BUILDING-DESIGN DECISION MAKING IN THE CONTEXT OF INTEGRATED DESIGN STUDIO: THE ROLE OF THE ENGINEER

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Abstract *— According to scientific literature and practical experience, interdisciplinary design teams are an often privileged solution for optimizing building design and for meeting sustainability criteria. Nevertheless, some previous studies suggest that engineering students are not prepared to play an active role in a design process, especially in its conceptual stage. Another aspect contributing to the fragmentation of the building design process is the digital environment and its inappropriateness for interdisciplinary collaboration. This paper proposes multidisciplinary team learning in the context of integrated design studio as a successful approach for both: achieving sustainable design solutions, and changing disciplinary cultures into integrated practices. The participation of building engineers in the design process is studied from two perspectives: ideation (design ideas generated or significantly modified by them) and empowerment (role of digital representation in this process).*

Index Terms —Building, Integrated design, Social learning

INTRODUCTION

Integrated design and data integration in product models have been widely recognized in research and in the construction industry as solutions to the challenge of fragmentation. For the past century, the design process (its work organization, planning and building design) has barely evolved; in addition, the division of tasks between design specialists in the professional practice has been transmitted in education and to the academic sphere.

Clients' demand entail design professionals to deliver a virtual model of the project instead of separate sets of drawings, and to work jointly in integrated design teams; thus creating an enormous pressure on education to rethink how design is taught to architects and engineers. Nonetheless, significant resistance to changes slow down the transformation of existing teaching practices and delay the opportunities to prepare students to work in integrated design environments. Architectural and engineering education follows the university structure and its faculty organisation and is therefore compartmented. Consequence of the current design education system include the fact that students acquire design competences that may be obsolete in their future practice and that they are not prepared to work within an integrated digital environment.

This paper presents the preliminary results of an teaching experiment in professional practices based on theories of social learning. The principle is to immerse students from various disciplines in engineering and architecture into an integrated learning environment (a design laboratory), in which they are asked to develop a holistic approach. This research specifically analyses how engineers adapt to an unfamiliar design studio environment, and how the environment impacts their ability to actively participate in the design process. The paper contributes to engineering education theory and presents an original perspective to teaching design and technologies. It also provides theoretical and empirical foundations to integrated practices.

ISSUES IN TEACHING INTEGRATED DESIGN

Integrated design has been recognized as the most effective way of meeting client requirements whilst generating a minimum of waste [1-3]. Innovating technology, including simulation tools, is core to the integrated design process (IDP). IDP is described as: *"…a collaborative process that focuses on the design, construction, operation and occupancy of a building over its complete life-cycle… The IDP requires a multi-disciplinary design team that includes or acquires the skills required to address all design issues flowing from the objectives."* [4]

The two main problems that should be addressed when exploring IDP with students in architecture and engineering are the development of fragmented mental models and cognitive inertia. Recent research findings on team performance highlight that, to be effective, members of an integrated team should develop a shared mental model [5, 6]. Shared mental models are socially constructed cognitive structures that represent shared knowledge or beliefs about an environment and its expected behaviour. They influence team member behaviour and improve coordination by enabling members to anticipate one another's actions and needs. Druskat [12] identifies three core components for developing shared mental model: (1) psychological ownership over team processes and outcomes, (2) a need for continuous learning, and (3) a need for heedful interrelating.

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Cognitive inertia is another phenomenon associated with two typical behaviours amongst experts of different disciplines. The first is "groupthink," a mode of thinking that people engage in when they are deeply involved in a cohesive in-group. "Groupthink" typically leads to an overestimation of the in-group, closed-mindedness, and stereotypes of out-groups. The second behavior, paradoxically, is "compartmentalization," a fragmentation of viewpoints and a lack of shared mental models. Such fragmentation may make it impossible for experts from different contexts to "speak the same language" and exchange ideas about a problem [7]. This problem is related to the barrier created by specialized knowledge and the division of work between disciplines in the traditional design process. Specialized knowledge actually hinders problem-solving and knowledge creation across functions [8].

TEACHING PARADIGMS

The core principle in integrated design is to shift the design effort upstream and to concentrate efforts in the phase known as project definition. In a linear design process, the architect is responsible for this phase where most of the decisions regarding the building design are made. The engineers are rarely involved during this phase and if so, they play an advisory role.

The conceptual phase is a complex process; "for it entails grappling with the articulation of a desired future state under high level of uncertainty" [9]. It is viewed by scholars as a process of solving a *wicked* problem. This is distinguished from a *tame* problem in both the challenges it poses and the identification of solutions. A *tame* problem is amenable to mathematical modelling. Problems are clearly defined and can be solved with a rigorously technical problem-solving approach based on scientific knowledge [10]. As the level of uncertainty decreases and the definition of the project become more precise, wicked problems evolve into tame problems: whereas defining the configuration and the shape of a building is a wicked problem, sizing a beam to support a given charge is tame. In the traditional division of work, architects are responsible for the wicked problems and engineers for the tame. Therefore engineers' inputs in the initial phases of design are challenging.

As opposed to architects who focus on finding holistic solutions to complex problems, in the design process, engineers are concerned about specifics on how things "perform" or "behave" within defined systems [11]. Thus, in the quest to develop a shared mental model with the other members of the team, engineers face the main challenges. Psychological ownership relies on the team's ability to agree on a shared set of rules and process for decision-making. The ownership is fragmented between architects' ideas and engineers' systems. The same could be said to the development of heedful interrelating. Architects are trained to solve wicked problems through the integration of the various perspectives expressed by clients, users and other professionals which is part of their training. Engineer training does not consider the acquisition of such skills for reflexive learning [10].

Therefore, mutual learning is the key aspect for engineers to capture complementary knowledge and skills. Team learning is defined as: "*Team members acquiring and sharing unique knowledge and information and examining what is helping and hurting team performance to continually improve as a unit*" [12]. This definition implies that team learning requires discussion on novel information and may include learning how to behave in multidisciplinary teams, learning new roles and skills, and altering old habits and behaviors. Team learning also requires growth in the team's capacity to manage itself as a unit, and to acquire, share and use knowledge to make effective decisions [12]. Cognitive inertia and barriers created by specialized knowledge or the traditional division of work may hinder engineers' ability to acquire the skills and position of power required to participate in the decision-making during the process.

A core difference between education in architecture and engineering is the teaching paradigm. Engineering education is deeply grounded in the positivist/cognitivist model. According to these theories, learning is an individual process of acquiring knowledge. Acquisition of knowledge is done within specific domains. Pedagogic practices are therefore based on a transfer of skills from one domain to the other [13]. Architecture education is closer to social learning theories (situated action and activity theory) which consider learning as a social phenomenon. Knowledge is created through interactions between the individual and the collective (situated learning) and between individuals, tools, and the collective. This raises the question on how education in engineering could evolve to address such differences.

PREPARING ENGINEERS FOR IDP

The reconfiguration of engineering practices cannot be achieved through incremental improvements. Replacement, restructuring, or demolition of the knowledge base has to occur [8]. The proposed approach immerses engineers into a situated learning context in the framework of an integrated design studio. Rare research on how to set the appropriate context to facilitate mutual learning increased the challenge. Several authors suggest that boundary objects could play a key role in generating and mediating learning in a context of an activity involving representatives from different practices [8, 14, 7]. Boundary objects are shared across different problem-solving contexts and facilitate the establishment of a shared context. " For example, sketches and drawings are a type of boundary object used by architects to communicate with the users or the other specialists. Design professionals are surrounded by these objects: tools for designing, validating and sharing [15]. Scientific literature also describes boundary objects as tools and technology that help different practices to build a common representation of a problem and its solution. They are not only perceived as

means to represent and share knowledge (mutual learning) but also as ways to stimulate the coproduction of new knowledge.

Rules and methods related to design practices are embedded in these objects. Engeström [9] suggests introducing complex configurational technologies, such as Building Information Modeling (BIM) to stimulate the generation of new knowledge. Selecting BIM technologies is appropriate, as major clients have started to require the use of such technologies to design their new facilities. The strategy adopted in the current integrated design studio is therefore to create an unfamiliar context for both architects and engineers that will challenge their acquired knowledge with BIM technologies.

Carlile [2002] identifies three levels of crossing boundaries between practices: (1) a *syntactical approach* is based on the existence of a shared and sufficient syntax at a given boundary, (2) a *semantic approach* provides a concrete means for individuals to specify and learn about their differences and dependencies across a given boundary by recognizing that differences exist or emerge over time, so individuals have different interpretations of a word or an event, and (3) a *pragmatic level* defined as the political category is the most challenging one. It involves a shift of power and influences the design process of architects and engineers, requiring the latter to think or act like architects and take an active role in the decision-making regarding not only technical or design options but also in responding creatively and positively when architects challenge their technical solutions.

CONTEXT AND METHODOLOGY

This study addresses two research questions: (1) how integrated design studio affects the place of the engineers in the decision-making process - in terms of ideas generation and team organization and (2) how technological environments influence their role in an integrated team?

A qualitative study was held in the context of a multidisciplinary design studio joining students in architecture (from McGill University) and in civil engineering (from the ETS-Montreal). They worked on a real project: a student facility building "The Home of the Students from ETS" (*La maison des étudiants de l'ETS*) and with special requirements for a sustainable building. In addition to the administrative, health and leisure services, the program includes a soccer field, a hockey arena, a swimming pool and an underground parking. Such a program requires a complex building with a variety of structural, systems-organization and spatial challenges.

Five teams of 7 to 8 students (which is the limit for a self-managed team) were composed as follows: 2 or 3 architects, 2 or 3 engineers in building mechanical systems, 1 or 2 cost estimation engineers and 1 structural engineer. The workload was proportional to their number. Students enrolled in this course expressed a clear motivation before the beginning of the studio and their engagement in the project was manifest. Architecture students were master's level students, in their first year, and engineering students were predominantly in their 3rd year of undergraduate.

Specific technological environment was provided for the collaborative experience in integrated design. Each team had an independent work-space, equipped with a PC, a projector, a printer, a discussion board (either a vertically standing interactive (smart) board, an interactive tablet, or an ordinary white board) and Internet and local network access, Students brought their own computers (mainly laptops). Software tolls offered to the students were: AutoCAD 2010, Revit Architecture 2010, SketchUp, Ecotect Analysis, Design Builder and D-Profiler (for design modeling and simulation), as well as TeamSpot (for co-situated collaboration).

The teams worked over three two days iterations (*charrettes*), separated by two-week intervals. Information sessions and software capsules were offered in-between the *charrettes*. For the verification process at the end of each step, the teams had to present their work and to demonstrate the value of their strategy in regard to sustainability, financial and technical feasibility and its compliance to the program. Feedback was provided by professors in the related disciplines. Experts from the industry and representatives from the administration and student association of the ETS were invited to the presentations too, thus assuring the participation of the client and the end-user.

The results were quite impressive considering the fact that most of the students were unfamiliar with the suggested software and technologies, and had never collaborated with other disciplines.

Methodologically, data was collected through semi-directed interviews and video recordings of all design sessions. Then, inspired by grounded theory and case study, the data was coded and qualitatively analyzed. The participation of four researchers in the interpretation process enabled a triangulation of the results

EMERGENCE AND EVOLUTION OF IDEAS

As expected, the observations indicated that the organization of the design process was mainly lead by the students in architecture, especially at the beginning of the *charrettes*. Many of the engineering students were discovering the creative architectural process for the first time. They were firstly surprised by how long it takes to come up with the main design idea (concept) of a project ("*it took us one day before being able to begin, before knowing which direction we take*" t.5); by the importance of attaining such an idea (concept, *parti*) ("*from this moment on, we could work…*"), as well as by the satisfaction that all team members experience when such a moment occurs ("*yes, we have it, we have it!*"). The fever of the creativity, though, caught up very quickly with the students in civil engineering and they

started participating in the design process by proposing ideas, some of which became central for the projects (hockey ring covered with synthetic ice; building with double envelope; deploy an ecosystem of plants which oxygenizes the air, etc.). They found this a rewarding and valorizing experience. In informal discussions, some students stated that this joint experience has profoundly changed their understanding of the design process.

The clash of professional "cultures" provided grounds for an interesting evolution of ideas: in team No3, a first concrete idea referring to the mechanical system was transformed by misunderstandings and analogies, to give birth to the main idea of their project "ecosystem". This process can be characterized as an intermittent divergence in the mental representation of an idea in the different team members, which is a prerequisite for creativity.

Overall, the progress of design ideas during the three intensive *charrettes* was quite incremental. All the teams affirmed that an evolution rather than leaps of ideas had occurred. This was explained by the limited timeframe and the extent of the project, but can be attributed to the responsibility before the other team members, which may have prevented the architects from changing any major idea once the development process has begun. This point could be reconsidered for future integrated design experiences, as it is not consistent with the initial idea that each following iteration would bring new creative ideas. A positive factor contributing to an incremental evolution is the rapid correction of any divergence from a "realistic" building by the students in engineering. This increases the efficiency of the design process as a whole.

ORGANIZATION OF THE TEAM WORK

Naturally, all *charrettes* began with a brainstorming session of various lengths (up to 3 hours). All students stated that they spoke freely and directly expressed their opinions. This was very important to determine a common direction. Brainstorming and discussions occurred later, during the design sessions too. Most of them included all team members, except when more specific problems had to be dealt with. An unexpected consequence of the integrated team design process was that the architects were obliged to decide on the development of the ideas quicker and that, as already mentioned, they felt somewhat obliged to stick to the initial idea.

Between the brainstorming sessions, the teams splitted into smaller groups or individually in order to work on different aspects or sub-problems of the design task. After that, they were gathering again in order to discuss the evolution of the project and to plan the steps to follow. The usual pattern was to split into mini-groups composed of students comming from the same discipline: architects, or enginners in building mechanics, etc. A different pattern was observed in only one of the groups (#3) where during the second *charrette*, mini miltidisciplinary teams were formed. They were working one after the other on three different aspects of the project (following a method of "cadavre exquis"). This organization of work proved to be very effective (team No3 has the highest evaluations).

Feedback from jury and instructors was essential for the evolution of the projects. Input from specialists in sustainable construction was highly appreciated. All of the teams have communicated by e-mail between the charrettes, with various intensity. Sometimes, 2-3 members, and often from the same discipline, exchanged mails on different questions. Prior to the last *charrette*, the exchanges gained in intensity. Team #3 held a physical meeting of all members.

In general it is possible to conclude that the organization of the team-work was appropriate for integrated design, as stated by a student in engineering : "*Normally, engineers receive the plans... you make the structure calmly, no frictions, but you have no interactions...; (Here) it's much time of preparation and conception, but there is much less addenda and changes during the construction*" (t.5).

ON SOFTWARE AND BIM

Technology for facilitating team communication was used all through the process by one team (the one which was situated in the collaboratory); two other teams used it partially, and the remaining 2 only tried it at the beginning. The reason for this rather limited use lays mainly in the unstable behavior of the software (TeamSpot) when used together with the CAD and BIM tools requiring much computer resources. The high number of students (8) wanting simultaneously to "take control" of the projected screen causes some coordination problems too. All these issues, together with the fact that this technology and the manner of collaboration were entirely new to all the students, brought to the use of paper and pen, or white board and pencil for the communication of ideas, as well as for their annotation and for planning of tasks. Time limitation was a factor pushing into the same direction too.

BIM and simulation software programs were offered for use to the students with the idea that an integrated common model of the building in design will make the integrated design process more effective and will serve as a boundary object between disciplines. In practice, data flow between the software tools for the different disciplines proved to be quite difficult and fragile. Two factors contributed to this: (1) the tools are not well tested and robust themselves, interoperability is not well assured; and (2) the students were not at ease with the BIM and simulation tools. The information capsules given before the *charrettes* were not enough for the successful learning of the technological tools. The tutors were relying that students will practice the software programs before the charrettes, but this did not take place. Time pressure was also a factor against the use of new tools: "*In 6 days, we had to learn everything from 0 to all: work in a team, the project, the software*" (t.1).

Most of the teams succeeded to produce a main model and to export it to simulation software. All teams created several variations of simulation evaluations for energy consumption, structure type and building cost. Despite the difficulties, they learned a lot and acquired a basis for future integrated design experiences. BIM and specialized simulation software, though, proved to be too discipline specific and not contributing enough to the integration of the team, but only to the integration of the digital model of the future building.

DISCUSSION AND CONCLUSION

In order to answer the research questions asked at the beginning of this study, we can affirm that the integrated design studio promoted and reinforced the place of the engineers in the decision-making process. They started by replicating patterns of behaviors observed in sequential design waiting for architects to find design solutions, but this changed quickly and considerably with the evolution of the integrated design experience. Their role in the team became more versatile and participative in terms of ideas generation, organization of the team and ownership of the project.

As far as the second research question is concerned, paper-and-pencil sketches proved to be the best boundary object, because of its ease of access and use, thus tending to reinforce architect's position of power in the team. BIM software sometimes had a reverse effect, making students focus on developing model within each discipline for specific purpose. But sometimes, boundaries were crossed and roles switched - very often at syntactic and semantic levels and more rarely at a pragmatic level (after [10]). Exchanging data between software required associating and sharing the related concepts and vocabulary which stimulated learning. Simulation software, despite many limitations, proved to have a positive effect on the overall project results and on learning sustainable building strategies.

Roles and behaviours evolved with each *charrette*. Feedback from each iteration exposed inefficiencies in the team process and weaknesses in integrating the outputs from various disciplines. It encouraged developing a common language to understand the comments covering architectural and engineering components of the project and to address them. We were expecting that iterations were going to stimulate the creative process, and incite the teams to generate new core concepts instead of sticking to their original ones, but the evolution of the ideas was quite linear instead. Some teams succeeded to develop shared mental model as early as the second iteration.

The joint studio proved the applicability of social learning theories to accelerate the learning of reflective knowledge required in the new context of integrated practices an information environment. It was evaluated as very positive and educative by the students. Architects got used to adjust quickly to constraints, learned the engineering vocabulary and integrated the reasoning. At the same time, engineers learned the power of creative design thinking resolve wicked problems and the role of visual representation to communicate ideas. According to an engineering student: "*It's interesting to bring this concept to the practice, it will be much more efficient, we will understand each other much better.* » (t.4)

The paper presents early results from the integrated studio. Detailed analysis of the interviews, working files and videos are necessary to consolidate our understanding of learning patterns within the design laboratory and the impact of tools and technologies as boundary objects to break barriers created by fragmented mental models, and accelerate learning or generation of new knowledge for integrating design practices.

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