Review of a Design Methodology in a Client-Based, Authentic Design Curriculum

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Abstract

The curriculum at a small, urban, private school is centered around a series of hands-on, client-based design courses called DesignSpine®. Projects are developed and completed through the entire academic year. Faculty serve in a dual role of technical consultants and as academic coaches through the program.

A faculty committee tasked with the responsibility to review, develop, and implement design course work performed a mid-semester progress report of student teams as part of a regular curricular review, and realized that a majority of teams were behind schedule for the prescribed project lifecycle and timeline. This realization from a collective team status update prompted a review of project expectations and milestone accomplishments across three levels of student teams (i.e. sophomore, junior, and senior). Design project teams in all three levels originally followed the same two semester project lifecycle, divided into four phases: Identify Requirements, Characterize Design, Optimize Design, and Validate Design, commonly referred to as ICOV. The status reports revealed that senior teams were on track with the prescribed project lifecycle, while the junior and sophomore teams required additional resources (e.g. time and faculty support). This performance evaluation prompted the faculty committee to develop new project timelines scalable to the skill levels of the project teams. Additionally, this assessment of team progress also provided an opportunity to redefine the project phases to better represent the types of problems historically researched by the teams and the sequence of tasks performed throughout the semesters. The committee rebranded the four-phase project lifecycle with custom phase definitions: Identifying requirements, Develop Preliminary Design, Develop Detailed Design, and Final System Design. The updated phase definitions were created to provide more structure for the student teams and better capture what the school's design process was in practice rather than in theory.

This paper will present the original and revised project phases and the review of the design process. This process should be of interest to programs with capstone experiences and other team design project courses.

Background

Engineering is a field that consistently updates with ongoing technological advancements. The employers of engineering graduates demand technical knowledge and other professional skills [1]; communication skills, teamwork, multidisciplinary work, desire for continuous learning, project management, critical thinking, self-drive, and motivation [2]. Therefore, successful engineering education must include more holistic aspects of engineering.

Project-based learning [3], hands-on laboratories and experiments, collaborative and multidisciplinary projects [4], and simulations and modeling are some demonstrated, effective methods used in educating engineering students. Most engineering programs incorporate capstone projects that are usually focused on a single discipline; these capstone courses usually implement these pedagogical techniques. However, authentic engineering projects are multidisciplinary, requiring multidisciplinary teams of engineers and other professionals from outside of engineering to work together. Therefore, multidisciplinary teamwork is an essential aspect of engineering education. Some institutions have practiced curricula that require multidisciplinary student teams to complete capstone projects [5]. However, the capstone experience typically takes place only at the senior level and there is little time for students to comprehend the entire design process and project management skills. To overcome the deficiencies of the capstone-only system, curricula have been developed that require students to complete projects at multiple levels of the program [5],[6].

The project-based curriculum named DesignSpine was developed by the faculty at the R. B. Annis School of Engineering at the University of Indianapolis. This program empowers students to complete authentic, client-based projects at the sophomore, junior, and senior levels. The program requires a set of clients each year; clients are local industry partners as well as other units and departments in the university outside of the school of engineering. A call for proposals is issued, and as proposals are submitted, faculty and staff interview potential clients to understand the problem and convey reasonable expectations. The projects must fit the academic schedule, and should not be crucial to the success of the client.

At the freshmen level the students are trained to work in teams and taught industry-focused project management and product development methodologies and tools. The DesignSpine curriculum is a two-course sequence, one in the fall semester and the other in the spring semester, at each academic level from sophomore to senior. The curriculum was first introduced six years ago and has been continuously improved based on faculty and student feedback. The original framework was the ICOV framework used in Design for Six Sigma (DFSS) [8] (Identify requirements, Characterize design, Optimize design, and Validate design) to define the project progress ‘gates’ for all academic levels. Each phase ended with a Gate Review, where teams would present progress thus far and a decision was made to continue with the project. In our academic environment, the project would be expected to continue, but teams may have to make significant adjustments.

Technical Demonstrations

Over the past several years, a series of technical demonstrations (tech demos) were added to the DesignSpine course sequences. Initially, the purpose of these tech demos was for students to demonstrate a minimum viable product. The demonstration would occur in the second semester of the course sequence, after the initial building phase, but before the final product handoff to the client. An additional tech demo was added at the end of the first semester, where the goal is for the team to identify, demonstrate, and evaluate the viability of critical components/subsystems/configurations of the design. Tech demos are graded against previously agreed upon custom requirements that are tailored specifically to the team's project and determined by the team in consultation with their tech demo committee. The tech demo committee was a consistent group of 4-5 faculty who established requirements for the tech demo and evaluated the team's performance during the technical demonstration. The first tech demo helps ensure that students order parts and start assembly (of at least the critical sub-components) of the end product. One practical benefit is that delays from out-of-stock parts, inappropriate designs and flawed processes are addressed earlier, and thus less likely to delay the project. In addition, new and replacement parts with long shipping times can often be ordered over winter break, improving overall time management. The tech demo emphasizes to students that planning out a design on paper, and implementing that design, are two different things. Our students learn that setbacks from unforeseen circumstances will occur, and time must always be set aside in order to account for these problems. In this way, the all-too-common problem of student procrastination can be mitigated.

A Summary of the New Project Phases

The DesignSpine program is constantly assessed by a faculty DesignSpine committee. This committee evaluates the progress of each project regularly, and noticed a propensity for second year teams to be significantly behind schedule, and, not surprisingly, require more faculty and staff assistance. Third year student feedback consistently showed that they felt rushed in the initial phases of their project. Students in their senior year were generally on track to deliver a final product. This led to a discussion of redefining both the definition and requirements of project phases and reasonable expectations for students in each year, with consideration to the academic aspects of the program (for instance, consideration of academic breaks, final exam weeks, etc.)

After the first five years of the program, the faculty developed new phase definitions based on both faculty and student feedback. These new phases are similar to the original ICOV model, but designed to fit our specific process. This paper discusses the changes made at each academic level of the DesignSpine curriculum.

The original ICOV model was reimagined by the faculty members overseeing the curriculum. A new four-phase project life cycle was developed. The new phases are: Identify Requirements, Develop Preliminary Design, Develop Detailed Design, and Final System Design. These phases were custom-defined to fit the year-long (two-semester) hands-on, client-based design courses at the school.

Each semester is 15 weeks long (including a final exam week, when the student teams do not have a mandatory meeting time). Note that the projects are mostly on pause during the winter break, except for school staff ordering/receiving items ordered by student teams before their departure for the winter recess. Note further that the final phase of the project depends on the level of the student teams. Sophomore (2nd year) and Junior (3rd year) teams end their project at Phase III, whereas the senior (4th year) teams go through all four phases.

Phase I: Identify Requirements

This phase includes organizing the team, understanding, and confirming the problem and project charter, developing a project plan, and identifying and understanding project requirements. This phase is very similar to the first phase of the original ICOV model. Project requirements will be identified through interactions with resources such as clients, customers, stakeholders, business mentors, and competition guidelines. Project requirements may also be classified into the following: Objective, Constraints, and Function.

At the end of this phase, the goals for the student teams include:

- Present a summary of project and problem statements (confirm scope).
- List requirements, constraints, and/or rules (requirement classifications).
- Identify the biggest, initial technical challenge the teams will investigate.
- Identify relevant resources (i.e., similar products, expert personnel, textbooks, manuals, prior course knowledge, etc.) needed to develop preliminary designs.
- Obtain client (or relative party) approval to progress to Phase II and develop preliminary designs.

Phase II: Develop Preliminary Design

This phase includes translating project requirements into functional requirements, non-functional requirements, and constraints. Additionally, this phase includes developing and evaluating solution alternatives, conducting preliminary tests to narrow down conceptual designs, and verifying proof of concept. Teams will end Phase II with a preliminary design (documentation) developed from research and investigation of multiple design alternatives.

At the end of this phase, the goals for the student teams include:

- Present preliminary designs and proof of concepts explaining fundamental technical principles associated with the project and current verification testing, research, or analysis to make informed design decisions (i.e., governing equations, calculations, socio/economic/environmental/safety factors, prototyping, etc.).
- Identify relevant resources needed to develop detailed designs.
- Obtain client (or relative party) approval to progress to Phase III and develop detailed designs.

Phase III: Develop Detailed Design

This phase includes transitioning from proof of concept to an engineered design by refining and improving upon the preliminary design. Improvements are learned from testing feedback and lessons from Phase II. As much as possible, real materials should be included in the prototype for continued testing, verification of system performance, and optimization of design features. Phase III ends with a detailed design (documentation) and an engineering prototype.

At the end of this phase, the goals for the student teams include:

- Present detailed designs and engineering prototypes.
- Explain design insights/decisions obtained from verification testing to optimize designs.
- Obtain client (or relative party) approval to progress to Phase IV and develop final system designs.

Phase IV: Final System Design

The concluding phase includes creating a pilot product constructed of quality materials, or alternative materials when appropriate. The pilot product is used for validation testing of the final system design. This phase concludes with the transfer of project deliverables to the client (or relative party) and closing the project.

At the end of this phase, the goals for the student teams include:

- Present final system designs, including validation testing and demonstration (if appropriate) of pilot products.
- Communicate the solutions and transfer deliverables to the clients (or relative parties).
- Obtain client (or relative party) approval of project closing.

Originally, each course had a schedule featuring a nearly even split among all four phases of the ICOV methodology, but given a few years of experience, especially in-person, post-COVID experience, adjustments were made. The schedule and deliverables in the second and third year featured more substantive changes.

Changes to the Second Year (29X)

ENGR 29X has instituted three phases, eliminating the final phase, now called Final System Design in the new DesignSpine project phases model. The new course progression goes from Phase 3, the Develop Detailed Design, to Phase 3B, which is best defined as extension of Phase 3.

The main benefit of this is that students will engage in continuous development and refinement of their project throughout the second semester of the course. Given that the second Technical Demonstration requirements for ENGR 29X are the same as previous years and require that a final or near-final product must be delivered, this encourages students to focus on the main deliverables outlined in their project charters without worrying about the product being 100% polished and deployment-ready.

The drawbacks of having a Phase 3B as opposed to a dedicated Phase 4 include possible student procrastination, students conflating a lack of a strict Phase 4 deployment with the product not having to meet all core deliverables outlined in their charter, and student frustration that main components of Phase 4, such as the transfer of deliverables and the project handoff, are still maintained.

ENGR 29X tightened up the timeline from previous years on the first phase, formerly Identify Requirements, in order to start students on the ideation phase of class, which is Develop Preliminary Design. This was managed through a few changes from previous course iterations. The first change that allowed students to fast-track identification of requirements was that students arranged a first meeting with their clients nearly as soon as their projects were announced. The students came prepared for the meeting with a Design for Six Sigma (DFSS) compliant questionnaire with question categories, and prepared actionable problem statements or translation worksheets with product requirements within days of the first client meeting. Some teams had multiple client meetings or interactions during the first three weeks of the course to refine product deliverables.

The second major change was that the Project Charter timeline for completion and overall level of thoroughness was bolstered from previous years. The faculty assigned as faculty advisers develop the first drafts of the project charter before summer break. The level of detail in these charters included defined deliverables that were reviewed by the DesignSpine coordinator, course coordinator, and laboratory staff, to ensure that they were reasonable for sophomore-level students, achievable given the time frame, and overall manageable in case issues arose within the team or from external sources.

One key component that the faculty team as a whole focused on from the first interview with prospective clients for ENGR 29X was the concept of outlining solutions ahead of time, thus focusing on *solvable problems*. The faculty and lab staff drafted potential solutions, talked through how difficult they would be for each individual project in multiple meetings, and provided written notes and a ranking when the faculty as a whole considered adopting (and assigning) a project to the sophomore students. There were three philosophies behind this approach: first, if faculty could not solve the problem, then perhaps the projects would be too difficult and not-appropriate for sophomore-level projects; second, the problem solutions themselves would provide test cases for various directions the students could pursue, and thus faculty could simulate and discuss potential issues ahead of time; and third, this helped faculty who are not experts in their assigned project's technical domain to be cognizant of what technical help they may need when guiding students through project completion.

Changes in the third year (39X)

The third year of DesignSpine focuses on developing the entrepreneurial mindset and competencies of the engineering students [4],[7],[9],[10]. The students go through the process of opportunity identification and evaluation, customer discovery with interviews, minimal viable product (MVP) design and development, business planning, and a business pitch presentation to different stakeholders from within and outside the university. Key feedback from the students who took the course focused on the short, one-week period allocated for idea generation. The DesignSpine Committee moved to change the structure of the two courses by introducing a *Phase 0* that extends for the first three weeks of the first semester during which the students can have sufficient time to generate and evaluate different product ideas. Table 1 shows the prior structure of the third-year entrepreneurial courses while Table 2 shows the new structure following the new phase definition.

Table 1: Overview of old program phases and timeline.

Semester (Course)	Phase & Associated Gate Review	Focus	Expected Timeline (Week)
I (ENGR 396)	1	Opportunity identification and customer discovery	1 - 8
I (ENGR 396)	2	Design of a minimum viable product (MVP)	9 - 15
II (ENGR 398)	3	MVP development (Build a prototype)	1 – 8
II (ENGR 398)	4	Validate the design, establish a business model, and present business pitch	9 - 15

Table 2: Overview of new program phases and timeline.

Semester I (ENGR 396)

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Phase	0	0	0	1	1	1	1	FB	1	GR	2A	2A	2A	TD	2A

Semester II (ENGR 398)

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Phase	2B	2B	2B	2B	GR	3	3	3	SB	3	TD	3*	3*	BP	

*Potentially business pitch prep
FB = Fall Break; SB = Spring Break; GR = Gate Review, BP = Business Pitch

In addition, based on the students' feedback, the DesignSpine Committee instituted a change in team formation process and timing. During the new Phase 0, students are allowed to come up with different product ideas collectively and are allowed to be a part of the group or team based on the product ideas that are of interest to them. This organic and student-led team formation is unlike that of previous cohorts where teams were formed by the faculty before the beginning of the course.

Similar to the revision in the second year, the DesignSpine Committee felt that the validate component was not a critical part for the usual consumer product centric entrepreneurial courses. The validate component of ICOV usually involves installing and testing at a client's facility and that is not a key focus of the entrepreneurial course. Consequently, the DesignSpine Committee reduced the number of gate reviews in the first semester course from two to one. The timing was also changed from around week 7 to week 10 to accommodate the three weeks for phase 0. Gate review 2 was moved to the fifth week of the second semester. Each semester has one technical demonstration (TD) included [4]. In order to effectively simulate the rapid product development required for new products introduction into the market in startups or other companies, the rubric for gate review 2 was revised to include not just quality of design decisions, but also some level of system development as shown in Table 3.

Table 3: Revised gate review 2 rubric to assess the level of systems development to simulate rapid product development and introduction to the market.

	Description	Example High Score (10)	Example Median Score (8)	Example Low Score (6)
Content				
Quality of Design Decisions	How well did the team defend their design decisions? Explanation of your initial concepts and how you got where you are. Include your design criteria and what design choices you have made. Provide evidence or justification of design decisions through calculations, research, consultation, testing, etc. Provide evidence of chosen design functionality (e.g., prior testing, test demo results, etc.).	Outstanding design decisions backed (explained) by significant use of relevant tools and materials. Evidence of design decisions and potential functionality clearly presented. Clear outline of a preliminary design to move forward to Phase 3.	Acceptable design decisions with moderate use of relevant tools and materials to explain how preliminary design was developed. Little evidence to explain design decisions and potential functionality.	Weak design decisions and little use of relevant tools and materials. Uncertain what the preliminary design is and missing justification/evidence of design decisions or functionality.
System Development Status	Level of system development (actual fabrication, system assembly, etc.) is an important part of product development. System development must be done to ensure that critical subsystems are identified and fabricated/assembled to provide preliminary results or proof (demonstration) of functionality. Please also highlight any identified system requirements yet to be developed.	Clearly identified and explained the roles of critical components/subsystems for system under development. Showed critical components/subsystems function, with some level of subsystems integration, to demonstrate desired system's performance. Demonstration indicates that team is on the right path and system will be ready for tech demo.	Some critical components/subsystems were not identified and explained for system under development. Functioning of some critical components/subsystems demonstrated but not well integrated and functioning together. Progress indicates some concerns that system will be ready for tech demo.	Critical components/subsystems for system under development not identified and roles not explained. Functioning of critical components/subsystems not demonstrated well. No integration or demonstration of critical components/subsystems functioning together. Progress indicates that it is unlikely that system will be ready for tech demo.
Test Plan for Phase 3	What do you still need to test/investigate/decide? What are your objectives and key performance indicators for any testing? Describe your testing methods (e.g., standards, number of samples, etc.).	Outstanding test plan to move into Phase 3. Clearly stated objectives (what will you be testing) with reasoning. Clearly stated performance indicators and testing methods.	Acceptable test plan for Phase 3. Know what they should be testing, but lacking necessary testing information (e.g., key performance indicators, testing methods, etc.).	Weak test plan for Phase 3. Little understanding of what still needs to be tested/investigated/decided. No testing methods presented.
Presentation				
Slide Presentation	Flow of presentation, appropriate visuals, value of material, and quality of slide layout.	High quality slides that are easy to follow and naturally flow with equal contribution.	Passable slide presentation with distributed contribution.	Disjointed slide presentation with lopsided contribution.
Interaction	Ability to field questions and ask cogent questions. Behavior and interactions with audience members. Evidence of effective mentor(s) engagement.	High quality interaction indicative of strong rapport, questions, and active listening. Provided strong evidence of mentor(s) engagement and inputs.	Acceptable interaction with audience through engagement and answering of some questions well. Provided some evidence of acceptable mentor(s) engagements and inputs. Medium quality interaction and engagement with audience, mentor.	Weak interaction indicative of poor rapport, few questions, and poor listening. No evidence of adequate mentor(s) engagement and inputs.

Changes in the fourth year (49X)

The fourth year is only slightly revised, as it continues to require all phases. The course design before implementing the changes to the phases had the following specified goals for the four key phases for the year-long project:

Phase 1 - Objectives:

- Finalized Project Charter
- List requirements or rules
- Provide sufficient research to identify the important design decisions
- Report any progress so far or results of experiments
- List of tasks to complete the project
- Senior Design project ABET requirements.

Phase 2 - Objectives:

- Propose, develop, and evaluate at least 3 conceptual design alternatives.
- Propose 1 single preliminary design you will move forward with in Phase 3
- Devise a test plan for Phase 3 & project management plan
- Reflection on project management style used
- **Note:** *Goal of GR2 is for the client to review three conceptual designs and select and approve the preliminary design that the team should move to detailed design, fabrication and testing in Phase 3.*

Phase 3 - Optimize Design

- Complete/redo any prior Phase objectives that were incomplete or inadequate.
- Fabricate system or sub-systems
- Perform tests (technical and/or users)
- Optimize critical design parameters

Phase 4: Validate Design

- Pilot test and refine prototype
- Validation
- Closing:
    - Full commercial rollout & handover to new process owner
    - Communicate solution and transfer deliverables:

After the phase definitions were modified, the phase goal wording was updated and refined to have more consistency across each level (29X/39X/49X). At the senior-level, Phase 4 remained since expectations for seniors are to have a finalized product and the seniors (in ENGR 196 & 198) are given twice as much credit and meeting time in Semester II for the design course. The updated Phase Definitions are specified in the syllabus. Beyond the phase definitions, the following material is included:

PHASES:

Phase I - Identify Requirements:

Project requirements may also be classified into the following:

- **Objective**: a feature or behavior that the design should have or exhibit. Normally expressed as adjectives that capture what the design should be.
- **Constraint:** a limit or restriction on the design's behaviors or attributes. Clearly defined limits whose satisfaction is a binary output.
- **Function:** a specific thing a designed device or system is expected to do. Typically expressed as "doing".
- **Mean:** a way or method to make a function happen. Solution-specific. Clients often think of examples they think are relevant.

Phase I Review Goals:

- Present a summary of project and problem statement (confirm scope)
- List requirements, constraints, and/or rules (requirement classifications)
- Identify the biggest technical challenge your team will investigate first
- Identify relevant resources (i.e. similar products, text, manuals, prior course knowledge, etc.) needed to develop preliminary design.
- Client (or relative party) reviews the project summary for approval to progress to Phase II and develop a preliminary design (Called "Phase Approvals")

Phase II - Develop Preliminary Design:

This phase includes translating project requirements into the following:

- **functional requirements**: specifies something the system should do
- **non-functional requirements**: specifies how the system performs a certain function
- **constraints**: limiting or restraining requirements

Phase II Review Goals:

- Present the preliminary design and proof of concept explaining fundamental technical principles associated with the project and current verification testing, research, or analysis to make informed design decisions (i.e. governing equations, calculations, socio/economic/environmental/safety factors, prototyping, etc.). **496 addition:** What did you learn from Tech Demo?
- Identify relevant resources needed to develop detailed design.
- Client (or relative party) reviews the preliminary design for approval to progress to Phase III and develop detailed design.

Phase III - Develop Detailed Design

This phase includes transitioning from proof of concept to an engineered design by refining and improving upon the preliminary design.

Phase III Review Goals:

- Present detailed design and engineering prototype.

- Explain design insights/decisions obtained from verification testing to optimize design.
- Client (or relative party) reviews the detailed design for approval to progress to Phase IV and final system design.

Phase IV - Final System Design
The pilot product is used for validation testing of the final system design. This phase concludes with the transfer of deliverables to the owner and closing the project.

Phase IV Review Goals:
- Present final system design, including validation testing and demonstration (if appropriate) of pilot product. What did you learn from Tech Demo?
- Communicate the solution and transfer deliverables to the owner.
- Client (or relative party) reviews final system design for approval of project completion.

Conclusion

The DesignSpine program in the R. B. Annis School of Engineering is a multi-year, hands-on curriculum where interdisciplinary student teams develop engineering solutions for projects for authentic, external customers. The continuous improvement of the curriculum led the DesignSpine committee to restructure the courses and redefine the design stages that were used. Students in their second year receive 'solvable' problems, with a charter that has been completely written by faculty. Teams spend the bulk of their time in the design phase. The third-year students focus on entrepreneurship, designing a solution to a problem they define. This year has seen the addition of a brainstorming and team-formation phase prior to starting the design, or Phase 0. Teams in their fourth year go through the complete design process, from problem formation to a handoff of a final product/process to their client. The stages of the design process were also redefined from the original ICOV model, found in the DFSS framework.

The first journey through the new paradigm is this current academic year, so a final assessment of the effectiveness of the changes remains to be completed at the end of the academic year. However, teams are almost entirely on schedule or significantly closer to the planned schedule than in the past few years as measured by weekly feedback from faculty advisors, which is certainly a positive indicator.

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