A new representational ecosystem for design teaching in the studio

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Simulation tools available in a design studio can be named Representational Ecosystem. It exists a variety, balance, exchange and interoperability amongst the elements of this ecosystem. Due to the monolithic approach introduced by generic 3D modelling software, which neither considers the multiplicity of representations nor facilitates abstraction, the current 'digital' paradigm fails to effectively support the co-design process in design teaching in the studio. This paper presents a case study that analyses the utilization of an immersive co-design environment called Interconnected Hybrid Ideation Space, amongst other kind of representations, during an undergraduate design studio. The epistemology and principles of this new representational paradigm for teaching the design studio are described: being bilaterally-hybrid, supporting multiple representations and scales, and fostering co-design.

Keywords: design education, collaborative design, virtual reality, design tools, representational ecosystem

The conventional workflow in the design teaching studios has been disrupted due to the widespread and premature introduction of computers and laptops as a substitute for the representational environment for design. This transition has been traumatic to the studio environment because the current digital paradigm largely ignores the gap between the traditional and digital tools of representation. We believe that there is a need to envision a new digital paradigm better integrated with the broader representational environment of the studio.

The design studio houses a variety of media acting as a *Graphical Simulation System* through which design intentions are exteriorized (Lebahar, 1983) for learning purposes. Visual media such as sketches, concept diagrams, plans, sections, elevations, perspectives, are accompanied by physical mock-ups and models, which are employed in simultaneous or progressive manner throughout the design process, while the project unfolds from initial exploratory concepts into finalized production drawings. In this paper we refer to the entirety of these different representational media as the *Representational Ecosystem*, because of their plurality and inter-supportive nature. This

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ecosystem, allowing multiple forms of externalization, discussion, and evaluation of the design ideas, is the epistemological context within which the participants of the co-design process (students, professors, clients, and collaborators) reflexively engage in the design development, teaching and learning (Schön, 1992).

The collective nature of the design studio supported by intuitive forms of visual and verbal conversation has been hindered by the introduction of the personal computer and more recently with the widespread utilization of laptops. Digital design and representation software need, in most cases, a high degree of specialization and this seems to encumber the co-design process and the knowledge transfer. This is because computers do not allow synchronization of reflexive design conversations with their related representations (externalization), or utilization of abstract, inaccurate and ambiguous representations during ideation discussions.

Another important factor to consider is the scale and the ways in which it is used in analog and digital forms of representation. Professional practice utilizes standard scales whether they be Metric (1:50, 1:200, etc.) or Imperial ($1/8'' = 1'-0''$, $1/4'' = 1'-0''$, etc.) because the scale of a drawing on paper is a crucial component for the communications during the development of the project. In addition, it is not only a geometric relation between the size of the drawn object and the real one, but also a grammatical convention that determines the type and amount of information that should be presented in a particular drawing. In digital media, scale becomes a concept that is purely geometric and not semantic: the representational language. Drawings are often created in 'full scale' (in terms of drawing units), however they are viewed in an arbitrary and fluid zoom factor on the screen or projector. The result is a total loss of reference and scale-awareness for the design student: One is left without a sense of a limit for how much detail needs to be depicted in a drawing, nor a robust comprehension of the actual physical size of the designed space or object in relation to its drawn image.

In disciplines such as architecture or interior design, representations only simulate the proportional relations of the design solution but do not deliver a first-person experience. Life-size models or imagery are not commonly encountered. While scaled representations are important tools for design, being able to achieve a full-scale, immersive understanding of the design object could greatly facilitate the creative process and help to make better collaborative design decisions. The lack of full-scale representations is an obvious deficiency for these disciplines, however this is equally true for those dealing with smaller or larger scales, such as industrial design and urban planning.

In this paper, we describe the integration of a full-scale, hybrid and immersive ideation environment named Interconnected Hybrid Ideation Space – HIS (Dorta, Kalay, Lesage, & Perez, 2011a) into the representational ecosystem for teaching during a semester-long 3rd year industrial co-design studio. Using this studio as a demonstrative case study, we envision a new paradigm that augments the existing environment with the benefits of a hybrid approach driven by the HIS (Since then superseded by the Hybrid Virtual Environment 3D – Hyve-3D) (Dorta, Kinayoglu, & Hoffmann, 2016), throughout the design process in design education, namely: immersive life-size visualization, freehand sketching, and local and remote collaboration. We argue that the main goal of a well-functioning representational ecosystem for teaching should be to achieve a comprehensive and closer view of the design solution. We describe the principles of such a representational ecosystem based on our observations on the case study where we used the interconnected HIS alongside a variety of representations belonging to the traditional learning design studio all the way from early phases of design to the final presentations. In an early study (Dorta & Kinayoglu, 2014), this new representational ecosystem was presented mostly focussing on its representations and principles, while in this paper its pedagogical contribution to the design studio is further analysed.

1 A comprehensive view: the epistemological dimension

Widely accepted theoretical models suggest that design is a reflexive (Schön, 1992) and social process (Bucciarelli, 1988) in which multiple participants engage in a collaborative conversation with each other and with the representation (Schön, 1992). Designers reflexively converse with the problem at hand creating and interpreting different types of visual and physical representations, and through this process emerging ideas are externalized. Complementing Schön's explanation of design as a graphical and verbal conversation, Lebahar (1983) theorized towards the necessity of a *Graphical Simulation System* (S) in the design process (Figure 1). The main goal of this system is to provide a testing ground on which ideas evolve and the design process moves forward. According to Lebahar's explanation, the design process sequentially progresses (t) towards the completion of an object model (O), which gets completed by the architect or designer (A) as the amount of uncertainty in the problem (shaded zones in P) decreases. This process alternates between synchronic states (t0…n) and diachronic leaps (the move from O to S′).

A good demonstration of this is the way designers and architects utilize sketches. In search of a design solution, the designer may redraw a sketch several times, sometimes tracing over existing lines in order to fine-tune a gesture or using multiple layers of tracing paper to create new sketches, each time making gradual changes in the drawing. It has also been shown that

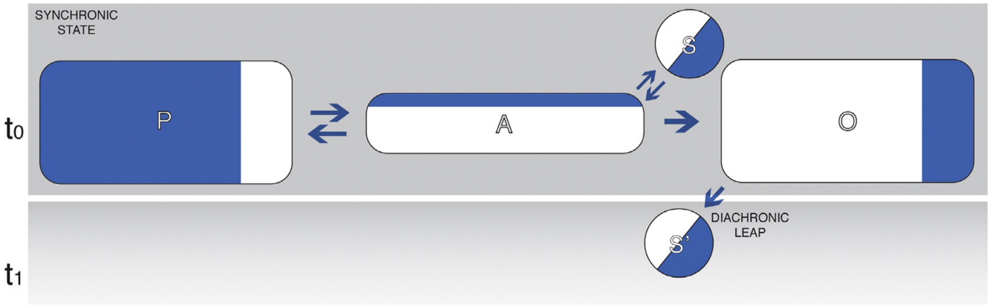


Figure 1 Lebahar's design process based on the Graphical Simulation System

the search towards a design solution through the use of graphical media necessitates the use of *re-representations* and multiple *representations* (Oxman, 1997). Designers routinely move back and forth between different views and scales of the same design object, switching between modes of representation as required by newer questions that emerge as the design solution evolves. For example, an architect may switch between a physical model and sketch-perspectives to see how the 3D composition of a building will be perceived from different views. A designer can do a quick ergonomic evaluation by testing out various alternatives of a door handle, producing a mock-up model or a rapid-prototype, while refining the profile of the same handle in a sectional sketch. No single representational model can assess the design problem in a comprehensive manner.

The need for an array of representational modalities in design can be further justified since each representational medium is associated with intrinsic knowledge structures (Oxman, 1997) and with characteristic affordances (Gero & Kannengiesser, 2012; Kalay, 2004; Kvan, 2009). Designers use different modes of representation to selectively navigate their attention from one design issue to another and apply design skills that are specifically associated with the chosen mode.

In Lebahar's *synchronic state*, the design activity takes place in a specific representational medium and aims to externalize the design task within the knowledge system and affordances of the simulation model in use. For example, at one state, one may be considering the overall placement and orientation of a building, by sketching over a 1:1000 site plan; at another moment s/he may be experimenting the visual effect of different massing options on a physical model. In the closer view, the design activity takes place in any single representational medium that is most appropriate to the design question at hand. In the bigger picture, the designer shifts back and forth between these mediums and scales and, as the design solution gets completed, the simulation model that should communicate the design ideas becomes less abstract and more rigid. This happens during the *diachronic* *leap* of design. Therefore, the shift back and forth between these mediums has to be adapted to the particular stage of the design process or learning process, since it is inadequate to initiate the ideation process with a representational medium where realism and accuracy are high and ambiguity is low.

2 A closer view: immersion and embodiment

Two of the most important premises of contemporary computational representations are visual realism and immersion. The former has found its place in the studio in the form of 3D renders and animations, albeit restricted to final phases of design development. The latter, namely the potential impact of immersion in design, has also been explored mainly in experimental settings which are collectively studied under the title of Virtual Design Studio (VDS) (Maher & Simoff, 2004; Schnabel, 2011; Schnabel, Kvan, Ernst, & Dirk, 2001). These include experimentations to teach design within collaborative Virtual Environments (VE) such as Active-Worlds™ and SecondLife™, and adaptations of multi-user game engines such as Torque Game Engine™ and Unity3D™. Even though the VEs in question are not intended primarily for design purposes, it has been shown that they could facilitate local and long-distance collaboration, in comparison to non-virtual, and offline collaboration scenarios (Maher & Simoff, 2004).

Those ‘immersions’ in the design environment are achieved through the proxy of on-screen avatars that inhabit the VE in lieu of designers themselves. These are not to be confused with full-scale immersive environments since they carry the inherent representational limitations of the picture frame. While it is important to use scaled representations for all phases of design, being able to have an immersive experience and interaction with the design object has several potential advantages.

First of all, full-scale immersion allows the immediate understanding of real life proportions of the design solution. Designers can think outside the picture frame and understand the life-size impact of the project. Secondly, in an immersive design and visualization environment, fully embodied interaction is made possible. Designers can have a more intuitive relationship to the design solution and interact with natural hand-eye-body coordination. This allows designers to make quick and intuitive decisions, as well as represent and evaluate them in real time. Finally, a shared sense of immersion may enhance collaboration in a co-design setting. When designers are co-located in the same simulation space, either physically or virtually, they are able to directly experience the same viewpoint. Co-presence has been shown to enhance collaboration (Dorta et al., 2011a).

3 Co-design as a teaching strategy

3.1 The studio critique

Design studios have been central to design education because design teachers used them to transfer their design thinking knowledge and expertise to students during the development of design projects. The pedagogical method commonly used, named the studio critique (crit), has seen great changes and its efficiency became doubtful since laptops were integrated as students' daily tools. In fact, in the last two decades, the 'crit', defined as a verbal activity, has been restrained to individual discussions between a student and the teacher about his/her work (Goldschmidt, Hochman, & Dafni, 2010). Laptops have transformed teaching in the design studio, most notably, by the type of representations students bring to the weekly one-on-one meetings that are so inflexible (visual representations sufficiently developed) and difficult to intuitively alter in response to the flow of teacher-student discussion that most teachings occur through verbal conversation, analysis and advice only. Moreover, Salman, Laing, and Conniff (2014) demonstrated that the use of CAD software by students has great impact in educational context by changing the design process: because of the immediacy of the software's visual feedback, students take longer time for shifting from one idea to another compared to sketching protocols. On the other hand, they take less time analysing the design problem and they spend most of the time focussing on detailing the proposed solution, deviating from the concept content and concentrating on operative moves, which become tiring and distracting (Salman et al., 2014).

An important problem take place in this kind of verbal exchange in design studios: most of teachers coming from practice, when they comment the students' work they usually provide feedbacks based on their professional experience and practical knowledge (Goldschmidt et al., 2010), without a clear understanding of critiquing or the pedagogy of critiquing (Oh, Ishizaki, Gross, & Do, 2013). Also, the hierarchical structure of design studios (practitioner-teacher/student) impedes the spontaneous interactions that could occur in problem-resolving situation (Dragan & Ganea, 2013). The flow of expertise gained of the master/students exchanges in the Bauhaus model seems to be lost or at least braked: projects were used to be done collaboratively and the apprentice was mostly formed through learning-by-doing with the master (Whitford, 2002).

3.2 Collaborative design learning environments

New structures of design studios have been proposed such as immersive collaborative learning environments and virtual design studios (Kvan, 2001; 2009). While, pedagogical issues are still raised, technological possibilities require the development of new interfaces, user testing, pedagogical structuring, and collaborative culture in order to achieve good educational results

(Stahl, 2011), generating new paradigms of teaching and learning, such as social and constructivist learning styles (Ştefan, 2012). The study of design participation and group dynamics within hybrid and augmented design studios is still an emerging field, however few studies specifically look at the role of the teacher and the dynamics of the group in Virtual Environments (Ştefan, 2012). Shao, Daley, Vaughan, and Lin (2009) report on the quality and quantity of communication and stress the need for spatial and material flexibility in Virtual Design Studios (VDS) to facilitate the intrinsic requirements of the design process and pedagogy. Della Vecchia, Da Silva, and Pereira (2009) emphasizes the communication within the interactions between studio teachers and students, appreciating that the VDS increases the (asynchronous) time for reflection delivering, therefore, more thoughtful feedback. Kvan (2001) noted that because students do not sit adjacent to a tutor the VDS requires adjustments in the communication channels since communication between the teacher and the student has to be more structured compared to face-to-face interactions. For example, the teacher cannot use discarded alternative representations during a desk 'crit', because he was not able to view them during the conversation. In on-line design studios pedagogical interaction is unbalanced since the student has more control over the work presented for review compared to the instructor (Kvan, 2001).

Bucciarelli (1988) states that developing a design solution is a social process involving a variety of participants with different skills, responsibilities and interests, who see the object of design differently. Discussions and negotiations are held between the participants who do not share the same mental representations of the design; although their views are not aligned, they manage to maintain a design conversation between them while preserving the ambiguity. Achten (2002) suggests that collaborative design is about collective sense building. Participant interaction is not only the sum of actual work, but also the reciprocal design proposal stimulating the design task by sharing information in an environment that encourages communication.

When understanding occurs in a collaborative learning context, learners are said to construct new knowledge (Stahl, 2000) by socially processing information with the group. Considering that at the heart of design there are 'ill-defined' problems (Rittel & Webber, 1973), the key to tackling those problems should be based on negotiation between the different stakeholders, since in the process of negotiation, the design team defines and redefines the problem. This back and forth between negotiation and problem redefinition in relationship to a potential design solution is what Dorst and Cross (2001) call the 'co-evolution' of the problem-solution, it is within this process that effective learning occurs.

In many studies collaborative learning has been considered as a subdivision of cooperative learning (Barkley, Cross, & Major, 2014). Cooperative learning has been originally approached by Piaget and Vygotski (Baudrit, 2005). Among the cooperative learning attributes that Baudrit identifies, we think that 'measured heterogeneity' and 'equal status' are relevant elements for the collaborative design studio. Collaborative learning changes the traditional vision of classroom teaching and authority. Also, it is characterized by 'symmetry of actions' and 'symmetry of knowledge', which means similar degree of expertise between learners but different viewpoints (heterogeneity) (Dillenbourg & Baker, 1996). This enhances the horizontal exchanges and the arguments when debating a relevant idea allowing at the same time to progress in knowledge acquisition (Dillenbourg, 1999). In fact, Bruffee (1993) states that people construct knowledge by talking together and reaching agreement.

3.3 Co-design teaching and knowledge transfer

Why co-design is important in design education? Co-design is basically defined as a team working together (synchronously) on a common goal, which is the same requirement for collaborative learning to occur. In the context of design education, collaboration comes in different shapes: *cooperation* is putting together design solutions (or part of design solution) that have been done individually, often asynchronously; *co-design* is when all participants are actively involved in furthering the design simultaneously (synchronously) (Achten, 2002), which best suits the needs of tacit knowledge transfer.

According to Kvan (2000) design collaboration in general is a far more demanding activity than doing a design project together. It demands an important sense of working as a team in order to obtain a relevant creative result. He argues that designers compromise and 'co-operate' often instead of collaborating (Kvan, 2000). Kvan further describes the design studio culture and processes using Schön's (1983) notion of 'knowing-in-action' (tacit knowledge) and 'reflection-inaction'. While ideas are explored the teacher helps them to unravel the intentions underlying these ideas using words and drawings. This way the implications of decisions are demonstrated (Kvan, 2001). For us is like 'doing design' in front of the students or co-designing with them. When the teacher also proposes ideas. Through these interactions teachers show to the students how they reflect-in-action and transfer tacit knowledge.

Among many factors that may hinder the tacit knowledge transfer between the instructor and the student, is the high level of proficiency demanded by computational modelling environments. This may cause the instructors, or in some cases students with lower levels of digital competency, to be insecure and frustrated (Basa & Senyapili, 2005). The software environment is not and environment that is agile enough even for the proficient designers to express their ideas quickly and fluently during a design conversation. In collaborative design configurations along with studio 'crits' where technological proficiency is unbalanced, it becomes very difficult for the instructor or other participants to fully engage the design process in order to descriptively suggest forward leaps during a review session. Instead of eliciting newer formal suggestions or revisions to existing design decisions, the dialogue often gets deadlocked in relatively unproductive verbal exchange (without design proposals), diminishing the pedagogical efficiency of the review session. Goffin and Koners (2011) point out the nonverbal, less explicit quality of tacit knowledge transfer, not easily shared by formal instructions. It is often described as 'know-how', or work related practical knowledge. The key to acquiring tacit knowledge is shared experience (e.g. observation, imitation and practice). The concept of design studio formalized at Gropius' Bauhaus, supported the transfer of tacit knowledge within design education by having 'Workshop Masters' instruct 'Apprentices/Students'. Which should be reinvented in the new context of co-design in education converting the teacher to a new role that fits this co-design learning situation. The teacher has also to design with the student in order to teach him/her how to design.

Moreover, Bruffee (1993) states that the responsibility of the teacher is to become a member among the students, in a community that searches for knowledge. The role of the teacher in co-design shifts often into coaching students in order to help them make conceptual connections or broaden the space of alternatives for addressing problematic situations which encourages iterations (Adams, Forin, Chua, & Radcliffe, 2016). Co-construction of knowledge takes place while peers elaborate or evaluate their partners' contributions through a critical discussion of ideas (Hausmann, Chi, & Roy, 2004). Collaborative learning can promote higher-order learning such as critical thinking. Compared to non-collaborative learning activities, collaborative learning fosters shared understanding, better information retention, and deeper processing (Jorczak, 2011).

4 *Case study: the augmented co-design studio*

The Augmented Design Studio was carried at the University of Montreal, School of Design (Quebec, Canada), in collaboration with two international partners from the industry, an American automotive company (Name withheld), and a design office (Design Innovation, Milan, Italy). We also collaborated with two academic partners: Université de Lorraine (France), where 4 graduate architectural students participated as structural consultants. The project subject was: *Lightweight structures offsetting impacts in automobiles*. Locally, 14 students were asked to work in teams of two, each one doing their own project. They were asked to collaborate with their teammates in developing their projects. Each two-student team met the instructor in the immersive co-design environment (HIS) once a week for a 1-h co-design session where proposals from both students were developed. They worked in the traditional studio for the remaining hours. Occasionally, a remote collaborator/critic from Design Innovation or the consultant−students from School of Architecture of Nancy joined the sessions using two additional HIS (one in Milan, at Design Innovation and one at Université de Lorraine-Metz) that were interconnected to the sessions. The co-design sessions were observed and recorded at a distance using another remote station located at the Hybridlab, University of Montreal.

We used as an immersive co-design environment the Interconnected HIS (Figure 2) (Dorta et al., 2011a) in the Augmented Co-design Studio. It is a co-design environment that allows immersive projection without headsets in a 360° semi-spherical display. The system facilitates intuitive design communication by allowing freehand sketching of each user at once via a pen-tablet device on top of anamorphic and 2D visualizations, and panoramic video feeds. It is possible to sketch on a variety of sources including panoramic images, prerendered realistic 3D backgrounds, and real-time views from a scaled (1:20) physical model through a panoramic video camera. The system can also display immersive (spherically anamorphic) videos. The interconnected HIS consists of multiple HIS units allowing real-time and immersive co-design between remotely located participants. The parties can interact with each other's designs and drawings by sketching in real-time. In addition, audio and video information are exchanged to allow for verbal and gestural interaction between participants.

The HIS, which allowed sketching over static anamorphic spherical images, has recently evolved to Hyve-3D (Figure 3) that allows also real-time collaboration (remote and local) and interaction in within 3D environments and sketching in dynamic 3D. Hyve-3D permits direct interaction through affine transformations of imported 3D geometries and 3D sketches for all the participants simultaneously using handheld tablets used as 3D Cursors. Hyve-3D immersive projection has also changed to an original spherical concave shape (not 360°), projecting the immersive image mostly in front of the users, and open to big audiences. Concerning the use of physical models in the Interconnected HIS, Hyve-3D can allow immersion in scaled physical models through photogrammetric techniques, producing a 3D geometry from multiple photos of the model. For more detail about Hyve-3D please see (Dorta et al., 2016).

4.1 Utilization of representational media in the HIS

Analyses were carried out using video and sound recordings collected during the studio sessions in order to observe representational media utilization through the evolution of the project. Group dynamics, communication and participant involvement patterns were assessed through the Design Conversations analysis (Dorta, Kalay, Lesage & Perez, 2011b). The objective was to

Figure 2 HIS. Shown partially opened for student presentations in this project

Figure 3 Hyve-3D

achieve an overall assessment of the rules and dynamics of verbal and representational exchange in a hybrid co-design setting as exemplified by the HIS, rather than to establish the superiority of this particular system to another.

In the co-design sessions carried out in the HIS, students were given the option to develop their designs using any combination of the following representational channels: 2D images, orthographic and perspectival sketching, 3D CAD models, physical models and 360° immersive video or stop-motion animations. Freehand sketching and verbal exteriorization of design ideas were encouraged throughout the workshop, while other means of representation were gradually incorporated as required by the evolution of the design process. As the representational requirements changed from abstract to rigid, CAD models replaced preliminary 2D and 3D sketches, and more detailed,

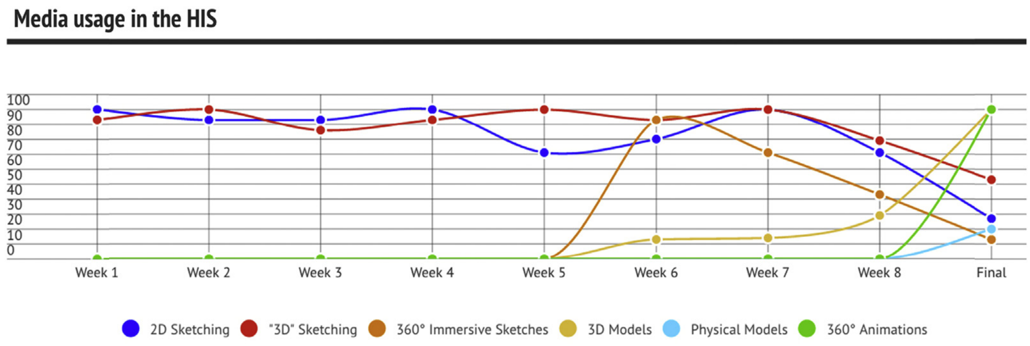


Figure 4 Comparative utilization of representational formats in the HIS throughout the case study

sometimes 3D printed models took the place of earlier draft mock-ups. However, in each phase of development, sketching was used as the primary channel of communication, for formalizing new design propositions and making annotations on existing ones.

For this research we relied on one form of observation and data collection: audio-video-recordings which were done using two local cameras: one for the general rear-view, showing participants and 70% of the projection screen, and one frontal camera, showing their faces and gestures. These videos were later analysed for representational media utilization frequency and design conversation analysis.

Figure 4 shows the evolution of the design communication and representation for the weeks during which the students utilized the HIS. The plot shows the percentage of students utilizing a particular mode of representation in the HIS, for each week the system was utilized. These include:

- **2D Sketching:** Sketches that do not include any representation of the third dimension, such as side views, photos, sections, plans etc.;
- **'3D' Sketching:** Pseudo-3D sketches that include orthographic or perspectival representation of depth. These sketches are not really in 3D like in Hyve-3D (as see Figure 3). They provide the illusion of 3D thanks to the anamorphic immersive projection technique;
- **360° Immersive Sketches:** Spherically panoramic anamorphic illustrations that were prepared in advance outside the HIS by the help of a given template (by hand or using a painting software);
- **3D models:** CAD models that were prepared in conventional modelling software and pre-rendered as spherically panoramic anamorphic images to be displayed in the HIS;
- **Physical models:** Models that were brought into the review sessions and presented/critiqued using the model stand and panoramic camera of the HIS;
- **4D 360° Immersive Animations:** immersive (spherically anamorphic) videos.

Throughout the semester, the students were able to go back and forth between the traditional studio environment and the HIS. In both environments, they were allowed to utilize digital tools and analog methods to develop their designs. The HIS allowed the students and the instructor to illustrate their discussions using sketches, and as the projects evolved, these were more frequently supported by more elaborate forms of representation. Sketches allowed spontaneous presentation of new ideas and quick annotations on pre-existing ones. It was not too surprising to observe that designers resorted to the use of sketches as a communication medium until the very end of the studio. However, it is important to note that 2D sketches were as dominantly utilized as '3D' sketches. This may be explained due to their relative economy: for it is more time-consuming to draw in 3D; or their specific affordances: as in some cases a section or plan may be a more effective tool to describe an idea in a concise fashion, then say a perspective.

Figure 5 shows the development of a student project in the successive phases of design. 2D and perspectival sketches were actively utilized for all sessions throughout the semester. In the beginning the blackboard (the 2D window of the HIS used to display non-immersive images) was more commonly utilized than the immersive 1:1 display; as the project progressed, there was an increase in the use of perspectival sketching. These were initially made on top of a background with a ground grid and a skeleton model of a car, provided as a workspace template. As students were able to produce their own 3D models, these replaced workspace templates. These models were displayed in the HIS as 360° renders. Students not proficient in 3D modelling used analog (scanned) or digital freehand sketches in the form of 360° spherical panoramas, using a geometric template for the spherical deformation. For the final presentation, the students produced an animation to communicate the functionality of their solution. These were made by rendering the 3D models by placing a special panoramic camera in the digital scene. Two students, who were not proficient in CAD modelling and animation software, worked with stop motion animation technique using physical models and a panoramic camera (Sony bloggie™) (Figure 6).

4.2 Group dynamics, conversation and participant involvement in the augmented co-design studio

As part of the wider context of our research, we analysed the verbal conversations between the participants of the collaboration sessions, using the Design Conversations framework analysis (Dorta et al., 2011b). This method involves the sequential breakdown of the co-design conversation into main conversational categories in order to be able to trace the evolution of a collaborative design process. The categories are defined by specific elements of the conversation that are: *naming* (identifying the focus of the design conversation),

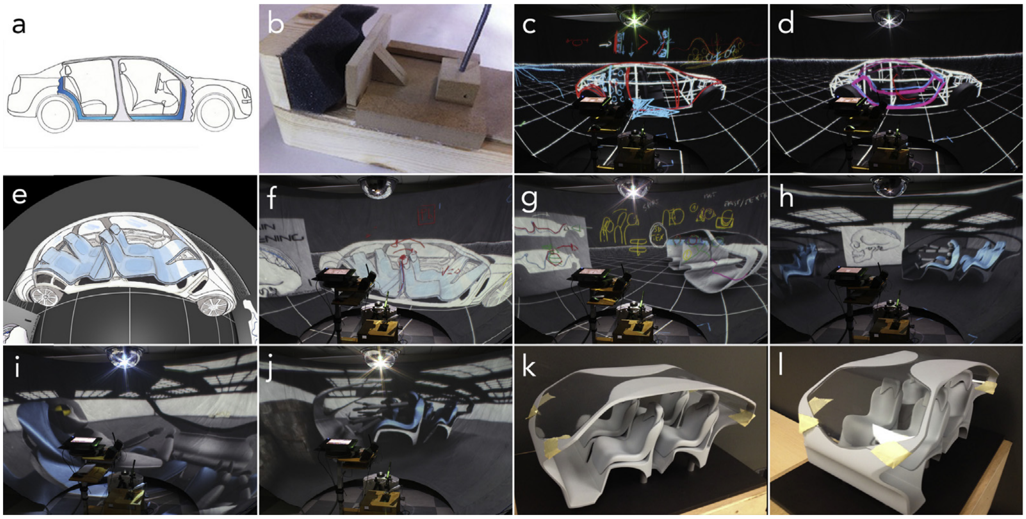


Figure 5 Development of one of 14 student projects: (a, b): pre-HIS concept studies. (c, d): 2D and 3D sketch-explorations in the HIS. (e, f): Anamorphic freehand (e) and immersive view (f). (g, h): Panoramic 3D renders and sketches. (i, j): Immersive animation, (k, l): RP final model

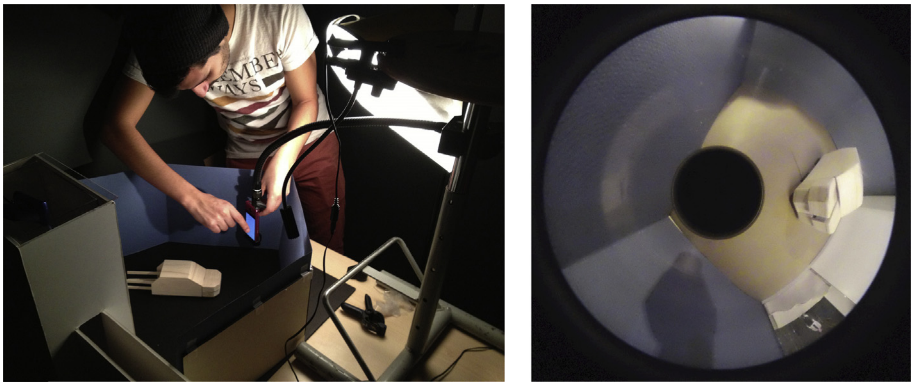


Figure 6 Preparing a stop-motion 360° immersive animation

constraining (describing the problem at hand), *proposing* (making a design proposal), *negotiating* (explaining or questioning regarding the given suggestion), *decision making* (agreeing, disagreeing) and *moving* (sketching, creating visual representations) (Dorta et al., 2011b). We focused our observation specifically on randomly selected samples from weeks 3 and 4 of the studio when the students were in the process of testing out their core concepts and engaged in active co-design with remote collaborators. We present a glimpse of the Design Conversation analyses illustrating the dynamic relationship between representational media usage and collaborative design conversations in HIS.

In order to perform the Design conversation analysis, one trained coder (one researcher) identified the frequency of the five elements of Design Conversation (naming, constraining, proposing, negotiation, decision making and moving) only during periods of co-design and concept presentations for review (between students, teacher and collaborators). The analysis was limited to the moments where the key concepts were reviewed for each student project. The selected examples last between around 6 to 14 min of relevant conversations related to these key concepts. These selected periods were considered meaningful since they were related directly to the development and proposition of key concepts and ideas, that were developed until the end. Moreover, the 5 elements of the Design Conversation framework helped to categorize these verbal exchanges (Figure 7). Moments related with technical problems and other irrelevant topics not related to the key concept development (presentation and co-design) were excluded from the analysis.

As shown on Figure 7, during these sessions all of the participants (students, instructor, and remote participants when they were present) were able to actively contribute to the design discussion and creation process. The conversation was observed to be democratic and egalitarian, as both the students and reviewers were able to present their ideas verbally and visually as well as interact with each-other's proposals through sketches. The concretization of design proposals in the form of drawings and sketches (*moving*) happened throughout the discussions, which would not have been possible during a regular design studio environment. Remote collaborators, when they were present, participated relatively more verbally than visually. However, both the student and the studio instructor contributed comparably to all elements of the co-design conversation process.

Figure 8 show the verbatim of these verbal exchanges detailing how meaningful they were for the development of the key concepts. The model that is observed seems to transcend the limitations of the presenter-and-critic model of the 'pin-up' review, which seems to be the status-quo in most contemporary design studio schools, where participation is imbalanced and hierarchic.

As a result of our initial observations we were able to conclude that a pedagogic environment where all parties are able to intuitively use the system and invited to visually express their ideas while they are speaking, as exemplified by HIS, is empowering for all of the participants. The preconceived hierarchy between the presenter and the critic dissolves, and the representational barrier generated by the software interface disappears. As a result, the playing field is levelled, giving all parties equal access to the shared representational medium therefore making it supportive for co-design.

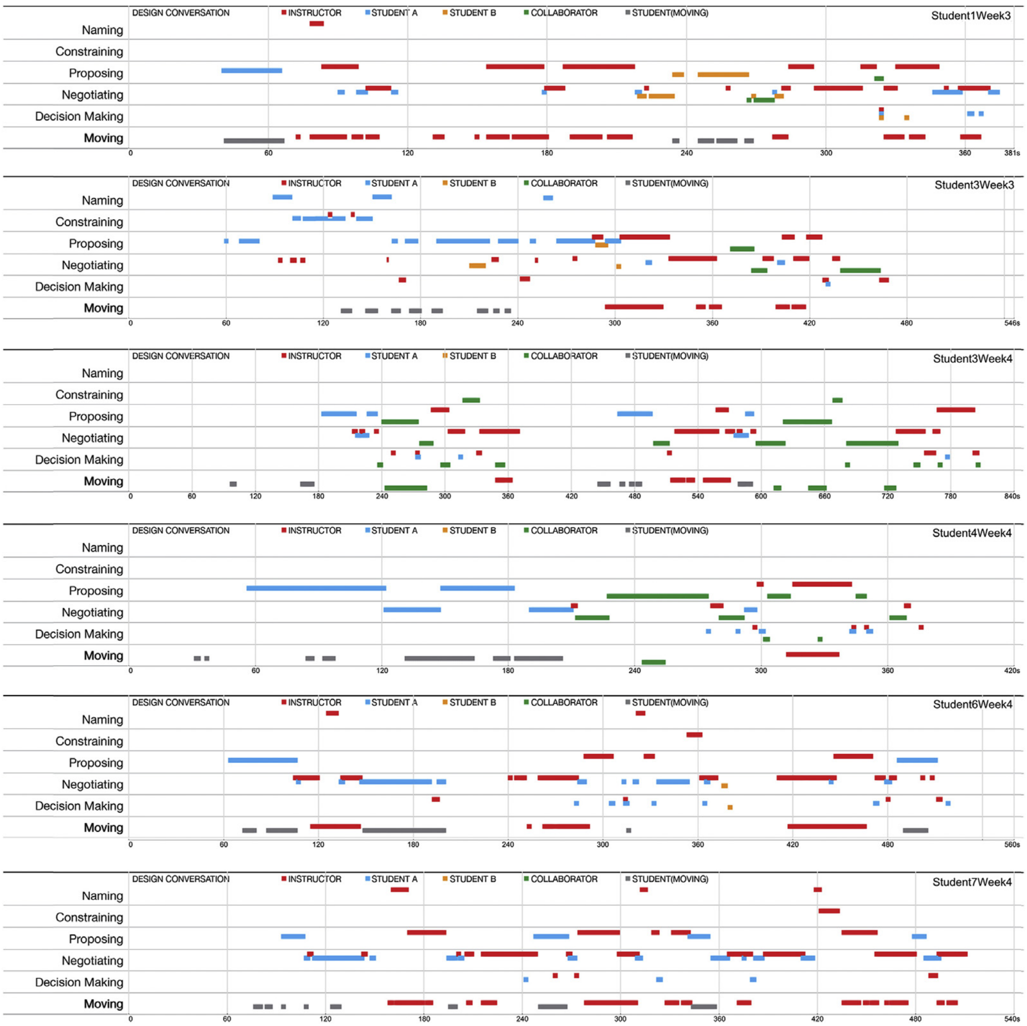
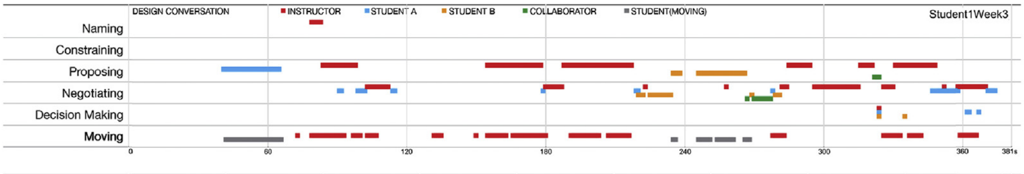


Figure 7 Group dynamics shown using Design Conversations framework from concept presentation sessions that took place during weeks 3 and 4. In the last two sessions no remote collaborator was present

5 *Principles of the new representational ecosystem for teaching in the design studio*

With the aim of describing the epistemological framework of the pedagogical co-design process and the role played by shared representations in the formation of design knowledge we present a revised version of Lebahar's model (Figure 9). As with the original framework, the co-design process also alternates between synchronic states and diachronic leaps. The amount of uncertainty associated with the Design Problem (P) is reduced as the Object Model (O) gets completed. Each co-design participant (student, teacher or collaborator) also has his/her individual levels of uncertainty (?) about the project.



(00:39) Student A: Imagine if this section would be made with several parts nested together, and just like a caterpillar, when there's an impact, they make a wave that will propagate like this. [Proposing] [Moving]

(01:18) Instructor: Here, in the main structures of the vehicle [Naming]

(01:26) Instructor: you can absorb the shock in a way like this [Proposing]

(01:29) Student A: and there is a deformation. That's it? [Negotiating-Questioning] and deformation will be this way [Negotiating-Explaining]

(01:37) Student A: It's like the caterpillar propelling by making little waves [Negotiating]

(01:41) Instructor: Ok. I remember when you told me about that you said you wanted to do it like that [Negotiating]

(02:33) Instructor: There's an important element here, it's to see if there are attachment points, or you could have deformations like this, I'll use red to sketch it… and fixation points like this. [Proposing] [Moving]

(02:56) Student A: Or you can do that on the side? [Negotiating-Questioning]

(02:58) Instructor: No, because there are rigid parts and others that are deforming like this (gesturing with hands, arms and whole body) [Negotiating- Explaining]

(03:06) Instructor: Or, we can guide the movement, I mean like a tunnel with a hollow beam providing a kind of structure which is like this [Proposing]

(03:11) Instructor: I will sketch it here [Moving]

(03:37) Student A: but this way if we put… [Negotiating-Questioning]

(03:38) Student B: Seen like this, I think it does already exist [Negotiating]

(03:41) Instructor: It already exists? [Negotiating-Questioning]

(03:43) Student B: Deforming beams embedded together [Negotiating-Explaining]

(03:53) Student B: What I found interesting about what she said earlier [Moving]

(04:04) Student B: Is to have the little moving parts in forms of waves when there's an impact they transmit this thing in this way, it won't crush, but it will regain its initial state [Proposing] [Moving]

(04:25) Collaborator: I don't know if it's possible [Negotiating-Questioning]

(04:27) Student B: No actually [Negotiating-Agreement]

(04:28) Collaborator: Precisely if it transmits a wave, so the energy, in the end what it becomes if it's not absorbed? [Negotiating-Questioning]

(04:37): Student A: The idea is to deviated it from passengers. [Negotiating- Explaining]

(04:41) Instructor: Yes, take it to this direction [Negotiating-Agreement]

(04:43): Instructor: Take it to the back for example. It can crush something in the back of the vehicle, so we transfer the impact from the front and push it to the back [Proposing]

(04:54) Instructor: This question makes me thinking about the whip, which transmits the wave, it's not the compression but the extension of an object [Negotiating-Explaining]

(05:14) Instructor: But if we have a chain, like the bike chain and… [Proposing]

(05:21) Collaborator: Yes, it has to have tiny components which work together [Negotiating-Explaining]

(05:23) Instructor: Yes, when I suggested the tunnel where these components are here [Moving] I mean that it will be an upper limit and a lower limit to lead the movement to this direction, the wave will take place but it will be inside this kind of tunnel [Proposing]

(05:34) Student B: Ah! [Decision Making-Agreement]

(05:36) Collaborator: Yes. [Decision Making-Agreement]

(05:48) Student A: It will continue to bend and will continue to do this (gesturing waves), [Negotiating-Explaining]

(05:50) Instructor: Yes, doing the way you wanted [Decision Making-Agreement]

(05:55) Student A: but this part is rigid, it will break?... (pointing the sketch) [Negotiating-Questioning]

(05:57): Instructor: Yes, but if you do it from a distance here [Moving] to reach there… [Negotiating-Explaining]

(06:00) Student A: Ok. [Decision Making-Agreement]

(06:03) Instructor: This will be a container of the curve [Negotiating-Explaining] [Moving]

(06:05) Student B: Ok [Decision Making-Agreement]

(06:09) Student A: and here at the same time, it allows to link all the vehicle structure to prevent its deformation. [Negotiating-Explaining]

Figure 8 Example of a verbal exchange (verbatim) of 380 s analysed with the Design Conversations Framework Student 1 Week 3

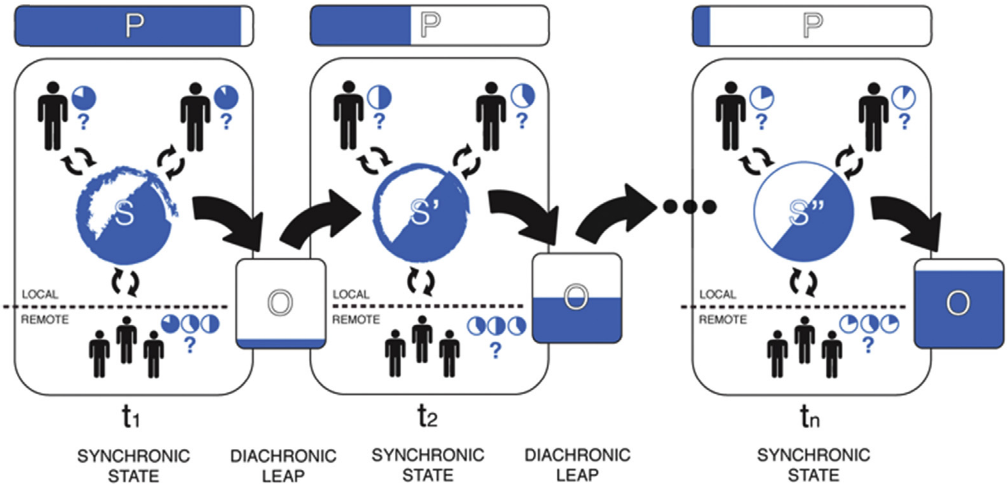


Figure 9 Diagram illustrating and the evolution of a design project in a co-design setting

Through communication and collaborative decision-making those levels of uncertainty also influence each other, and gradually decrease. At the end of an *ideal* design process, the uncertainty of participants and design problem should reach zero and there should be a complete and shared knowledge of the design object that all participants fully agree upon. In real-life design processes, this state is approximated or *satisficed* (Simon, 1973) but not always fully achieved.

In the *epistemological dimension* (O, P, ?), the process of co-design aims at reaching the shared knowledge transfer and understanding of what the design object ought to be. However, design interactions are made solely within the *representational dimension* which includes externalizing and exchanging such knowledge states through verbal communication and representational simulations (S′, S′, S″, …). In each *synchronic state* only one representational medium may be used. In the *diachronic leap* (when designers move between modes of representation) design decisions are actually consolidated.

In other words, the ideas carried from a section to a plan, or from a perspective to a model are traces of design decisions being made. The completeness of the Object Model (O) stands for the confidence of the designers in the final form of the design object (a shared consensus on the design solution) and this in turn corresponds to the ability to produce construction drawings and to make final specifications for the physical realization of the design object. Differing from Lebahar's original model, the role of verbal and visual communication (S) becomes centralized. In our model, the design representation ceases to be simply a proxy between knowledge states but an active, representational ecosystem that actually becomes a fostering context for co-design.

The principles of the proposed paradigm for the new Representational Ecosystem for teaching, as exemplified by our observations of our case study, are:

(a) To be *bilaterally-hybrid* (analog and digital) allowing back and forth between different skills and different realms, not only in one direction;

This means that the representational ecosystem must allow to each participant of the co-design teaching process to engage the representation according his or her representational skills or to choose the realm that represent better the knowledge to be transferred. As shown in the Design conversation analysis, the collaborators, teachers and students must be able to easily represent the knowledge they want to transfer (moving), with the technique they master better while respecting the rhythm of the design conversation without stopping the process to deal with the particularities and demands of one of the realms (digital or analog).

(b) To allow *multiple kinds of representations*, from graphical, physical to time-based media such as animations;

As observed in the case study (Figure 4), different participants select different kinds of representations to express their ideas following their design thinking progresses. Different dimensions (2D, 3D and 4D/graphical or physical) were selected to communicate aspects of the projects being adapted to receive and to provide the right feedback from the co-design team. In the beginning of the process and to easily express ideas, orthogonal and perspective sketches were more utilized all over the project. Immersive animations were used at the end to *impress* the clients and remote collaborators, showing immersive cinematics of the behaviour of the proposed structure.

(c) To allow the use of *multiple scales* including one-to-one immersion, giving the opportunity to better understand the proposed design proportions;

The use of the HIS allowed to be immersed in scaled easily made models (foam) projected life-size showing particular information. At the same time, the ability to go inside and outside immersive car representations, allowed different kinds of relevant solutions: solutions related to chassis, bumpers, car body materials, new car structure movements, cabin interior, etc. It seems that the easiness and freedom of the scale, combined to the two latter principles, allowed to better explain in detail a particular piece, or to show the impact of the whole movement of the structure without any limit and adapted to the needed level of knowledge. In the HIS, participants were able to sketch tiny details or diagrams as well as the whole car in 1:1, depending what they want to communicate. This potential is greatly improved in Hyve-3D as participants can sketch a tiny 2D detail for the local participants using only the tablet surface or using the 3D Cursor's Drawing area for remote collaborators (as the Blackboard used in the HIS), or even a 3D immersive 1:1 sketch of a whole city, using the immersive projection.

(d) To allow *active and intuitive co-design*, permitting rich design exchange and knowledge transfer, without becoming only a passive presentation tool for the latter steps of the process.

This means that the representation has to be flexible and democratic to allow each participants to easily engage with it, and to support the design conversation. Its ownership is shared and becomes common to the whole team. In the co-design process, since it is simultaneous, each participant recognize what has been done by the others. A render or a model (digital or analog) that cannot be easily sketched over it or transformed, does not allow active co-design, but only verbal exchanges, thus hindering the knowledge transfer and design learning through co-design-by-doing.

6 Conclusion

The current digital paradigm of the design studios, characterized by the haphazard substitution of traditional representations with generic computing and visualization tools, not only does not provide effective support for the design process but also hinder its productivity and design teaching. We analysed for the first time the position of the interconnected HIS as a binding component of the representational ecosystem of a semester-long design studio. We updated Lebahar's *Graphical Simulation System* to reflect current design practice and teaching, accounting for digital media and collaboration. The case study was implemented on the premise that the studio workflow should allow for a more *comprehensive* design process and a *closer view* of the design solution.

Through our observations we were able to explain that the HIS was useful for development and presentation phases of a design studio in addition to the ideation phase. The observations of this case study helped us to formulate the principles for a new representational ecosystem for the studio regardless of the actual technology utilized: to be *bilaterally hybrid*, to support *multiple kinds of representations*, to implement *multiple scales including full immersion* and to allow *active and intuitive co-design*.

We envision that the theoretical arguments of this paper could help the studio instructors, students and collaborators to recognise and ask for the right representation at the right moment during the design process, even if new representation technologies are present, to better communicate and transfer knowledge by actively engaging in the representation itself while relevant verbal exchanges are made. This case study opens the door to question the role and the use of different kind of representations in the studio, and the way participants talk during the review and how those reviews are done. In this new representational ecosystem, including an immersive collaborative hybrid environment like the HIS and now Hyve-3D as a bending component of different representational elements, design could be taught by co-design. And this teaching not only came from the professor, but from all the other participants: practitioners sharing their tacit knowledge and student sharing the particular knowledge they have of the project, thus allowing the co-construction of knowledge. In addition, the same way student learn design by observing and imitating how a problem is tackled or resolved by the teacher, instructors can be aware of the level of design skill the students develop in a particular stage of the studio. It is important to mention that in a hybrid teaching environment, the integration of any new technology into design teaching, has to respect and incorporate every other element of the existing representational ecosystem. The principles are set; implementations may vary.

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