AC 2011-222: MAKING IT REAL: SCALING UP INTERDISCIPLINARY DESIGN TO MODEL REAL-WORLD ENGINEERING ENTREPRENEURSHIP

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Abstract

In all but the largest companies, engineering has always been an inherently interdisciplinary practice: multiple engineering disciplines must collaborate effectively with each other and with other disciplinary experts to deliver products and services to clients. Some institutions, including our own, have responded to this observation by integrating innovative interdisciplinary teaming experiences into their engineering programs. Over a decade of experience shows that such interdisciplinary training is valuable, but that efficacy is limited due to the failure to integrate non-engineering disciplines. This paper reports on the iCubed project, a pilot effort exploring training in engineering entrepreneurship, in which project and course are modeled on commercial product development. A massively interdisciplinary team design project at the senior and graduate level was developed and executed with a team spanning seven disciplines in engineering, business, and architecture. We report on project planning, design, and outcomes, and offer a set of best practices distilled from this experience.

1.0 Introduction

The past several decades have seen fundamental changes in the way engineering is practiced in industry and consequently, the skills and capabilities needed by the modern engineer. Steadily decreasing time-to-market timeframes, globalization, and the need to react more nimbly to changes in the market have increasingly led to replacement of cumbersome monolithic design teams and projects with relatively small, agile interdisciplinary teams tasked with quickly exploring and developing a product concept. In addition to the core technical skills associated with their particular engineering discipline, industry now expects graduates to possess practical project management and professional skills, multi-disciplinary teaming experience, international and cross-cultural experience, communication skills, and some understanding of the market and societal environment in which the product will be deployed. In short, the modern engineer is no longer an isolated knowledge worker, but is now expected to function at many levels, ranging from product conceptualization, to risk and market analysis, to client interaction, to project management [1]. Many engineering programs have responded to this need by incorporating interdisciplinary design experiences into their core curricula [2-4].

Our own institution, Northern Arizona University, has been a leader in this area, introducing an innovative interdisciplinary curriculum spanning all engineering disciplines in the mid 1990s [5-8]. The Design4Practice program consists of a sequence of four design courses of increasing complexity, one in each year of the four-year engineering curriculum, that are required for all engineering majors. All courses are project- and team-based, with student teams working together on realistic projects for realistic clients. In additional to core disciplinary skills, strong emphasis is placed on written and oral communication, project management, teaming experience, and solution design and evaluation, i.e., on teaching the full spectrum of skills vital for success in modern engineering contexts. The Design4Practice program has been very successful, and the core concept has served as a model for similar programs introduced across the nation in the past decade.
Although the overall efficacy of the Design4Practice program in preparing graduates for real-world practice has been shown to be impressive [5], the interdisciplinary facets have proven to be stubbornly problematic, with problems in curricular integration, project selection, and supervision models leading to unsatisfying outcomes. In addition, we have become increasingly interested in substantially increasing the emphasis on engineering economics by integrating the business disciplines (marketing, sales, finance, procurement) to develop an educational model specifically aimed at engineering entrepreneurship, in which teams truly act as small engineering firms engaged in novel product development.

This paper reports on iCubed, a year-long pilot project undertaken to explore what it would take to design and deliver an advanced highly-interdisciplinary design experience modeled on real-world entrepreneurial design. The iCubed project brought together a team of 27 senior and masters level students from seven distinct disciplinary areas including engineering (mechanical, electrical, chemical, civil), computer science, architecture, and business (management, marketing, finance). The team was explicitly organized around the model of a small engineering company, with the goal of developing a market concept (including specification, design, and prototyping) for a compact, fully-automated biodiesel production unit for small communities or individuals. Details of the design (scale, materials, chemical process, nature of feedstocks) were purposefully left open; as in the real world, these facets would be investigated by the design team, with decisions driven by market economics. Ultimately, the team’s goal was to produce a working prototype along with a complete, compelling business plan capable of drawing the venture capital needed to develop the design into a commercial product.

In this paper, we describe the iCubed project in detail, including project planning, organization and monitoring of the student team, and project and assessment outcomes. These experiences are then used to drive a discussion of best practices in planning for massively multidisciplinary project experiences, models for organizing collaborating interdisciplinary faculty, and models for structuring large interdisciplinary student teams.

2.0 Icubed: Overview and Motivations

Interdisciplinary teaming has been a core facet of our Design4Practice program since its inception in the mid-1990s [5], with three of the four team-design courses originally centered around interdisciplinary teaming: the freshman level introductory course centered on small (5-7 person) interdisciplinary teams tackling a series of short simple "kitchen sink engineering" (e.g. toothpick bridges, simple batteries) design projects. At the sophomore level, small teams spanning mechanical, electrical, civil, and environmental engineering and computer science were to compete in building simple mobile robots to tackle a pseudo-realistic challenge, e.g., navigating mazes while picking up small objects. The junior level course was to focus on several large (30-35 person) teams spanning all engineering disciplines, working on a larger, more challenging real-world project selected by faculty, e.g., designing, prototyping, and testing an anaerobic waste digester for a sewage treatment plant. Although not required by the program, interdisciplinary projects were envisioned at the senior capstone level as well, where teams execute real projects solicited from actual industry sponsors.

Although the Design4Practice program overall has been very successful, the interdisciplinary aspects have proven to be challenging, resulting a slow deterioration of the interdisciplinary facets of the program, particularly in the upper division; only the freshman level course has
remained completely intact in this respect. In particular, our experience has been that the practical logistic challenges of interdisciplinary project courses grow exponentially with the scale and realism of projects, and can become overwhelming to the point of unsustainability. Early in the curriculum, interdisciplinary projects are relatively easy and efficient to offer, as students really don't have any specialized engineering skills yet, and thus can be treated and mentored as a homogeneous group, with all students working on all aspects of the problem. As interdisciplinary projects grow in complexity and realism, however, specialized disciplinary skills are required and individual faculty mentors for specific disciplines must be assigned to the course, leading to two very practical challenges:

- The organizational overhead becomes overwhelming, as a large group of faculty must continually coordinate pacing, subteam progress, and evaluation mechanisms. This overload eventually leads to course breakdowns, frustration and faculty burn-out for the program.
- As resources in higher education continue to shrink, it has also become increasingly difficult to assign five faculty to a single interdisciplinary course.

These practical challenges have forced a number of compromises as the program has evolved over the years. At the sophomore level, the level of complexity was reduced by introducing robotics construction kits, rather than making students fabricate their own robots from scratch; the primary focus was shifted to teaming and communication rather than technical skills. At the junior level, the large scale interdisciplinary projects were abandoned after several years due to the sheer difficulty of identifying suitable new projects with equal challenges for all disciplines each year, the extraordinary coordination overhead for participating faculty, difficulties scaling the course with varying numbers in different disciplines, and shrinking faculty resources. The junior level course remains, but with large team projects now done separately within each discipline. These developments have motivated us to consider whether more efficient, less resource-intensive models for organizing and managing technically challenging design courses might be developed.

A further problem observed in our Senior Capstone Design course is that many solutions produced by teams are discarded or require substantial re-working by the sponsoring company because, while technically sound, they are not marketable or cost effective. Although unfortunate, this is not entirely inappropriate or unrealistic, given that in a real corporate context, product development teams typically include experts in market analysis, procurement, sales, and finance. This has led to a growing interest in exploring the inclusion of business disciplines in our senior design courses.

The iCubed project was developed in response to the above motivations, as part of our ongoing attempt to revitalize the Design4Practice concept. Specifically, the project was motivated by the following goals:

- Explore the concept of teaching true engineering entrepreneurship, by extending interdisciplinary engineering teams to include students in business disciplines.
- Determine whether additional maturity and technical skills at the senior or masters level might make this a more suitable venue for an upper-division interdisciplinary design project.
Explore a two-tiered faculty supervisory model as the basis for offering large, technically challenging interdisciplinary project experiences, in hopes of reducing the organizational complexity and resource intensity of such courses.

A final motivating factor for the iCubed project was the global dissemination of interdisciplinary engineering education concepts. Among the many differences in philosophy and structure of engineering education between Europe and the United States [9], stubborn administrative and social boundaries between engineering disciplines have largely prevented the development of interdisciplinary curricula in European institutions. Our engineering programs regularly host exchange students from European institutions, and by far the most popular course with these students has been our interdisciplinary sophomore level design course; exchange students have often deplored the lack of interdisciplinary courses at their home institutions. This motivated an interest in piloting interdisciplinary design in a European institution.

The iCubed project was supported by and undertaken at the University of Applied Sciences in Dresden, (HTW Dresden), one of our long-standing international partner institutions. A key advantage of the HTW Dresden was the presence of both engineering and business disciplines within a single administrative unit, and existing programs in engineering economics and management. This eased administrative hurdles and provided an eager cohort of potential participants. Well-established contacts with HTW Dresden colleagues across disciplines, and the general interest in interdisciplinary design created by enthusiastic returning exchange students were also crucial.

The iCubed project was divided in two distinct phases, undertaken over the course of a year: A planning semester, in which the project was specified and developed, followed by offering of the course in the next semester. The following sections describe these phases and their outcomes in detail.

3.0 iCubed Project Planning Phase

A full semester of planning was incorporated due to the novelty of interdisciplinary design at the HTW Dresden and in German higher education. Major activities during this phase included:

**Recruiting a faculty leadership team.** A leadership team composed of HTW Dresden faculty were recruited; at least one faculty member from each participating discipline was required. These faculty served as technical advisors in developing and vetting potential projects, helped hand-pick student participants from their disciplines, and later served as designated technical advisors for their discipline.

**Selecting the project.** The project topic was not fixed at project initiation, but was left for specification during the planning phase, based on the expertise and interests of participating HTW Dresden faculty. Specific criteria for choice of project topic included:

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1 The name iCubed derives from the project goals: "Interdiziplinäre Integrierte Ingenieurausbildung", translated as "integrated interdisciplinary engineering education".
• The project should involve as many disciplines represented at the HTW Dresden as possible, and should offer comparable challenges for each of them.
• The design challenge should be comparable to the creative and technical complexity of a real industrial product development context, yet should not include overly novel research-driven problems.
• Development must be shaped by current market realities and real production costs.
• Ideally, the project should be interesting and relevant to the general public as well, to provide for maximum publicity and media interest.

These project criteria serve as the foundation for the overall course concept of engineering entrepreneurship, in which the student team is cast as a semi-independent consulting firm, working to develop a product prototype and complete business plan aimed at attracting venture capital for full-scale development.

Curricular Integration. Program curricula at the HTW Dresden are generally much more rigid than in American institutions. Thus, the program curricula for each of the participating disciplines had to be individually analyzed to find creative ways to integrate the planned iCubed course as a credited course experience.

Content Development. To get students up to speed on interdisciplinary teaming and real-world product development, lecture materials were developed to cover a range of topics ranging from intra-team communication skills, to engineering economics, to project management.

3.1 iCubed Project Planning Outcomes

The design of an automated, small-scale biodiesel production unit was ultimately selected as a project topic, with a leadership team of seven HTW Dresden faculty spanning five disciplines. The project topic also meets the criteria outlined earlier: Green energy is a visible and compelling theme, and the basic biodiesel production process is chemically simple, safe and well-understood. Central components (tanks, sensors, feed stocks) are readily available, and a number of commercial biodiesel stills are even available for home use (albeit non-automated). Importantly, the level of effort and technical complexity of design challenges for this topic were comparable across disciplines, as outlined in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1: Tasks by discipline in the design of a small-scale biodiesel unit.</th>
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<tbody>
<tr>
<td>Chem. Eng.</td>
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<tr>
<td>Mech. Eng.</td>
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<tr>
<td>Elect. Eng.</td>
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<td>Comp. Sci.</td>
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<td>Business</td>
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As planning proceeded, the project was expanded to include architecture and civil engineering as well, by positing the possibility that a larger, community-scale unit might prove to be the most economically feasible. These two disciplines were added and tasked with the design of a compact, energy-efficient "green building" concept for a larger-scale unit.

The faculty leadership team worked together to specify overall design constraints, locate lab spaces and equipment, and estimate the cost of required materials. Potential participants in the upper division and graduate levels were identified and recruited, and ways to credit the iCubed course into each student's curriculum were found; the results of this effort are summarized in Table 2.

**Table 2: Overview of curricular integration and students by discipline.**

<table>
<thead>
<tr>
<th>DISCIPLINE</th>
<th>CURRICULAR INTEGRATION</th>
<th>STUDENTS</th>
</tr>
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<tbody>
<tr>
<td>Chem. Egr</td>
<td>Senior level required elective</td>
<td>3</td>
</tr>
<tr>
<td>Mech. Egr.</td>
<td>Senior project management elective (1 student); Masters project (2 students); Project in senior level elective (2 students)</td>
<td>5</td>
</tr>
<tr>
<td>Elect. Egr.</td>
<td>1st Semester Masters Project elective</td>
<td>3</td>
</tr>
<tr>
<td>Comp. Sci.</td>
<td>Junior level project elective</td>
<td>3</td>
</tr>
<tr>
<td>Business</td>
<td>Project in two senior level courses (Market Analysis, Business management)</td>
<td>10</td>
</tr>
<tr>
<td>Civil Egr.</td>
<td>Project in junior level structures course</td>
<td>2</td>
</tr>
<tr>
<td>Architecture</td>
<td>Final Masters Project</td>
<td>1</td>
</tr>
</tbody>
</table>

The broad variety of curricular integration solutions was not intended and reflects the great difficulty we encountered in working to find acceptable ways to count the planned design course. Indeed, the inconsistencies in the way in which the experience was credited (as a project in an existing course, or as a distinct project course) ultimately resulted in substantial problems with course dynamics, as detailed in Section 4.

Finally, participating faculty were organized in a two-tiered supervisory model:

- **Project leaders:** responsible for overall course management including lectures, team meetings, mundane logistics, and all other functions associated with course delivery itself were assigned to the two authors.
- **Project advisors:** HTW Dresden faculty in the leadership team were assigned as technical liaisons for each of the disciplines, providing either direct advice, facilitating access to appropriate colleagues and specialized discipline-specific supplies and equipment.

The goal of this two-tiered approach was to explore a delivery model that concentrates the primary workload on just one or two faculty, while other faculty remain accessible for technical advise. Project advisors were regularly updated on project progress by the project leaders and, because they remained the instructors of record, grades for project work were ultimately reported to them. The potential scalability and efficiency advantages of this model is clear: projects and
course sections could be assigned to a single project leader, rather than involving one co-teaching faculty per discipline.

4.0 iCubed Project Execution

The iCubed interdisciplinary team design course was offered over the 15-week summer 2010 semester\(^2\). The course plan was based around four distinct project phases, with major team deliverables and design reviews (presentations open to the public) planned at the end of each phase:

- **Startup Phase (2 weeks):** Students are introduced to the project topic and goals, elect leadership, and organize the management and disciplinary subteams. Each subteam is tasked with researching their aspect of the problem, and developing a brief presentation introducing their team, their discipline in general, and the design issues that the subteam will be investigating (see Table 1), along with a preliminary list of specific technical questions to be addressed, and a rough work schedule.

- **Design Phase (6 weeks):** Disciplinary subteams work on designing and specifying their aspects of the problem, communicating with other subteams on issues spanning disciplines, supported by weekly team updates and group discussion. Important early deliverables are chemical process and specifications (chemical engineers), and specification of system scale, feedstocks, and general cost framework (business subteams). The phase ends with a formal team presentation of the design, and draft design reports from each subteam. Specified components and supplies are ordered.

- **Build Phase (5 weeks):** As materials arrive, subsystems are assembled and tested by subteams in early weeks, then brought together into a final design. The business subteams oversee this effort and continue research and development of the business plan. Designs are revised and refined as needed, and basic function of the prototype is established.

- **Delivery Phase (2 weeks):** Final refinements are undertaken as the final design report and business plan are completed. The project ends with a formal presentation, including demonstration of the prototype.

This semester plan was modeled on the junior-level design in the Design4Practice program (see Section 2) at our home institution.

4.1 iCubed Student Team

The student design team consisted of a total of 27 students from seven disciplines spanning engineering, business, and architecture, and was organized as a collection of discipline-specific subteams, as illustrated in Figure 1.

\(^2\) The German system is based on winter and summer semesters; the latter runs from mid-March to mid-July.
A three-person overall management team composed of a dedicated team leader and two assistants (from business management, mechanical engineering, and architecture, respectively) was responsible for developing and monitoring the overall project schedule, keeping subteams on track, and managing team meetings. The subteams were simply defined by discipline, except civil engineering and architecture, who worked as a distinct interdisciplinary subteam. The business students chose to further subdivide their large subteam based on assigned task area: Marketing and Sales performed market analysis; Procurement was responsible for finding suppliers, comparing materials, and negotiating prices; Finance was responsible for budgeting, cost tracking, and financing; and Legal for investigating applicable government regulations and patent issues.

4.2 Course Structure and Evaluation

Course delivery was based around one three-hour "all-hands" class meeting per week, attended by all project participants, and individual subteams meeting and working during the week as needed. The weekly class meeting was structured around three activities:

- Lectures: prepared course content on interdisciplinary teaming skills, engineering design process, engineering economics and cost estimation, and other non-discipline-specific information related to interdisciplinary teaming or engineering product development was presented.
- Team Updates: Led by the Management team, each subteam was tasked with a short status update, closing with information it currently was waiting on from other subteams.
- Interdisciplinary discussion: Based on the team updates, time at the end of the meeting was provided for subteams to exchange information, discuss information needs, and plan for targeted meeting outside of class.

The amount of time allotted to each activity varied as needed, with more time for lecture early in the term, and more time for updates and discussion as designs matured.

As an advanced course in team design, the learning goals of the iCubed course were centered around teaming skills, engineering economics and product development. A course assessment and evaluation schema adapted from interdisciplinary teaming courses in the Design4Practice program was deployed to assess learning outcomes, based on time tracking, effort distribution, and an extensive self-assessment survey given at the start and conclusion of the course.
4.3 Problems and Modifications Undertaken

As anyone teaching such courses can attest, team-based design courses are unpredictable and challenging to manage. The focus on novel design challenges in each offering brings inherent uncertainties regarding technology, processes, availability of materials, and difficulty of execution; this requires constant monitoring, high faculty engagement, and adjustments to schedule, pacing, and deliverables. This was particularly true in the context of the iCubed project: the project was novel and challenging, no such project had ever been undertaken at the institution before, and students and local faculty had never before been exposed to the interdisciplinary design course concept. The following subsections summarize some of the difficulties we encountered, and the adjustments made; these are distilled into broader lessons learned and best practices in Section 5.

4.3.1 Difficulty with open problem statements.

Although comprised of advanced, highly-motivated students with excellent technical skills in their disciplines, the team had great difficulty with the open nature of the problem statement. Students were baffled when asked to outline the major challenges and tasks for their discipline in the startup phase. The concept of having to explore the space of possible approaches, processes, and materials to first sketch an overall design solution in the abstract, followed by incremental refinement towards a concrete design was simply foreign to them. Electrical engineers wanted to know exact pipe diameters and tank capacities before even conceptualizing a control system design; mechanical engineers wanted to know the exact nature of feedstocks and unit scale before daring to conceptualize an overall mechanical concept. Extensive effort was required to teach them to, in fact, do just the opposite: conceptualize a possible solution, and then use this to drive an investigative and experimental agenda to refine the vision. As a result, the startup phase was extended to nearly four weeks, as subteams iteratively developed problem outlines and communication between subteams improved.

4.3.2 Difficulty communicating across disciplines.

The difficulty with open problem statements was exacerbated by the fact that many key specifications and boundary conditions for one discipline derived directly from the efforts of another. This dynamic was expected and directly reflects real world product development processes, where specifications for the final product evolve gradually from an interdependent interplay of efforts in various disciplines. For instance, the feedstocks to use depend on the relative cost and availability of feedstocks in the target market (marketing and sales) and on the chemical efficiency of various feedstocks (chemical engineering), and on regulatory constraints (business legal). What materials to use for tanks and other components depends on corrosiveness, heat and pressure (chemistry), safety and ease of construction (mechanical engineering), and cost limitations dictated by market (marketing and sales). Making efficient progress in this multivariate, highly interdependent and interdisciplinary design context is always difficult, and represents the core challenge and learning experience in a realistic interdisciplinary design course. In the iCubed project, we observed an extreme reluctance to communicate with, and especially to rely on other disciplines to move one's own design forward; this reluctance was far more stubborn at the advanced level than what we have observed in the lower level interdisciplinary Design4Practice courses offered back home at Northern Arizona University. It appears that, as specialization and competence in one's own discipline grows, students are increasingly reluctant to reach across disciplinary boundaries; one subteam actually researched
and attempted to develop their own chemical model of the biodiesel production process, rather than relying on the chemists for help. We addressed this problem by extending the design phase, adding lecture material to help students learn to understand their own competency boundaries and respect the expertise of others, and added structure to the weekly task reports and subsequent interdisciplinary discussion to highlight interdisciplinary dependencies, and shape interdisciplinary discussion.

4.3.3 Regulatory obstacles.
As the Design Phase progressed, various aspects of the design process were hampered by unanticipated regulatory obstacles surrounding the chemicals involved in biodiesel production: methanol and sodium hydroxide, chemicals that are relatively available in the United States, are extensively regulated in Germany, making home production of biodiesel impractical. Market research therefore had to be shifted mid-flow to other markets, with different feedstock cost profiles. Similarly, as the team prepared to move toward the build phase, the university's safety officer objected to even the small-scale (80 liter) prototype planned; the prototype was limited to five liter capacity, which not only threatened to require complete redesign and re-specification of all components automated regulatory systems, but also to destroy the realism of the challenge.

4.4.4 Logistic obstacles.
As the design matured and main components (tanks, valves, sensors) were specified and ready for ordering by the procurement team, further obstacles appeared: the university and vendor purchasing infrastructure turned out to be more complex than anticipated, meaning it could take three to four weeks to receive materials. Although assembling a basic biodiesel unit is quite simple, this delay threatened to push prototype completion well into or past the final delivery phase. A further complication discovered was that, under the European education model, final exams play the primary role in semester evaluation, and thus students are under tremendous pressure to prepare for these exams in the final weeks of classes. Students were therefore dismayed by our suggestion that a high pressure “build and refine” period before the final deliverable is common in project courses.

4.5.5 Adjustments made in iCubed deliverables.
As these obstacles were encountered, it became increasingly clear that our course schedule was too ambitious, and that adjustments to the targeted outcomes were required. This is, of course, not unusual in real world product development contexts, and learning to detect and deal with project slippage is an important project management skill. The student team was allowed to arrive at this conclusion on their own, based on the overall project and subteam timelines maintained by the leadership team. Extending the project timeframe (the real-world solution to project slippage) is not possible in academic contexts, forcing a change in project targets: the Build Phase of the project was drastically scaled back, and deliverables restricted to simulations and paper designs; no complete prototype was produced. Specifically, deliverables for each discipline were adjusted as shown in Table 3:

| TABLE 3: End products produced by iCubed team. |
|---|---|
| Mechanical Eng. | A full paper design, including numerical analyses for all components, a complete blueprint for the home-scale (80 liter) unit, and a completely specified parts list. |
Electrical Eng.  | A complete design of the sensor and regulatory systems to control filling, temperature and reaction monitoring, heating, valves and pumping between tanks. This control system was implemented in a numerical simulation model with a graphical interface.

Computer Sci.  | An web-based front-end user interface for the unit, showing state of all systems in a graphical interface, and allowing manual intervention to adjust parameters. A numerical simulation model was built to drive dynamic testing of the interface.

Chemical Eng.  | A completely specified chemical production process, including reactant quantities and optimal reaction parameters; a detailed lab report documented experiments performed to establish these specifications. The small scale reactor used by chemical engineers to experimentally produce biodiesel was used for demonstration purposes, along with vials containing the outcomes of various trials to illustrate pitfalls in the chemical process.

Civil Eng. and Architecture  | No change was necessary to the planned output of this group: they produced architectural drawing, structural analyses, and plans for in-ground safety systems for a community scale biodiesel plant.

Business  | No change was required to the output of this group: A detailed business plan was produced including a market analysis, analysis of competing products, analysis of patent and regulatory issues, a financial model for the prototype, a complete list of optimal suppliers of components specified in the design, and sample marketing campaigns.

5.0 Icubed: Insights and Lessons Learned

Although the iCubed project was in some ways similar to other experiments in teaching interdisciplinary design, e.g. [10], and even to the upper division Design4Practice courses back home at Northern Arizona University, the unique combination of features it embodied yielded valuable insights into the dynamics of massively multidisciplinary team design experiences. In this section, we discuss a number of these unique facets of the project, in an effort to extract a set of best practices for the design of such courses in general.

5.1 Lessons and Best Practices in Teaching Entrepreneurial Design

5.1.1 Managing large, massively interdisciplinary teams.

Incorporation of the business team and recasting of the course as entrepreneurial design added entirely new elements to the equation. The engineering design process, with its focus on brainstorming, decision matrices, and incremental refinement, is very different from the more straightforward, procedural work models in business. Also the inclusion of the business (particularly market research) exacerbated the serial dependencies that can exist in interdisciplinary design projects, i.e., one team’s progress on hold until it receives the work products of another. Specific lessons learned from analyzing the difficulties encountered in this area include:
• Plan projects with no more than four disciplines. Although a single project involving all disciplines is resource-efficient and may mirror the real world, the potential for serial dependencies between subteams grows exponentially with the number of disciplines. The central pedagogical value of entrepreneurial design would not change if the number of disciplines were limited. As we integrate the concept of entrepreneurial design into the ongoing revision of our Design4Practice program, we plan to pursue an opportunistic, distributed model: rather than a single section involving all disciplines, a set of smaller sections could be offered, centered around different, smaller projects engaging students from business and 1-3 engineering disciplines. This approach would also accommodate a broader variety of projects and make project selection easier, allowing for real-world projects that do not involve all engineering disciplines.

• Think explicitly about timing and loading of subteams. We spent considerable effort working to ensure that the technical challenges for all disciplines would be comparable, but did not extend this to sufficiently careful consideration of timing dependencies between teams. In particular, part of course planning should explicitly include construction of a Gantt chart to map key activities and their dependencies onto a timeline; focused collaboration of all disciplinary experts is required, to ensure that activity dependencies and duration are accurately represented. Not all timing conflicts will be exposed, of course, due to the inherent uncertainties of novel design projects, but at least some potential problems could be exposed and planned for.

• Consider giving some disciplines head starts. The most serious serial dependencies encountered in the iCubed project were introduced because the marketing and chemical engineering subteams (like all other subteams) had initial confusion and delays, and yet early results from precisely these teams were needed as soon as possible by other teams: basic market parameters (feedstocks, unit scale, cost), and overall chemical processes were needed by other teams to get traction. A better approach (albeit not feasible for iCubed) would be to actually task small teams in a preceding semester to perform this parameter-setting work, e.g., we could include a "pre-capstone" seminar course that precedes the capstone semester in the Design4Practice curriculum at Northern Arizona University, allowing for such research and preparation. Alternatively, one could sequence two Capstone projects, so that one Capstone team consisting of chemical engineering and business students develops a fully-parameterized product concept in one term, which is then developed into a prototype by a second Capstone team in the subsequent term.

5.1.2 Organizing Faculty and Students

The two-tiered supervisory model, with one or two faculty managing the team, and mentors for other disciplines more loosely involved, appears to hold promise as a method for reducing the faculty investment in interdisciplinary project courses. The main problem encountered in this area was that some students played off the more distantly involved faculty mentors (who assigned the ultimate grades) against the two faculty running the team: Students exaggerated workload and mischaracterized deliverables to convince faculty mentors to relieve them of deliverables or mitigate poor iCubed deliverable scores; conversely, some students justified modified or incomplete deliverables with the claim that mentoring faculty had required it. Such problems could generally be resolved through direct meetings between project directors and various faculty mentors, but created more overhead. In contrast, the model for organizing
students as a set of disciplinary subteams seemed to work well, with problems arising mainly from the different ways in which iCubed participation was credited for various students. Recommendations in this area include:

- **Similar participation models.** The model for integrating and crediting student involvement in the course must be uniform across all students. This doesn't mean they all have to register for the same course (though this would be ideal), but they should get the same credit under a similar catalog course description. This avoids motivational issues, resentments, and differing expectations for deliverables that arise when each subteam is receiving credit under a different heading.

- **Local and discrete project evaluation.** Whatever courses students register for to participate, faculty managing the team should be the instructors of record. Second-tier faculty mentoring disciplinary subteams could provide feedback on technical quality, but only as input to the project grade. If interdisciplinary projects are smaller and attached as modules or labs to existing courses, there must be consistency in how the project grade counts towards the final course grade, and this model must be strictly adhered to. This would avoid the negative dynamics between students and the two supervisory tiers that we observed in the iCubed project.

- **Partitions by discipline.** Organizing the student team as a set of disciplinary subteams managed by an overall management team seemed to work well: disciplinary subteams retained a sense of identity and a certain freedom to tackle their aspects of the problem as they saw fit, while communicating their task plan and progress to the management team. Some miscommunications and bad feelings arose because not all disciplines were represented in the management team; ideally, the nominal leader of each disciplinary subteam should also be included in the management team. It was important to have an overall project leader, however.

5.1.3 Integrating Entrepreneurial Design into Engineering Curricula.

Sometimes the value of something is not apparent until it's missing. The serious difficulties the team had with open ended design problems and interdisciplinary collaboration were surprising to us, and emphasized the value of the incremental approach to teaching design embodied in the Design4Practice program. By repeatedly exposing students to increasingly open-ended and increasingly complex team design challenges, the Design4Practice program slowly builds up skills in teaming and open-ended problem solving; students are ready for realistic challenges at the senior level. This leads to the following recommendations:

- **Design curricula to build up critical skills.** Don't make a senior or graduate level design course the first time that students are faced with a realistic design challenge. One or more preceding courses should involve realistic (pseudo-client, open-ended problem, typical industry deliverables) team-based design experiences of increasing complexity.

- **More structure for first-time learners.** If program structure does not allow for preparatory teaming experiences, the open-ended nature of design challenges should be reduced, with more structure in the form of initial constraints added to the problem statement. For instance, if we were to re-run the iCubed project, we would specify the feedstocks and chemical process, the scale of unit, and the overall geometry of the design solution in the
initial project specification. This reduces the realism of the experience, but would give inexperienced students immediate direction and instant design traction.

5.1.4 Interdisciplinary project courses in Europe.
The iCubed project yields some valuable lessons for European colleagues considering piloting similar courses at their institutions. One might argue that most of the surprises with logistics and regulations noted in Section 4 would never have happened to local faculty familiar with the local context and infrastructure. Our local colleagues on the leadership team failed to foresee these issues as well, however, though for different reasons: they had little experience with realistic project-based design courses. This leads to several considerations for future courses of this sort in European higher education:

- **Adaptation to semester dynamics.** Project-based courses typically build in intensity, peaking in a flurry of effort shortly before the final deliverable; this intensity requires even more effort in a large interdisciplinary team. Placing the final deliverable at the end of the term (its logical place) interferes with the unique dynamics of European higher education, where the last weeks are increasingly devoted to studying for all-important final exams. Design courses must be planned and scaled accordingly, by moving up the final deliverable, and planning lower intensity (e.g. reflection, report writing) activities in the final weeks.

- **Flexibility in curricula.** The difficulties in integrating the iCubed experience as a legitimate course into participants’ programs of study points to the need for added flexibility in curriculum design. An additional problem was that some courses in which we were forced to embed the iCubed experience required specific deliverables in some specific format; these were often incompatible with the deliverables planned for iCubed subteams, creating extra work for the unfortunate students. A more ideal solution would be to reserve an upper division elective for a team-based project course (whether interdisciplinary or not), defining the required deliverables for the course as generally as possible.

- **Faculty training.** Faculty involved in project courses will need to be trained to think explicitly about the logistical and regulatory implications of realistic design projects while planning courses. Examples include considering regulations and constraints on building prototypes, and planning in lead time for pushing materials orders through the local purchasing infrastructure. More generally, explicit effort should be invested in helping faculty adapt traditional expectations for course structure and dynamics to the more dynamic, flexible style of open-ended team design courses.

5.2 iCubed Learning Outcomes

As mentioned earlier, we implemented an assessment schema to gain insight into how much effort students invested, in kinds of work effort was invested, and what students learned through the course. The following assessment data were gathered during the course:

- Course minutes, in the form of written reflections by the two lead faculty for each weekly class session, detailing student reaction, suitability of the time allotment for various lecture topics and presentations, and general assessment of student understanding.
• Each subteam was required to record all hours spent on the course in an online spreadsheet monitored by faculty; each activity was recorded separately and assigned to pre-defined activity categories including research/literature search, meetings, writing, lab experimentation, design, build/test and analysis.

• An extensive self-assessment survey asked students to rate their own knowledge via a series of questions spanning four major topical areas: design process, engineering economics, oral and written communication skills, and English language competency. The survey was given once at the beginning and again at the end of the course to measure changes; a set of essay questions was attached the second time to allow for expanded commentary on various course aspects, similar to student course evaluations required at most institutions in the U.S.

• Peer evaluations within each subteam were also required for each major project deliverable. The evaluation approach was adapted from the one used in our Design4Practice courses, based on a zero-sum model where team members use points to distribute the total effort invested in a deliverable across all team members.

5.2.1 iCubed Assessment Outcomes

The results from all course assessment instruments were analyzed and combined to arrive at an overall course assessment. The course planning and organizational insights were described in Section 4; we focus here on statistics related to effort invested and student learning.

Figure 2 summarizes the time invested in various team activities by each subteam. Note that the last four bars represent the various subteams within the business subteam; total effort for the business disciplines should be seen as the sum of these categories. As a baseline consideration, the total credit expected for a typical course at the HTW Dresden is about 135 hours per student.

As indicated in Figure 2, effort invested varied significantly between the subteams. Specific highlights include:
• The engineering subteams invested the most total hours in the project, totaling more than twice the hours as the business disciplines.
• The largest per-person investment occurred for the one-person architecture subteam in producing a complete architectural concept, including scale models, realistic plan views, and complete blueprints. This was appropriate given that iCubed participation served as a complete masters project for this student.
• Preparing deliverables (written reports and formal presentations) commanded around 50% of effort invested in most teams; team meetings also weigh in heavily.

The skewing of invested effort towards the engineering disciplines is understandable given the project focus on developing an engineered product, but should perhaps be considered in adjusting course credit accordingly in future courses. The large amount of time required for “soft-skill” tasks like intra-team and interdisciplinary communication, and for creating reports and presentations reflects the value of learning these real-world skills; student comments in the evaluations uniformly expressed surprise at how much time and effort was required in this area.

In terms of learning outcomes, Table 3 generally shows overall class improvement in the four topical areas; scoring was based on a 5-point scale ranging from "1-no competency" to "5-professional competency".

<table>
<thead>
<tr>
<th>Topical Area</th>
<th># quest.</th>
<th>Points improvement</th>
<th>SDev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product development and engineering economics</td>
<td>7</td>
<td>0.43</td>
<td>0.79</td>
</tr>
<tr>
<td>Engineering design process</td>
<td>5</td>
<td>0.72</td>
<td>0.99</td>
</tr>
<tr>
<td>Communication, interdisciplinary, and teaming</td>
<td>9</td>
<td>0.42</td>
<td>0.68</td>
</tr>
<tr>
<td>English competency</td>
<td>2</td>
<td>0.21</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Although the relatively small number of data points prevent any statistically significant conclusions, Table 3 does show that, overall, students found their skills in each area to have improved somewhat during the course, with the largest improvement being shown in the design area. A closer examination of the self-assessment data by disciplinary subteam yielded the following insights:

• The mechanical engineering subteam reported improvement across all skill areas and over the largest number of questions (15); this subteam was also had the highest English competency.
• The electrical engineering and architecture subteams showed the highest overall improvement (average of all topical areas), with 0.7 and 0.6 points, respectively.

In sum, student self-evaluations showed that students felt that their competency in most areas had improved substantially; this numerical assessment was generally mirrored by written student comments.
Finally, peer evaluations showed that all students felt that work produced was produced equally by team members, i.e., only in two cases did a team member adjust effort distribution rating to indicate unequal effort, and these adjustments were very minor.

In summary, our assessment measures indicate that, despite the course modifications, stressful development timeline, and relatively high amounts of effort required, students found the iCubed project to be a positive and valuable learning experience. Many of the written comments emphasized how unique and different the iCubed learning experience had been, and indicated that realistic product development experiences of this sort should be included in the core curriculum.

6.0 Conclusion

The vast majority of engineering programs in the United States now include one or more project courses in the curricular core, in which students work in teams to solve realistic engineering challenges. Although such courses have been shown to be effective in preparing students for modern engineering practice, they often fail to emphasize the interdisciplinary nature and tight integration of market and other business aspects that shape industrial product development.

The goal of the iCubed project described in this paper was to explore an extension of team-based design curricula modeled around the concept of *engineering entrepreneurship*. Key features of this model include realistic product design challenges, tight interdisciplinary collaboration, and integration of the full range of business disciplines (market analysis, finance, procurement). The aim is for the student design team to function as a semi-independent product development group or small company; the end goals are a completed prototype and a compelling business plan ready to present to a venture capital group.

Our experience shows that the challenges at this level can be significant, but that the concept of courses based on the engineering entrepreneurship model is promising. Our experience revealed a number of pitfalls, requiring adjustments in course structure and targeted outcomes. Key insights are summarized in the following points:

- Inclusion of business disciplines in engineering design teams is beneficial, but changes the dynamics of the design process. Planning should include time and activities to bridge this larger disciplinary gap.
- The complexity of interdisciplinary design grows exponentially with the number of included disciplines resulting in slower progress. Smaller project teams involving business and one or two engineering disciplines would yield the same pedagogical effect while minimizing complexity.
- A two-tiered supervisory model could help reduce faculty resources invested in interdisciplinary project courses, provided that evaluation and supervisory structures are clearly delineated.

In sum, the iCubed project demonstrates that engineering entrepreneurship is an effective model for further improving project-based design curricula. We intend to incorporate the insights gained with the iCubed project into the ongoing redesign of our Design4Practice program at Northern Arizona University, particularly as we explore ways of extending the program to
integrate with a novel interdisciplinary Master of Engineering program recently implemented at our institution.

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Bibliography


