INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 05 MELBOURNE, AUGUST 15-18, 2005

TOWARD A THEORY OF DISTRIBUTED INTERDISCIPLINARY PROJECT-BASED DESIGN EDUCATION

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Keywords: Design education, Project-based Learning, Interdisciplinary Teams

1 Introduction

The efficacy of project-based learning (PBL) in design education has gained broad acceptance [1]. Moreover, when PBL takes place in teams, it resembles design practice more closely, and offers an attractive value proposition to educational institutions for producing highly employable graduates [2,3]. Therefore, most state of the art design curricula utilize PBL principles.

Some innovative design curricula also recognize the significance of interdisciplinary practice, and organize student teams such that different functions associated with key disciplines of design projects are represented. However, in reality, the majority of students usually belong to a single educational discipline, and some are simply asked to wear another discipline's hat for the duration of projects. There have been few structured attempts at recruiting students with backgrounds in different educational disciplines so that a true interdisciplinary setting is achieved. This scheme is particularly meaningful when complex design tasks are tackled.

The Project Oriented Learning Environment (POLE) is one such educational paradigm [4]. This paper describes the POLE platform, discusses an assessment methodology and a toolset that have been developed over three years, and presents key findings as the outcome of that assessment. The assessment outcomes are used to substantiate a theoretical framework for distributed interdisciplinary project-based design education.

2 Background

POLE is a learning system, founded by University of Applied Sciences Aargau (UASA) and extended in cooperation with several international universities such as ETH Zurich, Aalborg University, Universidad Politecnica de Catalunya, Barcelona, NTNU Trondheim, Bauhaus Universität Weimar, TU Delft and Stanford University. It operates in a reflexive context, taking into account the various cultures involved in order to create new teaching and learning methods. Students are at the core of this concept, and are given the opportunity to develop process-oriented expert knowledge through interdisciplinary teamwork. Simultaneously, they learn to work independently and to lead real-life projects. Their interaction is facilitated by the state of the art information and communication technology.

The POLE learning environment allows students to apply their theoretical knowledge in practical cases. As a part of interdisciplinary teams, students with academic backgrounds in fields such as architecture, urban planning, construction management, civil engineering, mechanical engineering, industrial design, and economics are given the opportunity to comprehend different disciplinary processes and acknowledge their relation to social, economical, and political dimensions of design projects.

Since 2001, the following seven projects, all originating from and funded by industry or government partners, have been completed using the POLE platform:

- Planning of a convention center and hotel for the new campus of a Swiss University
- Urban planning project for two adjacent but politically separated towns
- Architecture and the body: design of a sports facility in a historical area
- Corporate financial interest and sustainability
- Peak of relaxation: urban design and planning of a spa facility in the Swiss Alps
- SnowDive: design of a novel sports equipment for snow and sand
- Vertical classroom: design of a high rise university building

Typical class size of a POLE project is between 30 and 40 students, and team sizes vary from four to seven students depending on the nature and complexity of the project.

3 Assessment Methodology

Three of the seven projects listed in the previous section were formally assessed by the first and fourth authors of this paper between 2002 and 2004. The methodology that was used to identify, monitor, and assess key aspects of student experience was composed of a mixed set of research methods:

1. Ethnographic observations during project kick-off and product presentation meetings.
2. Ethnographic (unstructured) interviews held with students throughout the courses.
3. Ethnographic (unstructured) interviews and discussions held with the instructors throughout the courses.
4. Semi-structured feedback sessions held with students at the end of the project kick-off and product presentation meetings.
5. On-line surveys administered six and twelve weeks into, and four weeks after SnowDive.

Ethnographic observations, including the ethnographic interviews, were carried out by the assessors at the University of Applied Sciences in Switzerland. At the beginning and end of each project, participating students travel to the POLE headquarters, the “Spinnery,” a remodeled textile mill which is solely dedicated to POLE activities. The kick-off meeting lasts approximately one week, and is held primarily in the Spinnery, with occasional site visits to locations related to the project. For instance, during the SnowDive project, students traveled to the Alps to familiarize themselves with existing snow sports equipment. Also during the kick-off meeting, students are introduced to interdisciplinary design processes, a set of ICT tools, and a team of experts who have volunteered to serve as coaches. At the end of each project, students physically meet again to present their final designs, and in the case of product development projects, functional prototypes.

The semi-structured interviews were also carried out by the assessors during the kick-off and product presentation meetings at the Spinnery. In order to elicit feedback in a constructive and a structured manner, students were grouped together, and each person was initially asked to voice one thought starting with, "I like…" and a second thought starting with, "I wish…" This is a method that has been used in graduate design classes at Stanford University to promote in-class reflection [5]. Upon completing this method, students were then asked to provide feedback in any way they saw fit, and the responses were documented.

Three on-line surveys were administered during the most recent POLE course, the SnowDive project. Two of the surveys were administered during the course, more specifically, on the 6th and 12th weeks (December 2003 and February 2004). The third survey was administered three weeks after the course ended (April 2004) in order to capture student perceptions of the course after they have had a chance to reflect on their experiences while no longer being engaged in the course. The survey instrument consists of ten multiple-choice and three open-ended questions (Table 1). Participation in the survey was voluntary and anonymous.

Table 1. Survey questions and responses that were administered during SnowDive.

Survey Question	**Response Options**
Q1: Which institution are you attending?	[Participating Institutions]
Q2: What is your field of study?	[Participating Disciplines]
Q3: Since ______, how many hours per week on average did you spend working on your POLE project?	1-5 hrs. 6-10 hrs. 11-15 hrs. 16-20 hrs. 21-30 hrs. 31-40 hrs. more than 40 hrs.
Q4: Since ______, what portion of your project time did you spend for individual vs. group work?	1 = Mainly or nearly all group work 2 = Mainly group work 3 = Slightly more group work than individual work 4 = Even between group and individual work 5 = Slightly more individual work than group work 6 = Mainly or nearly all individual work 7 = Mainly individual work
Q5: Since ______, what percentage of your project time did you spend performing the following tasks? Scale 0 = None 1 = 1-10% 2 = 11-20% 3 = 21-30% 4 = 31-50% 5 = more than 50%	Acquiring information/knowledge (basic research) Acquiring ICT skills (learning ICT related tools) Acquiring new skills (learning tools & methods unrelated to ICT) Concept creation (sketching, brainstorming, etc.) Analysis (Analyzing acquired information and generated concepts) Concept realization (construction, prototyping, etc.) Concept evaluation (prototype testing) Project planning (defining, structuring, and monitoring tasks) Reflection (considering past experiences, work and process) Social tasks (conflict resolution, negotiation, coordination, etc.)
Q6: Up until this point, how satisfied are you with your POLE experience?	1 = Very dissatisfied 2 = Dissatisfied 3 = Neutral 4 = Satisfied 5 = Very satisfied
Q7: If you were given the opportunity to participate in another POLE project in your next semester, how interested would you be?	1 = Not interested (this semester's POLE project is not proving to be a good use of my time) 2 = Not interested (this semester's POLE project is proving to be a good use of my time, but participating in another POLE project would not teach me much more than what I am learning) 3 = Somewhat interested (there are several other classes I would rather be involved in, but I would consider it)

	4 = Strongly interested (it would be high on my "classes to take" list) 5 = Definitely interested (I would not think twice about signing up)
Q8: Would you recommend POLE to a friend?	1 = Definitely not 2 = Maybe, I would have to think about it 3 = Yes, without a doubt 4 = Not only would I recommend it, I would make sure that they take it
Q9: Participating in POLE has advanced my understanding of: (Please indicate if you agree with this statement with regards to each of the following fields) Scale 0 = Strongly disagree 1 = Disagree 2 = Agree 3 = Strongly Agree	Product Design Design Engineering Process Management Economics Mechanical Engineering
Q10: Participating in POLE has made me a better: (Please indicate if you agree with this statement with regards to each of the following fields) Scale 0 = Strongly disagree 1 = Disagree 2 = Agree 3 = Strongly Agree	Product Design Design Engineering Process Management Economics Mechanical Engineering
Q11: What do you like about POLE the most so far?	[Open-ended]
Q12: What is the most significant learning experience you have had in POLE so far?	[Open-ended]
Q13: What do you wish was different?	[Open-ended]

4 Survey Responses

Survey data were analyzed in two groups: responses to open-ended questions and multiple-choice questions. This section provides a detailed discussion of the two types of analysis.

4.1 Responses to Open-ended Questions

Responses to the three open ended questions (see Q11-13, Table 1) were grouped in conceptual categories. The categories emerged from the data; each category name was explicitly referenced in one or more of the responses provided by students. The tables presented in this section are the result of this synthesis (Tables 2, 3, and 4). The points (response categories) that were made by a higher number of respondents are listed at a higher row on the tables. The point that has been expressed by the highest number of respondents during each survey are marked with a black background, followed by other points which have been made by a high number of respondents in gray backgrounds. The October row refers to the outcome of the "I like-I wish" exercise carried out with the students during the final day of the kick-off meeting.

Table 2. Responses to open ended survey question, "What do you like about POLE the most so far?" The numbers indicate how many times a specific point has been provided as a response. The total number of respondents are indicated on the bottom row.

I LIKE…	October	December	February	April
Teamwork (Interdisciplinary)	6	13	10	11
Teamwork (International)	4	6	7	8
Teamwork (General)	4	2	2	0
Project Content (Realism)	2	2	2	5
Project Content (Product)	3	2	1	0
Improved Self-awareness	0	2	2	2
Number of Repondents:	~25	26	23	21

The findings outlined on Table 2 demonstrate that students, throughout the course, appreciated the interdisciplinary and international nature of teamwork POLE aims to promote. This finding confirms the fundamental premise of POLE as interdisciplinary and international teamwork is one of the main learning objectives of the POLE curriculum. Also, it is interesting to see that the students' appreciation of the realistic nature of the project increased a month after the project ended. Finally, it would have been desirable for the students to have appreciated their ability to own the project and the opportunity to improve their self-awareness of their own processes more.

Table 3. Responses to open ended survey question, "What is the most significant learning experience you have had in POLE so far?" The numbers indicate how many times a specific point has been provided as a response. The total number of respondents are indicated on the bottom row.

I LEARNED…	October	December	February	April
Communication	n/a	9	8	5
Teamwork (Interdisciplinary)	n/a	9	6	10
Teamwork (International)	n/a	0	0	2
Improved Self-awareness	n/a	0	1	3
Number of Repondents:	~25	26	23	21

Table 3 outlines the responses regarding what the students thought they learned (as opposed to the responses on Table 2 which indicate what they appreciated). Communication and interdisciplinary teamwork were clearly perceived to be two major learning outcomes.

Table 4. Responses to open ended survey question, "What do you wish was different in POLE?" The numbers indicate how many times a specific point has been provided as a response. The total number of respondents are indicated on the bottom row (each respondent was free to make multiple points).

I WISH…	October	December	February	April
More doing less lecture (Kick-off)	10	1	0	2
More Time	0	6	3	2
More International Participation	1	5	4	1
Experienced Team Members	0	4	1	1
Less Stress	0	0	0	2
More co-located Time	0	1	1	1
Number of Repondents:	~25	26	23	21

Most of the responses outlined on Table 4 explicitly indicate potential areas of improvement. The point that was voiced the strongest is that the kick-off week should involve more "designing" than "listening." There was a clear agreement with a majority of students that there should be more doing than lecturing during the kick-off phase. In December, the major concern was the limited time available for the project, which remained an issue for the rest of the course (some even complained about a stress situation in the final phase of building the prototypes.) It is also interesting to see that there are very few issues raised regarding the lack of co-located time, a common failure mode in distributed design projects.

4.2 Responses to Multiple-choice Questions

In this section, responses to multiple choice questions will be presented. Individual responses are averaged for different groups. Since the number of observations are small (n=~25 for the whole class, and thus, even lower for subgroups such as distributed students and economics students), the reported figures are not statistically significant. However, they might still be indicative of trends and significant phenomena.

Characterization of Time Spent on POLE

Three questions were asked in the survey regarding the time students spent working on their POLE projects. The first question (Q3, Table 1) was aimed at gaining an overall understanding of the number of hours spent by each student. The second question (Q4, Table 1) was intended to reveal if the students worked by themselves or collaborated with team members. Responses to Q3 and Q4 are outlined on Table 5.

Table 5. Time spent working on POLE projects in hours per week and the portion of time spent on individual vs. group work. The 7 point scale for the responses in the individual vs. group work column progresses is: 1 = Mainly or nearly all group work, 4 = Even between group and individual work, 7 = Mainly individual work. The individual responses from students are averaged for three groups: the whole class, local students (UASA), distributed students (NTNU, ETHZ, AU).

		Hours per Week	Individual vs. Group Work
ALL	DEC	21.0	4.0
	FEB	24.0	4.5
LOCAL	DEC	21.3	3.9
	FEB	25.0	4.2
DISTRIBUTED	DEC	20.4	4.3
	FEB	23.2	4.8

The reported numbers of hours spent on POLE, and on group work vs. individual work, increased slightly from December into February, which is natural for a project based course. The interesting observation is that distributed students spent slightly more time on group work than individual work when compared to local students although both groups spent about the same amount of total time per week. This might be related to the effort they had to exert in communicating with team-mates.

The third question regarding the time students spent on POLE (Q5, Table 1) was aimed at understanding more about the specific activities students engaged in. Responses to Q5 are outlined on Table 6. Overall, the time spent on each task and how that changed between December and February is similar for local and distributed teams. There are some expected trends: concept generation, concept analysis, and basic research time decreases, and concept realization time increases from December to February.

Table 6. Percent of project time spent working on different types of activities. The response scale is: 0 = None, 1 = 1-10%, 2 = 11-20%, 3 = 21-30%. 4 = 31-50%, 5 = more than 50%. Individual responses from students are averaged for three groups: the whole class, local students (UASA), distributed students (NTNU, ETHZ, AU).

		Basic Research	Acquiring ICT Skills	Acquiring New Skills	Concept Generation	Concept Analysis	Concept Realization	Concept Evaluation	Project Planning	Reflection	Social Tasks
ALL	DEC	2.0	0.9	1.2	2.5	2.5	1.2	0.6	2.0	1.3	1.6
	FEB	1.4	0.2	1.1	1.9	2.0	2.3	0.4	1.9	1.6	2.0
LOCAL	DEC	2.0	1.1	1.4	2.5	2.3	1.2	0.7	2.1	1.2	1.6
	FEB	1.1	0.2	1.3	1.7	1.9	2.4	0.5	2.0	1.6	1.8
DISTRIBUTED	DEC	2.0	0.6	0.8	2.5	2.9	1.1	0.5	1.9	1.5	1.6
	FEB	1.7	0.2	0.9	2.1	2.0	2.1	0.3	1.8	1.6	2.1

However, there are some unexpected trends as well. The first one is that time spent on acquiring ICT skills, which is low compared to other tasks to begin with, decreases sharply during the second half of the course and approaches zero. One would have expected this number to be much higher at the beginning since ICT is essential for distributed teamwork. Students might have already been familiar with these tools, or they might have underestimated their importance. In other words, the decrease in the activity indicates that either the students acquired/possessed the necessary ICT competence midway through the project, or they simply gave up on acquiring the skills—a potential failure mode. Another unexpected observation is the small amount of time spent on concept evaluation during the second half of the course.

Level of Satisfaction with POLE

Three questions were asked to assess how satisfied the students were with POLE overall. The first question (Q6, Table 1) directly inquired about the level of satisfaction with POLE. The second question (Q7, Table 1) inquired if the student would consider taking POLE again. The third question (Q8, Table 1) inquired if the student would recommend the class to another student. The responses to these questions were normalized, averaged, and treated as an "overall satisfaction with POLE" variable. The values are reported on Figure 1.

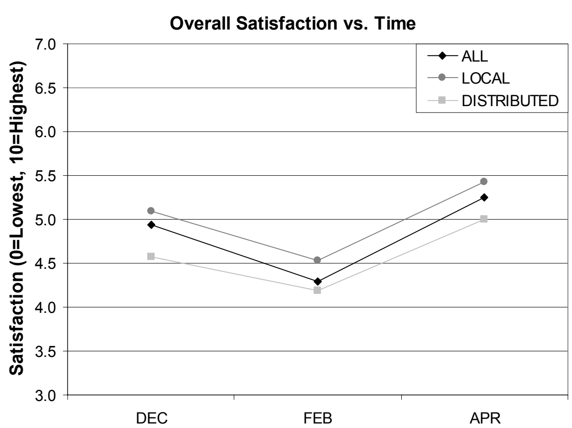

Figure 1. Overall satisfaction with POLE. For the details of the scale, see Q6-Q8, Table 1. The construct values are reported for three groups: the whole class, local students (UASA), distributed students (NTNU, ETHZ, AU).

The overall satisfaction values are slightly lower for distributed students as compared to local students. The values for both groups decreased slightly during the second half of the course, but rose above the initial values in April, approximately three weeks after the course was over. This suggests that students valued their experience more once they distanced themselves from the characteristically stressful final weeks of a design project.

Advancement of Disciplinary Understanding as an Outcome of POLE

Two questions were asked to assess students' perceptions of how POLE might have contributed to their understanding of the different disciplines represented in their teams. The first question (Q9, Table 1) directly inquired if the POLE experience helped them understand each of the disciplines better. The second question (Q10, Table 1) inquired if POLE made them a better engineer, process manager, etc. Therefore, the second question is different from the first one in the sense that it inquires if the gained understanding of a discipline had a perceived impact on the practice of a discipline. Responses from students belonging to each discipline and all students were averaged. Averages for the whole class, process management students, and product design designs are displayed on Table 7.

Table 7. POLE's perceived contribution to the advancement of the understanding of each field and its practice for the whole class (PD = Product Design, DE = Design Engineering, PM = Project Management, EC = Economics, and ME = Mechanical Engineering.)

	Understanding of the Discipline					Practice of the Discipline				
	PD	DE	PM	EC	ME	PD	DE	PM	EC	ME
DEC	2.1	1.8	2.0	1.7	2.0	1.8	1.6	1.9	1.4	1.6
FEB	2.0	2.1	2.3	1.4	2.1	1.5	1.5	2.1	1.5	1.7
APR	2.2	2.1	2.2	1.2	2.1	2.1	1.9	1.9	1.2	1.8

In general, students rated POLE's contribution to the advancement of the understanding of a field slightly higher than POLE's contribution to the advancement of the practice of the same field (comparing the PD values on the left with the PD values on the right, and likewise for the DE, PM, EC, and ME values). However, the differences are small, and not statistically significant. The ratings for each field, with the exception of economics, are close to 2.0 out of a 0.0 to 3.0 scale, which indicates that students perceived POLE to be effective in advancing their understandings of the disciplines.

The low ratings of the advancement of the understanding of the economic discipline indicate an integration issue. The specifics of the issue are not relevant to this discussion. What is relevant is that, in interdisciplinary design projects, integration of the thinking of different disciplines is challenging, and is often associated with breakdowns that can threaten the integrity of teams. It should also be noted that the survey instrument was effective in capturing the issue.

5 Ethnographic Observations

This section provides a detailed discussion of some of the key findings of the ethnographic observations and interviews.

Formulation of a Shared Project Vision in Teams

Design teams were strongly encouraged to negotiate and construct shared project "vision statements" during kick-off meetings. The vision statements were treated as a primary outcome of the kick-off phase. This was a significant intervention since it would have been rather challenging for students to be able to construct such an understanding once they proceeded to the distributed phase during which in-person interactions were not possible. The importance of this issue was recognized by the instructors, and students received guidance for addressing it. However, for many teams, the vision statement was not solidified during the projects—its concept was not broken down into design requirements—and remained abstract.

A specific example of this issue was the lack of integration of the economics students into the design teams during the SnowDive project. The financial/business requirements were developed by the economics students within the "economics students group" as opposed to the interdisciplinary teams the economics students were meant to be a part of, and were not communicated to the interdisciplinary team members. Similarly, the requirements that were developed by the other interdisciplinary team members were not communicated to the economics students. This resulted in the lack of negotiation of design requirements, and some of the prototypes that were presented during the final week were either without a well-researched, or with an unrealistic, cost target. Survey findings presented in Section 4 support this observation.

This issue was also encountered at varying degrees during the other two projects that were observed. Here, it is substantiated with quantitative data and a specific example. It is natural for this issue to remain in the foreground as promoting effective negotiation is one of the most significant challenges interdisciplinary PBL curricula face.

Finally, students were challenged with each others' disciplinary differences. At the end of the course, they acknowledged that process as a key learning experience. However, to date, interdisciplinary PBL design pedagogy does not seem to have produced an explicit method or mechanism for students to address that challenge.

Student Commitment Levels and Workload

Students from different institutions and with different majors participated in the course at different commitment levels. (It should be noted that students with no project based learning experience tend to underestimate the time commitment.) The realization of "what it takes to be in an intensive project based course" had mixed affects on the design teams. Some teams responded well and distributed the workload willingly and efficiently so that the students who had more free time shouldered the majority of the effort. In others teams, the students who shouldered the majority of the effort did not necessarily do so because they preferred it; they did so out of necessity and expressed discomfort.

This is a another common situation in PBL design education, especially in an interdisciplinary *and* international collaboration such as POLE. Intervening directly to regulate workloads among team members is not an effective response since managing the situation constitutes a learning experience for the students.

Coaching

At each campus, disciplinary advisors with backgrounds in academic and professional fields that were related to the ongoing design projects were utilized as "coaches," forming the backbone of a social network to support student learning.

Building on the previous qualitative observations and the survey findings, it was observed that the coaches' approach toward interdisciplinary work also had an impact on the generation and negotiation of design requirements. For instance, during the SnowDive project, coaches with economics expertise did not fully commit to interdisciplinary work, and encouraged the economics students to prioritize working with each other over working with their team-mates with different disciplinary backgrounds.

Also, the teams that leveraged the expertise of the coaches did so differently at different parts of the project. In the early stages, coaches were often used as "sounding boards" for ideas, and for identifying new ideas or conceptual directions. In the latter stages, they were approached with more specific questions and their domain expertise was specifically appreciated.

Information and Communication Technology (ICT)

During the kick-off phase, students went through a day of intensive ICT training, where they were exposed to the workings of the integrated information and communication software system used in the course in a lecture setting. The emphasis of the training sessions was on increasing the "technical" competency of the students so that they would be ICT "literate." The technical training sessions were necessary for promoting student confidence with using the technology. However, students were not fully exposed to why they would need to use ICT in the first place. This is a common issue in distributed design education as it is challenging for students to understand the rationale for ICT usage *while* learning complex design processes.

6 Generation of a Theoretical Framework

In this section, the assessment outcomes are used to substantiate the basis of a theoretical framework for distributed interdisciplinary project-based design education. The framework is characterized by the fundamental dimensions, phases, and outcomes of the learning activity.

6.1 Description of Fundamental Activity Dimensions

The framework accounts for four fundamental dimensions of the distributed multidisciplinary project-based design learning activity: requirements thinking, team identity, information communication and technology, and coaching.

Requirements Thinking

The most critical of the four fundamental dimensions is "requirements thinking" as it provides context for the others. In the initial phases of design projects, team need to be engaged in requirements thinking when developing identities, using ICT, and being coached.

The significance of forming shared vision statements was discussed as a qualitative observation. It was reported that teams had difficulty in extracting concrete and actionable interpretations from the vision statements. This is understandable since team members have a variety of cultural, national, and disciplinary backgrounds; a vision statement alone is too abstract to guide them toward a common team goal. Different backgrounds of team members influence them to read different meanings into a vision statement. As projects mature, these different meanings lead to conflicts and breakdowns.

Therefore, students should be encouraged to treat vision statements as a starting point, extend them by extracting explicit "design requirements" from them, and continuously negotiate the requirements. Design requirements can constitute the basis for a "living contract." It would also constitute a mechanism for more precise negotiation, and make each team member's participation and contribution to the team effort more visible. Insisting on the generation of disciplines specific design requirements might also address team integration issues.

If the multidisciplinary aspects of the interaction is considered, the learning experience can be structured by building on the vision statement, and asking each student to interpret the vision statement of his/her team from the perspective of his/her discipline when extracting design requirements. In other words, the design requirements design teams generate from their vision statements should be specific to disciplines.

Team Identity

In multidisciplinary projects, team identity formulation is especially challenging due to the diversity in academic, cultural and personal backgrounds of the students. Moreover, social theories of design perceive the communication and negotiation of such differences *as the design process* [6-8]. More specifically, after extensive ethnographic observations of designers in industry, Bucciarelli remarked that [8]: "Different participants think about the work on design in quite different ways. They do not share fully congruent internal representations of the design." He argued that each participant possesses an engraved set of technical values and representations, which act as a filter during design team interactions, and that the resulting design is not simply a summation, but rather, an intersection, of the products of the viewpoints of the participants. As Bucciarelli observed, the formation of a multidisciplinary team identity is a continuous and influential dimension of the design process; it occurs over the lifetime of a project. Breakdowns in identity formation reflect onto the design process and project outcome.

Information and Communication Technology

The distributed nature of the type of learning interaction promoted by POLE necessitates ICT deployment and usage. When design teams are "stretched" and "pulled apart" over geographically remote locations, their critical internal mechanisms, "what makes them tick," is often broken. ICT is one approach in attempting to "repair" what has been "broken."

The significance of providing ICT usage rationale was discussed as a qualitative observation. It was also noted that it is challenging for students to understand the rationale for ICT usage *while* learning complex design processes. In other words, an experienced designer, who has an advanced understanding of design processes, would be able to recognize the need for ICT and visualize scenarios in which it can be leveraged. However, a novice student designer lacks the experience to see such connections between the design process he/she is engaged in and ICT. Therefore, it is very common for students not to embrace ICT at the beginning of a design course, regardless of how much instruction they might be given on the topic.

Therefore, rationale for the need to adopt and use ICT should be made explicit. For instance, during project kick-off, short distributed collaboration exercises can be used as simulated scenarios in order to increase awareness. Also, the implications of effective communication on team performance should be discussed in depth before any such training session is held so that students can perceive their value in advance, and be more motivated to learn.

Finally, if the ICT infrastructure in remote campuses is not in place before the course begins, students will need to spend valuable project time on setting it up during the first few weeks. It is necessary for the participating educational institutions to make a full commitment to meeting this critical need as ICT is all the distributed teams have when it comes to communication.

Coaching

The coaching framework used in POLE is consistent with the recent recognition of the coaching concept within design education literature [9-11]. Coaches can be effective in transforming the formalized knowledge embodied in a design process to the tacit form students desire. When utilized with that in mind, coaches can draw on their own past as well as ongoing design practices in order to interpret and contextualize the intent of a process for students. In fact, it is critical that coaches engage in—at least as an observer—the ongoing product development practices of the students they are coaching; the relevance of the interpretations of coaches increases when they are grounded in the situations they are interpreting for. This differentiates coaches from domain experts, and coaching from consulting.

In an interdisciplinary context, coaches should have a working understanding of and commit to the interdisciplinary design methodology. While it is natural to focus on educating the students on interdisciplinary methodologies, it is important to remember that coaches are also a part of the equation and that coaches might not have been exposed to intensive interdisciplinary work themselves. Therefore, it is necessary to ensure that coaches are cognizant and open to the principals of interdisciplinary work.

6.2 Description of Activity Phases

The framework conceptualizes distributed multidisciplinary project-based design learning activity in three distinct phases: co-located kick-off, distributed conceptual design, and distributed specification-oriented design.

Phase I: Co-located Kick-off

The kick-off phase has four main purposes [12,13]. Firstly, teams are formed, and social networks are established among students and coaches for future collaboration. Trust building is also initiated. Core competencies of team members are recognized, and initial roles are defined.

Secondly, design tasks are introduced, and critical aspects of the project are considered and addressed by the community as a group, including the instructors, students, coaches, and support staff. Self portraits of community members are shared, which provide an opportunity to widen emerging social networks.

Thirdly, a preliminary project outline/plan is defined. At the end of the kick-off phase, the teams present their project plan, roles and commitment levels of team members, resource planning, and an information management framework to the community. Instructors and coaches provide closing observations and recommendations.

Finally, teams are introduced to the ICT framework to be used during the distributed phases. Students attend workshops and participate in exercises on ICT tools and their usage such as peer-to-peer communication networks, knowledge management systems, project management software, and videoconferencing technology. If ICT usage and tools are not introduced during the kick-off phase, they most likely will not be used actively during the rest of the project.

Phase II: Distributed Conceptual Design

The conceptual design phase is characterized by the production of several novel concepts relevant to the design task. User needs and competitive products are explored. Information on similar concepts, including patent searches, is gathered. The feasibility of the generated concepts is investigated by rapidly building and testing of a series of initial prototypes. Relevant manufacturing processes are considered, and initial cost estimates are generated.

A common failure mode in this phase is teams splitting up into disciplinary sub-groups. Instructors and coaches need to display extra sensitivity toward such splits, and remind students that discipline specific requirements need to be resolved via negotiation, and not isolation. The general thinking direction should be divergent. The distributed nature of the activity can be leveraged in order to further promote divergence since team members are not with each other to keep each other "in check." Also, having team members at multiple locations implies that a more diverse set of the local resources are available.

Phase III: Distributed Specification-oriented Design

During this phase, team are expected to build and deliver a functional prototype, or a proof of concept. Therefore, system-level thinking, detail design and implementation are particularly important. Prototype parts can be built in separate locations and sent to a dedicated location for assembly. Also, teams give a final presentation and deliver a design report documenting their development process and specifications of their design. Team members collaborate closely and focus their collective attention to realize these goals. The convergent nature of the activity and the pressure created by the approaching deadline result in a clear division of labor. It is normal for teams to split into disciplinary units and activities.

6.3 Synthesizing a Theoretical Framework for Distributed Interdisciplinary Project-based Design Education

A theoretical framework for distributed interdisciplinary project-based design education was synthesized by; considering the survey and ethnographic findings according to the fundamental learning activity dimensions; articulating how those learning activity dimensions are realized in the activity phases; identifying the key operational and pedagogical outcomes of each learning activity phase. The resulting framework is presented in the form a matrix in Table 8.

Table 8. A theoretical framework of distributed interdisciplinary project-based design learning. The framework accounts for four key dimensions of interdisciplinary learning activity across three activity phases, and identifies operational and pedagogical outcome for each phase.

	PHASE I	PHASE II	PHASE III
Team Identity Development	Team identity formation is initiated. Face-to-face interaction reduces projection and misinterpretation. Similarities & differences (in knowledge, skill, and preference) are established. Potential conflicts are sensed. Political associations are established. Social networks are established and widened. Trust building is initiated.	Team identity evolves. Divergent nature of the activity might accentuate the differences between perspectives further (once individuals are "on their own" they do "their thing"). Teams might be split up politically and functionally.	Team identity is defined. Teams that have successfully communicated and negotiated their differences through requirements thinking display well pronounced team identity. Teams that have not successfully communicated and negotiated their differences display multiple team identities, and may have a prototype that does not reflect comprehensive design thinking (ignorant of key requirements) or multiple disjoint prototypes.
Requirements Thinking	Requirements generation process is initiated. Team members identify requirements specific to their	Requirements thinking remains becomes the fabric of the interaction and provides context for distributed communication and work.	Requirements thinking is minimized. Focus shifts to the realization of the requirements that were generated during prior phases

	disciplinary backgrounds. Requirements thinking not only helps to communicate each individual's perspective, but also promotes them to reflect and evolve their own thinking and identity.		in the prototype.
ICT Usage	Basic ICT concepts, rationale, and skills are acquired. Skill acquisition needs to be done in a meaningful way. Context for using ICT should be communicated and integrated into team building activities, kick-off tasks, etc. A separate layer is established within the ICT network.	ICT infrastructure needs to be in place—students should not be expected to build it. If the ICT skills introduced in the kick-off are not applied and reinforced at the beginning of this phase, they will be forgotten for good. Highly contextual information in multiple media is shared.	Whatever ICT tools and skills are adopted by the end of Phase II are continued to be used. No new ICT tools and skills are learned. Coordination and rapid interaction gain a special importance as teams push to realize their design before the deadline.
Coaching	The concept of coaching is introduced. Coaches inform students of their domain expertise and personal background. Students form an initial understanding of the breadth of available expertise and mechanisms of leveraging it. Coaches are introduced to the coaching layer within the ICT network.	Coaching gains a critical role in maintaining the integrity and functionality of distributed teams. Breadth in the coaching network supports the exploration and divergent thinking of students. Coaches must have an understanding of interdisciplinary processes. Coaches keep in touch with what is happening in other projects via the ICT network.	Coaches support convergence when leveraged appropriately. They can even act as a team member in order to make things happen. Coaching is absent in teams who have not formed a working relationship with coaches in the prior phases.
Desired Operational Outcome	Shared Vision Statement. Commitment to Requirements Thinking.	Intensive communication and negotiation of and around requirements. Refined Vision Statement	Unified prototype which integrates and addresses a comprehensive set of requirements.
Desired Pedagogical Outcome	Ability to rapidly orientate with different, and often conflicting, perspectives.	Autonomous Learning within a "loose" social network.	Requirements Thinking as the facilitator of interdisciplinary distributed design work.

7 Conclusion

This paper presented qualitative and quantitative findings that were based on three design projects carried out by students as a part of the Project Oriented Learning Environment platform. The findings were used to substantiate the basis of a theoretical framework for distributed interdisciplinary project-based design education. The framework was characterized by considering the fundamental dimensions, phases, and operational and pedagogical outcomes of the design learning activity. If the framework can be extended and validated in other design education courses and platforms, it can serve as a guide to distributed interdisciplinary project-based design education. The methodology used in generating the framework, including the survey, can be used in other settings to extend the framework.

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