Exploring tutor-student interactions in a novel virtual design studio

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This exploratory case study investigates a novel adaptation of the virtual studio pedagogy. Students are located in authentic professional practice settings, while tutors remain on campus. Verbalisations of tutors' and students' discussions in 13 weekly sessions were characterized and measured using topic modelling and FBS analysis. Tutors and students exhibited large differences: Tutors' cognitive behaviour was generally more abstract while the students' was more concrete. Further, while tutors were more concerned with design communication, students engaged with specific issues in the manufacturing and organizational setting of their host. Tutor-student interactions did not change significantly over time, with most of the interactions taking place in the solution space. Categorical differences in topics between tutors and students were found that remained consistent over time.

Keywords: virtual design studio, case study, design cognition, reflective practice, design education

Expert designers know more than they can say. They develop knowledge that is personally constructed by engaging with and reflecting on tough problems in authentic contexts (Henderson, 1998; Schön, 1987). How best to 'teach' design then?

As the most well-known design pedagogy, the design studio has been the focus of significant research interest. Studies have investigated the role and characteristics of an effective tutor (e.g., Goldschmidt, Hochman, & Dafni, 2010; Uluoglu, 2000), and the nature of interactions between tutors and students

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(e.g., Khaidzir & Lawson, 2013; Milovanovic & Gero, 2018, 2020). While the studio has traditionally been the default design pedagogy in architecture (Lawson & Dorst, 2009), in engineering education teaching and assessing of design has been primarily accomplished through design review meetings (e.g., Hurst & Nespoli, 2019). Both pedagogies have traditionally relied on in-person interactions that occur in physical spaces within academic institutions. However, advances in virtual communication and collaboration technologies, including immersive and simulated design environments, have enabled new modalities of learning and teaching design at a distance (Jones, Lotz, & Holden, 2020; Lloyd, 2012; Rodriguez, Hudson, & Niblock, 2018; Sopher, Gewirtzman, & Kalay, 2019).

While the studio has been proven to be a successful design pedagogy, it cannot fully replace the learning that occurs when students are placed in authentic professional practice settings — in the *wild* (Ball & Christensen, 2018; Hutchins, 1996). Lawson and Dorst (2009) suggest that we should create design practices associated with universities that parallel the role that a 'teaching hospital' plays in medical education (p. 219). For students in co-operative (co-op) education programs, this 'clinical' dimension is available during co-op terms; however, reliable and qualified design tutors are not always available. It has, until the availability of effective virtual communication technology, been impractical for faculty to clinically teach students while they were deployed to various geographic locations on their internships.

The case study we report here centers on a unique academic offering that aims to bridge this gap: while the students are situated in an authentic professional setting in a co-op term, they regularly participate in *virtual design critiques* with an academic tutor situated in the students' home institution. This new pedagogical modality differs from the traditional studio in that it moves students to an authentic practice context, where opportunities to engage with messy indeterminate situations exist. It also offers students and tutors rich opportunities for problem finding, framing and construction, not normally available in a traditional studio because of the environment they are situated in.

1 Aims

Research on studio pedagogy, and a more comprehensive, scientific understanding of the interaction between tutor and student is relatively limited, particularly in engineering education. Given the importance of the studio pedagogy in teaching through reflective practice, the central role that interaction between tutor and student plays, and the diversity of modalities that the design studio takes, we are motivated to better understand how this new modality — the *virtual studio pedagogy set in a partially-situated design context* — may or may not improve the teaching, learning and assessment of design.

Rather than relying on instructor teaching inputs and student design output (i.e., design work) to inform, we aim to understand design behaviour in this setting and delve deeper to characterize interactions of students and tutors. We frame our research questions accordingly and ask:

1. How can tutor-student interactions in a novel virtual design studio be characterized and measured?
2. How do tutor-student interactions in a novel virtual design studio change with time?

The rest of the paper is structured as follows. In section 2, we review various design pedagogies and organize them according to a proposed framework in order to readily distinguish them. In section 3 we describe an implementation of the virtual studio in the partially-situated context of a program called *iCapstone* (Nespoli, Hurst, & Russell, 2018), on which this case study is based, and explain the data collection and analyses methods. The results of those analyses are presented in section 4. In section 5 we discuss our findings, both expected and unexpected, and detail implications for design pedagogy and future research directions.

2 Background

2.1 Developing artistry in the wild

There is a need for a more comprehensive treatment of professional formation, which includes knowledge less easily characterized, quantified and taught (Henderson, 1998). Schön (1987) described this as *artistry* – a kind of intelligence that is different from standard professional knowledge, "*an art of problem framing, art of implementation, and an art of improvisation – all necessary to mediate the use in practice of applied science and technique"* (p.13). He asks whether any programming can adequately deal with the "*complex, unstable, uncertain, and conflictual worlds of practice*" (p.12) and whether anyone, having studied and described it, can teach artistry by any means (Schön, 1987, as referenced by Henderson, 1998). Boisot (1995) and Henderson (1998) characterized this as uncoded and concrete/abstract knowledge.

Schön (1987) defines knowledge-in-action as that existing knowledge we apply to expected situations; in contrast, reflection-in-action comes into play when a situation unfolds in unexpected ways, where we must extend our expertise in unfamiliar domains. He further suggests that such reflective practice can be learned through exercising of reflection-in-action and that professional education can and should provide opportunities to do so. He advocates for the use of reflective practicums, of three types (as summarized by Henderson, 1998). The most advanced (or Type III) practicums feature reflection-in-action in the *swamp* of authentic professional practice. It is worth thinking about teaching design in the *wild*, and answering Schön's questions "*can the prevailing concepts of professional education ever yield a curriculum adequate to the complex, unstable, uncertain, and conflictual worlds of practice?*" (Schön, 1987, p. 12) and "*how education for artistry can be made coherent with the professional curriculum's core of applied science and technique*" (Schön, 1987, p. 14). The development of the Type III practicum, in other words.

2.2 A framework for design pedagogy

We synthesize our understanding of possible teaching, learning and assessment methods as a function of the learning environment and the communication mode in which they occur. Our motivation to do so was based on the need to show how the co-operative work term experience could be enhanced by the addition of an academic tutor, and at the same time how the traditional and virtual studios could be enhanced by immersing students in professional practice contexts. We present a framework in Figure 1 that displays design pedagogy as a function of these two dimensions: learning environment and communication mode. We denote three primary actors in this framework: academic tutors (A), students (S) and practitioner tutors (P). Additionally, we define a tutor who embodies both academic and practitioner knowledge (T), as for example surgeons (i.e., as continually active teachers, researchers and clinical practitioners). The vertical dashed lines between student and practitioner tutor denote a possible available interaction, dependent on the active engagement of a practitioner acting in the role of tutor, as opposed to the role of a manager.

In the vertical dimension we identify two known teaching contexts: academic and real world. The academic learning domain is characterized by achieving learning outcomes through intentional and systematic delivery of knowledge content through established teaching, learning and assessment methods. In engineering education, the main design pedagogies that are employed are the design studio and design review meetings. The practice learning domain is characterized by the learner learning from practice and from being situated in a practice setting. Here, a pedagogy of full immersion of tutor and student where Dewey's initial call for "education for, of and by, experience" (Dewey, 1938) is realized. In engineering education, this situated learning occurs in the context of clinical internships and co-operative work, or more broadly work-integrated learning (McRae & Johnston, 2016).

In the horizontal dimension the framework includes two broadly different communication modes: face-to-face and virtual. Development of virtual communication technologies and the recent COVID-19 pandemic have enabled the creation of new learning paradigms that replicate traditional face-to-face pedagogies (both those situated in the academic context and in the real world) through virtual communication. Examples of the virtual design

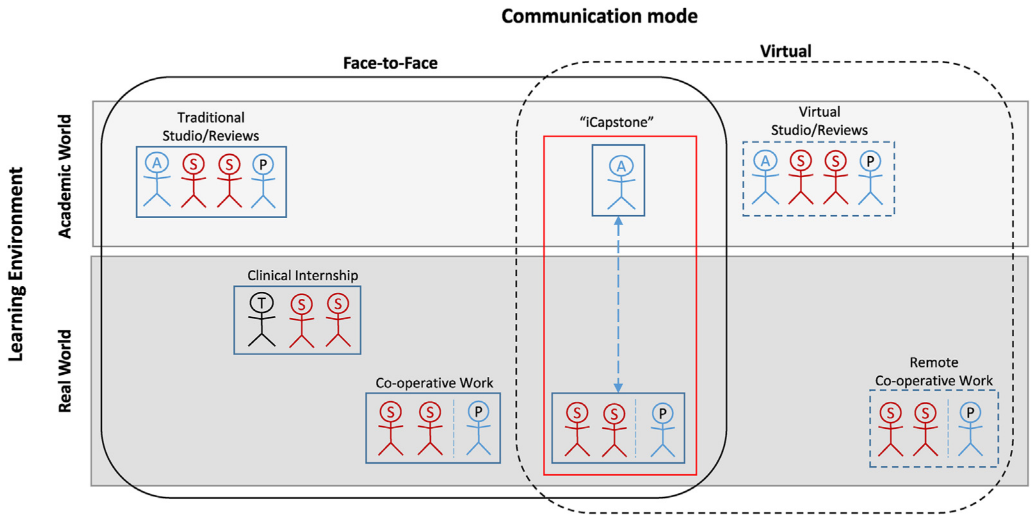

Figure 1 Design pedagogy as a function of learning environment and communication mode

studio in particular are well referenced in the literature (Jones, Lotz, & Holden, 2020; Lloyd, 2012; Maher, Simoff, & Cicognani, 2000; Rodriguez et al., 2018).

Virtual communication also facilitates a novel way in which the two learning contexts can be bridged through a new paradigm — *iCapstone* (Nespoli, Hurst, & Russell, 2018) — shown as a partially-situated pedagogy. Here a studio is created using virtual technology, where the academic tutor is on campus, and student and practitioner tutor are in the wild — a *semi-wild* pedagogy. Instead of problems being defined and given to students, as in a traditional studio, situating them in the real world affords the opportunity for students to discover needs on their own. It is this new pedagogy that is the focus of investigation in this case study. In the following sections we provide further background on each of the pedagogies comprised in this framework.

2.3 The academic environment

2.3.1 The design studio

The most well-known and proven mode of teaching design to date continues to be the design studio. The profession of architecture has been successful at retaining design at its core, and managed to continue to practice effective design pedagogy through the studio (Lawson & Dorst, 2009), with physical studio spaces having evolved to provide tutors and students flexible ways of promoting both individual and group activity. A major feature of the design studio pedagogy is the design critique (crit, sometimes also called tutorial), a learning-by-doing environment, a working and social space, where students undertake design projects under the guidance of experienced practitioner tutors. Here tutors must bring in knowledge and skills, but also values and an understanding of their role, and may take on many different roles (Goldschmidt, 2002; Lawson, 2019).

In his book, *The Design Studio*, Schön (1985) describes how tutors *show* or *tell* to get students to learn, resulting in a so-called search for a *convergence of meaning* between tutor and student around a design project. For this to occur, the context must be one in which the student is engaged in trying to do design, and where the acts of demonstrating and imitating, telling and listening, must take the form of a reciprocal reflection-in-action that goes on continuously. Here the tutor must develop a *coaching artistry* (Goldschmidt et al., 2010) where she must be able to have, or must be able to invent on the spot, a method of instruction suited to a particular student.

There is increased interest in studying this important pedagogy in a more quantified way. In a study of the design knowledge communicated during design critiques, Uluoglu (2000) describes the duality in the role of tutor as both an architect and educator, and the student as an architect and novice (learner). They also present an additional duality in the knowledge content: generalizable versus specific and personal. Goldschmidt et al. (2010) identify the importance of obtaining a more detailed and quantified understanding of interactions between tutor and student during a crit and moreover understanding and providing a method to characterize the tutor teaching performance. Khaidzir and Lawson (2013) propose a new methodology for analyzing tutorial conversations in a studio using a Cognitive Interaction Matrix (CIM) consisting of several cognitive dimensions, and demonstrate that it is possible to discern cognitive behaviour and interactional characteristics between tutor and student. More recently, Milovanovic and Gero (2018, 2020) explore a range of tools to analyze and describe participants' cognitive design behaviour and interactions in a design studio. In their case study, they employ several analytical methods, including protocol analysis, a coding scheme based on the Function-Behaviour-Structure ontology (Gero, 1990; Gero & Kannengiesser, 2014), problem-solution index and problem-solution indicator, and first order Markov models to describe and model cognitive design behaviour and interactions (Kan & Gero, 2017).

2.3.2 Design review meetings

Engineering education has relied primarily on design review meetings in design-based courses, including Capstone courses, as the main pedagogy for teaching and assessing design. Capstone design courses generally fit in the domain of the academic world, even though the broadly-defined problems, enhanced contextual elements and support from both industry and community partners can be relevant and well supported (Bauer, Strawderman & Stamm, 2012; Coyle, Jamieson, & Oakes, 2006; Howe, Rosenbauer, & Poulos, 2017;

Ward, 2013; Yasuhara, Campbell, & Atman, 2016). Perhaps one of the most notable such courses is Stanford's ME310 design course that has evolved into teams working collaboratively and internationally by responding to a partner provided design brief (Carelton, 2019).

Typically, design reviews occur 2-3 times during an academic term, and might involve instructors, faculty advisors, and industry practitioners (client and external examiners). The meetings are structured either as a presentation-then-question-answer type meeting, or one where questions are posed at any time during the presentation. These reviews may also include student peer review activity (e.g., Hurst & Nespoli, 2015). Such formats are less interactive than studio-based *crit* and *tutorial* based formats and have different purposes (Sater-Black & Iversen, 1994). Design reviews provide a status of the design whereas design critiques have a purpose of improving the design (Connor, 2015). In any case they are commonly used and therefore important formats for professional practice preparation.

Several recent studies have analyzed conversations and feedback given during these meetings, in particular the role of inquiry in teaching, learning and design performance (Cardella, Buzzanell, Cummings, Tolbert, & Zoltowski, 2014; Cardoso, Hurst, & Nespoli, 2020; Cummings, Tolbert, Zoltowski, Cardella, & Buzzanell, 2015; Huet, Culley, & McMahon, 2004; Huet, Culley, McMahon, Fortin, & Sellini, 2007; Hurst & Nespoli, 2019). Design Thinking Research Symposium 10 (DTRS10) in particular continued the tradition of analyzing design activity and comprises a rich collection of work from a number of design researchers analyzing a common and diverse data set of design review activity from several disciplines (Adams & Siddiqui, 2015). Researchers examine how students acquire design expertise through the scaffolding practices of an educator (McDonnell, 2016), how the work of coaching can be characterized as *design pedagogical content knowledge (PCK)* (Adams, Chua, & Radcliffe, 2016), and the importance of reflecting purposely on the feedback and coaching strategies instructors provide to students (Yilmaz & Daly, 2016).

2.3.3 The virtual studio

Technological advancements in virtual communication have created new opportunities for communicating online in a virtual setting, which has become an essential mode of communicating and functioning for educational institutions during the global COVID-19 pandemic. Virtual Learning Environments (VLE) incorporate this communication technology plus additional supports for learning, course content and management, assessment tools, collaborative whiteboards and design environments (e.g., mural.co). It is a shared virtual space for designing and learning design. For distance learning institutions VLE is an established and effective practice (Jones, Lotz, & Holden, 2020), and proven to be successful at developing design thinking skills (Lloyd, 2012). Physical studios are being successfully augmented, rather than being totally replaced, by the use of this technology as well (Rodriguez et al., 2018). Bender and Vredevoogd (2006) argue that this form of blended offering can enhance studio, by providing more targeted instruction to individual students and while serving a larger group of students.

2.4 Real world practice environment

Edwin Hutchins' book *Cognition in the Wild* (1996) is an account of an emergency situation on the bridge of a US navy vessel returning to port, highlighting the conditions under which, in this case, decision-making under pressure, is undertaken. Through this account, Hutchins refers to cognition that occurs in its natural setting, as opposed to an artificially constructed one, as in a classroom or laboratory. The aim of a professional educational program is to prepare students to be confident and successful in such contexts, where authentic design tasks reside (Goel and Priolli, 1996). Here the world is "complex, unstable, uncertain, and conflictual" (Schön, 1987, p. 12) – a *swamp* where messy, indeterminate situations exist.

There is great opportunity in these contexts for education through experience, however not all experiences are educative (Dewey, 1938). Knowledge that is acquired is personal and constructed (Boisot, 1995; Henderson, 1998; Polanyi, 1958), and uncoded (Boisot, 1995; Henderson, 1998). Being situated offers the opportunity to participate peripherally in professional activities, and is viewed as a special type of social development (Lave & Wenger, 1991). Rather than conditions being controlled and structured, participation and acting in this world takes place in widely varying conditions (Lave & Wenger, 1991). Learning becomes a combination of learning from others and learning from personal experience (Eraut, 2004). The knowledge available to be learned is implicit, largely invisible, and therefore participants may lack awareness of their learning (Eraut, 2004). Learning by doing in the real world, presents opportunities, but only when feedback on participant actions is rapid and unambiguous (Senge, 1990).

For students, learning while situated in real world practice, may or may not occur as part of an academic program. If a student's academic studies are formally integrated with a work-place or practice setting, as opposed to learners learning on their own, then this is referred to as Work-Integrated Learning (WIL) (McRae & Johnston, 2016). Key attributes defining WIL include: experience in a work-place setting, curricular integration, defined student outcomes that lead to employability, and reflection. Examples of WIL activities include co-operative education (co-op), internships, clinical placements, and field placements. It is important to note that the attributes defined above do not include the requirement for a tutor although one may be present (McRae & Johnston, 2016).

2.5 A partially-situated environment – 'iCapstone'

Current co-op experiences prove to be very valuable for student learning, professional formation and personal growth (Trede, 2012). However, the experiences lack the presence of consistent and qualified clinical instruction. Managers who hire the students, or team members that work with the students may not be tasked with teaching them about design, and may not have the formal design and pedagogical training to do so. Further, they usually have students tackling well-defined problems, despite the potential presence of many ill-defined opportunities in the settings. Established in 2016 at the University of Waterloo, the iCapstone program – *integrated*, *interdisciplinary* and *international* capstone design – is an example of a design pedagogy implemented in a real word practice context that adds a crucial clinical instructional element to the co-op term.

Inspired by the Stanford Byers Innovation Fellowship Program (Wall, Wynne, & Krummel, 2015), iCapstone places interdisciplinary teams of students in highly authentic professional practice settings, in the "wild", including settings that feature global, cultural and societal elements, where students can discover and engage closely with messy indeterminate situations on their own. This is a novel aspect of this programming. During the co-op term, students receive sustained *virtual* instruction – from design faculty (academic tutors) located at their home university – that guides them as they find, construct, engage with, and start to solve highly authentic design tasks in authentic professional practice contexts (Nespoli, Hurst, & Russell, 2018). The iCapstone program presents a novel adaptation of studio pedagogy where the students are located in the wild, in an authentic professional practice setting during their co-operative education term, and while tutors remain on campus – hence the emergence of a partially-situated modality. Using technology, tutors and students engage in mutual reflection-on-action and reflection-in-action every week in virtual design critiques, in effect creating a studio pedagogy but where students are located in the wild, discovering problems on their own, and therefore permitting the opportunity for tutors to instruct while they do so.

3 Research design

This exploratory case study of the iCapstone program investigates student-tutor interactions over the term using verbal protocol analysis of the virtual design critiques, analyzing their reflective conversations with the design situation and each other using two approaches: topic and interaction analysis.

3.1 Case study

This case study is based on an implementation of the iCapstone program. An interdisciplinary team of three senior engineering students – two mechanical, one management engineering from a university in Canada – was hired by a global manufacturing company and put on a 4-month long placement at a manufacturing facility in South America. As part of the programming, students were not given specific projects; rather, in the first 3 weeks of the term, they participated in an immersive orientation program where they learned about both commercial and operational aspects of the business. During this period they discovered over 200 needs and proposed two promising opportunities to address for the remainder of the term.

Beginning in week 3 of the term, the students (as a group) also began weekly virtual meetings (using the Skype platform) with two academic tutors located at their home university in Canada. The tutors were faculty members with significant combined experience in engineering design teaching and practice. In the meetings, tutors asked students to intentionally reflect on the problems they were engaging with, based on Schön's theory of reflective practice. More specifically, students were asked to reflect on what unfolded that was expected, and what unfolded that was unexpected (Schön, 1983). Occasionally, tutors also provided just-in-time instruction as the students' problems unfolded, often informally, but sometimes more formally in the form of brief prepared presentations (mini-lectures) on topics such as finding and formulating needs, performing a functional analysis, and engaging in intentional reflection. A snippet of how these conversations typically transpired is provided below:

S*tudent 1: [ ].. we discovered … a break-*

Tutor: A break?

Student 1: [crosstalk] yeah when we tested it actually, it won't work.

Student 2: As it stands right now.

Student 1: Yeah.

Tutor: Was that surprising?

Student 1: For the … the reason is surprising.

Tutor: What's the reason?

Student 1: I mean, I guess we should have checked but … it was something that … is so secure. The rail that we're riding on …

Tutor: Yes?

Student 1: We expected like minor inconsistencies, but they have variances up to three millimeters on it, in thickness.

Tutor: Oh.

Student 1: So sometimes it's 6–7 mm and sometimes it's just over 3.

Tutor: Well, yeah.

Student 1: Like it's … yeah.

Tutor: So-

Student 1: Like um …

Tutor: How do the current carts adapt for that variability?

Student 2: They ride all entirely on the wheels.

An overview of the main topics of discussion in each learning session is provided in Figure 2. The focus of the first two weekly sessions was on the students' efforts in trying to capture management's needs and priorities. By week 5, they had narrowed their scope to two potential project topics; one of them – improving the productivity of a production line – would become their primary focus in the remainder of the term. By week 10, students had designed a preliminary model of a new cart to go on the production line, and by week 12, they had created a prototype, which they were able to share and demonstrate to the tutors. After testing of their cart prototype on the production line, the students discovered that the design did not work as intended, because of reasonable, but unverified, assumptions they had made about the state of key interface elements of the production line. In the last two sessions students continued to discuss their progress in the production line project, and the unexpected magnitude of adjustments they needed to make to the design. A common thread in the weekly discussions was also the effect of the local culture on the students' work and the challenges of operating in an organizational culture different from what they were accustomed to in Canada.

3.2 Data collection

In all, 13 sessions, each about 1 h in length were video recorded using Camtasia - a screen recording technology. For redundancy, sessions were also audio recorded using a separate recorder. Both the video and audio recordings were conducted by the tutors. Video recordings were transcribed using an external transcription service. Due to the frequent occurrence of words specific to the geographical location and the manufacturing domain, the transcriptions underwent an additional quality check to ensure those terms were properly captured. The separate utterances from the two tutors and three students were aggregated into tutor and student entities. Thus, the final data set contained all verbal utterances produced by the meeting participants in the 13 sessions, indexed by session number and author type – tutor or student.

3.3 Methods

3.3.1 Topic analysis

The objective of this analysis was to extract the main topics of discussion in the tutoring sessions and to investigate how those topics differed between students

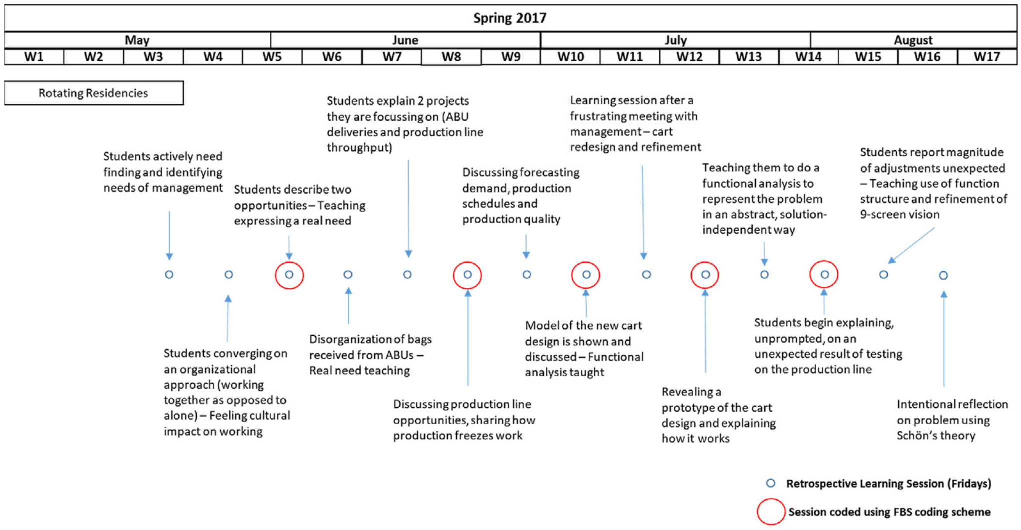

Figure 2 Timeline of events and retrospective learning session topic summaries

and tutors, as well as across time. Given the small data set, the non-standardized nature of the text due to the fluid conversation that it captured, and the limited and mostly colloquial vocabulary used, it was not feasible to use sophisticated topic modelling algorithms and tools, such as LDA (Blei, Ng, & Jordan, 2003) or Word2Vec (Mikolov, Sutskever, Chen, Corrado, & Dean, 2013). Instead, a custom procedure was developed that combined some automated text analytics with manual clustering, as detailed in Figure 3.

Text analytics was implemented in the Python programming language using the Natural Language Toolkit (NLTK) (Bird, Loper, & Kline, 2009). First, a pre-processing of the text resulted in a list of verb and noun word stems. These words were used to create over 1300 "synonym groups", generated based on the rule that a word in the text is assigned to a synonym group as long as at least one other word in the group is its synonym. Of these, the most frequent 121 were kept for further analysis.

The next stage was conducted manually. Two of the authors on this paper served also as the tutors described in the study, so had the advantage of using that experience to assist with the categorization, using a "commonsense" (Liu & Singh, 2004) approach. For example we knew that organizational issues were present and so it was natural to categorize for this once we saw significant frequency of occurrence of words related to that topic. After reviewing all synonym groups, one of the authors iteratively clustered the synonym groups by similarity, resulting in 12 emerging topics. Then, one of the other authors independently assigned each of the synonym groups to one of those 12 topics. There was substantial agreement between the two, $\kappa = .67$ (95% CI, .613 to

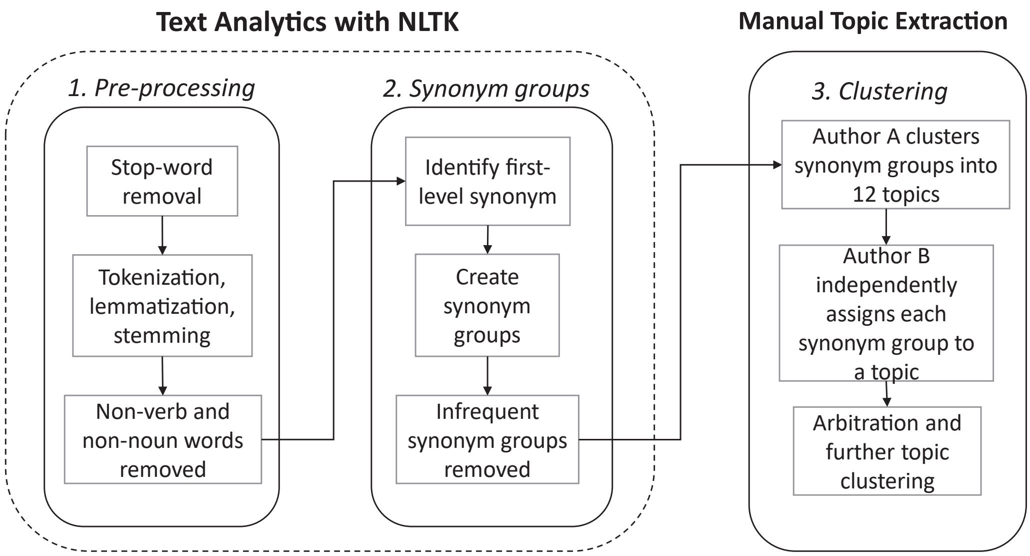

Figure 3 Process of topic extraction

.782), p < .0005. Next, through discussion, disagreements between assignments were resolved and some of the topics were further combined, resulting in 7 final topics, each containing 6 to 26 unique and non-overlapping synonym groups. The final topics and example words categorized in each topic are presented below:

· *Abstraction – Theory*: theoretical abstraction of the design process in terms of goals, requirements, functions, and specifications, at different system levels (e.g., "characterize", "constrain", "formulate", "represent", "specify", "function", and "requirement").

· *Abstraction – Applied:* application of the abstraction above to the specific design tasks (e.g., "capacity", "cost", "eliminate", and "streamline").

· *Communication:* (e.g., "interpret", "comment", "communicate", "convince", "present", and "document").

· *High-level Manufacturing:* manufacturing process at the system level (e.g., "automation", "energy", "factory", "line", "maintenance", "operation", and "produce").

· *Low-level Manufacturing:* manufacturing process at the sub-system level (e.g., "bag", "bond", "box", "cart", "cement", "chain", "fit", and "glue".)

· *Organization:* the larger company, its units, and management levels (e.g., "company", "department", "union", and "manager").

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· *Money:* finance, budgeting, and purchasing matters (e.g., “buy”, “invest”, “money”, “order”, “salary”, and “quote”).

Finally, a frequency table was produced with the number of times words assigned to each topic were uttered by the tutors and the students in each session. This frequency table formed the basis of a correspondence analysis between topics, authors (tutors and students), and session number.

3.3.2 Design co-evolution and interaction analysis

Designers’ reflective conversations with the situation can be characterized as a co-evolution between the design problem and solution spaces (Dorst & Cross, 2001; Maher & Poon, 1996). We model designers’ cognitive activity as they move through these spaces using the Function-Behaviour-Structure (FBS) ontology (Gero & Kannengiesser, 2014), which describes design activity as composed of six design issues: requirements (R) coming from sources external to the designer, function (F) or purpose of the design solution, expected (or desired) behaviour (Be) of the solution, the solution’s structure (S) in terms of its components and their relationships, the solution’s (or structure’s) actual behaviour and attributes (Bs), and the external representation (or description) of the solution (D). The design issues of R, F, and Be relate to cognitive activity in the problem space ($\mathcal{P}$), whereas S, Bs, and D relate to the solution space ($\mathcal{S}$). Thus, analyzing design activity through the FBS ontology provides a systematic way in which participants’ verbalizations can be mapped into the problem and solution spaces.

In this case study, we study participants’ reflective conversations in the virtual design studio of the iCapstone program and how tutor-student interactions shape this reflective activity. We thus characterize tutors’ and students’ activity in the virtual design studio as a series of *transitions* in a two-dimensional space spanned by: (1) *movements* in the problem-solution continuum, and (2) *interactions* between student and tutors (Figure 4).

In our analysis, we employed think-aloud protocol analysis techniques on the natural verbalizations of tutors and students — a common practice in design cognition research. Five of the thirteen learning sessions (in weeks 5, 8, 10, 12, and 14), which tracked the progression of the production line project, were chosen for this analysis. While students were also involved in one other major design project, sessions related to the production line project were specifically chosen for this analysis as students were able to make the most progress (including a couple of prototype iterations) on it. The transcripts of the discussions held in those five sessions were coded using the FBS coding scheme by two trained coders. The first coder segmented and coded the text based on occurrence of design issues. The segmented text (without the codes) was then passed on to the second coder, who coded each segment independently and re-segmented when necessary. Overall, the two coders had moderate inter-rater agreement, $\kappa = .592$ (95% CI, .677 to .706), $p < .000$. Next, the two coders participated in an arbitration session where they resolved any disagreements in their segmentation or coding. Finally, the design issues were mapped into problem ($\mathscr{P}$) and solution ($\mathcal{S}$) space codes.

The dataset generated contained all design issues (according to the problem/solution space) produced by meeting participants in the 5 sessions that were analyzed (a total of 3148), indexed by session number and author type – tutor (T) or student (S). Pairs of adjacent issues formed *transition units*, which were then categorized according to the type of *tutor-student interaction* (S > S, S > T, T > S, or T > T) and *problem-solution space movements* ($\mathscr{P} > \mathscr{P}$, $\mathscr{P} > \mathcal{S}$, $\mathcal{S} > \mathscr{P}$, or $\mathcal{S} > \mathcal{S}$) – resulting in a total of 16 transition types.

In Table 1 we illustrate how the verbalizations previously provided in Section 3.1 were coded using the FBS ontology and then mapped to problem ($\mathscr{P}$) and solution ($\mathcal{S}$) spaces. Each pair of adjacent lines forms a transition unit. For example, the transition from lines 15 to 16 in Table 1 describes a tutor-to-student interaction and a movement from the problem space to the solution space.

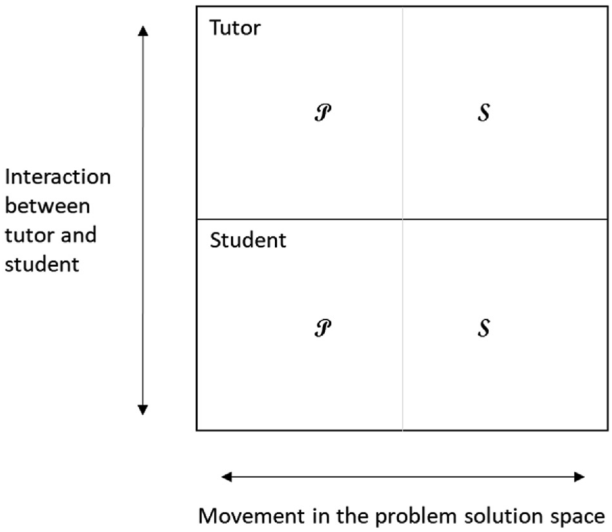


Figure 4 Reflective conversation in the design studio as transitions *in a two-dimensional space defined by problem space,* $\mathscr{P}$, and solution space, $\mathcal{S}$, for both tutor and student

Exploring tutor-student interactions

4 Results

4.1 Topics of discussion across participants and time

The goal of the topic analysis was to identify the main topics of discussion in the design critiques and investigate how these differed between participants and over time. In total, across the 13 sessions, 4125 non-unique instances of words categorized under one of the 7 topics were uttered − 57% by the students and 43% by tutors. Figures 5 and 6 provide a descriptive overview of the prevalence of the seven discussion topics as uttered by tutors and students, and over the course of the 13 learning sessions, respectively. When comparing students to tutors (Figure 5), we find that tutors have more frequent utterances of words in the topics of Abstraction-Theory and Communication, while students are more dominant in the topics of Manufacturing (at both high and low levels), and Abstraction-Applied.

Across time, some patterns are also observed with regards to the prevalence of topics in particular weeks (Figure 6). For instance, the topic of Abstraction-Theory is most dominant in week 15, perhaps due to the tutor providing instruction on constructing a function structure in that session. In contrast, the topic of Abstraction-Applied is most dominant in week 7, which is when students worked to formulate two specific needs. The topic of Communication is most frequent in week 11; in that session students shared their frustration about some recent miscommunication they had had with management. Words in the topic of Low-level Manufacturing are most frequently uttered in week 6, when students explained the problem of disorganization of bags received from

Table 1 Example of verbalizations coded as design issues and allocated to problem or solution spaces

	Source	*Verbalization*	*Design issue*	$\mathcal{P}/\mathcal{S}$ space
1	S	No, we discovered … a break-	Bs	$\mathcal{S}$
2	S	yeah when we tested it	Bs	$\mathcal{S}$
3	S	actually, it won't work.	Bs	$\mathcal{S}$
4	T	Was that surprising?	Bs	$\mathcal{S}$
5	S	I mean, I guess we should have checked but … it was something that … is so secure.	Bs	$\mathcal{S}$
6	S	The rail	S	$\mathcal{S}$
7	S	that we're riding on …	Bs	$\mathcal{S}$
8	S	We expected like minor inconsistencies,	Be	$\mathcal{P}$
9	S	but they have variances	Bs	$\mathcal{S}$
10	S	up to three millimeters	S	$\mathcal{S}$
11	S	on it, in thickness.	Bs	$\mathcal{S}$
12	S	So sometimes it's 6−7 mm	S	$\mathcal{S}$
13	S	and sometimes it's just over 3.	S	$\mathcal{S}$
14	T	How do the current carts	S	$\mathcal{S}$
15	T	adapt for that variability?	Be	$\mathcal{P}$
16	S	They ride all entirely	Bs	$\mathcal{S}$
17	S	on the wheels.	S	$\mathcal{S}$

Associated Business Units (ABUs), and in week 14, which is when students explained some issues with getting their prototype to work as intended.

To explore the relationship between the three factors under investigation — participants, time, and topics — and to uncover categorical patterns, a correspondence analysis was plotted in a two-dimensional graph (Figure 7). The results cover 70.3% of the variance across the two dimensions. When interpreting a correspondence analysis graph we note the placement of the points in relation to the origin, the two dimensions, and to each other. To facilitate this analysis, k-means clustering was used in two ways — with clusters created around the seven topics (Figure 7a) and by enforcing a number of clusters (three, as in Figure 7b). With few exceptions, the tutors and students sit on different sides of dimension 1, implying a categorical difference between them. Further, we note that the various clusters are either homogeneous (tutor or student only), or at least dominated by one or the other.

In most weeks, students are on the left half of the graph, where the topics of Money, Manufacturing (both Low-level and High-level), Abstraction-Applied, and Organization are also located. An analysis of clusters shows that the clusters around these topics contain mostly the utterances originated with the students, indicating that they closely related to student participants. There are two exceptions to this. First, we note tutor utterances in weeks 6 and 14 clustered with the Low-level Manufacturing topic (in both graphs). As mentioned above, in these weeks students discussed issues about the disorganization of bags and when testing their design prototype. We also note that tutor utterances in weeks 8 are 12 are clustered with the topics of Abstraction-Applied and Organization. In these two weeks, students discussed available opportunities in the production line and explained how production freezes worked (week 8) and later demonstrated a new proposed cart prototype for the production line (week 12).

In contrast, in most weeks, tutors are found on the opposite side of dimension 1 (right half of the graph), where the topics of Abstraction-Theory and Communication are also located. Nine of the 13 tutor points on the graph are clustered around those two topics. These two clusters are near-

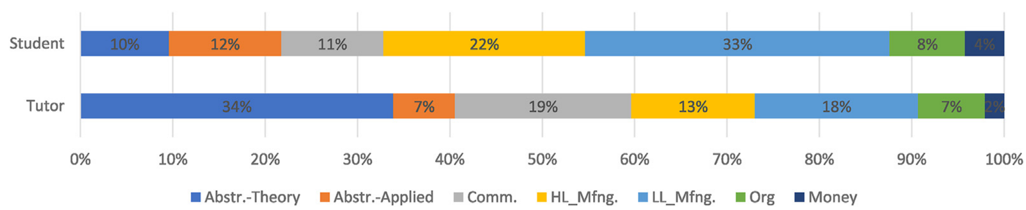


Figure 5 Distribution of topics for tutors and students

Exploring tutor-student interactions

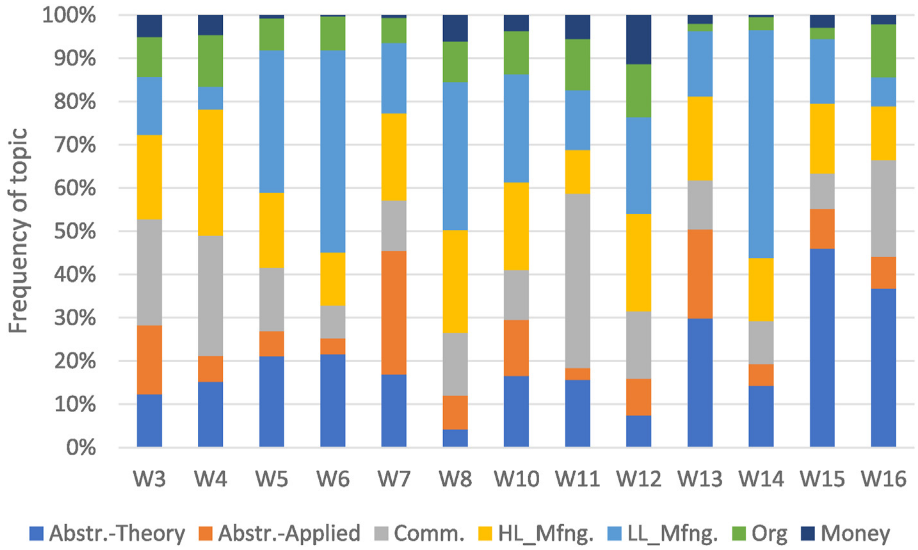
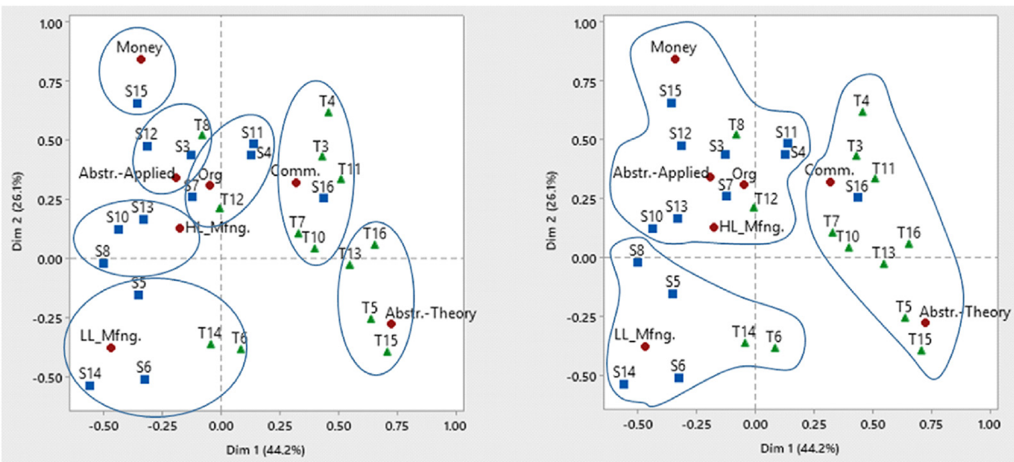


Figure 6 Frequency of topics by week



(a) (b)

Figure 7 Correspondence analysis plot of discussion topics (red circles) and utterances made by students (blue squares) and tutors (green triangles) in each of the 13 weekly sessions. K-means clustering: (a) around topics and (b) through specified 3 clusters. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

homogeneous in their membership, with the only student utterance near these topics being in week 16, which is when the lead tutor guided the students in an intentional reflection on the problem using Schön's theory (Schön, 1983).

Given the "divide" between tutors and student revealed above, we pay special attention to any instances in which tutor and student utterances in their respective weeks are located in the same quadrant of the correspondence analysis graph. There are only four such instances: weeks 4, 11, 14, and 16. We have previously discussed the instances of weeks 14 and 16. In the other two instances (weeks 4 and 11) students and tutors are located in the same quadrant as the topic of Communication (top-right). In week 4, discussion centered around finding opportunities for improvement in the plant and the students' experience of organizational culture. In week 11, the main topic of discussion was the students' miscommunication with company management. Interestingly, the discussion in both weeks 11 and 14 is dominated by an unexpected and frustrating occurrence (miscommunication with management and poor performance of the prototype, respectively).

Finally, we observe the relative location of the various topics. First, the topics of Abstraction-Theory and Abstraction-Applied are located away from the origin and on opposite sides of both dimensions, pointing to a strong categorical difference between the two. This is surprising; we would expect the two topics to be strongly related to each other. Second, the topics of Money, Low-level Manufacturing, and Communication sit furthest from the origin, and each in separate quadrants, indicating differences in their occurrence by author and across time.

Overall the topic analysis suggests two interesting patterns. First, tutors and students differ significantly in what they talk about. While tutors are doing more of the design "teaching" – tutoring the students in formalizing and communicating their design problem and activity, students are more likely to discuss concrete details related to their design (within the specific manufacturing setting). In other words, the students – who are situated in the "real world" context of their cooperative placement – seem to be far more concerned with practical matters about their design, while the tutors' dominant activity is connected to design teaching and communication. Second, tutors and students are more likely to "converge" into similar topics of discussion whenever challenging or unexpected events occur, which force a change from the regular pattern of interaction.

4.2 Interaction analysis

The goal of the FBS analysis, as used here, was to uncover participants' interactions as they moved between the problem and solution spaces. Students generated a majority of the FBS design issues (2469 in total), of which 2102 (85%) were in the solution space and 367 (15%) in the problem space. Tutors generated a total of 731 issues – 559 (76%) in the solution space and 172 (24%) in the problem space. All pairs of adjacent issues formed transition units; 3131 such instances were identified in total. Figure 8 presents the distribution of all transitions, according to problems-solution movements and tutor-student interaction types. The following are observed:

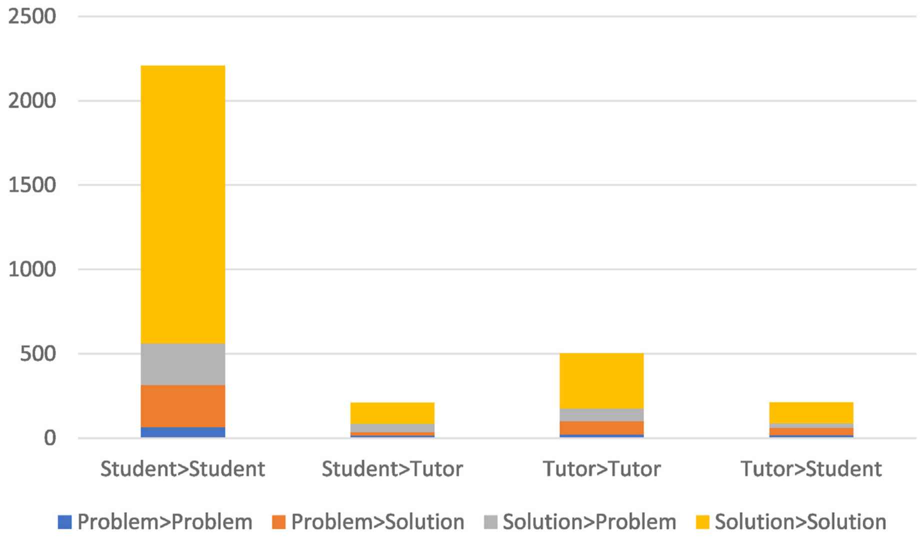


Figure 8 Number of problems-solution space movements for each of the four types of interactions

- First, most of the **interactions** are between students (70.5%) or tutors (16%) alone, with only just over 13% being between tutors *and* students.
- Second, most of the **movements** (71%) begin and end in the solution space. The remainder (25.3%) are between the problem and solution space, in both directions. Only 3.7% of movements are within the problem space.
- Finally, more than half of all **transitions** take the form of student-student interactions within the solution space. Other notable transition types are students' bi-directional movements between the problem and solution spaces (15.8% of total) and tutors' movements within the solution space (10.4% of total). All other transitions occur with frequency 4% or less.

Evidently, the most frequently occurring transitions are those that are within students and (less so) within tutors. It is important to note that student-student and tutor-tutor interactions can frequently occur within the same "turn" — that is, a long verbalization by a participant is typically broken down into multiple FBS design issues and respective $\mathcal{P}/S$ codes, resulting in a number of transitions that are endogenous to that participant. All transitions that include a tutor-student interaction, however, imply turn-taking between these two types of participants. To better analyze the latter type, which are of most interest in this analysis, we extract transitions comprising tutor-student interactions alone and re-normalize their distributions accordingly. Next, following from the model described earlier in Figure 4, transitions are visualized as arrows in the two-dimensional space of problem-solution movements (horizontal direction) and tutor-student interactions (vertical direction). In each week, the distribution of each of the 8 types of transitions is calculated and the resulting frequencies grouped into five categories, visualized by colour: from transitions occurring with frequency lower than 15% (in green) to those occurring with frequency higher than 45% (in red), as presented in Figure 9.

The week-by-week comparison reveals a number of patterns. With the exception of weeks 5 and 12, tutor student interactions occur predominantly in the solution space. In week 8, this accounts for 76% of all transitions. In that week, most of the learning session was spent with students describing how the production line and production planning works.

When the interactions include the problem space, the most common pattern of this movement is (bidirectionally) between the problem space of the tutor and the solution space of the student. In particular, we observe that this transition becomes dominant in week 12, when students spent time describing their designed prototype, explaining how it worked and the extent to which it met requirements.

In contrast, the "reverse" transition, involving bi-directional movements between the solution space of the tutor and the problem space of the student occurs infrequently, never crossing the 15% threshold in any of the weeks.

Finally, we also observe that tutor-student interactions within the problem space are infrequent (less than 15% of all interactions in each week), except for week 5, where we they constitute 24% of all interactions. That week, students discussed two potential design problems and the tutor provided instruction on expressing the real need.

Taken all together, the above indicate that while certain transitions – especially those centered on the students and the solution space – dominate across the term, during important design milestones such as when the problem is formulated, and the designed prototype presented and verified, transitions that involve the problem space and the tutors increase in frequency.

5 *Discussion*

The literature on design education points at two important, but seemingly contradictory ways in which effective design teaching and learning can occur. In academic settings, the design studio has proven to be an effective design pedagogy (Lawson & Dorst, 2009; Schön, 1985), a learning-by-doing space where students work on design projects under the guidance of experienced tutors, typically within the confines of physical spaces, but increasingly also virtually through virtual learning environments (Jones, Lotz, & Holden, 2020; Lloyd, 2012). On the other hand, critical design learning occurs in authentic professional (practice) contexts. For students, such opportunities may be available during co-operative terms (internships) in industry (McRae & Johnston, 2016; Trede, 2012);

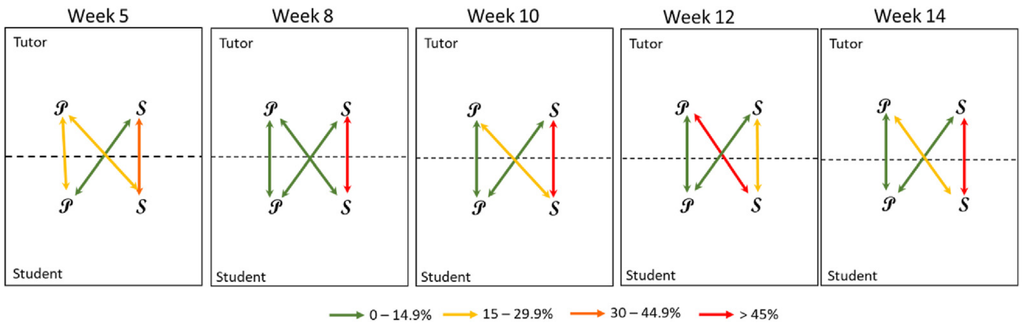


Figure 9 Transitions visualized according to frequency of occurrence — normalized to consider tutor-student interactions only

however, these contexts may lack reliable and qualified design tutors. The case study under investigation here describes a "best of both worlds" scenario, an innovation in design pedagogy that sits between a traditional studio modality set in a campus context and a fully-situated clinical internship set in real world professional practice. Specifically, while the students are situated in an authentic practice context in industry as part of a co-op term, they participate in a weekly virtual design studio, under the guidance of an academic tutor located in their home institution (in an academic setting) (Nespoli, Hurst, & Russell, 2018).

5.1 Characteristics of tutor-student interactions

The purpose of this study was to understand how the teaching and learning of design might occur in this novel pedagogy. Specifically, we sought to characterize tutor-student interactions and observe how they might change throughout the duration of the co-op term. These aims were articulated as research questions, the answers to which are summarized below.

1. *How can tutor-student interactions in a novel virtual design studio be characterized and measured?*

We have applied analyses that aimed to more deeply characterize and comprehend cognitive interactions in the virtual design studio between tutors located on campus and students located in professional practice. The study demonstrates the effective use of protocol analysis on tutors and students' verbalizations during weekly design critiques. We took two methodological approaches to analyze the data. In the first approach, we performed topic analysis through natural language processing. In the second approach, we saw participants' reflective conversations with the situation (Schön, 1985, 1987) as a co-evolution between the design problem and solution spaces (Dorst & Cross, 2001; Maher & Poon, 1996). Using the FBS ontology (Gero & Kannengiesser, 2014; Milovanovic & Gero, 2018, 2020) we modelled this co-evolution as transitions combining: 1) movements between design issues related to the problem space and those related to the solution space, and 2) interactions between tutors and students. We note that this methodology is not restricted to this novel virtual design studio pedagogy and it can be generalized to all pedagogies represented in the framework in Figure 1.

When looking at movements in the problem-solution space and their relationship to tutor-student interactions, we note that a majority are conducted by students alone, with just over 13% of interactions being between tutors and students. There are several reasons for this finding. First, the tutors' approach to teaching was to ask students to reflect during the design critique sessions, and in so doing most of the verbalizations come from the students' reflections or experiences from the week. Second, low interactions between participants, including between tutors and students, are expected (as observed for example by Milovanovic and Gero (2018). We speculate that interactions are further reduced in this case due to the virtual and remote nature of the interaction, which was also often affected by an unreliable video connection. Prior studies have found that communication via video-conference reduces the back-and-forth (or turn-taking) between participants and increases the length of each turn when compared with face-to-face interaction (van der Kleij, Maarten Schraagen, Werkhoven, & De Dreu, 2009). Enhanced virtual communication (e.g., 3D virtual world) can reduce some of these effects, by facilitating for example communication via avatar-enabled non-verbal cues (Anderson, Dossick, Iorio, & Taylor, 2017). The altered nature of communication between tutors and students in the virtual design studio may have important ramifications for the nature and quality of tutoring.

2. *How do tutor-student interactions in a novel virtual design studio change with time?*

Both study approaches pointed at similar patterns of cognitive behaviour and interactions. As expected, the distribution of the main topics of discussion reflects to some extent the progress of the project, with some topics becoming more prevalent in certain weeks. What is surprising, however, is that *differences* in the topics discussed by tutors and students — as revealed by both descriptive and correspondence analyses — change little with time. Tutors appear to focus much more on the theoretical abstraction of the design problem and its communication, as was intended by them, in order to take advantage of the novel studio pedagogy they established. In contrast, students are more preoccupied with practical considerations related to their project and the setting in which they are immersed, including manufacturing issues (at both system and sub-system levels), organizational and financial aspects, and the formulation of their design problem. When deviations from that patterns are observed, they are typically a result of significant and unexpected events, as is, for the example, the unexpected finding that the designed prototype had not functioned as intended in week 14. These events likely prompt tutors and students to engage more heavily with a common specific problem for a sustained portion of the meeting.

Similarly, the dominant transitions remain unchanged in each week, with most tutor-student interactions occurring in the solution space. This is particularly evident in week 8 where students revealed production line opportunities for improvement, notably expressed as solutions, as opposed to needs/problems. By contrast we note much less frequent movement in the problem space between tutors and students over time. The only deviations from this pattern follow some key or unexpected events in the term. One such example is in week 5, where students describe two problems they found, and tutors taught a lesson on needs discovery and identification. Here we find an increased frequency of tutor-student interactions in the problem space — a desirable result for the pedagogical intent. Where tutor-student interactions follow movements between the problem and solution spaces, the data reveals generally more frequent movements between the tutor's problem space and student's solution space, compared with tutor's solution space and student's problem space. Students' tendency to generate and develop solutions without sufficient attention to understanding the problem is well documented in the literature (Atman et al., 2007; Becker et al., 2018). Crismond and Adams (2012) prescribe a number of strategies that design instructors can employ to help students, including by generating functional descriptions of desired solutions and conducting effective problem framing and scoping. These approaches were intentionally part of the explicit design instruction and tutoring provided to students in the case study, confirming that the intent of the programming has been achieved.

5.2 Pedagogical implications and future work

The novel virtual design studio investigated in this case study demonstrates how the co-operative work term experience could be enhanced by the addition of an academic tutor, and at the same time how the traditional and virtual studios could be enhanced by immersing students in a real world context, in the *wild*. The latter affords students the opportunity to discover and engage with undefined and ill-defined problems (*messy, indeterminate situations*), as opposed to being given well-defined problems in an academic context (Crowther, 2013). This in turn affords tutors an opportunity to teach and facilitate the learning of problem discovery, analysis and formulation in these *messy, indeterminate situations*.

In our framework (Figure 1) we distinguish between academic tutors (A) and practitioner tutors (P). In this study, we explored the nature of interactions between the students and the academic tutor. Future studies could also investigate the nature of student interactions with a practitioner tutor (company mentor), so common with co-op students employed at companies. Recent research in asking whether academics and practitioners design differently has raised some important questions about the requirements for effective design tutoring (Hurst, Nespoli, Abdellahi, & Gero, 2019).

Our proposed framework also describes a third type of tutor (T), who embodies both academic and practitioner knowledge and skills. We envisage that the co-op dimension of cooperative programming could evolve into a 'teaching hospital' (Lawson & Dorst, 2009, p. 219). Here the tutors are the clinicians. There is an opportunity for the tutors, either academic or practitioner tutors, to further develop as clinicians toward the 'surgeon-like' tutor (T) where they practice not only teaching consistently in the wild, but practising consistently in the wild. We further envisage an opportunity for such clinical faculty to participate in person with students for all or part of their co-op terms, as an enhancement to the proposed teaching method. This could develop into recurring sabbaticals for clinical faculty teaching in cooperative programs, for example.

This was an "in-situ", exploratory study and we are thus cautious that these findings may not generalize to other, similar settings. Further, the interaction analysis did not measure the *quality* of the interaction or quality of the verbalizations from either the tutors or the students. Nevertheless, within this case study, we have learned some important things about how tutor-students interactions occurred in virtual design critiques and while students were in the design wild. More studies are thus needed to compare the difference in participant interactions between co-located and virtual design studio contexts, which has broader implications for design pedagogy at a distance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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