Design, Build, and Submerge: Project-Based Learning for Naval Engineering Education

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This Ocean and Marine Engineering Division paper presents an open-source, low-cost K-8 engineering activity set developed by two regional flagship universities around the largest submarine producer. The goal is to seed early interest and skills aligned with naval engineering. The activity set includes three navy-focused activities as follows:

(1) *Additive Manufacturing* with 3D-pen design sprints,
(2) *Build a Boat* for buoyancy and stability, and
(3) *Build a Submarine* for watertight design and materials reasoning.

Each activity includes clear goals, materials, facilitation guidance, safety, assessment rubrics, and classroom adaptations. We share the design rationale based on theory, implementation steps, and a classroom practice plan focused on students' engineering practices according to Next Generation Science Standards (NGSS) [1] performance expectations. The paper contributes a coherent "mission arc" that can be introduced as the ideal engineering design thinking steps (plan -build -test -iterate -present) that is usable across activities with open resources for educators. We invite collaboration on multi-site studies to examine learning gains and broadening participation in naval engineering pathways.

Background and Motivation

Modern naval engineering concepts are often introduced far too late in the educational pathway to influence students' career awareness and development. Early National Academies reports on Shipbuilding Technology and Education focus on university and workforce-level preparation (naval architecture, engineering, apprenticeships), essentially treating naval engineering education as a postsecondary/technical topic rather than a K–12 staple [2]. Publicly available naval and shipbuilding education efforts, such as open source maritime course outlines, are typically designed for secondary and higher education rather than elementary or middle grades. However, research indicates that decisions about pursuing Science, Technology, Engineering, and Mathematics (STEM) careers are often made well before students reach college. By the end of middle school, many have already set a likely path, and shifting their aspirations after that point becomes considerably more difficult [2]. For example, a study tracked a national U.S. cohort and found that 8th-grade science career expectations were a powerful predictor of later degrees [3]. Students who expected a science career in Grade 8 were far more likely to earn a physical science/engineering degree than those who did not, even after controlling for achievement and background. In line with this, other studies found that students typically decide whether or not to pursue STEM careers no later than the end of middle school [4, 5] . Together, this suggests that introducing STEM concepts only in late secondary or postsecondary education is likely too late to substantively shape many students' career awareness and development. This motivates our efforts to embed naval design contexts into K–8 engineering activities. Accordingly, we present three such activities and discuss their pedagogical alignment with the NGSS engineering design standards [1].

The Mission Arc

In this paper, we use mission arc to describe the recurring sequence, *plan - build - test - iterate - present,* that structures all three engineering activities. Our mission arc is not intended as a new model of engineering design or engineering learning; rather, it is a pedagogical wrapper that operationalizes core principles from the *Framework for Quality K–12 Engineering Education* [6], the *P–12 Engineering Learning Framework* [7], and NGSS's guiding principles [1]. Specifically, we derive the mission arc by re-expressing Moore et al.'s Complete Processes of Design (POD), Strimel (2021)'s three dimensions of engineering learning, and NGSS science and engineering practices in language that is developmentally accessible and reusable across activities.

Moore and colleagues' framework [6] defines 12 key indicators of a quality K–12 engineering education, with Complete Processes of Design (POD) at the center. POD comprises three phases—Problem and Background (POD-PB), Plan and Implement (POD-PI), and Test and Evaluate (POD-TE)—and emphasizes that engineering design is an iterative process in which students revisit earlier stages to improve their solutions [6]. Our mission arc compresses and renames these phases in student-friendly terms: *plan* foregrounds problem scoping and background research (POD-PB and early POD-PI), *build* corresponds to planning and implementing design solutions (POD-PI), *test* aligns with testing and evaluating prototypes (POD-TE), and *iterate* makes explicit the expectation that students cycle back through POD phases to refine their designs. The final step, *present*, extends [6]'s indicator for Communication Related to Engineering (Comm-Engr) by requiring students to share and justify their design decisions and results to peers and teachers.

At the same time, the mission arc is structured to ensure that each phase engages American Society for Engineering Education (ASEE)'s three dimensions of *the Framework for P–12 Engineering Learning* [7]: Engineering Practices (e.g., engineering design and materials processing during build and test), Engineering Knowledge (e.g., forces, buoyancy, material properties applied while planning and evaluating solutions), and Engineering Habits of Mind (e.g., creativity, persistence, collaboration, systems thinking, and conscientiousness cultivated throughout planning, iteration, and presentation). In this sense, the mission arc uses these frameworks as the backbone of our engineering learning principles. It translates their key indicators and dimensions into a coherent, repeatable trajectory of activity that can be enacted across open-source lessons while remaining tightly aligned with established definitions of quality K–12 engineering education.

Activities Overview

In the curriculum design, all three activities (Additive Manufacturing, Build a Boat, Build a Submarine) are intentionally structured to follow the same five-phase mission arc:

plan - build - test - iterate - present

so that learners encounter a consistent sequence of engineering moves across contexts.This explains that each activity has a *plan* moment (e.g., problem framing/understanding the challenge, sketching, material choices), *build* a phase (e.g., constructing the artifact), testing phase (e.g., trying the boat/sub/structure against clear criteria), an *iterate* opportunity (e.g., revisions or at least explicit "what would you change and why?" reflection), and a *present* moment (e.g., share-out, or whole-class discussion of designs and results).

During classroom implementation, we recognize that local constraints may limit the depth of iteration and presentation. Accordingly, we recommend that teachers or facilitators abbreviate the *iterate* phase when needed (for example, one quick modification rather than a full redesign cycle) and handle the *present* phase more informally (for example, verbal share-outs instead of formal presentations). While the degree of emphasis on individual phases (especially iteration and presentation) may vary, the full mission arc is embedded in every activity's teacher materials and prompts, preserving a common engineering learning structure across the set.

	Mission Arc				
Activities	**Plan**	**Build**	**Test**	**Iterate**	**Present**
Additive Manufacturing	Sketch load-bearing structure or custom tool; identify constraints and materials	Use 3D pen and filament to fabricate the structure or tool	Check height, stability, and/or whether the tool can successfully turn the nut/bolt	Strengthen weak joints, adjust geometry, or redesign tool features based on test results	Share design choices, test outcomes, and proposed improvements with peers/teacher
Build a Boat	Frame the challenge; sketch hull shape; choose materials (and cost options for middle school scale up)	Assemble boat from given materials	Place in water to see if it floats; add weights until it capsizes or takes on water	Adjust hull shape, sealing, and weight placement; describe how you would redesign the boat	Compare boat designs in a quick share out activity; explain or discuss shape or sealing
Build a	Learn about	Construct	Submerge	Analyze	Report which

Submarine	submarines and watertight design; sketch a submarine to keep the "sailor" dry	a submarine body, seal seams, and enclose paper "sailor"	submarine; watch for bubbles and then check if the sailor has dissolved	where leaks occurred; modify sealing, materials, or configuration to improve dryness	designs kept the sailor dry and why; connect to real submarine design and safety

Activity 1: Additive Manufacturing

In this activity, students use handheld 3D-printing pens to complete three challenges:

1. designing a load-bearing structure,
2. constructing the tallest free-standing structure they can, and/or
3. creating a custom tool to turn a nut and bolt.

Engineers routinely rely on a range of techniques, skills, tools, and processes, and K–12 students likewise need opportunities to use and connect these elements [6]. In our framing, techniques are step-by-step procedures for specific tasks, skills are a person's ability to carry out those tasks (e.g., drawing schematics, creating flowcharts), tools are objects that make work easier (e.g., rulers, calipers, CAD or Excel software), and processes are series of actions taken to achieve a particular end (e.g., manufacturing or production systems, distinct from the engineering design process itself). For grades 4–8, this activity also aligns with NGSS's treatment of engineering design, which positions students as defining problems with criteria and constraints, generating and testing solutions, and using evidence from tests to improve designs [1]. In particular, students engage science and engineering practices such as defining problems, developing and using models, planning and carrying out investigations, and constructing explanations and designing solutions, as well as the crosscutting concept of structure and function.

In Additive Manufacturing, each challenge begins with a *plan* phase in which teams sketch and annotate their ideas on paper, identifying constraints such as height, stability, and load capacity, developing skills in representation and communication while defining the design problem and its criteria/constraints in NGSS terms. Students then *build* with PLA filament and printing mats (Figure 1), practicing techniques for layer-by-layer deposition while using the 3D pen as a contemporary engineering tool within an additive manufacturing process; this phase engages NGSS practices of developing and using models and constructing solutions. During the *test*, they evaluate whether their structures stand, reach the specified height, or successfully actuate the nut and bolt, thereby planning and carrying out investigations and informally analyzing and interpreting data about performance. Failures (e.g., buckling, weak joints, non-functional tools) prompt *iteration*, as students analyze what went wrong and revise their geometry, joint design, or construction strategies, mirroring NGSS expectations that learners use evidence from tests to improve engineering solutions. In a final *present* phase, teams share their designs, performance results, and proposed improvements, and discuss how additive manufacturing techniques, skills, tools, and processes might be used in real naval and engineering contexts, supporting NGSS emphases on argumentation and communication.

Mapped to the frameworks, this activity foregrounds POD, Science, Engineering, Mathematics (SEM) Knowledge (e.g., forces, stability, measurement), and ETools (intentional use of engineering techniques, skills, tools, and processes), alongside EThink (creativity, learning from failure, managing trade-offs) and P–12 Engineering Practices in design and materials processing. Simultaneously, it provides a concrete enactment of NGSS-aligned engineering design learning for upper elementary and middle grades, integrating science and engineering practices, crosscutting concepts, and core ideas within a coherent design challenge [1].

Figure 1. Additive manufacturing activity.

Activity 2: Build a Boat

This activity positions students as "boat‑building engineers" challenged to design a vessel that floats and carries as much weight as possible (Figure 2). The lesson opens with a *plan* by eliciting prior knowledge ("Have you built a boat before?") and introducing basic concepts such as buoyancy, balance, and different boat materials. Students sketch blueprints, have a teacher review their plans with "why" and "tell me about" questions, and only then visit a materials "store" to select supplies. These nuances mirror the Problem and Background and Plan and Implement phases of POD [6].

During *build*, teams construct boats from cardboard, cups, tape, and other low-cost materials; in the middle-school extension, a cost system adds realistic budget constraints. Students *test* together around a water bin. They first ask “Does it float?” and then progressively add weights until boats capsize or take on water which makes performance visible and shared. This naturally leads to *iteration* as students consider where they placed weights, how hull shape affected stability, and how they would redesign for next time.

The closing discussion can serve as the *present* phase where students compare hull shapes, name what worked or failed, and connect their models to real ship design vocabulary (e.g., hull, ballast, stability, capsize, load). In framework terms, the activity strongly enacts POD, SEM (density, forces, area, and balance), and EThink, while also cultivating Teamwork and Engineering Communication as students negotiate design choices and share results. It simultaneously engages P–12 Habits of Mind (systems thinking about hull–water–cargo interactions, collaboration, optimism in redesign) and Engineering Knowledge about buoyancy and naval vessels.

Figure 2. Build a boat activity in a 4th grade classroom.

Activity 3: Build a Submarine

In this activity, students build on what they learned from boats to design a watertight submarine that keeps a dissolvable "sailor" dry (Figure 3). The *plan* phase orients students to submarine function and safety. They learn what submarines do, how ballast tanks control buoyancy, and why material permeability and porosity matter. Students then sketch designs and justify their material choices before visiting the materials "store," again enacting the Problem and Background and Plan and Implement phases of POD.

Students build submarines from everyday materials (cardboard, foil, cups, tape) and place the paper "sailor" inside. During the *test* phase, each submarine is submerged while teams watch for bubbles and then open the vessel to check whether the sailor has dissolved. This vivid success criterion can drive *iteration*: leaks prompt analysis of seams, materials, and geometry, and students speculate about how to redesign for better performance and safety under pressure.

In the *present* phase, students report on which materials and shapes best resisted water, connecting their prototypes to real submarine engineering and the stakes of protecting people and equipment underwater. This lesson also engages POD, SEM (properties of materials, pressure and buoyancy), ETools & Processes (integration of materials and sealing methods), and EThink (reasoning about risk, reliability, and learning from failure). It also advances P–12 Habits of Mind (conscientiousness about safety, collaboration, systems thinking about hull–water–air interaction) and Engineering Practices around design and materials processing.

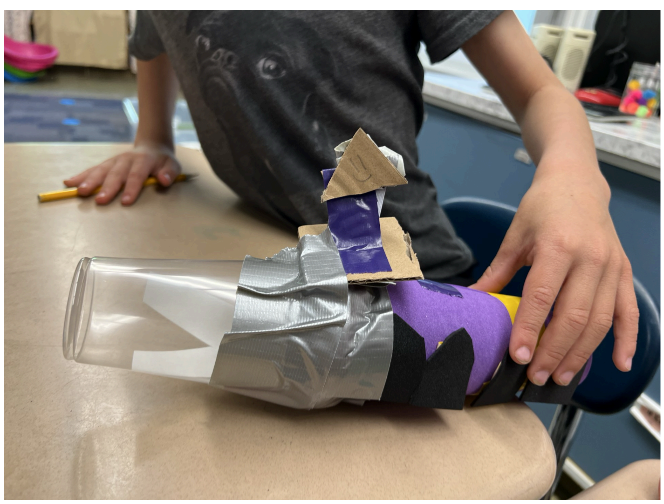

Figure 3. Submarine prototype prior to testing.

From Design Intent to Classroom Practice

The overall design intent of the project is to support meaningful project-based learning experiences in which students engage with a complete design experience, including making design decisions, testing outcomes, and reflecting on potential improvements. While this intent is embedded in the activity design, its realization in classroom settings is shaped by practical constraints, including limited and variable instructional time, classroom logistics, and the developmental needs of the target age group. As a result, classroom enactment often reflects adaptations that preserve core learning goals while adjusting sequencing and emphasis.

Across implementations of the open-source activities, the largest portion of instructional time was consistently dedicated to building and designing. Testing and discussion typically followed and were allotted roughly comparable amounts of time, though the exact pacing varied depending on the length of the classroom visit. Rather than following a fully linear or staged design cycle, these phases were frequently blended to support student engagement and classroom flow.

One common adaptation involved the timing of student communication. Since testing often caused designs to degrade (particularly in activities involving water) students were typically asked to share their designs before testing. This ensured that all groups had an opportunity to explain their ideas and reasoning before structural changes occurred. Following this brief introduction, designs were tested in front of peers, and students were immediately prompted to reflect on how their design performed and to identify one change they would make if given additional time.

Although iteration is a central component of project-based design learning, classroom time constraints rarely allow for substantial physical redesign. Instead, iteration most often occurred through verbal and conceptual reflection. Students' responses to post-testing prompts were used to guide whole-class discussion and to connect observed outcomes to formal concepts such as buoyancy, balance, stability, and symmetry. In this way, opportunities for sensemaking and reflection were embedded directly within the testing process rather than positioned as a separate concluding activity.

Embedded evaluation and feedback

Consistent with the practical focus of the current phase of the project, data collection during implementation emphasized feasibility, engagement, and instructional value rather than formal learning gains. Teacher feedback served as the primary source of evaluative data, providing insight into classroom usability, pacing, and alignment with grade-level expectations. Informal post-implementation discussions contributed to understanding how the activities functioned in authentic settings. Facilitators used brief, in-the-moment reflection prompts with students following testing to elicit evidence of understanding and to support discussion of design principles. Questions such as “How did your design perform?” and “What is one thing you would change?” functioned both as formative evaluation and as instructional scaffolds, allowing facilitators to assess students’ emerging understanding while maintaining the flow of the activity.

Limitations

The Navy STEM open-source activity set is intentionally designed as an accessible, facilitator-friendly entry point to K–8 engineering design. In that spirit, several limitations should be made explicit for researchers who may adopt these materials as an intervention, study their impacts, or compare them to more established K–8 engineering curricula.

Two of the core activities are designed for ~60–90 minutes, and the lesson plans explicitly allocate substantial time to building (e.g., “announce build time – approx. 30 minutes” in *Build a Boat*), followed by a single testing sequence and closing discussion.This structure supports engagement and feasibility, but it can constrain opportunities to enact multiple redesign–retest cycles, which are central to “optimizing” design solutions in NGSS-aligned engineering (especially in grades 6–8, where expectations include analyzing test data across solutions and iterative modification toward an optimal design) [1]. As a result, “iteration” may be enacted primarily as verbal reflection rather than physical redesign, which affects both learning opportunities and what researchers can validly claim was observed.

Some lessons assume resources that may not be uniformly available. For example, “Additive Manufacturing” requires 3D printing pens, printing mats, and PLA filament, and both Boat/Submarine activities require water bins and testing setups. These requirements can influence who can adopt the activities, how smoothly they run, and how comparable implementations are across various educational settings.

Current evaluation approaches mentioned in the open-source activity set may not support strong causal or standards-based learning claims. While the presented teacher feedback and informal student reflection prompts are appropriate for usability and feasibility, it may limit the kinds of learning claims that can be defended without additional measures. The K–12 engineering education literature emphasizes the need to clearly define expected learning outcomes and to use research methods that can validly elicit and assess those outcomes [8]. In addition, national reports highlight persistent challenges in monitoring and evaluating outcomes for different contexts and call for clearer metrics and stronger measurement approaches [9]. Future researchers using these activities should plan for aligned assessments if the goal is to make claims about NGSS engineering outcomes.

Future Work

The next phase of this work will strengthen the evidence base by moving from usability-oriented feedback to outcomes-focused research designs that can support defensible claims about student learning aligned to NGSS engineering design and related science and engineering practices. In particular, future studies should pair these activities with brief, developmentally appropriate assessments that capture

- students' ability to define criteria and constraints,
- the use of evidence from testing to justify redesign decisions, and
- the quality of design communication during presentation and reflection.

These measures should be explicitly aligned to the mission arc phases (plan - build - test - iterate - present) to preserve coherence between the instructional model and the evaluation model.

A second line of future work should examine implementation variability and the fidelity of the mission arc model in various classroom contexts. Since time constraints often compress iteration into verbal reflection rather than physical redesign, a key research need is to operationalize iteration format (e.g., no redesign, one quick modification, or multiple redesign–retest cycles) and study how iteration format and time allocation influence outcomes. Complementing this, we recommend developing lightweight fidelity tools (e.g., teacher logs and/or brief observation checklists) that document phase timing, materials substitutions, classroom logistics, and how the present phase is enacted (informal share-out vs. structured presentation). Such instruments would enable multi-site studies to separate the effects of the activity design from the effects of local enactment choices, while also providing actionable guidance for educators adapting the open resources.

In addition to NGSS-aligned outcomes, an important planned extension is to embed an explicit assessment of student creativity in engineering design using the Engineering Creativity Assessment Tool (ECAT) framework developed alongside this project [10]. The ECAT factor structure has been defined through exploratory analyses, but confirmatory validation is still pending. Accordingly, near-term work will first confirm the ECAT measurement model with an independent sample and establish reliability and validity evidence prior to using ECAT scores as study outcomes within the Navy STEM activity set. Once confirmed, ECAT-aligned scoring guidance can be integrated into the mission arc so that creativity indicators are captured during plan (idea generation and constraint negotiation), build/test (novelty–functionality trade-offs), iterate (evidence-based transformation and elaboration), and present (justification and communication of design intent).

Finally, future work should extend beyond immediate classroom outcomes to examine accessibility and pathway-relevant indicators. Since the activity set is motivated by early interest formation, future research should include measures of student interest, perceived relevance, and emerging engineering identity and investigate how participation structures (e.g., team roles, facilitation moves, and communication routines) support broadening participation. Parallel work is needed to strengthen scalability and sustainability, including research on teacher professional learning supports (e.g., short onboarding modules, facilitation videos, troubleshooting guides) and access-oriented implementation models (e.g., lending libraries, low-cost substitution kits, and no-water/no-special-equipment variants).

Acknowledgement

The UConn-URI Navy STEM Coalition recognizes the critical support from the ANCHOR contract, managed by General Dynamics Electric Boat and funded by the U.S. Navy through the Maritime Industrial Base Program, which enables continued investment in workforce development and STEM education. The ANCHOR contract builds upon activities supported by the Department of Defense National Defense Education Program (NDEP) grant #HQ00342110016. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the University of Connecticut, the University of Rhode Island, General Dynamics Electric Boat, the U.S. Navy, or the Department of Defense.

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