

Integrated 2D Design in the Curriculum: Effectiveness of Early Cross-Subject Engineering Challenges

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Given that novel discoveries and industrial applications occur at the interface of traditional disciplines, SUTD is indeed a unique institution where the students are given a greater focus on multi-disciplinary education and research. Dr Yong is part of the SUTD biology team teaching introductory biological sciences to all Freshmore students. These students will eventually become a special group of well-rounded engineers and architects for the future. Dr Yong is a biochemist and plant eco-physiologist by training and received his BSc (Hons) and MSc degrees from the National University of Singapore (NUS). His PhD was awarded in 2001 by the Research School of Biological Sciences, Australian National University. Between 2003 and 2004, Dr Yong was the US Fulbright Scholar with Brown University, USA where he focused on climate change sciences and policy issues, and science education. As an educator, Dr Yong had nurtured many students at the two universities (Nanyang Technological University [NTU] and NUS) in Singapore. For his excellent and sustained innovative teachings, he was awarded the 2003 and 2006 Teaching Excellence Awards at the National Institute of Education, and the 2006 Nanyang Award for Teaching Excellence.

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Abstract

Multidisciplinary engineering design is difficult in the undergraduate years. It is particularly so in the early Freshman and Sophomore years, since the students have not enrolled in a breadth of subjects. Multidisciplinary problems are often left to latter years, thereby leaving the students with an incomplete picture of how course subject matters relate and fit in a larger view of engineering and design. A novel approach to multi-disciplinary engineering education was instituted in the Freshman and Sophomore years at the Singapore University of Technology and Design. During a particular term, all courses simultaneously attacked a common design problem. The courses stopped coursework for one dedicated week and instead simultaneously worked on the design challenge problem engaging the subject matter of those courses. Herein this is referred to as the *2D design challenge*, where the design problem is multidisciplinary, but exclusively restricted to the domains of the courses being taught. This research effort finds that the approach generated highly effective learning on the multidisciplinary nature of design problems. Results also include a statistically significant impact on student perceptions of their ability to solve multidisciplinary design problems. As an example, courses in biology, thermodynamics, differential equations, and software with controls were merged in a design challenge problem of developing a perishable food delivery system composed of unrefrigerated unmanned ground vehicles. It is recommended that successful 2D challenges require instructors to establish a-priori a chain of requirements linking the design activity in each course. Effective execution of a 2D design challenge ensures that the design problem has co-dependent requirements from each discipline. These requirements cannot be independently determined in isolation. This then allows for creative interdisciplinary solutions to be developed.

Introduction: Multidisciplinary Engineering Education

An observed difficulty in engineering curriculum is finding means to educate students in multidisciplinary engineering design problems. Modern-world engineering problems are often described as no longer solely within a single discipline. For example, traditional mechanical engineering designs often now involve software, controls, electronics and perhaps biology, etc.

One primary difficulty in posing multidisciplinary design problems in the undergraduate curriculum is that within the student body of a course there is variety in the past courses and experiences. An instructor can only expect students to have taken the pre-requisite courses, which thereby limits the range of multiple disciplines that a project can cover. Further, instructors from these other disciplines are typically not available during the course project for learning and consulting on issues from these other disciplines. Therefore, most engineering curricula wait until the later undergraduate years to begin exposing the larger multidisciplinary problem space to students, through project courses with instructors from multiple disciplines. Unfortunately, this approach delays big-picture understanding of design and how the subject area materials learned by the students integrate.

This paper presents the approach and data on the positive efficacy resulting when students are provided short, one-week, design challenge problems to exercise disciplinary content from all courses a student is enrolled during a term. This problem type is herein referred to as a *2D design challenge problem*. The activity replaces all coursework at the university for an entire week. A literature review was conducted to determine if such an activity is likely to be of value to students.

Introduction: Related Work

Others have reported on the need and progress for incorporating design into the engineering curriculum, notably into the traditional engineering courses^{6,7,11,25,26,31}. It is also well established that active learning improves student outcomes as supported here^{1,2,3,12,15,19,20,21,24,28}. Wood et al³⁰ report a survey of global engineering educators indicating 90% seek more active learning in their courses. Knight¹⁷ reports on the many factors that explain the increased outcomes from active learning compared to traditional lecture and problem set based learning. These comparative factors include: the observation that lectures are not conducive to good listening given the inability to actively listen (e.g., repeat back what was spoken), critical thinking is not exercised when following the logical progressive derivation approach of lectures, the human limited attention span of 10-15 minutes, the repeated nature of lecture and course book material, and the focus of most lecture materials on the abstraction phase of learning.

There are also reports on efforts to integrate multiple disciplines in the early undergraduate years through small-scale projects, similar to the effort discussed here. Roedel et al.²⁹ report on a Freshman year effort to integrate calculus, physics and English through projects lasting over 5 weeks. These include a catapult, a Trebuchet, and a bungee drop mechanism. The pedagogical challenge included keeping the project material difficulty aligned over the time period with student material being taught. Beaudoin and Ollis⁴ report on efforts to develop short, 3 day design projects on common technical products, including the bar code, photocopier, water purifier and optical fibers. Hussman and Jensen¹⁶ report on using a small autonomous vehicle competition as a motivator for designing a UAV to which several courses provide necessary engineering skills and understanding. Material to contribute to the design of the UAV became an integral aspect of the course subject matter. Wood et al³⁰ discuss effective practices in designettes, similar to charettes in architecture studies, or small-scale design problems inserted at arbitrary points in the engineering curriculum. Guidelines are presented for effectiveness, these supported development for the guidelines also use in this effort. The projects aim to engage and motivate students with individual confidence in the learned materials.

Gomez-Puente et al¹³ provide a literature review of design based learning of engineering subjects, and how reports of such courses relate or not to good professional design practice. Hassan et al¹⁴ report on a multi-course methodology to coordinate all projects undertaken throughout the undergraduate years to build throughout toward solving industrial problems. Chesler et al.⁹ report on an introduction to design course where they make use of virtual epistemic games focused on design trade-offs and client conflict management. In groups of 5, they solve the design projects in 11 hours.

The approach here is less ambitious in curriculum coordination and planning structure than any of these efforts; rather this paper discusses a multidisciplinary experience targeting a single term, orchestrated in the courses offered during that term. This is simpler in scope, requiring more limited coordination of four courses rather than an entire sequence of courses.

Introduction: Pedagogical Objectives

The pedagogical foundation for the 2D Design Activity rests in the Kolb learning model¹⁸, which describes the complete progressive cycle of learning experiences. As shown in Figure 1, this model is based on four fundamental progressive experiences needed for learning: concrete experience, reflective observation, abstract conceptualization and active experimentation. In the Kolb model of learning, the goal for any course or teaching activity is to follow this progression of student led learning, and to act as a facilitator in the natural inquisitive exploration that will occur in this progression.

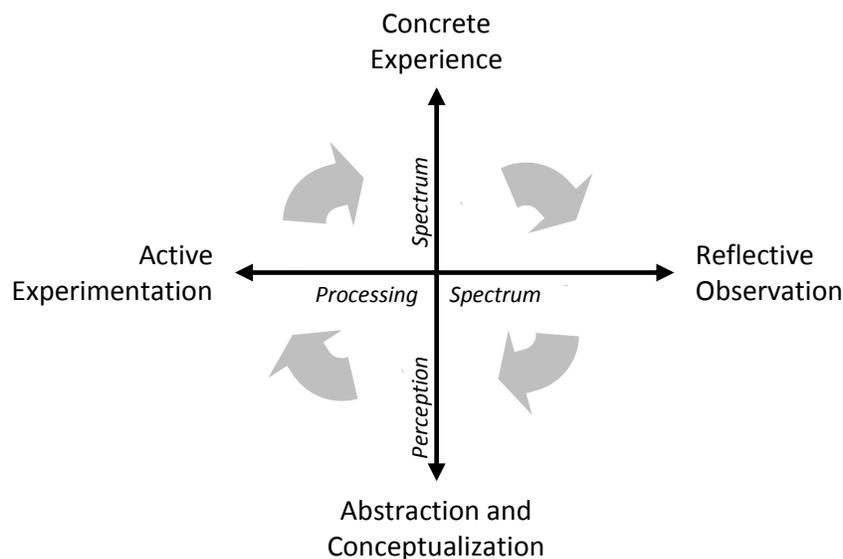


Figure 1: Kolb's learning model. For engineering analysis courses, the 2D Design Activity is ideal to provide either the concrete experience or the active experimentation phase in the Kolb learning model of the engineering material.

For such active learning progression, the Kolb model generally starts with a concrete experience in the subject matter. Without benefit of the understanding of the disciplinary course material, the student attempts to solve the design problem anyway. Students usually attempt a trial and error experimental approach, typically with less than ideal results. For example, in the thermodynamics course, students might be asked to design a cooler to keep perishables cold. They can do this by generating concepts using structural and insulating materials, but are unclear how thick to make such elements before being trained in heat transfer modeling. Trial and error is used.

After such an experience, the Kolb model follows immediately with a reflective observation of that experience. In the thermodynamics example, instructors can reflect with the students on the

numerous sets of prototypes, which had to be built to achieve the design goal. These prototypes varied in thickness of insulation, and difficulty of building. Sometimes performance may not correlate with effort or time spent building. This motivates the students to want to learn material on heat transfer to do better on this project, and further generates interest in subject matter explanations.

The following progressive phase of abstract conceptualization is to provide the theory and principles needed to understand and work within the domain. This step is often at the heart of most engineering analysis courses. Students are lead through the derivation of the physical balance relationships and application of advanced mathematics to provide new understanding of the problem they previously experienced. In the thermodynamics example, students learn the differential equations of heat transfer modes, and compute solutions to design requirements such as time for a mass of perishables to rise to a maximum allowable temperature for a given insulation thickness.

Finally, the Kolb model asserts the education is not done until the students are given another concrete experience to apply this newly understood knowledge in a new application. After and only after this second active experimentation phase have students begun to understand the learned material. In the thermodynamics example, students are given another related heat transfer design problem, such as determining required insulation to keep a perishable mass warm instead of cold, or a different mass, etc. A key feature in the engineering context, however, is to keep the experiences concrete as real physical projects rather than simply textbook problems. Seeing the design prototype work properly (or not) and being able to do something about it through engineering analysis is the key motivational element of the Kolb learning model.

As a platform for the fourth Kolb phase of active experimentation, integrated design activities are applied and provide a concrete multi-disciplinary problem for using the course subject matter in a much more real world context than a subject textbook problem. This ought to occur late in the term, in the fourth or third final week. Following the same example of the combined biology and thermodynamic design problem, understanding of the biological principles of exponential growth rates and temperature dependency allows the students to define the perished limit. This is accomplished by generating an exponential curve of time and temperature combinations.

The learning objectives of this integrated design, as adapted from that proposed by Wood et al³⁰:

1. Ideation and concept generation. These outcomes consider divergent thinking and expansive idea generation.
2. Opportunity and needs analysis. These outcomes consider analyzing need and context, to clarify why the problem exists and what the problem is.
3. Quantification of open-ended problems. These outcomes consider convergent thinking, modeling and analysis, reduction and simplification.
4. Effective resource utilization. These outcomes consider prioritization and trade-offs with limited or unused resources such as schedulable time, finances, or resources.
5. Reflection, observation and hypothesizing. These outcomes consider reflective practice, including personal responsibility and professional growth.

In summary, the objective is a one-week multi-disciplinary design activity that either motivates or exercises the course subject matters, and also challenges the students on design thinking.

Means for student progress against these objectives can all be incorporated into the 2D Design Activity. Doing so increases the active learning effectiveness of the activity.

Introduction: Curriculum Context

Singapore University of Technology and Design (SUTD) is developing a unique approach to multidisciplinary engineering education. As described by Magee et al²², the pedagogy is technology and design-centric, rather than engineering-science centric. Design, as an academic discipline, cuts across and integrates all curricula.

At the individual engineering course level, short design projects or activities are conducted in direct relation with the course's learning objectives: this constitutes the *1D Design Activity*. As was discussed in the related work section, this approach of mini-design projects to exercise course material is not new in engineering education.

The *2D Design Activity* using *2D design challenge* problems are novel. During the first 3-term Freshmore year (SUTD's first 3 contiguous terms) all students in a class are required to attend the same four courses together. During each of these 3 terms, a one-week long design activity directly related to the content of the 4 parallel courses that are conducted. This constitutes the 2D Design Activity. The article here focuses on this activity as a platform for multidisciplinary design education. The example discussed in this paper occurred during the student's third semester, carried out during the 3rd Term of the Freshmore year for the SUTD students of the Class of 2015.

Beyond the 1D and 2D Design Activities, students will pursue more expansive design activities, namely *3D Design Activities* that incorporate learning from earlier courses, and finally a *4D Design Activity* that asks the student to incorporate design into their experiences outside of their coursework²². They will encounter these in their junior and senior years. Being a new University in its second year of teaching, these 3D and 4D Design Activities are still in the process of being fully incorporated. The pedagogical hypothesis is that the 1-4D framework provides an improved learning paradigm for multidisciplinary engineering; this relative efficacy should be evaluated. This paper here discusses results of an implemented 2D Design Activity within this larger context being developed and implemented.

The next section introduces technical details of the specific 2D design challenge concept on which assessment herein was based. This assessment provides statistical data on efficacy of the 2D approach from the perception of the students and what they felt they learned. Lastly, a discussion section is provided that expands difficulties encountered in correlating the success at 2D with differences in grades within the core subject courses.

Assessment: Description of the 2D Design Challenge

This section focuses on the details of 2D Design Activity proposed in the form of a design challenge to an entire Freshmore class (318 students in total). It is worth highlighting that the SUTD Freshmore year is a common core curriculum year for the students of the four undergraduate degree programs offered: Engineering Product Development (EPD), Engineering

Systems Design (ESD), Information Systems Technology and Design (ISTD), and Architecture and Sustainable Design (ASD). These constitute the so called four “pillars” of study at SUTD.

In that framework, our 2D Design Challenge takes place at the pivotal moment when students have to declare their future major, i.e. the pillar of their choice. It is quite clear that running this 2D Design activity at such an early stage in the students’ engineering training presented the team of instructors with clear challenges for developing and selecting a problem:

- Identity a theme cutting across all three engineering science subjects and biology.
- Make the activity challenging despite the limited technical grounding of the students.
- Ensure that this engineering design project has a certain level of real-life relevance.
- Make the project relevant to engineering, hardware, software, and architecture students.

Simultaneous with these challenges, the pedagogical objectives stated earlier to provide experiential active learning of the subject course materials are applied as well as experiences in design thinking.

The four subject courses in the term included:

- Engineering in the Physical World: a course in thermodynamics, heat transfer, and fluids.
- Introduction to Biology: a course in biology, from biochemistry to ecology.
- The Digital World: a course on circuits, programming and controls.
- The Systems World: a course on matrix equations and optimization.

A design project was sought that simultaneously exercised the subject matter of all four courses.

The design problem developed was called “AutoMilk” and asked the students to develop an autonomous personalized delivery system of perishable milk for the city state of Singapore. The problem statement was to provide proof of concept prototypes for several key aspects of this system. The problem statement included that the Government of Singapore was interested in developing an autonomous unmanned ground vehicle (UGV) transport system for home food delivery, including milk. The system was to be composed of battery powered UGVs operating on dedicated paths throughout the city.

Student teams typically consisted of five members. The teams were highly interactive during the problem solving process. Teams developed a report for each course that highlights the relevant aspect of the multidisciplinary design problem to that course. The same team members worked together throughout the entire project. Teams met during scheduled lecture and recitation periods to work on their projects. There was a high degree of camaraderie, and sharing of test equipment along with other resources between teams. It was expected and observed that the full 12 hours of in class time (3 per course) and 24 hours of individual work time (6 hours per course) were applied to the design activity. This was the typical allotment, although some individual teams spent more or less time.

The students need to demonstrate three key prototypes:

- 1) an insulated container for holding milk cartons,
- 2) the software algorithms to dispatch UGVs on deliveries, and
- 3) the controls software to move a scaled UGV over a scaled course representing the Singapore city.

In addition, the problem solving process employed by students drew upon theory and practice from design methodology; including systematic brainstorming, and concept selection tools.

Each of these deliverables could not be completed without integrated multidisciplinary thinking. This construction amongst deliverables is key to a successful 2D design challenge. That is, by definition a 2D design project includes requirements from each incorporated course, and to meet that requirement the students must minimally make use of material from at least two subject matter courses. This is shown in Figure 2 for the example discussed here.

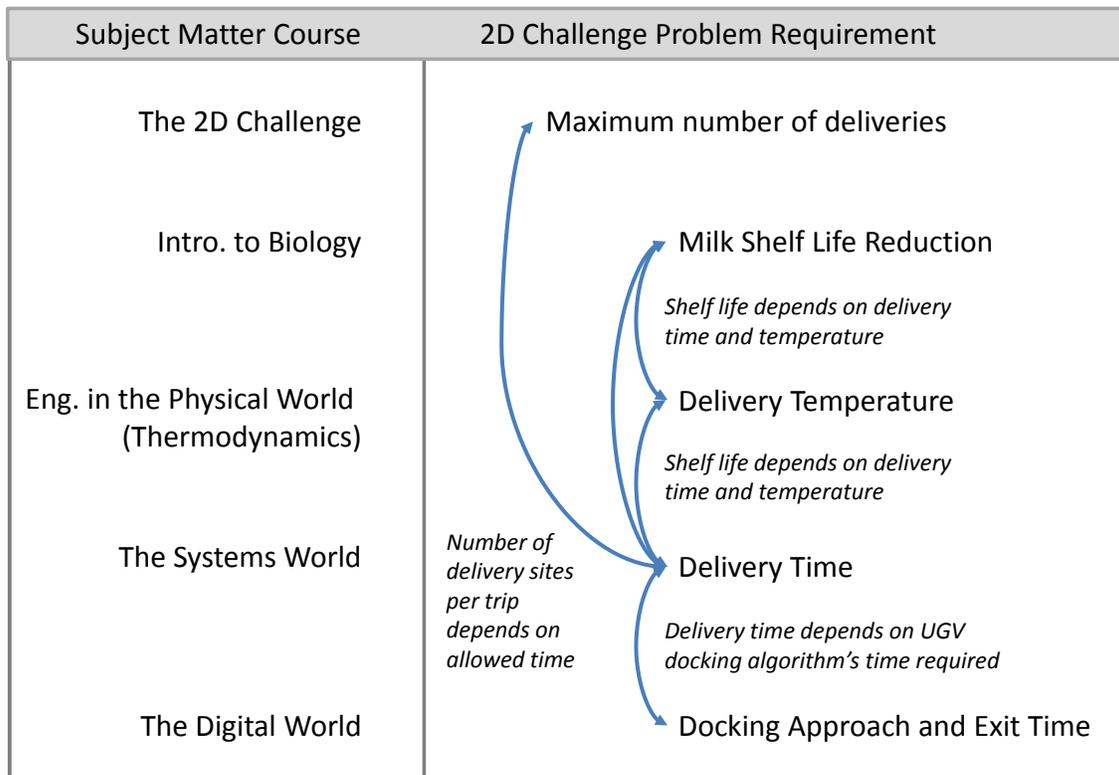


Figure 2: Relation amongst key design requirements of the project compared with the associated subject matter courses. It is critical that each subject matter requirement be codependent amongst at least two courses to ensure multidisciplinary learning.

To complete the first deliverable, one could conceivably isolate this to two subjects, the biology and thermodynamics courses. As shown in Figure 3, the biological shelf life of milk is well established as a function of temperature. Shelf life varies from approximately 2 weeks when well refrigerated, to hours or minutes as warming occurs¹⁰. To make a delivery in an unrefrigerated battery powered UGV, a container must be designed with adequate insulation. This presents a thermodynamics and heat transfer design problem. However, to ensure efficient delivery dispatching, the delivery container must be also sized in terms of the number of cartons of milk per container, to permit multiple delivery sites per UGV delivery trip.

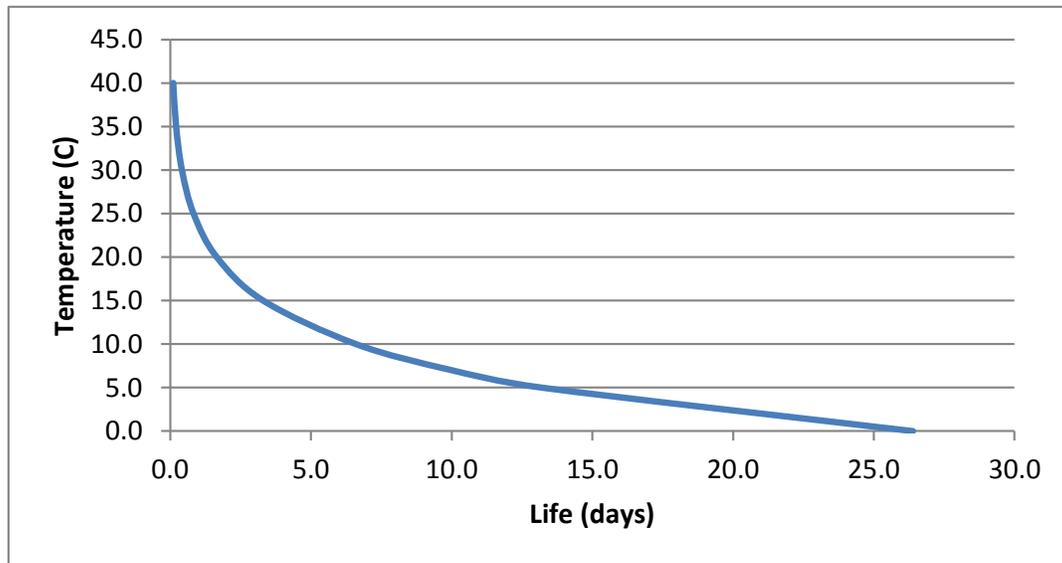


Figure 3: Biological Shelf Life of Milk¹⁰.

An allowable percentage of the 2 week shelf life lost to the higher temperature delivery must be defined, such as 1% loss. Applying this to the function in Figure 3 defines a maximum time allowed at any elevated temperature for delivery. This set of material was discussed before the 2D week in the biology course. This discussion included the underlying mechanisms of milk spoilage that generate the curve of Figure 3: bacterial growth, and protein-taste changes.

Students can then apply the thermodynamics and heat transfer concepts to analyze their designs. Equations for milk temperature as a function of time can be derived to select and size alternative insulation materials. This set of material was discussed before the 2D week in the thermodynamics course. Using models and equations, the students developed models to trade-off these quantities as part of the project design process. The resulting maximum delivery time and temperature was required to be demonstrated in a thermal prototype of the student crate design. Examples are shown in Figure 4 from the course.

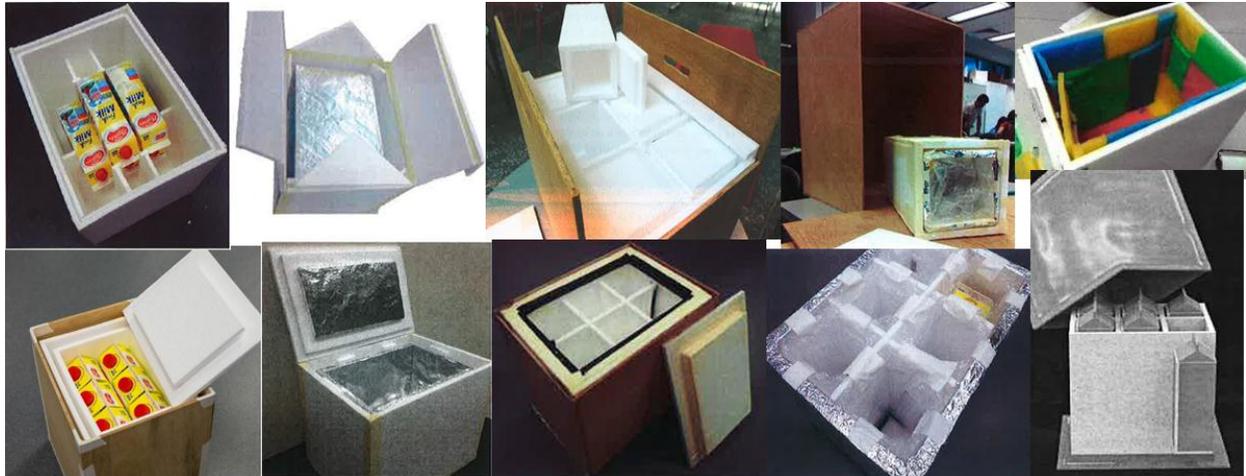


Figure 4: Example thermal crate designs, required to demonstrate adequacy of the insulation material thickness. Note the variety in design concepts given only a single thermal insulation requirement.

The next 2D design deliverable was to develop and demonstrate a set of dispatching algorithms to complete all milk deliveries in minimal time using a minimal number of UGVs. These traveling salesmen optimization problem formulations were discussed in the systems course. Notice, though, the maximum delivery time determined from the thermal crate design has a direct impact on the dispatching problem. This is another example of the multidisciplinary aspects of this challenge.

Providing all of the deliverables therefore required consideration of the materials from all four subject courses, and an approach to structure and sequence the interdependent decisions amongst the deliverables.

Assessment: Evaluation Procedure and Outcomes

The question exists over how effective 2D challenges are at student learning. It is not clear they are more or less effective than not doing the 2D challenge and instead use the historically applied methods of standard lecture and recitations as a means to train engineers. To scrutinize this, several assessment methods of the 2D challenge approach are made. First, the students complete pre- and post- questionnaires of their perceived knowledge and comfort level at solving engineering problems, including multidisciplinary, disciplinary, and problems outside their discipline. Secondly, these results are compared with graded outcomes of the 2D challenge project. For each course included in the challenge, the students received a grade for the constitutive aspects of the total challenge related to that course. Within each course, this independently assessed 2D grade contributed to 10% of each total course grade.

Assessment: Student Self-Efficacy

For the first assessment to determine efficacy of the 2D design approach, the students were asked (but not required) to complete identical survey questionnaires before and after the one week activity. Likert scale type questions were posed as to comfort level and interest in combined materials from inside and outside the course. This type of assessment approach has been demonstrated and validated for similar applications by various authors^{5,8,27}.

The first survey question concerned the integration of disciplinary material often considered far from engineering, namely biology. The degree to which the biology subject matter was exercised in an integrated manner with the remaining engineering courses was of particular interest.

How comfortable are you solving engineering design problems that ensure biological requirements?

- a) *They are easier than almost any other design problems.*
- b) *A bit easier than almost any other design problem.*
- c) *Can't say.*
- d) *A bit more difficult than almost any other design problem.*
- e) *Much more difficult than almost any other design problem.*

This question was designed to detect any change in comfort at working with design problems that incorporate both biology and thermodynamics. The students were given such a problem in the 2D week, and so if the students were capable, their comfort level should increase. The results are shown in Figure 5.

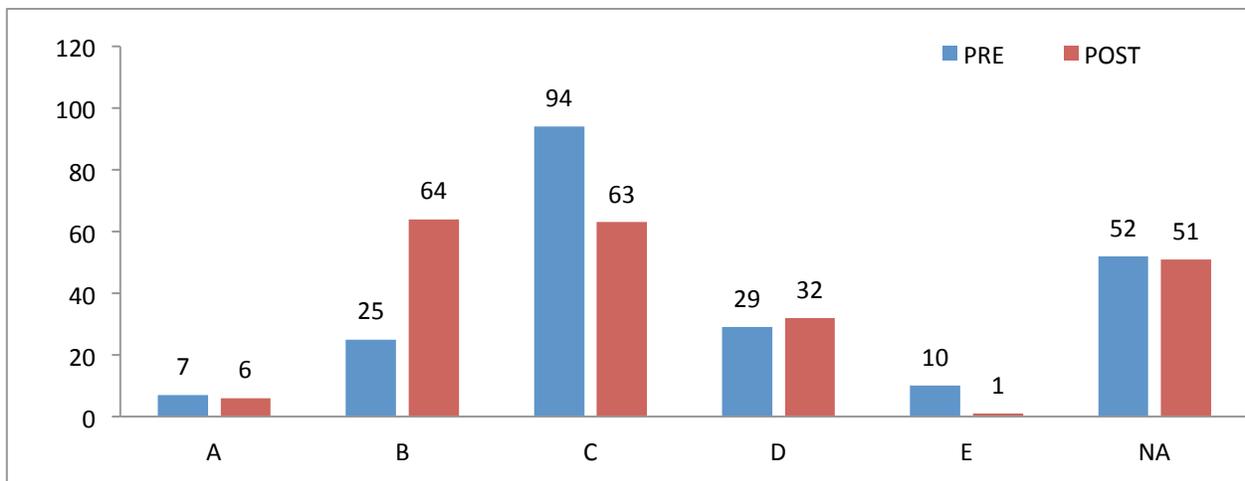


Figure 5: Comfort level differences in solving engineering design problems with biology requirements from 1 week of 2D challenge problem solving, where A is the strongest confidence level and E is the weakest.

The results show a clear shift upward in comfort levels in solving engineering problems with biology requirements. After 1 week of 2D activity, roughly 15% of the class shifted up a level from being unsure to realizing they can solve such multidisciplinary design problems as easily as any other single-discipline engineering design problem. Statistically, a paired t-test analysis for mean shift in the data results in a p-value of 0.0092, indicating a rejection of the null hypothesis of no difference between in mean between the pre and post questionnaire. There was a statistically significant improvement in outcome.

A second question was asked about how effective the students felt the 2D design challenge would be at creating learning of multi-disciplinary design. The question asked was:

How much do you think you will learn (did you learn) in this 2D experience on how the course material integrates in real problems?

- a) Looks to be very worthwhile on understanding how the 4 courses' material integrates in real problems.*
- b) Looks to be reasonable on understanding how the 4 courses' material integrates in real problems.*
- c) Can't say. Not clear or unclear.*
- d) Looks to be a stretch to learn how the 4 courses' material integrates in real problems.*
- e) Looks to be a waste of time, and will provide very little understanding how the 4 courses' material integrates in real problems.*

As asked before and after the 1 week 2D activity, this question was designed to detect any change in perceived learning about solving multidisciplinary design problems. The results are shown in Figure 6.

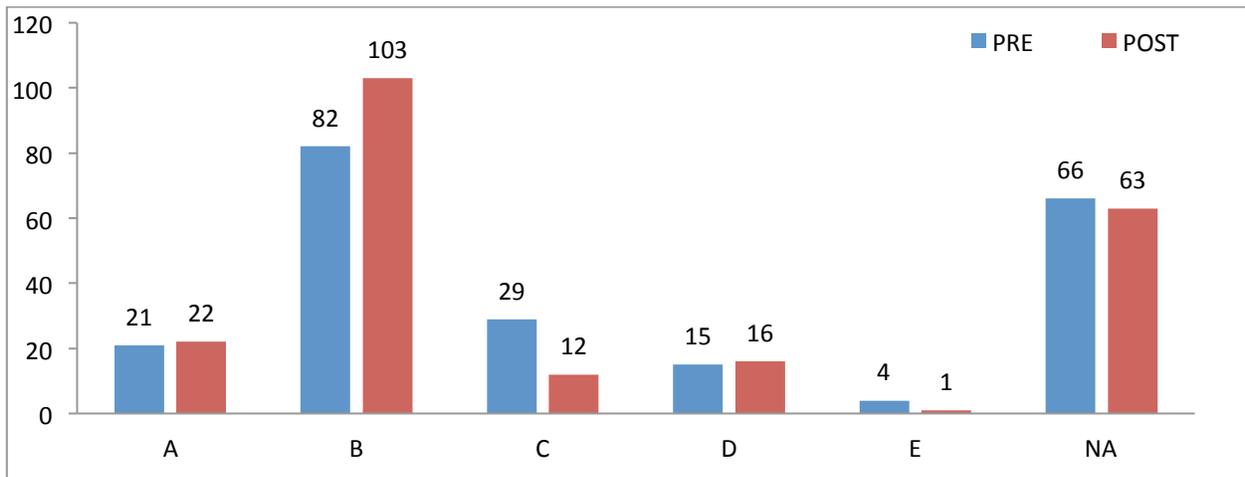


Figure 6: Differences in self-stated ability to solve multi-disciplinary engineering design problems from 1 week of 2D challenge problem solving, where A is the strongest confidence level and E is the weakest

The results show a clear shift upward in how the students felt the 2D challenge exercised multi-disciplinary engineering problems. Roughly 10% of the class shifted a level up from being unsure about the 2D experience to feeling reasonable that the 2D experience helped them learn about solving multi-disciplinary engineering design problems. Statistically, a t-test analysis for mean shift in the data results in a p-value of 0.013, indicating a rejection of the null hypothesis of no difference between in mean between the pre and post questionnaire. There was a statistically significant improvement in perception that the 2D design challenge provided learning on multidisciplinary engineering design.

The students were also asked additional questions as checks on the survey. After one week of 2D, one would not expect a significant change in students' perceived ability to solve 1D engineering problems within the course subject. Questioning this, there was no statistically

significant shift in students' perceived ability to solve thermodynamics problems before and after the 2D experience. This stability is expected. Further, when similarly questioned, there was also no significant shift in students' perception of how much non-disciplinary expertise is needed by engineers in their discipline. It was high in both cases. This is not surprising and as one would expect, the students are aware of the multidisciplinary need in today's modern world; they had already given this question a high initial rating.

Finally, students were asked if they will enjoy (pre) or did enjoy (post) the 2D challenge.

How much do you think you will learn (did learn) in this 2D experience on how the course material integrates in real problems?

- a) *Very much so.*
- b) *Somewhat.*
- c) *Can't say. Not clear or unclear.*
- d) *Unlikely.*
- e) *No way. I hate 2D.*

A statistically significant shift in response was observed, with a t-test p-value result of $9.4e-07$. The students significantly changed their minds about the 2D challenge, from 23% of the students expecting a neutral or negative experience before 2D shifting down to 10% at the end of the exercise. There was an associated increase of 5% of the student body that rated the 2D challenge in the highest category and really enjoyed the experience. This can also be seen in Figure 7. Overall, the students very much enjoyed the 2D challenge. Forming a one-week multidisciplinary design challenge restricted to the materials from the courses they are currently taking is an effective means to motivate students to learn multi-disciplinary engineering.

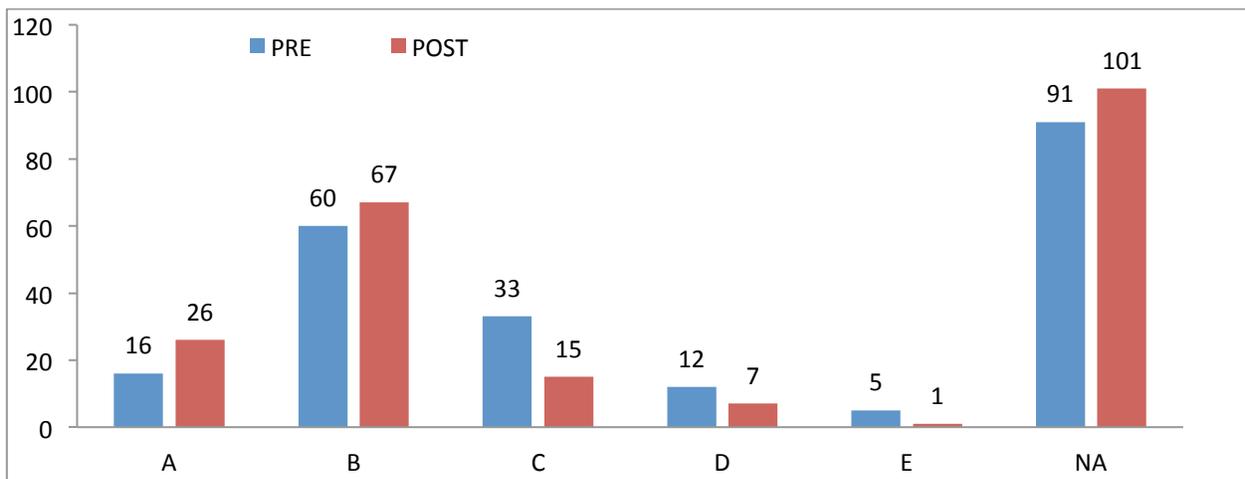


Figure 7: Differences in self-stated anticipated and post-facto enjoyment of the 2D challenge problem solving, where A is the strongest confidence level and E is the weakest

Assessment: Grading

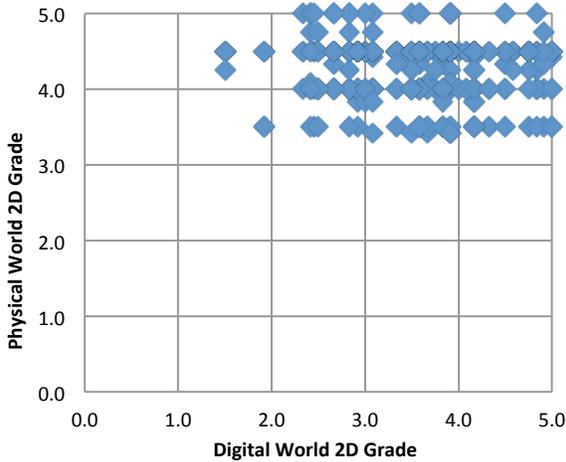
While the survey questionnaires point to students' perceptions of learning, a question might be to determine the efficacy of the 2D design approach at solving multidisciplinary problems. This is more difficult to assess, and will likely take a much longer time period to assess reflectively in future years of undergraduate education or even in the first years of working practice. On the other hand, subject matter course grading is perhaps a natural first point of assessment. Students with higher grades on the 2D project presumably can express information about the subject more exactly.

Our grading approach was based on letting the project itself drive multidisciplinary integration, and to complete the 2D project grading in separate tracks. Each course graded their portion of the 2D project in isolation from the other courses, and in isolation from the remainder of the subject matter course grading activities. For example, the biology course evaluated all student understanding of biological processes of milk spoilage, including sugar breakdown, taste change, and bacterial growth levels. This portion of 2D was graded in isolation of the thermodynamics course, which graded the project on the thermodynamics and heat transfer design. It was noted that over-all team grades (for the activity) were higher than individual grades in other portions of the course.

Notice as designed by the instructors, the project allowed for subject matter course grading in isolation from each other course in a natural way using the requirements flow (Figure 2). For example, the biological analysis formed a biological requirement, which then provided constraints on thermodynamic variables, as a shelf life versus temperature equation. The thermodynamics course simply graded the use of this equation to design the thermodynamics and heat transfer properties, without need for much consideration of the biological basis of the equation, and vice versa for the biological course grading.

Unfortunately, it must be reported that this isolated grading approach perhaps proved to not be as effective as had been hoped. Individual course contribution grading to 2D perhaps proved a questionable means of assessing understanding of the integrated, larger context of multidisciplinary engineering. To see this, consider if a student understands the integration of the materials of two courses on a design problem. Then presumably that student must have done well on the project in both courses. Similarly, students who did not understand the integrated context would do poorly. Such a distribution of students would be supported by evidence of correlation among the grades of the independently assessed disciplinary course contributions to the project.

No such correlation was generated among the 2D grades. The 2D project grades from each course bore near zero correlation, as shown in Figure 8. While some students did well in all courses and understood the project, apparently equal numbers of students understood only the project content of one course well and the project content of other courses not all.



a

PW = Engineering in the Physical World
 Bio = Introduction to Biology
 DW = The Digital World
 Sys = The Systems World

r^2	Bio	Sys	DW	PW
Bio	1	0.26	0.00	0.13
Sys		1	0.00	0.18
DW			1	0.01
PW				1

b

Figure 8: Lack of correlation amongst grading of 2D projects across the different subject matter courses when 2D is graded on individual subject matter content of the 2D experiences: (a) scatterplot, digital world and physical world correlation only (b) correlation coefficients between each course.

This grade-based argument logic would then assert the students did not learn multidisciplinary skills. However, that conclusion is in direct conflict with the student self-assessed results and the opinions of the faculty who observed students effectively engaging materials from multiple courses.

Alternatively, another explanation of the lack of grading correlation is the grading does not reflect student understanding of what must be known from the disciplinary course to complete the project. Based on scrutiny of the grading rubrics from each course, this appears the much more likely the case, and reinforces guidance and commentary on methods to grade projects in courses.

The grading for the 2D courses typically followed a grading rubric assigning points for various features of the project deliverables. For the thermodynamics course, a report was required for grading purposes. The report was graded on 7 aspects: objectives, performance requirements, design concepts, concept selection, design sizing equations, prototype build results, and experimental validation. While seemingly logical, these criteria are not strictly necessary for an effective thermodynamic design, and only 1 of 7 points ensure the students understand the biological basis for the design requirement. The grading schemes therefore reflected the individual course objectives (learning thermodynamics) and did not reflect the 2D objective of integrated learning. The 2D grading did not grade multi-disciplinary design; it graded the small disciplinary content of the large multi-disciplinary design problem. A score was assigned to each aspect, and the final grade was the sum of these aspects.

This was confirmed when studying the correlation of the 2D grades assigned in each subject with the overall final grades in each subject. In the systems course, the correlation was 44%, and in the thermodynamics course the correlation was 30%, which is about what one would expect between hands on laboratory grades and overall subject matter grades. When each subject

course grades a 2D project alone on the subject matter contribution to 2D, then those grades will not correlate, and do not grade the multidisciplinary nature of the 2D exercise.

In hindsight, this result gave pause to the course instructors on grading. All participants felt 2D was worthwhile, and all could point to projects demonstrating the students did well understanding integration amongst the courses. A possible future approach would be to have the instructors jointly define grading rubrics and score the projects together. The need for this joint or integrated grading is clear from the correlation results. Overall, it was found that grading integrated multidisciplinary design courses would require more than the standard approach to grading disciplinary materials applied. Additionally, instructors could formally record observations of students during the procedure. These observations could be used as a tool to compare results between semesters. This will be attempted in the future.

Conclusions

The 2D Design Activities was found to be a useful approach to introducing students to effective multi-disciplinary engineering problem solving early in the undergraduate curriculum. Beyond single course 1D design problems, it allows more difficult problems to be presented that address issues outside of the scope of a single course. Yet, it is not completely open-ended in scope, the design problems must be contained to that within the current enrolled courses.

This report described SUTD'S first wave of students. They have explored 1D (single course) and 2D (multi-course) design activities so far in the curriculum. The students, who applied the AutoMilk problem described in this paper, had previously encountered two other comparable 2D projects. The first was a cannon design (linking chemistry and physics), and the second was an intelligent home project (linking circuits, design, and humanities arts and science on Descartes 'human intelligence'). Those efforts are not described in this paper for length reasons. A second set of students is now going through a similar 2D problem sequence. The results from these other projects appear to be progressing according to the same pattern. Their 2D is not yet complete, data collection and analysis is ongoing.

The researchers found that for implementation to be successful, the instructors must create a chain of project requirements amongst the course subject matter. Design requirements from all covered courses must be defined such that accurately fulfilling them requires incorporating analysis from at least one other discipline. The requirements must be co-dependent across disciplines.

An example of such a 2D requirement is to develop thermal properties (coolness) such that the biological aspect (freshness) is also met. This was actually one of the challenges for students in approaching the AutoMilk design problem; students discovered that translating the biological health and safety requirements into a thermodynamic design requirement was difficult. This type of design requirement translation is a very real-world scenario and highlights the criticality of 2D type design projects, as this was also a new type of problem for students.

The dedicated and contained one-week timeline was also found to be useful. Since more than this allotted time generates excess activity away from the disciplinary courses, and creates a design

problem that is unnecessarily large against the real need for active learning of technical course subject matter.

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