Expanding Low-Fidelity Maker Activities to Foster Entrepreneurial Mindset and Systems Thinking in Engineering Education

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Work in Progress: Expanding Low-Fidelity Maker Activities to Foster Entrepreneurial Mindset and Systems Thinking in Engineering Education

Abstract

Engineering students often struggle to connect fundamental concepts with the complexity of real-world systems. In environmental engineering for example, students may find it difficult to conceptualize mass balance when multiple physical, chemical, and biological processes interact. To address this challenge, a low-fidelity maker activity was developed to help students visualize environmental systems and apply mass balance principles through creative prototyping. Students in a senior environmental engineering course designed and built physical models of their system-level projects using simple materials such as cups, sticks, and foil. The activity enhanced curiosity, teamwork, and conceptual understanding while bridging the gap between theory and application.

Building on the success of this preliminary work, this Work-in-Progress project, emerging from the KEEN MakerSpark: A Framework for Developing Entrepreneurial Minded Making Activities workshop, aims to expand and disseminate maker-based strategies that align with the 3Cs of the Entrepreneurial Mindset: curiosity, connections, and creating value. The project includes refining the mass balance activity, developing new low-cost maker activities across multiple engineering disciplines, and producing faculty toolkits with implementation guides and assessment rubrics. A validated pre/post-assessment instrument will be designed to evaluate student growth in systems thinking and entrepreneurial mindset outcomes. By promoting creative, hands-on learning that strengthens conceptual mastery and mindset development, this project contributes to preparing future engineers who are both innovative thinkers and systems-oriented problem solvers.

Motivation

Engineering students often struggle to connect foundational analytical concepts to the complexity of real-world engineering systems. In environmental engineering, principles such as mass balance are frequently introduced as algorithmic procedures applied to well-structured problems. In professional practice, however, engineers must navigate ill-structured, dynamic systems characterized by interacting physical, chemical, and biological processes, competing constraints, and ambiguous objectives. Research shows that proficiency in solving structured classroom problems does not reliably transfer to workplace problem solving, where knowledge must be integrated across domains and adapted to uncertainty [1]. As a result, students may demonstrate procedural competence while lacking systems-level understanding. Persistent difficulties in reasoning about accumulation, feedback, and time-dependent behavior suggest that systems thinking competencies do not naturally emerge from traditional instruction alone [2]. Intentional activities that represent and examine system structure would help students to integrate concepts across scales and contexts rather than to compartmentalize knowledge across courses.

Hands-on, maker-based learning approaches offer a potential opportunity for addressing this gap. By externalizing ideas through physical artifacts, students can visualize relationships, test assumptions, and iteratively refine their understanding [3], [4], [5]. Low-fidelity maker activities are particularly attractive because they are scalable and adaptable within analytically rigorous core courses without requiring specialized infrastructure. For more than two decades, engineering education has been emphasizing the development of EM competencies, such as curiosity, making connections, and creating value, as complements to technical proficiency [6], [7]. However, EM remains variably defined in the literature, and assessment approaches often rely on perception-based measures that do not fully capture application within technical problem contexts [8], [9]. Required engineering courses therefore present a dual challenge: how to cultivate systems thinking and EM reliably within technical content, and how to assess their development meaningfully.

Although maker-based pedagogies and EM initiatives have independently gained traction, fewer efforts have intentionally integrated systems reasoning, EM development, and hands-on learning within upper-division analytical courses. This Work-in-Progress paper describes the expansion of a low-fidelity maker activity implemented in a senior environmental engineering course to support systems-level reasoning through creative prototyping. The project aims to align maker-based strategies with the KEEN framework [7] while developing assessment approaches that capture both systems thinking and EM development within authentic mass balance contexts.

Background

Systems Thinking in Engineering Education

Systems thinking has become a critical competency for engineers working in complex socio-technical environments. Rather than focusing only on linear cause and effect relationships, systems thinking emphasizes understanding interactions among components, feedback processes, temporal dynamics, and evolving behavior. In engineering practice, this includes recognizing how accumulation, delays, and nonlinear interactions shape system performance over time. Jonassen et al. [1] characterize workplace engineering problems as ill-structured, involving multiple solution paths, competing constraints, and distributed expertise. These problems require engineers to observe situations holistically rather than apply isolated procedures. Research in system dynamics education demonstrates that learners frequently struggle with reasoning about accumulation and dynamic behavior, even when mathematically proficient [2]. The difficulty is in constructing accurate mental models of how system structure generates behavior over time. From an instructional standpoint, these findings suggest that systems thinking must be intentionally cultivated through learning experiences that engage students in representing and reasoning about system structure [1], [2]. Constructivist scholarship further suggests that externalizing relationships through artifacts or collaborative modeling may support the development of more coherent mental models [5].

Maker-Centered Pedagogies

Maker-centered learning draws from constructivist and constructionist practices, which suggest that knowledge is constructed through active engagement and artifact creation [5]. In engineering contexts, project-based and maker-based approaches encourage students to prototype, test, iterate, and explain their reasoning. These processes align closely with professional engineering practice, where understanding emerges through experimentation and refinement. Research on makerspaces demonstrates that prototyping activities can enhance engagement, technological fluency, and interdisciplinary problem framing [3], [4], [10]. It should be noted that the educational value of making is not limited to high-tech maker space opportunities. Low-fidelity prototyping has been shown to promote conceptual understanding, communication, and design reasoning while being accessible and scalable within traditional courses [4], [5].

Recent studies also highlight the sociocultural dimensions of maker education. Studies of culturally contextualized making illustrate how artifact creation supports identity development, belonging, and agency in engineering learning environments [11]. Further analyses of maker education emphasize its potential to promote inclusive participation and support diverse ways of knowing [12]. These perspectives position making not only as a pedagogical technique but as a framework for knowledge construction and engagement. Despite this growing body of work, the maker literature focuses on introductory design courses, extracurricular makerspaces, or co-curricular innovation programs. Less attention has been given to how maker-based approaches can support analytical reasoning in upper-division engineering courses, where modeling and conceptual integration are essential.

Entrepreneurial Mindset in Engineering Education

Entrepreneurial mindset (EM) has become a prominent framework for broadening engineering education beyond technical content. The KEEN framework conceptualizes EM through the interconnected dimensions of curiosity, connections, and creating value [7]. Within engineering contexts, EM is not limited to venture creation but instead emphasizes opportunity recognition, systems framing, and value-driven problem solving. Empirical studies suggest that embedding EM within engineering coursework can enhance engagement and innovation capacity [6], [13].

However, there are still persistent challenges in conceptual clarity and assessment [8]. EM is variously defined as a set of traits, cognitive dispositions, behaviors, or value orientations, leading to inconsistency in how it is implemented within curricula. Assessment efforts have produced instruments intended to measure entrepreneurial thinking in engineering students [9], yet validated, discipline-integrated tools remain limited. Many instruments rely on self-report surveys, which may capture behavioral shifts but do not directly measure application within engineering problem contexts. There are still ongoing needs to develop EM habits. These needs include instructional approaches that embed EM within technical coursework rather than isolating it in entrepreneurship electives, and assessment strategies that capture evidence of EM habit development especially in complex analytical tasks.

Collaborative Prototyping and Shared Mental Models

Collaborative learning theory provides an additional perspective for understanding how maker-based activities may influence reasoning. Shared mental models which are common understanding of system structure and task goals have been shown to support coordinated team problem solving and proactive behavior [14]. When learners collectively construct representations of system dynamics, they align their conceptual models and develop more integrated perceptions. Low-fidelity prototyping tasks that require teams to physically represent and explain system behavior may therefore function as mechanisms for developing both systems thinking and entrepreneurial framing. By visualizing assumptions and discussing interpretations, students may improve their shared understanding while engaging in EM oriented thinking.

Rationale for This Work

When considered together, the literature on systems thinking, maker-centered pedagogy, entrepreneurial mindset, and collaborative learning suggests a meaningful intersection. Systems thinking asks students to reason about process, feedback, and interactions within complex systems. Maker-based activities give students a way to visualize those structures, explore ideas, and revise their thinking. Entrepreneurial mindset encourages students to frame problems as opportunities, consider stakeholder value, and navigate trade-offs in uncertain contexts. Collaborative prototyping supports shared understanding and active engagement in the design process. Although each of these areas has been studied individually, fewer efforts have intentionally combined low-fidelity maker activities with EM principles to support systems-level reasoning in technically challenging engineering courses. This study builds on that intersection by exploring how structured, accessible maker activities aligned with EM may help students develop deeper structural reasoning, value-informed decision-making, and collaborative problem-solving skills.

Activity Implementation and Preliminary Findings

The maker-based mass balance activity was implemented in a senior-level environmental engineering design course during Week 4 of a 15-week semester, once in a rough format in Fall 2024 and again in revised format in Fall 2025. Students (n = 41 (in 2024), n = 52 (in 2025); teams of 3 to 5) were engaged in semester-long system-level design projects addressing complex environmental challenges (e.g., oil spill remediation, microplastic removal, PFAS treatment, wildfire runoff impacts, surface water nutrient management, …).

The activity followed a structured 3-hour in-class protocol (see Appendix for the updated activity instructions and rubric):

1- System Boundary Identification (20 minutes)
Teams explicitly defined system boundaries and identified key inputs, outputs, and transformation processes using literature-based flow rates, pollutant concentrations, and regulatory limits, as applicable to their projects.

2- Low-Fidelity Prototype Construction (120 minutes)
Using accessible materials (paper cups, pipe cleaners, foil, cotton balls, index cards; see activity description teams constructed physical models representing system components and labeled mass balance elements (Q, C, accumulation, reaction/removal).

3- Peer Explanation and Q&A (40 minutes)
Each team delivered a ~3 minute explanation followed by structured peer Q&A focused on:
- System boundary justification
- Mass balance completeness
- Assumptions and regulatory constraints

4- Individual Reflection (post-activity, 300 words)
Students submitted structured reflections

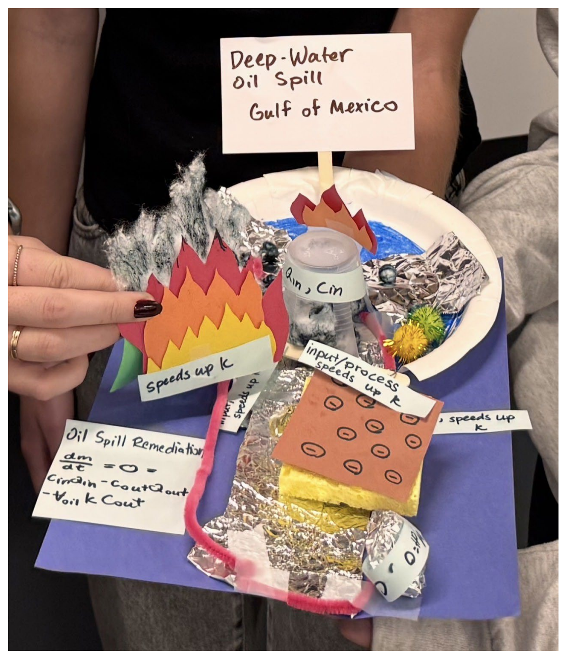
Data Sources and Analysis

Student learning data was collected through (1) structured individual reflections (300 words; N = 88 across two offerings, with five non-submissions) and (2) rubric-based performance ratings from the 2025 implementation. The reflection prompt asked students to describe how the activity influenced their understanding of mass balance, system-level design, and project development. An inductive thematic analysis approach was used to examine reflections [15]. Responses were first open-coded to identify recurring patterns related to systems reasoning, integration of treatment approaches, quantitative grounding, value framing, and collaborative processes. Codes were iteratively grouped into higher-order themes through constant comparison across reflections from both course offerings. To enhance analytic credibility, themes were reviewed across both cohorts (Fall 2024 and Fall 2025) to confirm pattern consistency. Because the study utilized classroom artifacts rather than interview transcripts, the analysis focused on conceptual patterns rather than statistical generalization [16].

In the 2025 offering, a structured rubric (see Appendix) was used. The rubric consists of four equally weighted criteria: model quality, clarity of explanation, accuracy of mass balance representation, and reflective insight. Rubric levels (Beginning, Developing, Proficient, Advanced) were aligned with activity learning objectives. The maker activity draws on research suggesting that external representations support structural reasoning in dynamic systems [2] and that maker-centered, project-based environments promote deeper conceptual engagement and integration of technical and entrepreneurial thinking [3], [10], [17]. The focus on stakeholder constraints, regulatory limits, and value-aware decision-making aligns with established entrepreneurial mindset frameworks [6], [7], [9], [13]. Collaborative peer explanation and shared model refinement are also consistent with research on shared mental models and proactive team problem-solving [14].

Prototype Examples

Example 1: Oil Spill Bioremediation Model



One team modeling marine oil spill remediation physically represented oil mass using aluminum foil and microbial degradation using cotton balls (Pseudomonas). Their mass balance incorporated degradation rate (k), oil volume, and time-to-removal (~1.15 years for 98% removal under assumed kinetics). The team also considered other techniques that would be an immediate response to the oil spill, such as in-situ burning and adsorbent material use to soak up the spill. Working through the model, the team realized that the latter solutions, even though more immediate would cause air pollution and solids wastes as the adsorbents would need to be carefully disposed of. During peer questioning, the team revised their model to explicitly account for time dependence, recognizing that steady-state assumptions were inappropriate for large-scale spill dynamics.

Example 2: Harmful Algal Bloom (HAB) Clay Flocculation and Wetland Integration Model

One team addressing harmful algal blooms constructed a nearshore "bloom box" model to represent nutrient inflow, algal biomass accumulation, toxin production, and treatment removal. The team predicted expected algal cell numbers/m^3 of water to be treated, and made an assumption on the concentration of toxins to be released. The team developed their protype for a process where removal was represented through poly-aluminum modified clay flocculation. Based on literature-informed assumptions, they modeled approximately 95% algal cell removal and 70–90% toxin reduction. During peer questioning, classmates challenged the ecological implications of sediment-bound toxins. The team subsequently revised their prototype to include upstream nutrient management (constructed wetlands) to reduce bloom intensity prior to flocculation. This revision shifted the design from a single-point remediation strategy to a layered intervention model incorporating prevention, in-situ treatment, and sediment considerations. The discussion also prompted the team to clarify regulatory thresholds and explicitly justify system boundary selection.

Evidence of Systems-Level Reasoning Through Maker-Based Modeling

Analysis of student reflections (N = 88 full course cohort between two offerings (with 5 students not submitting reflections) revealed six dominant themes: (1) structural visualization of systems, (2) multi-layered intervention framing, (3) quantitative grounding of design decisions, (4) emergence of entrepreneurial mindset dimensions, (5) productive conceptual struggle, and (6) collaborative sense-making. Together, these themes suggest that low-fidelity maker activities supported systems-level reasoning while maintaining technical rigor.

Structural Visualization and Boundary Identification

The most consistent theme across reflections was that physically constructing a model helped students "see" system structure in ways that equation-based work alone had not. Students described improved clarity regarding:

- system boundaries
- inflows and outflows
- accumulation and transformation
- relationships between concentration and flow

Many explicitly contrasted prior abstract mass balance problem-solving with the representative modeling experience. Rather than solving for a single unknown, students described reasoning about how pollutants moved through interconnected subsystems (e.g., upstream runoff → bloom formation → toxin removal). This shift reflects advancement from technical calculations to systems reasoning.

"Seeing these processes as a model made it easier to grasp how physical, chemical, and biological treatments interact in real-world scenarios."

From Single-Solution Thinking to Layered Intervention Strategies
A second strong pattern was a shift away from isolated treatment framing. Across projects including oil spill remediation, nitrate removal, PFAS treatment, wildfire runoff management, and harmful algal bloom mitigation, students repeatedly concluded that no single intervention would be sufficient. Instead, teams described layered strategies such as:

- upstream prevention combined with downstream remediation
- mechanical removal paired with biological degradation
- best management practices integrated with physical treatment

Students noted that their physical modeling process revealed interaction effects that were not initially apparent. For example, some teams realized that improving one parameter (e.g., flow diversion) would alter downstream concentrations or ecological impacts, requiring additional adjustments. This indicates developing awareness of interdependence and coupled system behavior.

"Even though a constructed wetland is important, it cannot be the only preventative solution."

Quantitative Anchoring and Regulatory Awareness
Contrary to concerns that maker activities might reduce technical rigor, reflections demonstrated substantial quantitative grounding. Students incorporated:

- EPA regulatory limits (e.g., PFAS = 4 ng/L)
- Removal efficiencies (e.g., 95% algal toxin removal)
- Estimated flow rates
- Reactor sizing considerations
- Time-to-remediation calculations

In several cases, students described calculating the magnitude of removal required to meet regulatory standards before constructing their models. This suggests that the physical representation did not replace analytical reasoning but instead anchored it within realistic constraints. Students also referenced the need to verify assumptions, consult regulatory sources, and justify parameter selection. These behaviors indicate integration of mass balance reasoning with real-world policy and design constraints.

"We calculated that 2,000 metric tons of bacteria would be needed to remove 98% of the oil."

Emergent Entrepreneurial Mindset Behaviors

Although the reflections were not explicitly prompted around entrepreneurial mindset language, elements of KEEN's 3Cs: Curiosity, Connections, and Creating Value, emerged naturally.

Creating Value: Students frequently referenced stakeholder impacts, ecological trade-offs, and cost considerations. Some noted the importance of meeting regulatory standards to protect public health, while others discussed feasibility in rural or resource-limited contexts.

Connections: Many reflections described linking upstream causes to downstream consequences (e.g., wildfire → runoff → sediment transport; agricultural runoff → nutrient loading → algal bloom). Students also connected environmental processes to social and regulatory systems.

Curiosity: Students identified unanswered questions, uncertainty in removal rates, and gaps in regulatory clarity (e.g., microplastics standards). Several described how the activity surfaced new research directions for subsequent project phases.

"Alum sludge is an ethically sound solution because it is a waste product and would be cost effective to implement in our solution."

"This activity taught me to include more outside factors, such as economic and physical impacts on the agricultural industry and local residences."

These patterns suggest that the maker structure may scaffold value-oriented design thinking without requiring explicit EM framing during the activity itself.

Productive Conceptual Tension

Not all reflections were uniformly positive. Some students reported confusion regarding reactor classification (e.g., CSTR vs. plug flow reactor), uncertainty about abstraction versus real-world variability, or desire for clearer instructions.

However, these comments often appeared alongside deeper engagement with system complexity. For example, students described difficulty reconciling idealized reactor equations with heterogeneous environmental systems. This suggests productive tension rather than disengagement. The activity appears to have surfaced the limitations of simplified models, encouraging students to deal with variability, assumptions, and design constraints.

"I struggled to relate my understanding of specific international water development practices with a more abstract reactor process."

Collaborative Sense-Making

Finally, students consistently emphasized teamwork. Reflections described dividing system components, negotiating system boundaries, sharing research findings, and refining scope collectively. The physical artifact functioned as a shared reference point that supported shared understanding. Even students who questioned the necessity of physical modeling acknowledged its role in fostering alignment and idea exchange.

"It was the first lengthy discussion we've had as a team, allowing us to narrow and expand our focus."

Across both offerings, the maker activity appears to have supported both individual conceptual understanding and collaborative systems reasoning.

Preliminary Quantitative Findings

In addition to qualitative reflections, rubric scores (see Appendix) from the activity (in 2025, n = 49) were analyzed. 79 % of the students achieved Proficient or Advanced ratings for the overall rubric rating for the activity, suggesting strong understanding of the mass balance concept, its connection to their projects, regulations and human/ecosystem health. In future iterations, a short pre/post systems-thinking concept inventory will be implemented to examine measurable growth.

Assessment Strategy and Ongoing Expansion

The work will further build on the preliminary implementation by integrating three complementary assessment streams:

1- Artifact-Based Evaluation: structured improved rubric scoring of physical models (see Appendix)
2- Reflection Analysis: continue to detect evidence of systems reasoning and EM behaviors.
3- Planned Pre/Post Measurement: (new) adaptation of validated systems thinking instruments [18] and entrepreneurial mindset scales (e.g., KEEN-aligned (COMPASS) [9], [19]).

This triangulated approach addresses prior critiques of EM research relying solely on perception-based measures. To evaluate the impact of the expanded maker activities, an adapted mixedmethods assessment approach will be used. A pre/post measurement, adapted from existing validated measures, will assess student growth in systems thinking and entrepreneurial mindset outcomes aligned with the KEEN 3Cs [7]. Data sources will include student artifacts, reflective writing, and rubric-based evaluations of prototypes. Quantitative data will be analyzed to examine changes over time, while qualitative data will be coded thematically to identify patterns in student reasoning and mindset development. The pre/post instrument is being developed through an iterative process: an initial item pool is generated from validated scales (Doyle et al. [18] for systems thinking; COMPASS [19] and Li et al. [9] for EM), then will be reviewed for content alignment by two faculty with expertise in engineering education and environmental systems. Pilot administration is planned for Fall 2026 with inter-rater reliability checks on open-response items. It shall be noted that the systems thinking and entrepreneurial mindset are treated as distinct constructs in this work, since they can overlap conceptually. Systems thinking is accepted as: identifying system boundaries, accounting for accumulation and transformation, and reasoning about dynamic behavior. EM, following the KEEN 3Cs, is operationalized around curiosity (questioning assumptions, exploring alternatives), connections (linking technical decisions to broader ecological and social context), and creating value (stakeholder framing, trade-off reasoning, cost-feasibility). In practice these can reinforce each other: recognizing that a system has stakeholders is both systems-level and entrepreneurially-oriented, but the rubric and instrument will keep them in separate sections with distinct indicators so that evidence for each can be evaluated independently.

Student artifacts will be evaluated using a structured rubric that assesses both the physical model and associated explanation and reflection, each evaluated on a four-level scale (emerging to advanced). The model quality and accuracy criteria assess students' ability to identify and represent system inputs, processes, and outputs, while the explanation criterion captures students' capacity to articulate mass balance reasoning and connect the model to their design goals. A post-activity written reflection will further provide insight into how the maker activity supported conceptual understanding and informed subsequent design decisions.

Together, these measures enable triangulation across survey responses, artifacts, explanations, and reflections, strengthening the credibility of the assessment approach. This strategy balances feasibility with methodological rigor and supports iterative refinement of the activities and associated faculty toolkits, consistent with prior work demonstrating the value of combining self-report and artifact-based assessments [1], [10], [17].

Cross-Disciplinary Adaptation and Implementation

The low-fidelity model framework is adaptable across engineering domains. Chemical Engineering Example: Students would physically represent heat flows, work outputs, and system boundaries using craft materials. The activity structure would transfer directly, and the governing equation would be different. Structural Engineering Example: Students modeling load paths in truss systems could physically represent force redistribution and failure propagation using elastic bands and sticks. Inputs (loads), internal forces, and boundary constraints could be labeled to visualize equilibrium and conservation of forces.

Resource-Limited Institutions: The activity requires no dedicated makerspace. Materials cost per team is approximately $2–10. Alternatively, digital sketch-based modeling can be substituted to reduce waste while preserving structural reasoning goals.

Work-in-progress

Building on the positive outcomes of the preliminary implementation, this Work-in-Progress project aims to expand the scope and impact of low-fidelity maker activities to support systems thinking and entrepreneurial mindset development. The original mass balance activity is currently being refined based on student feedback and instructor reflection, with attention to clarity, facilitation, and alignment with learning objectives. In parallel, additional maker activities are being developed for application across multiple engineering disciplines, prioritizing adaptability, scalability, and minimal resource requirements. The main outcome of this ongoing project is the development of faculty-ready toolkits that include activity descriptions, learning objectives aligned with the KEEN 3Cs, facilitation guidance, and assessment rubrics. These materials are intended to support dissemination and adoption across diverse courses and institutions, including programs with limited access to formal makerspace infrastructure.

This Work-in-Progress contributes to engineering education by demonstrating how intentionally designed, low-fidelity maker activities can promote system-level analytical reasoning while promoting entrepreneurial mindset outcomes. By supporting accessibility, assessment, and faculty usability, the project aims to provide adoptable resources for educators seeking to integrate hands-on, mindset-oriented learning into their courses. Data collection and product development are ongoing, with planned completion by Fall 2026. Future work will include reporting assessment findings, sharing representative examples of student prototypes, and expanding dissemination through professional networks and publications.

While many classroom innovations remain local interventions, this work contributes theoretically by positioning low-fidelity making as a cognitive scaffold for systems reasoning in analytically rigorous contexts. Unlike makerspace research centered on fabrication access, this study examines how constrained materials can bring out structural reasoning, regulatory awareness, and value framing. By integrating systems thinking, EM, and collaborative mental model theory, the project extends maker pedagogy into upper-division technical coursework.

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Appendix

Maker Activity: Modeling Mass Balance in Environmental Systems

Objective:

The purpose of this activity is to engage students in a hands-on project that helps them reflect on their design projects. Students will use basic supplies to build a physical model representing the concept of mass balance for an environmental/treatment system they are designing.

Learning Objectives:

After participating in this activity, students will be able to:

1. **explain** the concept of mass balance and how it applies to the environmental system/process for their project.
2. **identify** key inputs, transformations, and outputs within their environmental system, considering the regulatory limits for the solution(s) they are designing and creatively express this system building a model.
3. **apply** problem-solving and creativity to represent complex environmental processes using simple materials.
4. **articulate** the relevance of mass balance in their design project through visual and oral presentations.
5. **use real-world data** to refine their models, incorporating literature-based flow rates, contaminant concentrations, and regulatory constraints.

Materials Provided:

- Paper cups, Paper plates
- Colored paper, Index cards, Post-its
- Pipe cleaners, Popsicle sticks, Straws
- Glue, Tape, Scissors, Ruler
- Elastic bands, String
- Pompoms, Cotton balls, Cotton swabs
- Paper clips, Thumbtacks
- Markers, Aluminum foil

Instructions:

1. **Reflect on Your Design Project:**
    - Reflect on the environmental issue you are addressing in your design project.
    - Identify the major components of your environmental/treatment system and the key inputs, outputs, and transformations of materials that take place within it to meet applicable regulatory limits.

- Consider how mass balance applies to the system (e.g., how mass is conserved, what materials enter and exit, and how they are transformed, removed or persist).

2. **Design Your Model:**
   - Using the provided materials, design and build a physical model that represents the mass balance concept for your environmental/treatment system.
   - **Important Components to Include:**
     - **Inputs** (what comes into the system, such as water, contaminants, chemicals).
     - **Processes** (how materials are transformed, treated, or removed within the system).
     - **Outputs** (what leaves the system, such as treated water, waste products, by-products).
     - Use different materials to symbolize different components (e.g., cups could represent tanks, pipe cleaners could represent pipes, etc.).
3. **Create Labels for Your Model:**
   - Use small pieces of paper or tape to create labels for different parts of your model. Clearly indicate which parts represent inputs, processes, and outputs.
   - Label key points of mass balance (e.g., flow rates, concentrations).
4. **Prepare an Explanation:**
   - Be ready to explain how your model demonstrates mass balance in your system.
   - Consider the following questions:
     - How does your model represent the flow and transformation of materials/pollutants?
     - Where are the major points of pollutant/material input and output?
     - How does the mass balance concept apply to your design?
     - What have you discovered about your design through this process?
     - How could your design be improved?

Expectations:

1. **Creativity & Clarity:**
   - Use the provided materials to clearly and creatively model your system. The model should visually represent how mass balance is maintained in the environmental/treatment system, with different materials used to represent the various components.
2. **Accuracy:**
   - Ensure your model accurately reflects the processes in your design and the principles of mass balance. The model should show how inputs are processed and converted into outputs within the environmental/treatment system.

3. **Explanation:**
    - Be prepared to give a short presentation (~3 minutes) explaining your model to your peers and instructor. During your explanation, discuss:
        - The significance of the mass balance concept in your design.
        - The inputs, processes, and outputs of your environmental/treatment system, and how they relate to your design's goals.
        - Any challenges you identified when creating the model and how you addressed them.
4. **Reflection:**
    - After presenting your model, write a brief (300 word) reflection discussing:
        - how this maker activity helped you visualize the mass balance concept and its application to your design,
        - write out the mass balance equation with the information you have identified from literature and regulatory resources (as applicable: indicate flowrates, concentrations of pollutants, efficiency needed for pollutant removal),
        - discuss the treatment process you will pursue,
        - any insights you gained and how you might apply these to your project moving forward,
        - how your team collaborated, distributed workload, shared responsibilities,
        - provide any other comments, especially on the activity, if you have any suggestions to make it better.

Assessment Criteria:

- **Model Quality** (25%): The model is creative, well-constructed, and clearly represents the mass balance concept.
- **Clarity of Explanation** (25%): The team provides a clear and accurate explanation of the model, the mass balance concept, and its relevance to their project.
- **Accuracy of Mass Balance Representation** (25%): The model accurately depicts inputs, processes, and outputs within the system.
- **Reflection** (25%): The written reflection is thoughtful and shows an understanding of how the mass balance concept applies to the team's design project.

Deliverable Timeline/Deadlines:

- The model will be created and explanation will be presented in class on Wednesday, XX/XX/XX. Please make sure to stay on task to complete your model within 2.5 hours to allow time for presentations and Q&A.
- The written reflection is due on Monday, XX/XX/XX.

Additional Notes:

- Feel free to use any other materials or components you think will help you better express your environmental/treatment system and its mass balance.
- This activity is meant to be fun and engaging—focus on how creatively you can represent a real-world environmental issue using simple materials!
- You need to do literature search to identify the components of your mass balance, such as flowrates, typical concentrations, limits for the output (regulations or research findings), expected treatment performance, etc.

Rubric for Mass Balance Model Activity

Criteria	Emerging	Developing	Proficient	Advanced
Model Quality (Conceptual clarity, construction, system boundary)	Model is incomplete or unclear. System boundary is not identifiable. Inputs, processes, and outputs are missing or poorly organized.	Model represents general idea but lacks structural clarity or consistent labeling. System boundary is implied but not explicit.	Model clearly represents system boundary, inputs, processes, and outputs. Construction and labeling support understanding.	Model demonstrates exceptional structural clarity and organization. System boundary is explicit, logically organized, and creatively enhances systems understanding.
Accuracy of Mass Balance Representation (Technical correctness, conservation logic, regulatory integration)	Mass balance is incorrect or incomplete. Key terms missing. No integration of regulatory or literature data.	Mass balance structure is partially correct but includes inaccuracies or weak assumptions.	Mass balance is technically sound. Inputs, outputs, and reaction/accumulation terms are accurate. Regulatory limits or literature data are referenced.	Mass balance is precise and professionally articulated. Quantitative data (flow rates, concentrations, efficiencies) are integrated and aligned with regulatory standards. Assumptions are explicitly justified.
Clarity of Explanation (Systems reasoning, design relevance, trade-offs)	Explanation lacks clarity or connection to project goals. Limited discussion of system interactions.	Explanation describes model components but lacks depth in systems reasoning or trade-off analysis.	Explanation clearly connects mass balance to design decisions and project goals. Assumptions and interactions are reasonably articulated.	Explanation demonstrates strong systems thinking. Clearly articulates boundary conditions, trade-offs, regulatory context, and implications for design improvement.
Reflection (Equation articulation, insight, teamwork analysis)	Reflection is minimal. Mass balance equation is missing or incorrect. Limited insight into learning or teamwork.	Reflection includes equation but lacks integration of data or regulatory context. Insights are surface-level.	Reflection clearly articulates correct mass balance equation with relevant data. Provides thoughtful insights and describes team collaboration.	Reflection demonstrates deep structural reasoning. Equation includes literature/regulatory parameters. Discusses trade-offs, future design refinement, and meaningful teamwork dynamics.

Draft: Systems Thinking and Entrepreneurial Mindset Development in Engineering Instrument

Purpose:
This instrument is designed to assess growth in systems thinking and entrepreneurial mindset within environmental engineering mass balance contexts. It includes Likert-scale items and one applied scenario question.

Instructions:
For Section A and B, indicate your level of agreement using the following scale:
1 = Strongly Disagree
2 = Disagree
3 = Neutral
4 = Agree
5 = Strongly Agree

Section A: Systems Thinking Items
1. I can clearly define appropriate system boundaries when analyzing an environmental engineering problem.
2. When given a process diagram, I can accurately identify all relevant inputs, outputs, and accumulation terms.
3. I understand that mass balance requires accounting for all material transformations, not just inflow and outflow.
4. I can distinguish between steady-state and dynamic (time-dependent) mass balance situations.
5. I consider how spatial or temporal scale affects system behavior and design decisions.
6. I can identify and justify assumptions used in a mass balance model.
7. I consider regulatory limits (e.g., MCLs, discharge standards) when evaluating system outputs.
8. I recognize how multiple treatment processes interact within a larger system rather than functioning independently.

Section B: Entrepreneurial Mindset (EM) Items
9. I explore multiple alternative configurations before finalizing a system design (Curiosity).
10. I actively seek connections between technical analysis and broader environmental or societal impacts (Connections).
11. I consider stakeholder needs and long-term value when evaluating engineering solutions (Creating Value).
12. I question assumptions and seek additional information when modeling complex systems (Curiosity).

13. I evaluate trade-offs between efficiency, cost, sustainability, and equity in design decisions (Creating Value).

Section C: Applied Systems Thinking Scenario

Scenario:

A river receives agricultural runoff containing nitrate at 36 mg/L. The flow rate is 1,800 m^3/s. A treatment wetland removes nitrate with 75% efficiency before water re-enters the river. The EPA standard for nitrate in drinking water is 10 mg/L.

In 150–200 words, explain how you would structure a mass balance for this system. Include:

- The system boundary
- Inputs
- Outputs
- Any assumptions
- Whether steady-state is appropriate and why