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Combining Engineering Design and Stage Gate Processes in a Multidisciplinary Engineering Technology Capstone Course

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This paper outlines Purdue's School of Engineering Technology's (ET) capstone education structure utilized over the past decade. Implemented in a mandatory, two-semester, multidisciplinary course for all majors, the focus is on integrating the stage-gate process for project management with the engineering design cycle for effective problem-solving. This paper details how the stage-gate process is used to manage the project stages, while the engineering design cycle identifies relevant activities during each stage. Additionally, it identifies the necessary material and infrastructure for course implementation. The paper concludes with a discussion on challenges and lessons learned over 10 years. By sharing this capstone pedagogy, we aim to showcase a successful approach to ET capstone that others may wish to incorporate.

Keywords: Stage-Gate, Engineering Design Cycle, Project Management, Engineering Technology

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Introduction

Purdue's School of Engineering Technology (SoET) provides hands-on, applied education for careers in engineering technology fields such as electrical, mechanical, manufacturing, and industrial engineering technology. To support this goal, all SoET students must complete a two-semester multidisciplinary capstone course that provides opportunities to work on industry-sponsored, real-world projects. This situates learning within authentic industry experiences, allowing students to apply their knowledge in practical settings and to prepare them for professional roles in the engineering technology (ET) field. Such an approach is intended to assist students in developing competencies in:

1. **Engineering Design:** Emphasizing the skills necessary for defining, designing, and developing ET solutions to achieve cost, performance, and user-interface goals.
2. **Project Planning and Management:** Studying techniques for effective project planning, scheduling, and management throughout the engineering design process.
3. **Integration of Professional Skills:** Incorporating communication, teamwork, global and societal concerns, and ethical considerations into projects.

This paper explores how the Purdue capstone course combines a non-linear nine-step engineering design process with a linear six-gate stage gate project management process in terms of course structure, design deliverables, and required project resources. Overall, this approach was chosen in order to facilitate both structured project management (stage-gate) and the use of problem -solving and iterative design processes (engineering design cycle).

Defining the Engineering Design Process

An engineering design process is a structured approach to problem solving that generally includes; defining the problem; researching; generating ideas; developing, evaluating and refining concepts; documenting; and ultimately producing a final solution[1,2]. Purdue SoET capstones implement a nine-phase engineering design cycle. The phases and major activities of each are:

1. **Problem Identification:** Defining the problem, customer needs, constraints, and goals.
2. **Research:** Reviewing existing solutions, related technologies, and applicable engineering principles.
3. **Requirements Specification:** Articulating specific, measurable, and verifiable statements as to what the product or system must achieve or possess.
4. **Concept Generation and Down Selection:** Brainstorming and generating multiple concepts to solve the problem, developing prototypes or models of selected concepts for evaluation (throw-away prototypes), assessing and evaluating the concepts against criteria for selection.

5. **Design:** Producing a detailed mechanical, electrical, and/or software description using appropriate models, developing prototypes or models of final concepts to proof functionality (proof of concept prototypes), creating technical data package (TDP).
6. **Prototype and Construct:** Creating designs in high fidelity (engineering prototype) in accordance with TDP.
7. **Systems Integration:** Combining the engineering prototype with other systems.
8. **Verification**: Evaluating the system to ensure it meets the defined requirements and specifications.
9. **Delivery**: Transfer of product, documentation, or other deliverables to the client.

In practice, these design phases are often revisited and reevaluated based on outcomes of later phases, such as cyclical repetition between neighboring phases (i.e., iteration) or returning to much earlier design phases based on new information, objectives, or constraints (i.e., feedback)[5], resulting an applied process that is highly non-linear.

Defining the Stage Gate Process

A stage-gate model is a framework for managing projects by dividing them into distinct stages separated by decision gates. At each gate the project undergoes evaluation to determine whether the project advances to the next stage, gets revised, or is terminated[3,4]. As such, the stage gate process follows a predominately sequential linear flow, with the process moving in a step-by-step manner. Purdue SoET capstones employ a six-stage, six-gate process. During each stage, distinct phases of the engineering design cycle are emphasized, and at each gate, specific design artifacts are reviewed and evaluated. Purdue SoET capstones stages and gates are:

- **Stage-Gate 1 - Project Proposal:** Emphasizes phases one to three of the engineering design cycle. Student design teams produce design artifacts including a written problem statement, research report, and an engineering requirements table. The gate evaluation is based on the course instructor and industry mentor's review of the deliverables as presented by student teams in both an oral presentation and written report.
- **Stage-Gate 2 - Conceptual Design Review:** Emphasizes design cycle phase four. Teams produce multiple initial concept designs (digital and physical), conduct down selection between designs, and propose a preliminary proof-of-concept design. Gate evaluation of these design artifacts is based on oral presentation and written report.
- **Stage-Gate 3 - Preliminary Design Review:** Emphasizes design cycle phases five and six at a preliminary level. Teams produce a physical proof-of-concept prototype focusing on demonstrating feasibility of the design. The gate evaluation is based on an oral presentation, written report and a demonstration/evaluation of the proof-of-concept prototype against the engineering requirements defined in Stage 1.
- **Stage-Gate 4 - Critical Design Review**: Emphasizes design cycle phases five and seven at detailed level. Teams produces a Technical Data Package (TDP) including: mechanical drawings, circuit schematics and simulations, software documentation, system architecture documents, and manufacturing and production plans. Gate evaluation is based on review of TDP for: technical viability of the design; clarity, completeness and accuracy of the drawings; and feasibility (capability, cost, and manufacturability).
- **Stage-Gate 5 - Engineering Protype Review (EPR)**: Emphasizes design cycle phases six and seven at engineering-prototype level. Teams produce an engineering prototype and TDP change control documentation. Gate evaluation is based on evaluation of engineering prototype against engineering and functional requirements, as well as overall build quality.
- **Stage-Gate 6 - Customer Acceptance**: Emphasizes design cycle phases eight and nine. Teams produce a test plan and a verification report. Teams transfer the product, documentation and other deliverables to the customer.

Combining Engineering Design and Stage Gate Processes

Integrating the engineering design cycle with a stage-gate project management process involves aligning the iterative nature of the design cycle with the linearly structured stages and decision gates of the project management framework. Figure 1 depicts the overall combination of the two processes into the course structure used in Purdue SoET capstones. Important features include:

- The stages of the stage-gate process are used to provide the linear structure for guiding student design teams through their projects. They are therefore used directly to form the overall weekly course and deliverable schedule over the two-semester sequence.
- The iterative phases of the engineering design cycle are emphasized during different stages and are used

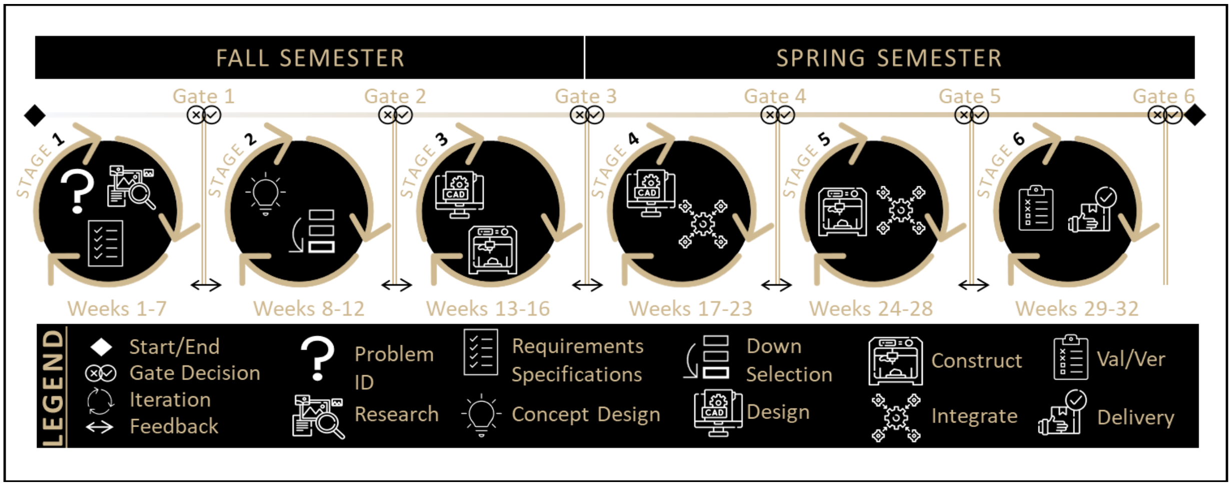

Figure 1. Combination of Engineering Design Cycle and Stage-Gate Process

to inform the specific activities and design artifacts that students work on/create during each stage.

- Students demonstrate design artifacts produced via application of the engineering design cycle at the gates. Feedback on performance is given by capstone faculty and/or project mentors. Corrections and improvements to design artifacts are made before proceeding to the next stage.

SoET Capstone Course Materials

Table 1 describes the required resources and materials typically required to complete projects. Currently, SoET capstones teams budgets are $2000, which teams must manage so that the funds cover all project expenses. In some cases, additional funding or in-kind contributions are provided by project sponsors basis to cover high-cost items or services. Required resources column describes the material and infrastructure necessary for project teams to complete each project stage. Cost + Items column identifies the cost of the project stage relative to the overall project (Low < 10%, Medium <25%, High >25%) and common cost items occurring during the associated stage.

Challenges and Lessons Learned

Combining the stage-gate process and the engineering design cycle has been a successful framework for guiding students through the complexities of real-word engineering challenges. However, there are practical limitations to their application in a classroom setting:

- Real-world gates serve as decision points to proceed, make modifications, or halt the project. In capstones, there is pressure to proceed in order to follow the course schedule. Modifications are typically made contemporaneously with the activities of the subsequent stage, and projects are very rarely (if ever) cancelled.
- Time and financial constraints routinely prevent all necessary activities from being performed within a given project stage. For example, insufficient throw-away-prototyping to generate sufficient data for down selection during the concept design phase.
- Real-world projects can allocate time to project stages to account for the differing complexity of phases. For example, new products may focus on stages one to three, whereas facility upgrades may spend lots of time in stages five and six. Capstone uses a single inflexible schedule for all projects as managing multiple projects timelines would be too cumbersome.
- The linear nature of the stage-gate model can limit the adaptability needed in a creative and exploratory process like engineering design. It can hinder the flexibility required for students to explore innovative ideas that might not fit into predefined stages.
- The structure is well-formed for projects that produce physical products or engineering processes. It works less well for projects that generate information or data.
- Details of stage-gate processes and the engineering design cycle can vary greatly across industries (if they are even used). Industry sponsors will likely have different conceptions and preferences for their application that do not align with those being used in the class. This can result in conflicting advice given to student teams, causing confusion and uncertainty regarding how to proceed or what to do next.

Table 1. SoET Capstone Course Materials

Project Stage	Required Resources	Cost + Items
Project Proposal	None	Low • Travel to Customer Site • Technical Literature
Concept Design	Low Fidelity Materials	Low • Sketching Supplies • Throw Away Prototypes
Preliminary Design	Medium Fidelity Materials Machine Shop Electronics Lab	Medium • Proof of Concept Prototype
Detailed Design	Mechanical and Electrical CAD Tools Programming Software	None
Construction and Integration	High Fidelity Materials Machine Shop Electronics Lab External Fabrication	High • Tooling • Engineering Prototype
Customer Acceptance	Project Specific Test Facilities	Low to High • Test Facility • Testing Materials • Destructive (Test) Prototype • Transport to Customer

Conclusions and Next Steps

This paper has introduced the integration of the engineering design cycle with the stage-gate project management process in Purdue's SoET capstone course as a framework for guiding students through real-world engineering design projects. By merging elements of both processes, students gain the skills necessary to tackle multidisciplinary projects and develop innovative solutions. Despite its effectiveness, this approach presents challenges. Looking ahead, future research could explore:

- The impact of the linear nature of the stage-gate model on students' ability to engage in creative design processes and alternative models that may better accommodate design exploration.
- Adaptations or supplements to the stage-gate model to suit projects generating information or data.
- Mechanisms for reconciling differences in expectations or methodologies between academia and industry, especially regarding stage-gate processes.

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