What is the biggest thing you took away from these workshops for the Llacamate Project?*
- *How might these workshops be useful for the Huacapongo project?*

Qualitative analyses of survey data were conducted by identifying and grouping recurring themes found within the student's responses.

RESULTS

This section presents the results and findings from the GMB workshop in three parts. The first part showcases students' pre-workshop models as they compare to the group's model to highlight similarities and differences in models' complexity and structure. The second part focuses on our observations during the workshop, particularly focusing on what students appeared to be learning, The third part discusses common themes resulting from the post-workshop survey.

Model Comparisons

For space, only two of the six pre-workshop models are shown below (Figures 3 and 4). Of the six student models, these two models represent the most complex and least complex, as they relate to our complexity evaluation criteria presented below in Table 1. Although the two models vary markedly in complexity, neither model indicates the polarity of influence between factors. In the same way, and as a result, neither model explicitly identifies feedback loops. This was most likely because neither of these two students (or the other four students for that matter), knew of SD diagramming techniques. Immediately this observation demonstrates one of the key benefits of GMB: as a tool that creates an effective and unified approach to describe a complex problem.

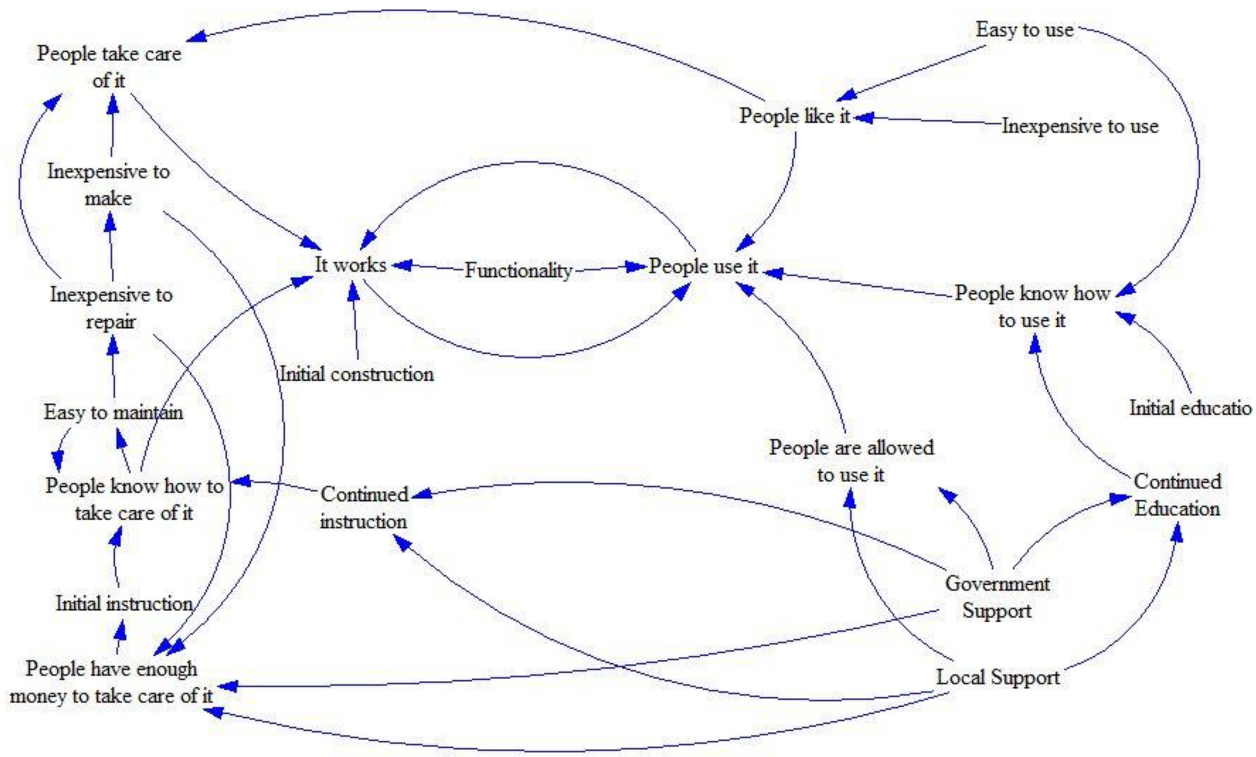

Figure 3. The most complex student model

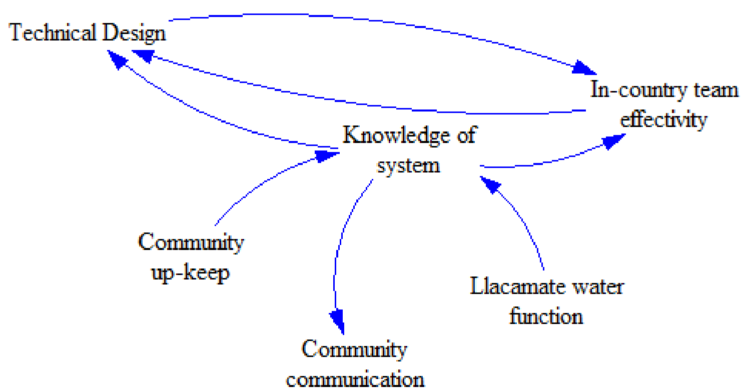

Figure 4. The least complex student model

Table 1 compares the complexity across all six students' models with the group's model by looking at the number of factors, influences (arrows) and feedback loops. As was mentioned, none of student models explicitly identified feedback loops. It is interesting to note that the maximum number of factor influences (35) from the students' models was less than the number of influences from the final group model (42), in spite of having a far greater number of factors (21 as compared with 10). However, students often used less generalized factors. For example, in the diagram in Figure 3, the student listed factors that included, "people use it," "people know how to use it," "people are allowed to use it." These are all factors that could conceivably be placed under a more generalized factor, for example, “community use.” Wording this specific explained why the model with the highest number of factors (21 in Figure 3) still had less influences than the group model had (10). Overall, the results in Table 1 showed that the group model exhibited more complexity than individuals’ models based on the higher number of connections drawn and feedback loops identified. In addition, as a group, the students identified more thoughtful factors aggregated together. Considering this explanation of student and group model factors, it appeared that the students were better able to frame the complexities in the Llacamate project once presented with the SD model building principles and components and once allowed to work as a group to identify model factors and influences. A list of the factors and their definitions used for the final group model is shown in Table 2, and the final group’s model is displayed in Figure 5.

Table 1. Complexity comparison between models

Measure	Individual Models (min)	Individual Models (mean)	Individual Models (max)	Group Model
Factors	6	13.33	21	10*
Influences	7	17	35	42
Feedback Loops	N/A	N/A	N/A	1178
*Original number of factors reduced to 10				

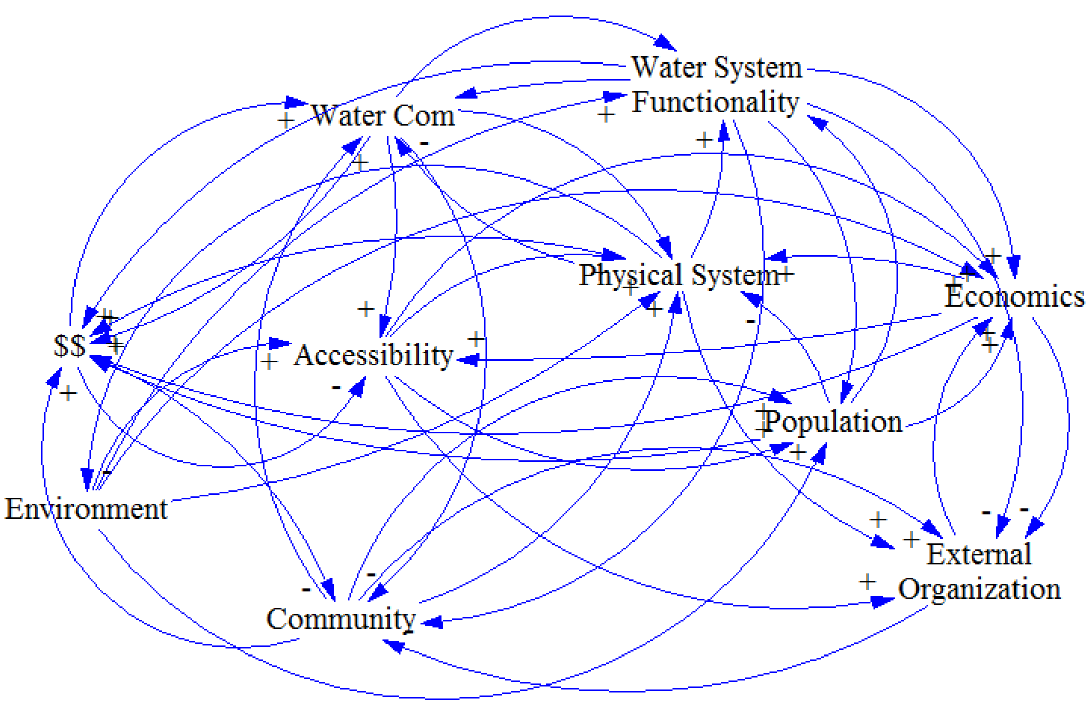

Figure 5. The final group model

Table 2. Group model factor definitions

Factor	Definition
Water System Functionality	The overall performance of the water system at any point in time related to water quality, quantity, and continuity of functionality
$$	Available funds for the operation and maintenance of the water system, gathered through the collection of monthly tariffs
Water Com	The presence of the Llacamate water committee to manage the project
Accessibility	The connectivity of Llacamate to other communities and urban centers
Environment	Water resource availability and quality. Landslides damaging the system
External Organization	The presence of EWB or some other outside organizations in the community
Community	Community members, and their use of the water, and desire for the water system (demand)
Population	The number of people in Llacamate and the surrounding region
Physical System	The technology that is used and materials installed. Very closely related to system functionality and performance
Economics	The economic status of the area

GMB Workshop

While the complexity metrics above presented one aspect of the benefits of GMB for these students, the finer subtleties of how the group interacted when building their model demonstrated additional benefits of the GMB workshop.

During session 1, two themes became apparent among the students' discussion: the use of project specific experience and context to build the group model, and the awareness of students' role in their project. The first of these themes was evident as the students brainstormed factors and influences between factors. For example, "environment" was one factor that the students had agreed upon; however, as they considered the "environment" factor's influence on the other factors, the team recognized that this factor needed to be better defined for Llacamate. Here, one student noted that they were not discussing a "hypothetical situation, but Llacamate specifically." The group then decided that the "environment" factor primarily represented landslides and droughts—the two most common natural disaster concerns in Llacamate. This improved detail, specific to their project's context, then allowed the team to better consider whether or not the "environment" factor directly influenced other factors.

Students in session 1 also demonstrated a growing awareness of their role in the project. Often, one student would suggest that one factor influenced another, and another student would counter that suggestion through the use of a story. In one case, as students considered which factors were influenced by the "external organizations" factor (understood by the group to represent their EWB team), a student offered that their EWB team influenced the community positively. Another student countered that she was not sure that the influence was positive, telling the team that on her last visit to Llacamate she noted that now that the community had electricity, which was made available in part by the team's assistance erecting solar panels, many community members were preferring to watch television rather than play their daily games of soccer. Those students who had not travelled on the latest trip were shocked in disbelief. As the discussion continued, the students reflected on their indirect influence on the community and wondered as a team how they could avoid that kind of "damage," as they called it. Throughout the session, the students became aware in instances like this one of their team's role in the project. One student's comment summarized the team's learning well when she realized, "Our external organization *indirectly* effects water system functionality!" As the team worked through the factors' influences, they began to recognize their non-central role to the long-term success of the project.

Session 2 proved influential on the students' learning as well. In this session, as the students discussed the feedback loops within the group model, they recognized tangible action items to improve the functionality of the water system. For example, one feedback loop that the group discussed was External Organization → Physical System → Water System Functionality. One student shared that she witnessed this loop when their design expertise influenced a better system design, which then improved system functionality. Another student, agreeing with the previous student, noted that if the physical system broke, the community may need the external organization to help fix the system. This alerted the team to their need to transfer trouble-shooting knowledge to the community with one student asking aloud, "Do we have that [knowledge] outlined anywhere?" The team recalled a previous meeting at which they determined that they *should* get trouble-shooting documents together for the community and that they had failed to do so. The session's discussion prompted the team to prioritize getting those documents to the community, along with other action items.

Session 2 also highlighted students' growing awareness of the complexities of their project. The feedback loop Water System Functionality → Community → Water Committee prompted discussion about power and gender relationships in the community using specific names of community members and specific relationship dynamics that some team members were privy to. Certain team members were not as keenly aware of the power imbalances and expressed surprise to learn about such information. In other cases, feedback loops such as Water System Functionality → Economics → Population and Water System Functionality → Economics → $$ → Water Committee elicited discussion about unintended consequences such as farmers loosing land and causing division among community members. The team began drawing additional mental feedback loops not provided to them on the sheet of paper. For example, the team wondered what their influence was on the economics of the region when they traveled to the community. They asked reflective questions to each other such as: Were the wages that they paid for food and community members' time fair? What were the indirect effects of taking community members from their work during the team's visits? The discussion about reduced soccer playing among community members resurfaced as the team wondered about unintended consequences, and the team expressed new awareness of the complexities of their project, both positive and negative. Over time, students recognized both the technical and the social sides of their project, particularly noting the importance of the social side which they claimed to have previously downplayed. One student commented on the importance of people in the success of their project by stating that the community and their "happiness" was "foundational to everything." Through discussion of feedback loops, the team recognized that the project was much more complicated than the physical water system, and they decided that the community was the most important factor in their project's long term success.

Post-workshop Survey

In addition to the workshop sessions themselves, many common themes emerged in students' responses to the follow-up survey that highlighted the benefits of the GMB workshop. In total, ten common themes emerged. These ten themes along with exemplar quotes were:

- **Tangible understanding of factors:** *I had only a vague hope for the future of the water system, rather than specific ideas of the factors that will influence long-term functionality"*.
- **Time to reflect:** *"I didn't take the time to think [before the workshop] about how the different aspects of the community affect each other."*
- **Making connections/interconnectedness:** *"It was awesome to see how the many aspects were connected, and how these relationships affect the success of the project."*
- **Recognition of team role:** *"My favorite thing that we discovered was just how small of an influence we as an external organization have on the long-term sustainability of the project."*
- **Learning as a group:** *"Taking into account as many variables as we did clarifies a lot of things between team members, and as well ensures that all experiences and ideas are expressed."*
- **Respect for system/complexity:** *"I took away that the factors are more interrelated than I could've imagined on my own."*
- **Value of modeling for other contexts:** *"I think we really need to do these workshops for Huacapongo because the better we understand the dynamic of the community and our own role in the project the stronger the partnership and better the project will ultimately turn out."*
- **Promotes teamwork:** *"One of the most valuable impacts will be that the entire team will start thinking about system dynamics of a project like this, and realize some of the underlying complexities that it's hard to see at the outset."*
- **Importance of community/social** *"It really made me realize how much of the long term sustainability relies on the community and how important training and community is for these types of projects."*
- **Action Items:** *"The biggest action item was that we need to really get some engineering plans together and printed out next semester to give to the leadership, in case they need to hire an engineer to take a look at the system."*

While ten unique themes are presented, these themes may be grouped into two benefits that are in line with the benefits of GMB described in literature: (1) providing a tool to aid in and improve understanding of complexity and (2) enabling the basis for thoughtful strategic action. Table 3 below shows the break-down of the ten themes into these two overarching benefits, denoted as either “complexity” or “action.” We must note that this table groups the ten factors into generalized benefits, and, in a number of cases, themes could conceivably be designated as benefits for both action AND complexity.

Table 3. The break-down of themes into two overarching benefits

Action	Complexity
Recognition of team role	Tangible understanding of factors
Value of modeling for other contexts	Time to reflect
Promotes teamwork	Making connections/interconnectedness
Importance of community/social	Learning as a group
Action Items	Respect for system/complexity

CONCLUSIONS

In this study, we explored the use of a GMB workshop for EWB students at the University of Colorado Boulder involved with a water project in Llacamate, Peru. Specifically, this tool was used because we believed that it could provide a tangible way for students to think in systems about complex engineering problems. The aims of this study were to introduce GMB to a group of EWB students and to explore how the exercise improved their understanding of the systemic interaction of factors that influence the sustainability of their water project in Llacamate. In aligning with this objective, we set out to answer research questions related to how students identified important factors; what they learned while diagramming the interaction between factors; and what they learned about the project overall through the modeling process.

Through the comparison between individually drawn pre-workshop models and the final group model, it was seen that working in a group appeared to improve the team’s ability to identify important factors, connections and feedback loops. Additionally, the GMB process appeared to effectively enable a means for students to improve understanding on project complexity, which thereby facilitated the identification of future action items to help the team improve the long-term functionality of the project. Overall the educational benefits observed in this study agreed with what literature indicates as key benefits of GMB workshops, specifically, improving ideas for strategic action by facilitating a workshop with a common set of tools to appreciate complexity.[14,16-20] This study was limited in its focus on one GMB workshop at one specific institution with one specific student project team; however, this study demonstrates an exciting potential for future GMB workshops as a tool to more tangibly improve engineering students’ systems thinking abilities. We feel this study makes a compelling case for future work that explores the use of this tool across a wide spectrum of contexts within engineering education and beyond.

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REFERENCES

1. ABET. Criteria for Accrediting Engineering Programs, 2012 - 2013 [Internet]. 2011 [cited 2013 Sep 16].
2. National Academy of Engineering. Engineering as a Social Enterprise. Washington, D.C.; 1991.
3. National Academy of Engineering. The Engineer of 2020: Visions of Engineering in the New Century. Washington, DC: National Academies Press; 2004.
4. National Academy of Engineering. Educating the Engineer of 2020: Adapting Engineering Education to the New Century. Washington, DC: National Academies Press; 2005.
5. Colledge TH. Chapter 1: Rationale. Convergence: Philosophies and Pedagogies for Developing the Next Generation of Humanitarian Engineers and Social Entrepreneurs. United States of America: IJSLE; 2012.
6. Fortenberry NL. Foreword to Cambridge Handbook of Engineering Education Research. Cambridge Handbook of Engineering Education Research. New York: Cambridge University Press; 2014. p. xxv – xxvi.
7. Bugliarello G. Emerging and future areas of engineering. Engineering: Issues, Challenges and Opportunities for Development. France: UNESCO; 2010. p. 56–9.
8. Shuman LJ, Besterfield-Sacre M, McGourty J. The ABET “Professional Skills”–Can they be taught? Can they be assessed? J Eng Educ. 2005;94(1):41–55.
9. Lathem SA, Neumann MD, Hayden N. The Socially Responsible Engineer: Assessing Student Attitudes of Roles and Responsibilities. J Eng Educ. 2011;100(3):444–74.
10. Richmond, B. System Dynamics/Systems Thinking: Let’s Just Get On With It. International System Dynamics Conference in Sterling, Scotland; 1994.
11. Wolstenholme, E. System Enquiry: A System Dynamic Approach. John Wiley & Sons Inc; 1990.
12. Luna-Reyes L., F., Anderson, D.,L,. Collecting and Analyzing qualitative data for system dynamics: methods and models.
13. Meadows, D. Thinking in Systems: A Primer. Chelsea Green Publishing; 2008.
14. Vennix, J. Group Model Building: Facilitating Team Learning Using System Dynamics. Wiley, 1st edition; 1996.

15. Jones, N. A., H. Ross, T. Lynam, P. Perez, and A. Leitch. Mental models: an interdisciplinary synthesis of theory and methods. Ecology and Society 2011;16(1):46.
16. Anderson, D., F., Richardson, J., P., Vennix, J. Group model building: adding more science to the craft. System Dynamics Review 1997;13(2):187-201.
17. Hovmand P.,S. Community Based System Dynamics. Springer Science and Business Media; 2014
18. Bérard, C. Group Model Building Using System Dynamics: An Analysis of Methodological Frameworks. The Electronic Journal of Business Research Methods 2010;8(1):35-45.
19. Wolstenholm, E., F. System Dynamics in Perspective. J. Opl. Res. Soc. 1982;33:547-556.
20. Cavaleri, S. and Sterman, J.,D. Towards evaluation of systems thinking interventions: a case study. System Dynamics Review 1997;13(2):171-186.
21. Richardson, G.,P. Teamwork in Group Model Building. University at Albany;1995
22. Rouwette E, Korzilius, H., Vennix, J. Modeling as persuasion: the impact of group model building on attitudes and behavior. System Dynamics Review 2011;27(1)1-21
23. Rouwette E. Does Group Model Building Work? Evidence from and Comments on the Paper by Videira et al. Syst. Res.2012; 29:620-623
24. Vennix J. A. Forward: Group Model Building, art, and science. System Dynamics Review 1997;13(2):103-106
25. Visser, M. System dynamics and group facilitation: contributions from communication theory. System Dynamics Review 2007;23(4)453-463.
26. Vennix 1993. Group model-building: what does the client think of it? In The Role of Strategic Modeling in International Competitiveness, International System Dynamics Conferences; 1993.
27. Luna-Reyes L., F., Martinez-Moyano, I. J., Pardo, T. A., Anthony M., C., Andersen, D., F., Richardson, R. P. Anatomy of a group model building intervention: building dynamic theory from case study research. System Dynamics Review 2006; 22(4)291-320.
28. CU EWB. Llacamate Final Report. University of Colorado Boulder. EWB-USA; 2012
29. Sigmon, C. Live and Learn: EWB-USA Water Project Monitoring in Peru. Masters Report. University of Colorado Boulder;2011.
30. Ventana Systems Inc. VENSIM. http://vensim.com/
31. Bossel, H. Systems and Models: Complexity, Dynamics, Evolution, Sustainability. Books on Demand. Norderstedt, Germany; 2007.
32. Huz, S., Andersen D.F., Richardson, G.P., Boothroyd, R. 1998 – A framework for evaluating systems thinking interventions: an experimental approach to mental health systems change. System Dynamics Review 1998; 13(2):149-169.