Industrial Design Education as Innovation Broker through Making, Pivot Thinking, Autopoiesis and Expansive Learning

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Abstract

This article elaborates on design research in a final capstone industrial design studio unit and on the application of outcomes over eight years within a School of Engineering and its recent incarnation as School of Computing, Engineering and Mathematics. Research and curriculum innovation linked students to the new global design-driven innovation agenda as knowledge workers leading by creativity and intellectual capital. An international design studio project with a professional design agency style was embedded in the first instalment of the research. Students worked as junior designers with industry experts who couched them with a work integrated learning approach. A second instalment expanded to learning concurrent and agile development. An open program recognised students' backgrounds and experiences to create a community of learning curriculum through critical making, pivot thinking, autopoiesis and expansive learning. These contributed to also establish CDIO (conceiving, designing, implementing, operating) and STEAM (science, technology, engineering, arts, mathematics) initiatives as ways to procure evidence and facilitate production. Technology effects on design knowledge flows were addressed with participatory action research, information and communication technologies, human-computer interaction, e-manufacturing, fabrication and rapid prototyping tools. Findings indicated the need to update design education to achieve modern design artefact and knowledge construction. The greatest challenge was behavioural rather than technological. Institutional preconditioning assumed students as consumers and education as transmission skill transfer. A shift to transformative learning was possible by empowering participants to work within modern industry integrated benchmarks and achieve unique value propositions and minimum viable products that were ready to market outcomes

Key words

autopoiesis, constructionism, critical making, expansive learning, pivot thinking, transformative pedagogy

Introduction

This article elaborates on an eight-year research project in a final capstone industrial design studio unit. There was two years' preparation, three years' design research with ethics approval and another three for applications of outcomes to improve education (after a two years' interval). The article adds to another paper explaining technology within an international design studio (IDS) project attached to the unit (Author, 2010). This paper focuses on participants' behaviour, cognitive and social learning through *critical making*, *pivot thinking, autopoiesis* and *expansive learning*. Research showed new levels of meaning and knowledge construction when students became active learners and junior designers within a design agency-like environment. Historically, design education was embedded in goods-centred economies and attached to specialised niches, machineries and places of work which owned the means of production. Designers mostly executed briefs handed down from employers or clients with expertise mainly based on crafting, manufacturing and aesthetic flair. Digital technologies and globalisation progressively changed this landscape since the 1970s. New competency gaps turned innovation and productivity towards soft skills, information technology intensive industries (IT), information communication technologies (ICT), and new forms of manufacturing. Today, this shift requires graduates to satisfy market and social demands with novel forms of creative intelligence. Education has been slow in recognising students' need to transition from artisan craftsmanship and computer operation trial-error empiricism, to a knowledge workers' participatory, connected, intellectual, portable and scalable design intelligence based on science-based experimentation, simulations, decision theory and systems thinking (Friedman, 2012).

Design education intermediates between technology, society and environment by transferring technical skills to students on hard technology for manufacturing (e.g. CAD, machinery) and aesthetic appeal (e.g. sketching, modelling). A bachelor course represents intensive learning that saves years of on-the-job training. However, that intermediation does not maintain education as indispensable today. Knowledge flows are redefining design artefact and its practice. A complex intangible web of meaningful interactions among people, technology and their environment are also dematerialising design (Figure 1). There is a growing gap between design education and leading innovation benchmarks. Appropriately, this research aimed to answer the question of: *how design education can add meaningful value to students and industry, so they create new means of production and social progress through leading knowledge and design-driven innovation?* Four subsidiary questions supported this inquiry as:

1. Does typical industrial design education comply with innovation benchmarks?
2. Do students' background and institutional conditioning influence design intelligence?
3. Do student differences require customisation of learning?
4. Is it possible to transform students' attitude to learn current value proposition demands?

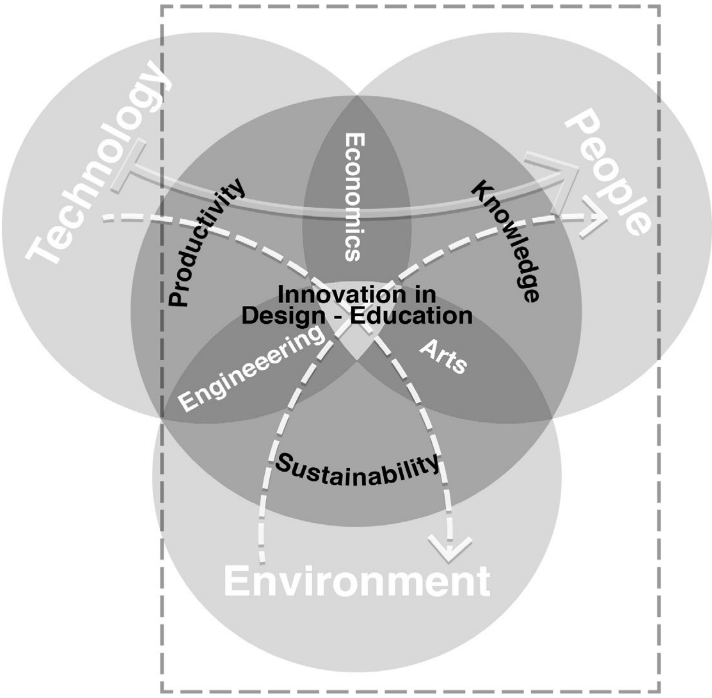


Figure 1. Environment, people and technology push-pull. Reprinted from Novoa, 2012.

Method

The project investigated design education as innovator broker based on following co-occurring processes that have individual and collective implications:

1. **Autopoiesis** (auto = self, poiesis = creation, production): Individual's ability to behave as a cognitive system that self-generate knowledge to create, produce and maintain itself in relation to others (H Maturana & Varela, 1973),
2. **Expansive learning:** Social activity that constructs new knowledge by communication, interaction and use of cultural and ethnographic artefacts, tools, symbols and language (Engeström, 2001)
3. **Pivot thinking:** Reasoning that reframes problems and move in new directions
4. **Critical making:** Hands-on process-oriented workshop framework that merges physical and conceptual exploration to discover and construct new knowledge through design artefacts

Autopoiesis

Autopoiesis, from cellular biology, is useful for explaining a student's capacity for self-creation and self-production of knowledge as an on-off interaction between a living system and its environment. This is opposite to self-reproduction that means making redundant copies (e.g. artefacts) with no information value. Traditionally, a student's environment was affected by dominant institutional and teaching models. They controlled by reproducing activities that avoided real consciousness in lethargic environments. However, design learning requires self-creation and self-production with dynamic behaviours that elicit cognition. Knowledge generation can express autopoietically like a cell (e.g. amoeba) that moves from one position to another seeking nutrition. There is a connection (known as *structural coupling*) between a cell's motor-sensory activity and its environmental stimulae before an area is exhausted and the cell goes elsewhere. A learner's conduct should be similar by self-producing efferent (Latin *efferens*: to bring or carry out) responses (behavioural, intellectual, motor and sensory) to commands triggered by external input. This cycle allows cells/learners to build internal cognitive models capable of interpreting and interacting with their environment. Movement to a new position would result from comparing actual and predicted signals and feedback mechanisms that allow forecasting new events and situations for learner's experience (Flanders, 2011; Lyon, 2004; Humberto Maturana & Varela, 1980; McGann, Ortner, & Dirks, 1991). Particularly, a learner's feedback mechanism should include social signs, reasoning, and interaction with and influence on the environment (Figure 2). Autopoietic complexity can increase the more activities cross boundaries with other systems, ranging from:

- First-order: Individual learner self-producing system values
- Second-order: Structural coupling between learners as living systems
- Third-order: Coupling between learners as organisms through distributed teams and organisations

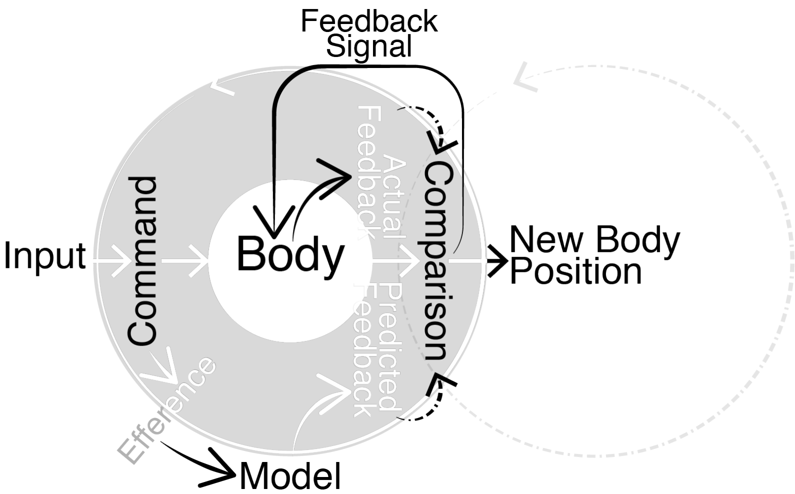


Figure 2. Autopoietic model. Adapted from Maturana & Varela(1980).

Expansive learning

Expansive learning (EL) belongs to the third-generation cultural-historical activity theory (3GCHAT). It emerged from developmental work research (DWR) in Finland that collaboratively innovated normative constrains in the workplace, technology and organisations. DWR researchers carried out active intervention through participatory action research (PAR) that enabled participants' customisation, ownership and capacity to create their own means of knowledge construction, meaning and purpose. Engeström (1995); (1999a, 1999b, 2001, 2005, 2014) proposed it when revising Vygotsky's activity theory (AT). AT broke with dual Cartesian models of society with a triad that included mediation of artefacts between humans' actions. Human psyche no longer could be understood separated from cultural means. Knowledge construction depended on individual zones of proximal development (ZPD) ranging from what is learnt independently to what cannot as it is beyond reach (Figure 3). A teacher or other student could qualify as a *more capable other* and assist in a process of individual externalisation (as act of de-automating self-reproduction) and of internalisation of learning (as act of absorption of new self-production) before progressing into a new stage (Koskinen, 2009; Mingers, 1997; Vygotsky, 1980).

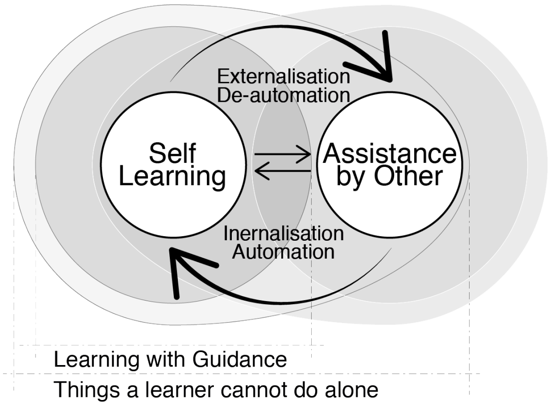


Figure 3. **ZPD model. Adapted from Vygotsky, (1980).**

EL updated AT to incorporate cultural and historical social construction of knowledge by dealing with collective and simultaneous contradictions that neither Autopoiesis nor ZPD explained. Its basic conceptual model is an activity system comprising psychological, social and institutional dimensions (community, rules, division of labour) that influences activity, subject, mediating artefacts, object and outcomes. A minimal expression of 3GCHAT contains two interacting activity systems that contribute their own community multi-voices (points of view, traditions, interests), historicity (activities over time) and contradictions (source of change, development) in the way that individual objects and outcomes produce a common new distinctive object and outcome, hopefully better than their separate contributors. Because that interaction, each participant, activity and artefact have the opportunity of radical expansive transformation through reconceptualised objects. Creativity and the making of new artefacts are the most important because of their role in producing novel social patterns and transformation of activity contents. (Figure 4).
EL comprises a four-reflective contradictions cycle process of deconstruction, reconstruction, trial and re-adjustment as follows:

1. Primary contradictions: Need state
   A. Ethnographic analysis
   B. Historical causes
   C. Revealing systemic structure contradictions
2. Secondary contradictions: Transformation
   A. Empirical and historical analysis
   B. Modelling new solution

3. Tertiary Contradictions: Resistance (with user consultation)
    A. Testing iterations of the new model
    B. Implementing new model
4. Quaternary contradictions: Realignment
    A. Reflecting on process, new model, practice, etc.
    B. Consolidating new practice
    C. Spreading it as new learning, codifying new rules, etc.

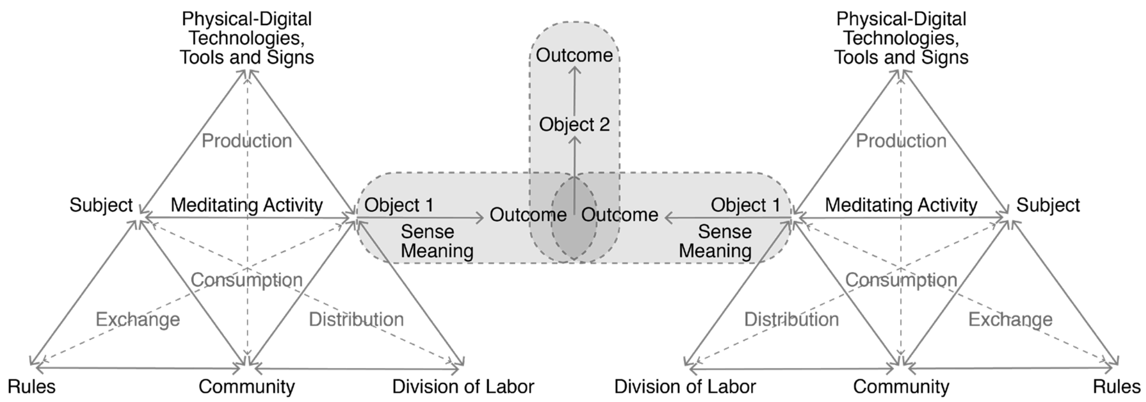


Figure 4. ***3GCHAT minimum two activity system. Adapted from Engeström, (2014).***

Pivot thinking

Pivoting among perspectives (result of data, prototypes and simulations) is essential for *critical making* that embraces modern design heuristics as an evolutionary process (i.e. experimenting, discovering, creating evidence, theorising) that helps framing problems and solutions through user contextualisation, consultation and customisation (Robinson & Pallasmaa, 2015). This requires co-production and theorising through making to articulate a new dialogue with: higher cognitive load, user culture understanding and contributions from other disciplines. Pivoting assists prominent thinkers' calls to redefine industrial design discourse, from non-transferrable craft methods and trial-error empiric skills to new, easy-to-transfer competencies that adapt methods across contexts and platforms (Buchanan, 2001; Krippendorff, 1995). Design should benefit from collaboration and scaffolding coming from more evolved disciplinary histories (Poggenpohl & Sato, 2009). Yet, it cannot be a naïve application of those disciplines as templates.

Cognitive shift needed a framework. Students were marked by legacy lacking definition of what is design innovation. Their education ranged from convergent engineering (scientific approach of facts and calculation) to divergent artistic (process often immersed in a fog of creative mystery and misconstrued as subjective aesthetic value) perspectives. By contrast, design intervention pivots non-linearly among perspectives, to investigate uncertain problems and propose diverse possible solutions (Guilford, 1967). Similar to Boden (2004); (2009), M. F. Schar, Leifer, Hinds, and Shavelson (2011), M. Schar (2015), a taxonomy for innovation would assist in eliminating the vagueness associated with traditional design education. As per Table 1, it would align with knowledge construction evolution (from conventional creativity studies onto creative industries mapping, neuro-scientific and innovation theories), and current distinctions for innovation and creativity at different levels of complexity. Disciplinary domains were proposed to build logic knowledge through forward-thinking and meaning-making based on empathy, prototyping, iterations, deduction, induction and abduction of ideas. Heuristics were to provide multiple possible, novel, internally-consistent answers to research involving user participation before narrowing down to the most plausible solution. Innovation was to be considered as either a singular expression or a mix of domains at either three cultural and conceptual complexity levels:

1. Combinational: Most common, it associates and generates relevant still unfamiliar arrangements of familiar ideas (e.g. visual collages, cartoons, heart as a pump metaphor).
2. Exploratory: Testing stylistic rules and conventions through novelty to expand them (e.g. incremental innovation, product upgrade)
3. Transformational: Quantum leap of innovation with shock impact through arresting new ideas or artefacts that dramatically redefine behaviour, conceptual space and norms (e.g. evolution theory, electricity, light bulb).

Table 1. Taxonomy for innovation as per complexity and heuristic domains

Levels of Complexity		Domain Problem Solving	Heuristic Theme	Problem Solving Tools	Outcome
Combinational		Engineering	Analyze your way forward	Equations, Analytics	Single point best answer
		Business	Optimize your way forward	Maximizing, Satisficing	Single point sufficient answers
Exploratory		Design	Build your way forward	Empathy, Prototyping, Iteration	Multiple possible novel answers
		Artistic	Feel your way forward	Qualitative, Experiential	Multiple possible balanced answers
Transformational		Research	Logic your way forward	Deduction, Induction, Abduction	Internally consistent answer

Note. Adapted from Boden (2004); (2009) Schar (2015); Schar et al. (2011)

Critical making

Critical making is a transformational approach that focuses on open and process-oriented community-based peer production. Thereby, learning becomes contextualised experience that assists the building of new socio-technical imagination and elicits analytical viewpoints on institutions, practices and norms (DiSalvo, 2009; Dunne, 2005; Dunne & Raby, 2001; Ratto et al., 2011; Ratto & Hockema, 2009). Making has departed from last century's evocative aesthetics. Then, designers' prowess was intended to increase sales by preconditioning consumer behaviour with styling. Design education was teacher-centred with closed briefs, top-down theory, hands-on and computer skills transfer. Today, globalisation and technology have shortened the distance between theory and practice to imperceptible levels. Speed of change is inverting traditional order to making and then theorising, while making is redefining relationships between people, design, manufacturing and digital technologies. Critical making becomes intelligent creation of knowledge. As per Speaks (2003), "[t]hinking and doing, design and fabrication, and prototype and final design become blurred, interactive and part of a non-linear means of innovation." (Speaks, 2003, p. 192) Now, design value adds by defining and embracing producer-user knowledge co-production instead of accepting *fait accompli* products. Artefacts embody evolving knowledge via agile prototype iterations based on consultation, failure testing, distribution, adoption, and reconfiguration by users at different levels. Design artefacts retain currency if they stay meaningful through ease of use, users' experience and intervention (e.g. communication, interaction, networking, re-programming) instead of brand experience, as it was before.

Results

The project focused on how to upgrade design education from old-style skill transmission to modern transformative project-based learning (PBL) over eight years. A five stages timeline evolved from:

1. Contextualisation and preparation (2005-2006) to
2. PAR/DWR benchmarking (2007-2009),
3. Stage 2 evaluation (2010-2011),
4. PAR/DWR application of lessons learnt (2012-2014),
5. Stage 4 evaluation (2015-2016).

Contextualisation and preparation (2005-2006)
Starting in 2005, the research intended to overcome educational shortcomings that made students less employable after graduation. Strategically, the unit had to:

1. Identify and fill skill gaps between education and industry expectation
2. Teach latest technology
3. Transform skills into competencies that enabled students figuring out current complexity (business, design, social, sustainability)

PBL was meant to bring together knowledge from different course streams through making (e.g. graphics, management, sciences). However, evidence showed discrepancies between pursued learning outcomes and results. When compared against approved template, students lacked "understanding of new product development" (NPD), "examination of regional and global design strategies", "design responsibility towards users", and "capacity to simulate and realise solutions against the background of modern complex contemporary contexts". The unit ran for a 17-week semester with a convergent and 'closed brief' approach (specific requirements and outcomes to execute) directing students to craft a one model (e.g. lamp makeover) with restricted variations and some degree of aesthetics. The unit mainly comprised two stages. First, a technical package evaluation with minimal aesthetic flair ideation (six concept sketches). Second, a model fabrication complemented by 3D computer renderings of the same concept (three posters). The model had to be a polished exhibition block model (shell lacking functionality) with minor features (e.g. on-off light switch). Students worked on a few vague scrapbook-like sketches and a technical package report. A polished model and smooth 3D renderings did not add meaningful results for students. Many neither had preparation nor dexterity for hands-on modelling. Symptomatic of the course, the unit did not match our School of Engineering's STEM (science, technology, engineering, mathematics) aims towards integrated interdisciplinary learning and critical thinking within authentic contexts.

The first task for this research was breaking from transmission teaching and adjusting to a 14-week semester. Until then, students followed a sequential execution process similar to 1960s–1980s Phase Review's assembly line manufacturing (R. Cooper, 1996; 2001; 2008, 2014). The work was managed as a relay race. Tasks passed from one to the next, without commitment throughout. Accountability and iterative processes were missing. Backend micromanagement mechanisms controlled the unit, while cycles of open consultation, discussion, experimentation and discovery were neglected. Students' routines were allopoietic (allo = different, other) as they reproduced things unrelated to the self-creation needed to evolve their learning, unlike living biology. Observation, self-feedback, adjustment and self-production mechanisms were switched off (Figure 5). Consequentially, a unit makeover pilot tried to establish the following:

- Pragmatic constructionism (different to social constructivism) via collaborative learning-by-making and learning-through-playing. Essential to creativity, students independently played and pivoted by hacking, constructing and reconstructing in a tinkering process of building design as new knowledge artefacts (Harel & Papert, 1991; Papert, 1980, 1986).
- Models as series of low fidelity (Lo-Fi) to high fidelity (Hi-Fi) prototypes that expressed design heuristics and critical making, instead of just one polished block model.
- International design studio (IDS) project trial with overseas design programs used to benchmark and develop a new direction for the local course, with active participation of students, industry and government official partners.

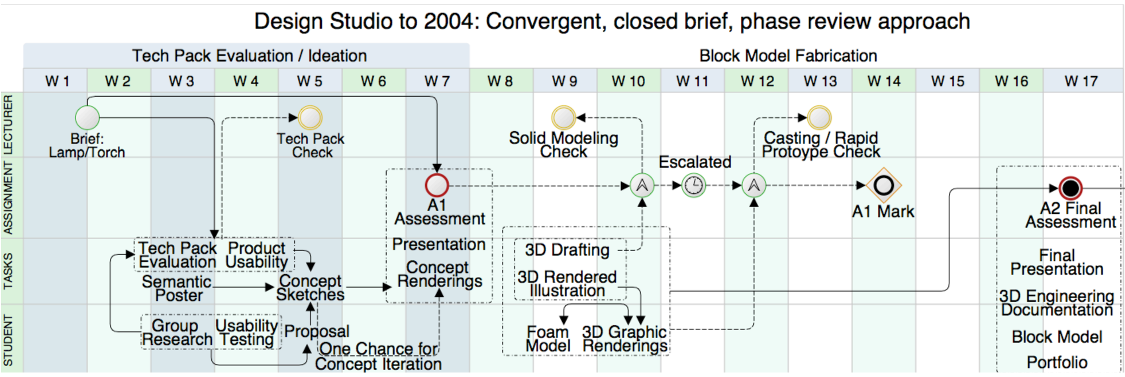


Figure 5. **Unit process flow before and after 2005. Curriculum transformation towards framework of inquiry**

PAR/DWR benchmarking (2007-2009)

The new unit invited students to work in open brief projects with an overarching theme of "learning-through-playing" and IDS with a professional design agency setup. Participants were empowered to transform their mind-sets, collaborate and resolve social systems through making, pivoting and empathy (Rouse & Rouse, 1991). Individual topics (e.g.

children toys, elderly rehabilitation, health and wellbeing) took them out of their comfort zone as projects no longer ran on assumption. Students liaised with final users to frame contradictions, areas of conflict, and to identify design problems to resolve. Practically, students learnt how to observe reality (e.g. historical, social), inquiry, identify barriers, collect data, reflect, interpret, and design through grounded experimentation and Lo-Fi to Hi-Fi prototypes used as user probes.

PAR and ethnography helped to build frameworks for activity systems that identified the natural setting of activities (the field), actors (subjects, community, institutions, tools), cognitive, cultural, environmental and social places, clusters and networks of action and meaning (mediating artefacts, division of labour, object, outcome). Contextual inquiry assisted to build workflow models to configure design research around personas, case studies, context, scenario and design iterations progressing towards a final working prototype (Beyer & Holzblatt, 1998; Crabtree, 2006; Holtzblatt, Wendell, & Wood, 2004). EL's four-reflective cycle process complemented a CDIO (Conceiving-Designing-Implementing-Operating) initiative that promoted an engineering education capable of leading the creation and operation of new products, processes, and systems. This sorted out the stresses between technical fundamentals; contextualised activity and experiential learning that enabled students to understand technology's impact on society (E. Crawley, Malmqvist, Ostlund, & Brodeur, 2007; E. F. Crawley, 2001).

Expectations changed from the previous program that accepted work as complete when it reached concept proposal only. Now, projects were final only after demonstrating a project's implementation, operation (use, adoption) and completion of CDIO/EL process. Final working prototypes proved their worth when trialled in real-life scenarios, with unique value propositions (UVP) and minimum viable products (MVP) at levels close to those of manufacturing in Asia. CDIO facilitated improvements of personal, interpersonal, system building, technical and management skills and work processes (methods, tools), while EL contributed the missing cultural, ethnographic and participatory methods critical to understand real user (student, final user) needs and the complexities of NPD team-based environments. STEM was also promoted to build technical and scientific evidence for projects.

By week 5, students' submissions comprised the entire previous curriculum for a semester. Work was presented via a Pecha Kucha pitch (20 slides in 6.5 minutes) and a report to stakeholders that rationalised user observation, consultation, context and problems framing, analysis, mental and concept visualisations, critical making, brief, Lo-Fi and block model concepts. The next nine weeks depended on peer review verdict (classmates, lecturer, industry coaches, final users). Projects with poor reviews were sent back for revision, while week 14 deadline stayed the same. Projects moved from Lo-Fi to High-Fi prototyping with partial-to-complete functionality systems and artefacts that users could interact with. Pivoting between research, iterative making and prototyping was critical for reflection and design. Students produced five-to-seven functional 3D physical models, virtual models, manual and machine-driven shaping, 3D printing, coding and human computing interaction (Figure 6).

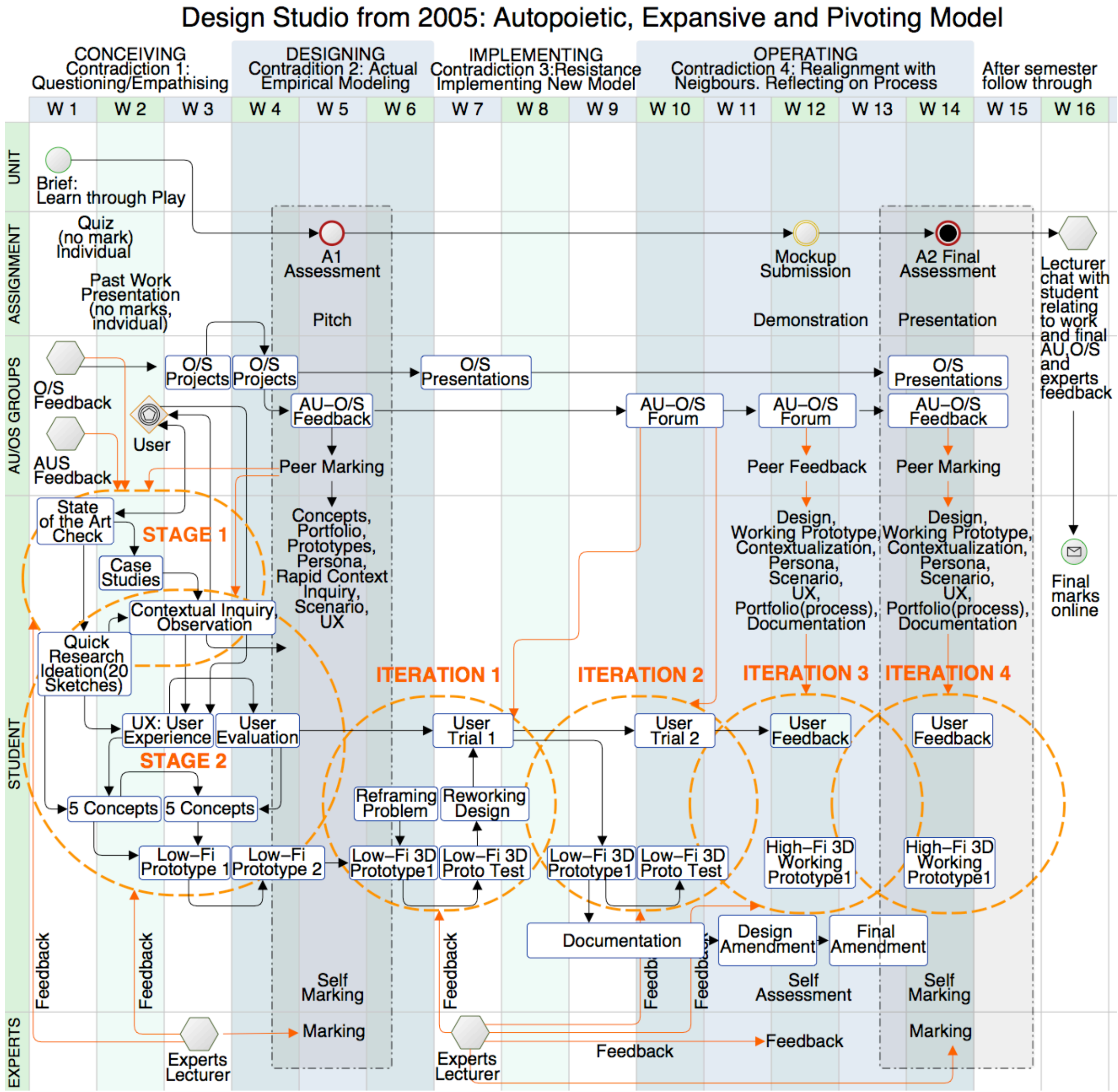


Figure 6. Unit process flow from 2005 as critical making, EL, DWR, HCD, CDIO, STEAM, UVP, MVP

Students customised innovation for their national market and others abroad. They understood users are no longer limited by geography. Participative collaboration helped students to find common issues to solve (e.g. cognitive development, obesity, aging market). MVP and UVP development benchmarks were kept as those of manufacturing and to attract financing partnerships. Quality of work, peer review, self-marking and reporting showed how students had a quick learning curve, became responsible and owned their projects from start to end. Design artefacts and projects were treated as arguments needing sound and corresponding physical, verbal, visual and written narratives. Students recorded every step through thick descriptions containing diaries, sketches, photos, and videos to explain meaningful actions and behaviour in context. Borrowing from Geertz (1972); (1973, 1993), students learnt how to structure annotations, diaries and visualisations by using a customised version of thick description. Step-by-step self and fieldwork reporting (e.g. interviews, PAR, observation, surveys) documented data, ideas, rationales, artefacts (e.g. sketches, concepts, photos, prototypes, videos) and process to explain actions, behaviour and cultural context. Narratives interpreted users' extroverted expressions, to give them meaning in:

- Semiotics terms,
- Revealing artefacts and systems "deep play" of human activity, beliefs and social discourse,
- Producing, coding (audio and video transcripts) and evaluating user events

The unit further grew onto transdisciplinary STEAM (Science, Technology, Engineering, Arts, Mathematics) championed by the Rhode Island School of Design. The 'A' denotes the arts as creativity, design, socio-cultural studies, language and liberal arts (e.g. ethics, logic, rhetoric). All provided higher-order thinking skills needed since learning and social complexity cannot be solved by science and advanced technology only (Guyotte, Sochacka, Costantino, Kellam, & Walther, 2015; Guyotte, Sochacka, Costantino, Walther, & Kellam, 2014; Maeda, 2012; Somerson & Hermano, 2013) Collective knowledge construction reformulated the unit as a self-learning organisation where students, users, industry experts and lecturer were team members (Senge, 1990). Participants peer assessed and marked each other based on evidence (e.g. research, heuristics, prototypes, user trials). They role played successively (e.g. client, designer, user, manufacturer, mentor, supplier, team member, cross group review) and formed experimentation and feedback chains for class forums (Figure 7).

This change was significant for students in relation to ICT as well. They used digital and open source tools to progress from Web 1 (instruction) to Web 2 (personalisation) and Web 3 (semantic use, knowledge creation and management). There was added complexity when international projects required synchronic and a-synchronic communication within and outside class time. Local and international participants, guest and mentors (Australia, Canada, Chile, Germany, U.S.A, Finland, Netherlands) communicated through physical, face-to-face, digital, mediated, simulated and virtual technologies. Weekly AARNet video conference lectures were held with national and international guests (industry, politics, design experts). Social networking worked as early form of product lifecycle management (PLM) and distributed e-Manufacturing. Students later shared and updated work via Blackboard, blogs and e-portfolios connected with social services (e.g. Facebook, YouTube, Delicious, Drop.io). They coded and designed digital and physical simulations with traditional hand-on tools, machinery, C++, Arduino and 3D printing (Figure 8, 9, Table 2).

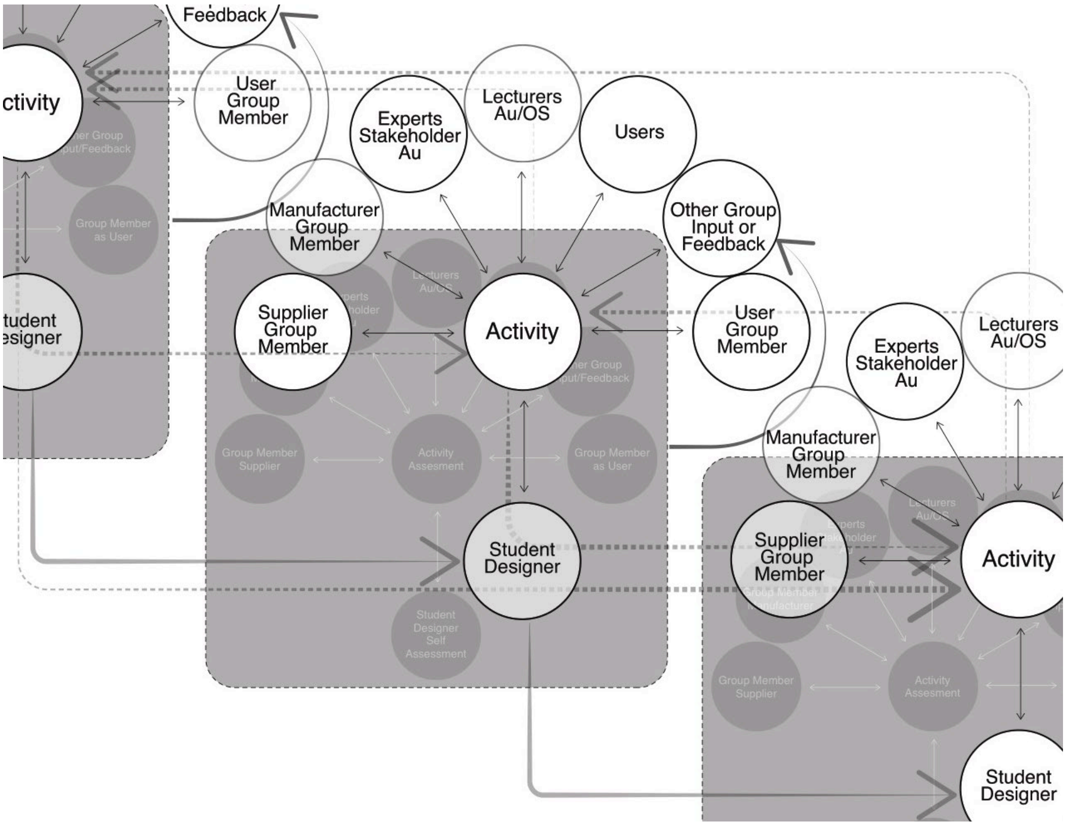


Figure 7. Participants self-learning role swapping in Australia and also with overseas from 2005

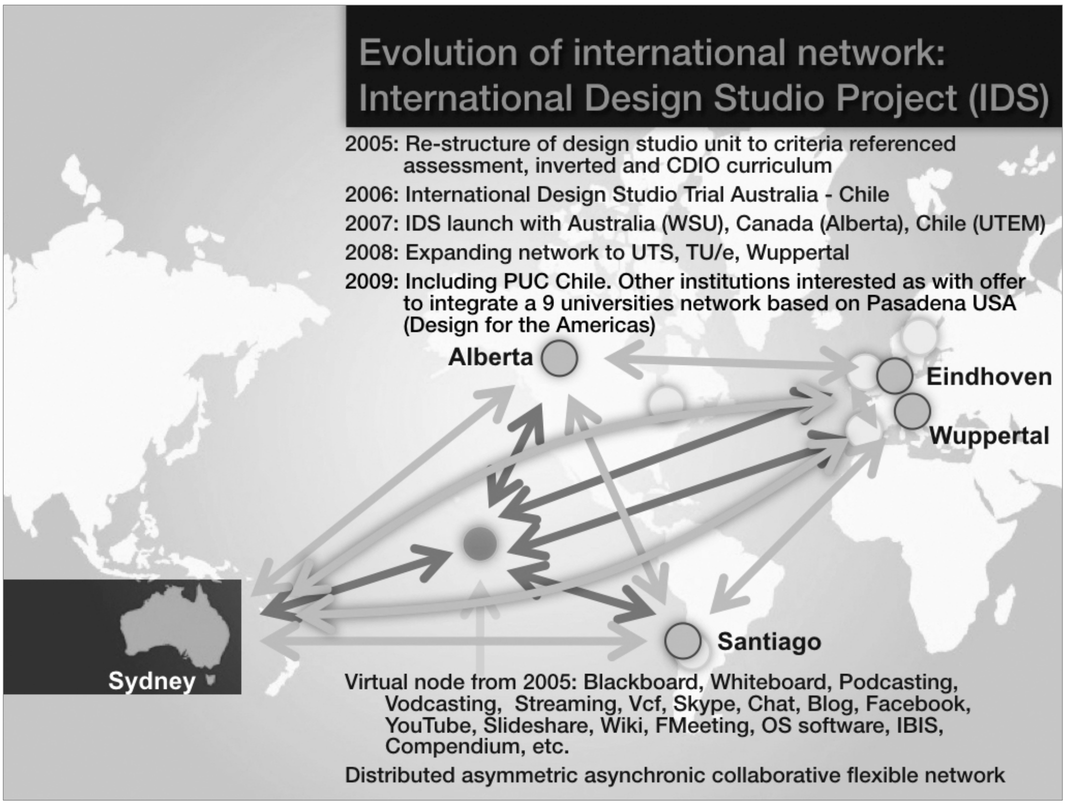


Figure 8. IDS network

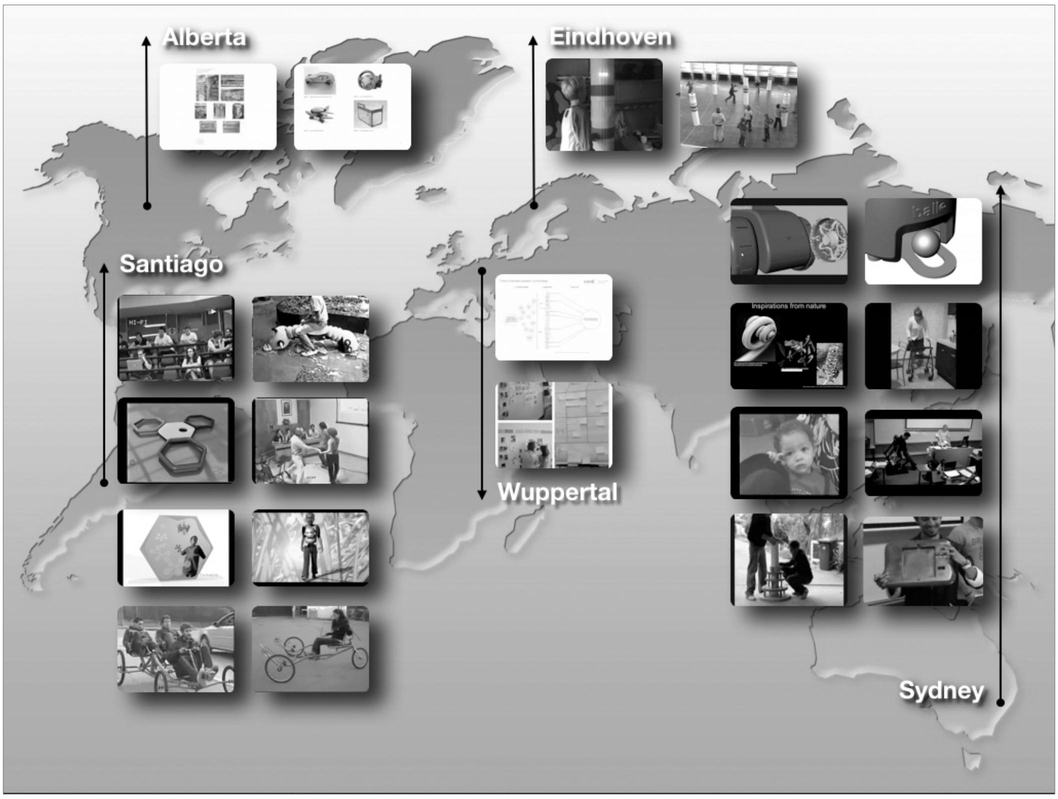


Figure 9. Students work, mentoring and examples

Stage 2 evaluation (2010-2011)

Stage 3 evaluated students' learning dynamics and outcomes for the period 2007-2009. However, PAR/DWR was suspended for this period. The course turned to a conservative mode of delivery that had worked for decades. This was seen as a natural reaction to disturbance of the status quo. Work and benchmarking disrupted the local traditional transmission teaching model. Still, data gathered had to be checked for relevance, so that lessons could be applied modularly and transferred to other cases for future opportunities. This research was based on the argument that the industrial design industry, its market, stakeholders and users have changed since the start of our 21st century. Globalisation and technology diffusion have broken conventional divides among disciplines, geography, hard and soft technology and production. In Australia, traditional-trained industrial design and its employment have dropped in the last three decades because they depend greatly on hard technology. Importantly, production has moved to nearby Asian countries at a cheaper cost and increasing quality. These countries are already moving into the creative domains of NPD and innovation. Hence, design education needs to embrace that change with new forms of collaboration, communication, learning, production and work.

Over five years, the project transformed the capstone unit from an industrial age teacher-centred approach to a 21st century inverted curriculum with student/user-centred and agile development focus. Participants critically made design statements through prototyping and user participation with unique problem framing, solving and new elucidations. They moved quickly through making, theorising and formulating new knowledge with iterative visualisation and testing. Inquiry, conceptualisation and design progressed in cycles from Lo-Fi to Hi-Fi prototypes. As per Egger (2000), Lo-Fi was a lowtech and low cost remedy for tunnel visions. Purposely, students were discouraged from beginning with technical specification and high-resolution modelling. Instead, they explored mental and conceptual modelling of human-centred design (HCD) alternatives following observation, consultation and experimentation. Regardless of individual backgrounds, experience and skill, participants became comfortable with using a mix of post-it notes, paper, cardboard and foam block models, building and enacting scenarios. Then, they easily translated learning into high-level Hi-Fi physical and digital artefacts to meet and test user needs.

Table 2 Technologies used in the project

Traditional Technology skill sets: Physical – Face to Face					
	2005	2006	2007	2008	2009
	STEM		STEAM		
	Project Management: i.e. Mind/concept swim lanes, mapping, planning, agendas, meetings, worksheets, Gantt charts, minutes				
	Research: Design heuristics, design thinking, human-centered design, action language, participatory, observation, quantitative and qualitative, combinational, exploratory, transformational, thick description and ethnographic, etc.				
	Drawing skills: E.g. Conceptualizing, mapping, sketching, renderings, hand-drawing line and painted illustrations				
	Prototyping: E.g. Paper, block, working models, handcrafting, fiberglass, silicone, foam, wood, metal, vacuum forming, etc.				
	Presentation Skills: E.g. Felt and acrylic renderings, watercolor, pen, pencil, gouache, etc.				
New Technology skill sets: Digital – Simulation, Virtual					
Web	Web 1: Instruction	Web 2 : Personalization		Web 3: Semantic – KM and Creation	
	2005	2006	2007	2008	2009
			Student exchange		Chilean student exchange
3D CAD	3D CAD Parametric for Manufacturing: SolidEdge, SolidWorks □ 2D output (working, control and specification drawings) □ 3D Parts and assembly and STL output 3D CAD Polygon for Visualization (i.e. Rhino, 3D Max, VRay, Blender) 3D Rapid Prototyping: Additive StereoLithoGraphy (SLA), Fused Deposition Modeling (FDM), Stratasys, Object, Magic, STL / IGES, etc.				
Blended Learning	Blackboard vUWS (Assignments, Lectures, Podcasting, Discussion Board, etc.) Podcasting and Vodcasting (Participants recordings and broadcasting) Chat / MSN Messenger				
Project Management	**Mind/concept mapping software: MindMap, FreeMind, NovaMind, etc. Management software: MsProject, OpenProject, GanttProject, etc. Flexible and Distributed Manufacturing: □ Product Lifecycle and Data Management (PLM, PDM), □ Introduction to Advanced Device Management (ADM)**				
Mediated Comms		Video Conferencing (AARNet3) Virtual weekly classroom across the Pacific Skype, iChat, MSN Messenger Live			
Design		Coding, Programming Website Design Blogs			
Social Networking			**Delicious (web pages and bookmarks sharing) Facebook (lecturers and students exchange, online unit curriculum) ooVoo (video chat) Slideshare, You Tube, Wikis**		
Knowledge Management				Dropio (academic exchange) Semantic web (ontologies) OS broadcasting (i.e. FMeetings) OS Issue-Based Information System - IBIS: Compendium (information, ideas, arguments), VUE (integration of digital resources), XMind (project, knowledge management) EndNote, RefWorks Reference Finder, Treemaker	
Knowledge Management					**OS broadcasting OS KM (i.e. Compendium server based) Second Life (storing and exchange)**

Note. Reprinted from Novoa, 2010.

Students' thick descriptions and self-assessments helped to further understand factors that the official university qualitative surveys, called Student Feedback on Units (SFUs), did not cover. Three examples show the virtues of customising projects to stakeholders and final users. A South Sudanese refugee student had difficulty integrating technical skills and practice meaningfully (e.g. high-resolution 3D printing), in contrast with other students from stable families settled for generations in Australia. PAR/DWR triggered learning when he matched his experience, skills, and interests with user needs relating to the reconstruction of his home country, that was to gain independence in 2011. His work influenced his decision to go back and assist with developing educational resources for literacy (English, Dinka, Nuer, etc.), numeracy and STEAM. His approach was based on bottom-up community participation and training, basic industrialisation of raw, recycled and upcycled local resources, open source distribution and sharing of design plans and instruction (Figure 10).

Figure 10. South Sudan design for development (D4D) project for community reconstruction

Numerous students also focused on external competency benchmarks instead of internal pass-mark goals. Several stated willingly they 'did not reach the expectations and standards that all the others have done' These students asked for a fail mark and re-enrolment while 'looking forward to the next year's' unit again. They persisted even after an extension for submission was offered. They thought they had not upheld standards and said it would be unfair on the rest of the class to be given an extension for submission as that did not align with industry framework on deadlines. School management noted such a display of student ethics occurred for the first time in the University's records.

At the other end, several students obtained jobs after presenting their capstone unit work. Others received contract offers for commercialisation. Among them, a high-tech engineering arms industry recruit shared:

> "you have brought a business sense to me and other students, something that has been sorely forgotten. I would especially like to thank you for pushing me in your design studio unit, this produced fantastic results and really challenged not only myself, but the others in my group to produce a production ready concept for market. The end result was a contributing factor to my successful job interview with

> the defence industry beating mechanical engineers with more experience for the placement."

Students' outcomes merited consecutive invitations to exhibit publicly in Sydney CBD's historic Customs House. Reviews noted their quality rivalled graduating fourth-year Honours projects. There were 96 thank-you letters received after the unit and graduation following the 2007-2009 research phase. Many participants noted they completely understood the learning shift promoted in the unit once they were working in the industry. Subsequently, the University conferred the project with a 2012 University Citation Award for Outstanding Contributions to Students Learning. (Figure 11).

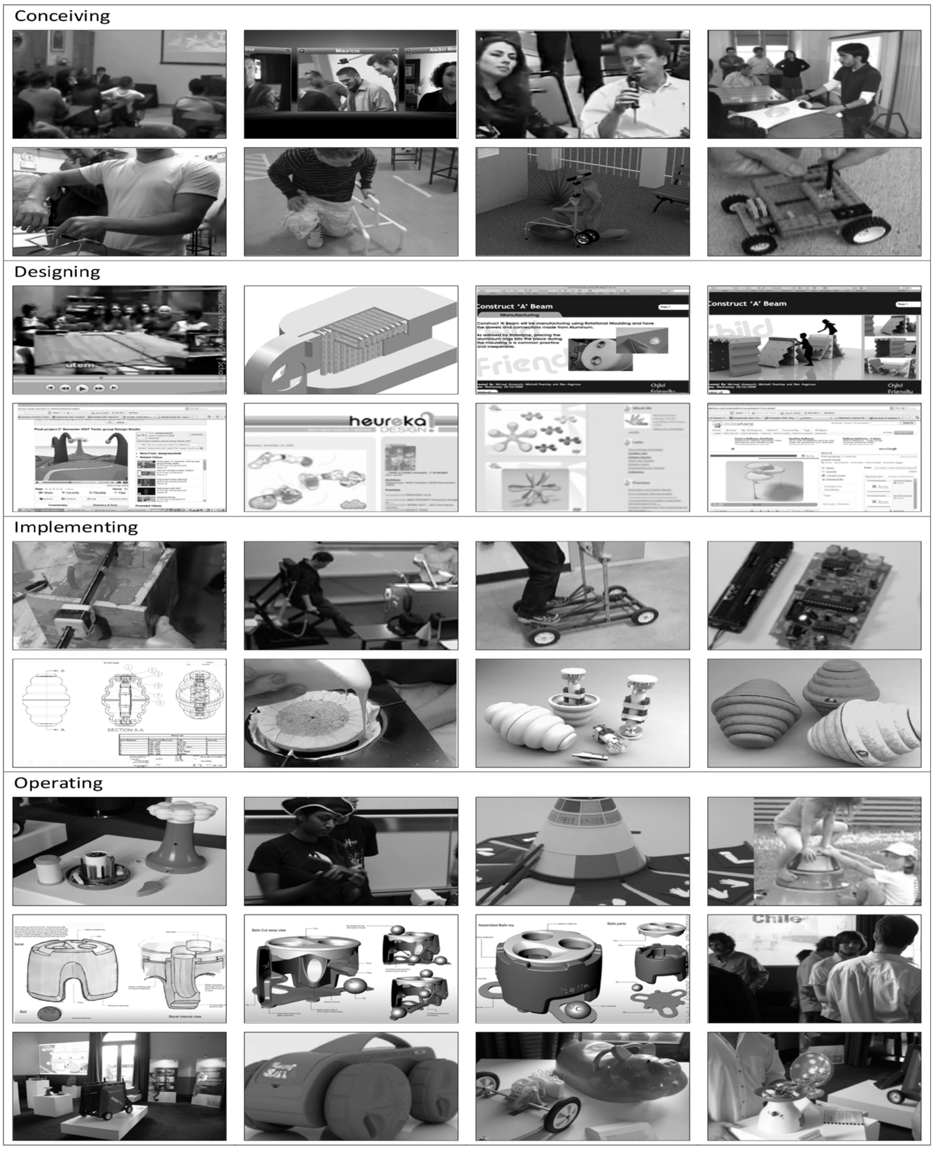


Figure 11. Participants' CDIO/EL process

The PAR/DWR approach found deeper learning issues than official measurements could uncover. 25 volunteers participated as case studies each time for over three years from a total of 119 students plus others from low socio-economic status (Low-SES) who attended free of charge. Qualitative analysis was based on students' comments, feedback, participation, recommendations and work (visual, written, verbal, thick descriptions, etc.).

Importantly as pre-project diagnosis, students were asked to fill a quiz and show what they considered their previous best and worst work at the beginning of the semester. They then answered a post-project quiz and offered comments. Two forms of qualitative assessments were chosen to understand data gathered. Multidimensional parallel coordinates helped in assessing complex sets of information among participants as directional trends that had no typical natural order in traditional teaching. Those visualisations would prove customised DWR viability beyond assessment marks despite participants' backgrounds, experiences, socio-economic status, provenance and geographies for education and upbringing. ANOVAs (analysis of variance) were also used to assess whether there were potential statistical variations and significant differences among participants' work in the same period and over three years. Plotted observations would show how reliable the applied methods were, while taking into account potential year-to-year changes (e.g. different cohort, infrastructure, regulation, technical and workshop support).

30-dimensional variables were plotted into a multidimensional parallel coordinates' visualisation. Among them, 27 distinctive variables that comprised students' quizzes, assignment components (e.g. research, concepts, development, modelling, testing), and students' descriptions and assessments (self-inspection, individual, allocated group, cross group review) were measured binarily in reference to three main factors:

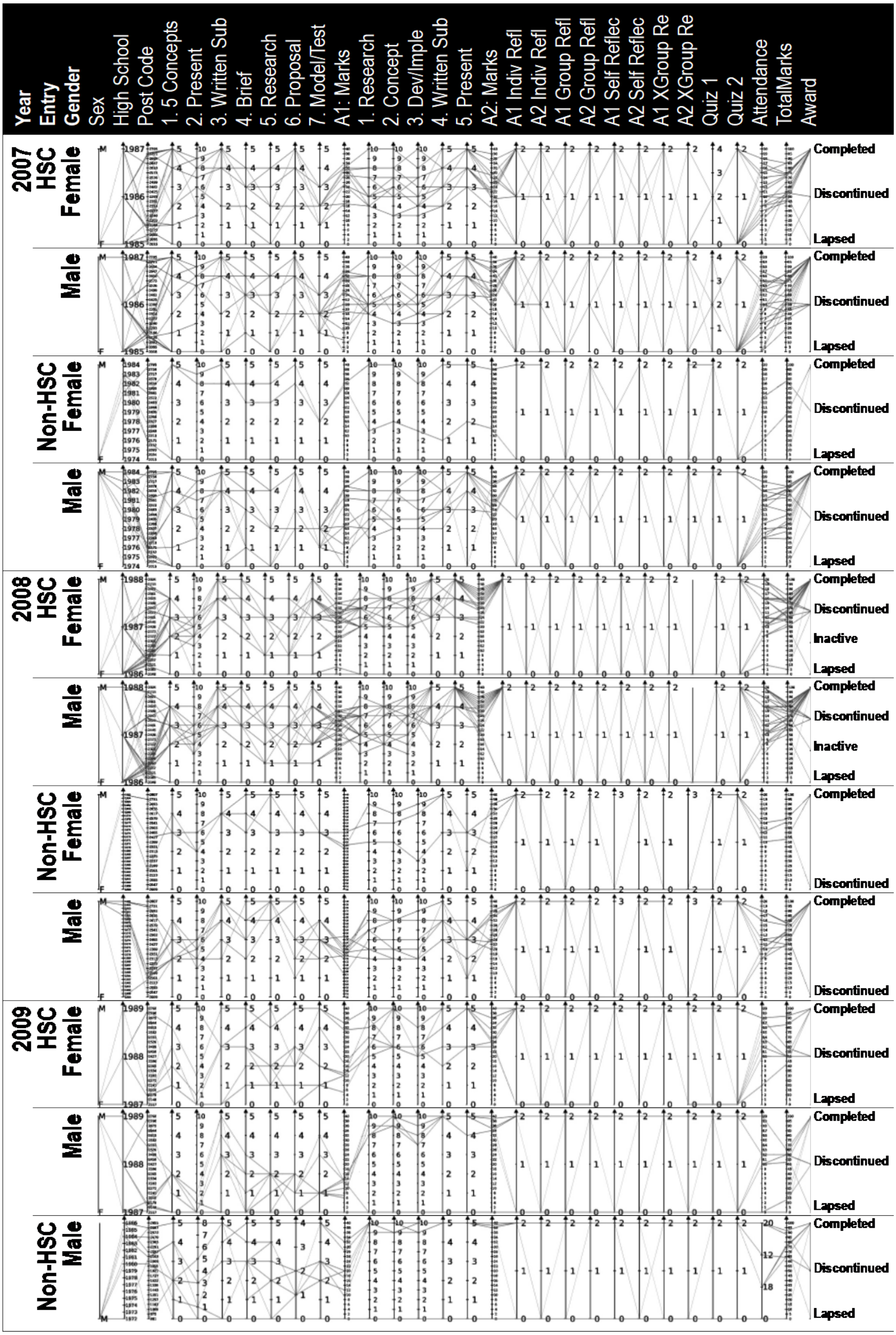
Age: That divided direct-entry students to the course who were school leavers with high-school certificate (HSC) and non-direct entry who were mature students (Non-HSC)

Gender: To distinguish differences in learning modes

Postcode: This was used as indication of background, economic status and provenance, as per demographic statistics.

Plotting and scaling showed similar linear correlation on order and rotation among age and gender. Blushing demonstrated that females achieved proportionally higher than males in tasks relating to contextualisation and data analysis. Meanwhile, males moved up quicker and scored higher than women in relation to research by making, development and modelling. Visualisation supported PAR observations that women performed well in networking and detailing while males did with manual work. The latter were less engaged and communicative than the former at the start of the unit. Although all improved progressively, initial negative (inverse) correlations relating to teamwork collaboration confirmed doubts that students were trained for it when they reached senior year. Non-HSC participants had higher retention, completion rate and achieved better marks than HSC participants proportionally. Postcodes indicated that students came mainly from three areas characterised by middle-class blue-collar population with a high multicultural mix (Asian, European-Mediterranean, Middle-East, Latin American). Still, location did not precondition individual outcome. Private or public schooling did not show significant difference relating to critical thinking, 2D and 3D visualisation, method and process of design. Those abilities and STEM literacies were below standard at the start of the unit. However, writing skills were stronger in students coming from private school. Regardless of age, gender, postcode and SFU results, plotted observations moved upwards over time towards positive relationships in the unit (Table 3).

Table 3. 2007-2009 Multidimensional parallel coordinates for HSC and Non-HSC.



Two factor ANOVAs were applied to participants' work to see whether plotted observations indicated significant reliability. Three null hypotheses were prepared to test:

1. No difference between students' traditional teaching (evidenced through part of assessment 1) and new learning methods (demonstrated with assessment 2)
2. No difference among assignments over a three-year period
3. No interaction effect among dependent over independent variables in the tests

ANOVAs presented students' marks as attribute independent variables (rows) in relation to two practical assignments representing dependent variables (columns) presumed as results of the manipulation of independent variables. Significance was to be demonstrated by a P-value of less than 0.05 threshold (95% level of confidence probability) and whether the F-value (variance of a group means among groups) was larger than the F-critical (boundary between significance and non-significance).

The first three ANOVAs without replication (Tables 4, 5, 6) for individual years showed the new teaching approach influenced unit learning in the last two years but had no significance in 2007. Conversely, 2007 and 2008 showed significant individual improvements while 2009 did not. Some correlation was seen with SFU Likert results (shown further). A last ANOVA with replication (Table 7) assessed the three years longitudinally and led to recommend to:

- Reject the first null hypothesis and support the alternative
- Accept the second null hypothesis that validates methods longitudinal consistency
- Reject the third null hypothesis and validate interaction effect and influence of dependent variables (assignments) over independent variables (students).

PAR/DWR application of lessons learnt (2012-2014)

This research restarted after a two-year hiatus while another academic delivered the unit on traditional mode. The opportunity came about when statistics showed the standard transmission model for education was insufficient (e.g. student attrition at 50%, negative student satisfaction surveys for the course). A vision for a student-centred, industry and socially integrated curriculum was proposed. The 2005-2009 research period on this capstone unit served as proof of concept for course makeover. The 2012-2014 stage would pursue to achieve reliability, consistency of measure, and outcomes that could be transferred to other circumstances.

New students to the unit said they knew about this capstone's high expectations since starting their degree. They welcomed the opportunity to work in this PAR/DWR phase. However, they also felt challenged by its standards. This time, digital and ICT tools were upgraded. The course was supported with new computing and collaborative learning spaces, workshop, 3D rapid prototyping lab (25 low-to-high resolution units), and an e-portfolio Pebble+ (Blackboard complimentary) grant that simplified the many ways students developed projects online and social networking. This instalment kept the model as before while taking further steps to enhance the design of NPD work with:

- Scaffolding of three assessments that fed and overlapped each other with a concurrent engineering process
- Agile development based on participants collaboration and critical making
- Work integrated learning (WIL) of real life projects supported by industry coach-experts
- Benchmarking to prove outcomes' consistency and validity outside the University and within industry and the public

Each assessment fit complete CDIO/EL's four-reflective contradictions cycles every four weeks. Assessments complexity increased to a level equivalent to junior/mid weight designer in the industry. Learning-by-making and learning-through-playing empowered students to own their projects and develop associative, concurrent, multi-layered, multi-literate and deep learning. Brief releases started with:

- Week 1 "Assignment 1: Rapid Contextualisation (Closed Brief)" intended to quickly form a collaborative community that produced from Lo-Fi prototypes to operational proof of concepts. The fast pace of work pushed students to abandon passive habits acquired with transmission teaching. They experimented, built, tested, rode and raced against each other a cardboard 1:1 scale vehicle in three weeks. Then, they did a post-mortem, amended projects, did further testing and marked themselves in reference to other students and international benchmarks.

Table 4. 2007 ANOVA Two Factor Without Replication

Anova:'Two'Factor'Without'Replication

2007 SUMMARY

Student'No	Count	Sum	Average	Variance
2	2	68	34	2
3	2	68	34	0
5	2	70	35	18
8	2	67	33.5	4.5
12	2	68	34	0
15	2	42	21	32
16	2	37	18.5	4.5
20	2	44	22	162
21	2	68	34	0
22	2	67	33.5	4.5
25	2	60	30	2
28	2	57	28.5	24.5
30	2	70	35	18
36	2	67	33.5	4.5
39	2	67	33.5	4.5
41	2	70	35	18
44	2	30	15	200
45	2	37	18.5	4.5
47	2	70	35	18
49	2	70	35	18
54	2	57	28.5	24.5
56	2	68	34	0
61	2	38	19	8
64	2	37	18.5	4.5
67	2	70	35	18
Assessment'1	25	705	28.2	63
Assesment'2	25	762	30.48	55.76

ANOVA

rce'of'Variati	SS	df	MS	F	P'value	F'crit
Rows	2320.72	24	96.6966667	4.38268621	0.00029299	1.98375957
Columns	64.98	1	64.98	2.94515788	0.09901781	4.25967727
Error	529.52	24	22.0633333			
Total	2915.22	49				

Table 5. 2008 ANOVA Two Factor Without Replication

Anova:'Two'Factor'Without'Replication

2008 SUMMARY

Student'No	Count	Sum	Average	Variance
4	2	60	30	8
7	2	59	29.5	84.5
8	2	59	29.5	84.5
9	2	58	29	98
11	2	59	29.5	24.5
12	2	59	29.5	40.5
13	2	60	30	72
14	2	43	21.5	12.5
16	2	3	1.5	4.5
19	2	56	28	0
21	2	64	32	18
27	2	42	21	72
32	2	59	29.5	60.5
38	2	57	28.5	4.5
42	2	62	31	2
43	2	60	30	0
44	2	60	30	0
45	2	62	31	2
46	2	63	31.5	4.5
47	2	64	32	8
48	2	62	31	2
49	2	64	32	8
51	2	45	22.5	4.5
52	2	46	23	8
54	2	62	31	2
Assessment'1	25	640	25.6	35.8333333
Assesment'2	25	748	29.92	61.4933333

ANOVA

Source'of'Variati	SS	df	MS	F	P'value	F'crit
Rows	1944.12	24	81.005	4.96303482	0.00010643	1.98375957
Columns	233.28	1	233.28	14.292658	0.00091563	4.25967727
Error	391.72	24	16.3216667			
Total	2569.12	49				

Table 6. 2009 ANOVA Two Factor Without Replication

Anova:'Two'Factor'Without'Replication

2008 SUMMARY

Student'No	Count	Sum	Average	Variance
4	2	60	30	8
7	2	59	29.5	84.5
8	2	59	29.5	84.5
9	2	58	29	98
11	2	59	29.5	24.5
12	2	59	29.5	40.5
13	2	60	30	72
14	2	43	21.5	12.5
16	2	3	1.5	4.5
19	2	56	28	0
21	2	64	32	18
27	2	42	21	72
32	2	59	29.5	60.5
38	2	57	28.5	4.5
42	2	62	31	2
43	2	60	30	0
44	2	60	30	0
45	2	62	31	2
46	2	63	31.5	4.5
47	2	64	32	8
48	2	62	31	2
49	2	64	32	8
51	2	45	22.5	4.5
52	2	46	23	8
54	2	62	31	2
Assessment'1	25	640	25.6	35.8333333
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ANOVA

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Rows	1944.12	24	81.005	4.96303482	0.00010643	1.98375957
Columns	233.28	1	233.28	14.292658	0.00091563	4.25967727
Error	391.72	24	16.3216667			
Total	2569.12	49				

Table 7. 2007-2009 Assessments 1 and 2 ANOVA Two Factor with Replication

Anova: Two-Factor With Replication

SUMMARY	Assessment 1	Assesment 2	Assessment 3	Total
2007				
Count	25	25	25	75
Sum	705	762	298	1765
Average	28.2	30.48	11.92	23.5333333
Variance	63	55.76	18.41	113.711712
2008				
Count	25	25	25	75
Sum	640	748	374	1762
Average	25.6	29.92	14.96	23.4933333
Variance	35.8333333	61.4933333	23.04	79.0911712
2009				
Count	25	25	25	75
Sum	448	766	1561	2775
Average	17.92	30.64	62.44	37
Variance	180.326667	158.906667	4472.34	1915.81081
Total				
Count	75	75	75	
Sum	1793	2276	2233	
Average	23.9066667	30.3466667	29.7733333	
Variance	109.842523	89.661982	2006.25874	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	9094.56889	2	4547.28444	8.07351981	0.00041551	3.03766731
Columns	1905.50222	2	952.751111	1.6915711	0.18666111	3.03766731
Interaction	32473.2711	4	8118.31778	14.4137452	1.9001E-10	2.41344398
Within	121658.64	216	563.234444			
Total	165131.982	224				

- Week 3 “Assignment 2: Industrial Device (Semi Open Brief)” release of Lo-Fi to Hi-Fi design, implementation and operation with five WIL industry coaches’ WIL.
- Week 4 Assignment 1 presentation and marking overlapped with “Assignment 3 Open Brief” major assessment release where students applied the learning gained to date with a full CDIO/EL resolution.
- Week 8 Assignment 2 presentation, collective and individual self-assessment.
- Week 14 Assignment 3 presentation with a chance to present revisions of previous assessments.

Similar to the 2007-2009 PAR/DWR stage, students were able to compress traditional semester models into four weeks. That realisation helped setting up concurrent NPD processes that simulated design work in the industry. Again, students said they had worked more in this unit than in any other in the course before. They commented the faster pace CDIO/EL cycles became an effective trigger for learning, critical making and design. Their self-esteem was boosted when invited to participate on national competitions. With no precedent in the course history, students won commendations, second and first awards over three years in events dominated by other prestige and better financed universities. Awarded students earned a one-year internship and mentoring with the industry. Their projects were taken further into commercialisation (Cormack, 2013 - 2015). These awards resulted from one assessment of four weeks in the unit. This was in contrast to other universities' entries, where the whole semester was dedicated to this students' competition project.

Stage 4 evaluation (2015-2016)

This final evaluation checked on PAR/DWR stage 4 findings in relation to PAR/DWR stage 2 to confirm consistency and reliability. The former comprised international students' participation to lesser degree than the latter. However, its main focus was to benchmark against institutional and industry standards locally. A 2012-2014 revision of students' written comments, notes and 112 outcomes (as a sum of three assessments per year over three years), showed similar to Stage 2 when handling large variables of qualitative data (e.g. multidimensional parallel coordinates, ANOVAs). Outcomes demonstrated a quick shift in students experience from transmission teaching to transformational learning can be possible and benefits them.
Official data and qualitative surveys supported this research's aims and outcomes. The Australian cohort was unique. Data for the unit was incomplete until 2007. Nevertheless, it showed the University hosted the largest number of Low-SES students in the country. 60% were first in a family attending university. They came from any one of 150 nationalities and ethnic groups (Universities Australia, 2016). Equity issues were only measured since 2012 and other data was not detailed on per unit basis. Information gathering relied on students' willingness to offer it (e.g. Low-SES, private or public school, first/second/third generation migrant, Ma Engineering students in the unit). The industrial design program intake mirrored the national productivity decrease in manufacturing with a downward attrition trend for a decade (22 students per year inferred). This trend that averaged to 50% retention started to revert in 2013 (Table 8).

Table 8: Students enrolment 2007-2014

Year	2007	2008	2009	2010	2011	2012	2013	2014
ID Course Enrolment	230	197	176	168	158	144	132	142
D&T Course Enrolment	83	87	72	104	91	74	83	82
ID/D&T Course Enrolment	313	284	248	272	249	218	215	224
Attrition based on previous year	-15	-29	-36	+24	-23	-31	-3	+9
Unit Enrolment	47	50	22	39	39	41	49	22

Note: Reprinted from data provided by Western Sydney University's Office of Quality and Performance, 2016

SFUs' qualitative psychometric surveys comprised 13 items Likert scales and voluntary comments ('best', 'need improvement') that showed the following results for the 2007-2009 and 2012-2014 periods (Table 9)

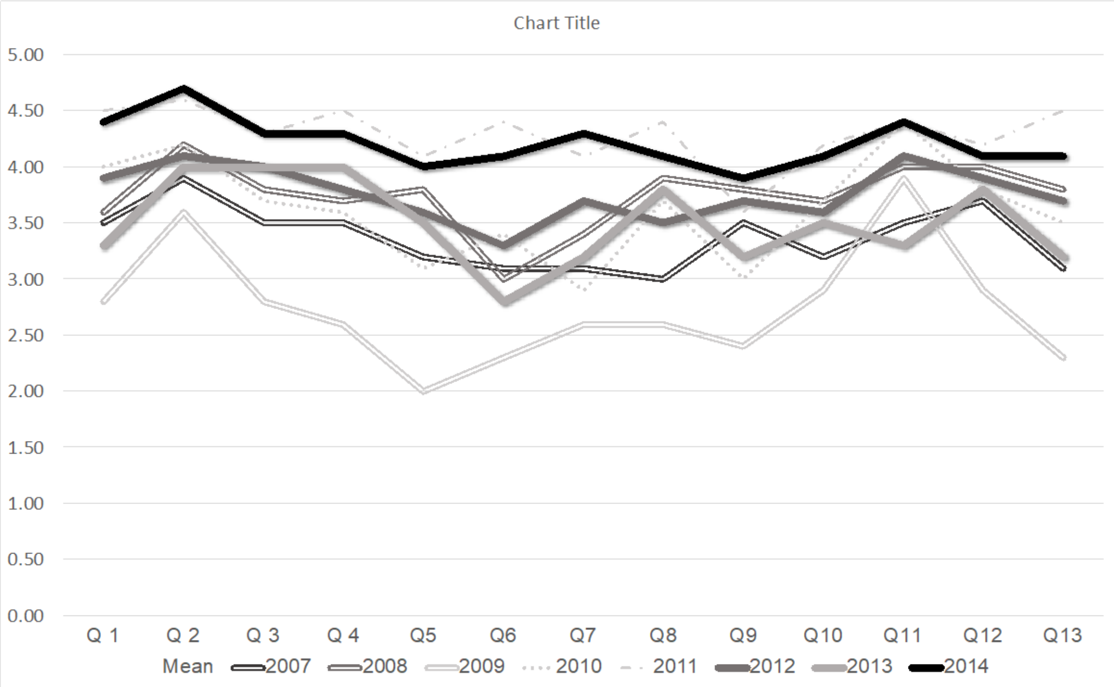
1. Positive 2007-2009 and 2012-2014 relevance on equity, fairness, critical thinking, analysing, problem solving and communicating skills
2. Negative 2007-2009 feedback on assessment methods and guidelines. Unpacking data and overall experience year per year revealed that:

   a. 2007-unit feedback was below the School mean as students were the first group experiencing this disruptive transformational model.
   b. 2008-unit feedback overall experience was parallel with the School mean
   c. 2009-unit overall experience was below the School and University mean, as students pointed to sudden loss of design studio workshop, machinery, resources and technical support
3. Positive 2012-2014 feedback on assessment methods and guidelines was either equal or better than traditional teaching results in the form of:
   a. 2012-unit overall experience above 2008 results.
   b. 2013-unit downturn was likely to suffer from sampling bias result of a total 13% response. The University statistician commented that participants who are in disagreement fill surveys more than those who are fine with a unit.
   c. 2014-unit overall experience was mostly above the School/University mean.

Psychometric attitude surveys revealed further limitations relating their inherent kind of measurement and potential numerical errors. Several studies (Backer, 2012; Centra, 2003; Denson, Loveday, & Dalton, 2010; Greenwald & Gillmore, 1997; Kulik, 2001; Marsh, 2007; Ory & Ryan, 2001; Pegden & Tucker, 2012; Theall & Franklin, 2001) showed that those tests work better with direct individual skill-task acquisition are partial against transformational learning since the latter becomes evident over time beyond a singular unit. Psychometric attitude surveys measure isolated units with the assumption that students know what the benchmarks in education and industry are. Therefore, it is difficult to distinguish whether feedback is objective about a unit or reflects parallel issues or legacy from previous units. Also, universities use them to assess academic performance and promotion. Subsequently, academics may fall into strategies to avoid adverse response, influence perceived benefits or grades leniency.

For example, this eight-year research revealed students' background and insularity from design and innovation mainstreams were not visibly enhanced by the time they reached the unit. 2009 SFUs were the only platform for students to express their views at the front-end when losing workshops, labs, equipment, and technical support for this capstone unit and the course. Numerous students did not know that loss belonged to larger changes to infrastructure that proposed the industrial design course should be taught through digital simulation in students' laptops. Likewise, the University statistician identified the 87% of students who did not fill the surveys was as meaningful as the 13% that responded them in year 2013. This research foresaw a group, such as the latter, would be dissatisfied since EL requires students' self-reliance and ownership. Stages 2 and 4 comparison showed SFUs improved visibly from 2012 alongside fixing the course's direction and infrastructure problems that allowed for critical making and pivoting to blossom. Students concentrated on bridging gaps they had between previous teaching, industry and user benchmarks pursued in the unit. The last three-year period showed similar or better results than the School and University mean averages and targets; many of those still based on transmission teaching models.

Table 9. 2007-2009, 2012-2014 Qualitative psychometric attitude results



Year	2007	2008	2009	2010	2011	2012	2013	2014
Unit Enrolment	47	50	22	39	39	41	49	22
Quantitative Survey Feedback (Results in Graph above)								
SFUs Returned	26	40	14	23	28	26	6	7
Response rate (%)	41	74	56	56	67	62	13	27
Qualitative Survey Feedback								
Best Aspects (No. of comments)	20	19	2	N/A	N/A	17	6	6
Unit Learning (%)	90	95	100	N/A	N/A	82	100	100
Unit Management (%)	5	5	0	N/A	N/A	6	0	0
Technical Support/Space (%)	5	0	0	N/A	N/A	12	0	0
Needs to Improve (No. of comments)	19	19	12	N/A	N/A	15	7	6
Unit Learning (%)	10	10	0	N/A	N/A	0	0	0
Unit Management (%)	42	42	40	N/A	N/A	94	100	100
Technical Support/Space (%)	48	48	60	N/A	N/A	6	0	0

Likert Qualitative Psychometric Attitude Survey (13 Items)	
1. Unit Content: Unit covered what outline said it would	2. Relevance: I was able to see relevance of this unit to my course
3. Learning Design: The learning activities in this unit have helped my learning	4. Assessment Activities: Assessment in this unit have helped me learn
5. Assessment Feedback: I was able to learn from feedback I received in this unit	6. Assessment Guidelines: There were clear guidelines for all assessment tasks in this unit
7. Learning Resources: The learning resources provided helped me to engage in learning	8. Learning Flexibility: The unit provided a reasonable amount of flexibility for study
9. Learning Spaces: Teaching and learning spaces used for this unit were adequate	10. Workload: The amount of work required in this unit was reasonable
11. Equity/Fairness: In this unit, people treated each other fairly and with respect	12. Generic Skills: This unit helped me develop my skills in critical thinking, analyzing, problem solving and communication
13. Overall Experience: Overall, I have had a satisfactory learning experience in this unit	

Note: Reprinted from data provided by Western Sydney University's Office of Quality and Performance, 2016

Discussion

This research proposed active participation of students, industry experts, government officials and final users to figure out interactions not usually considered between people, technology and their environment. It focused on two areas currently challenging for industrial design. The industrial age productivity models are no longer enough when the profession is now globalised and dematerialising, while educational institutions also experience an increasing gap between their offerings and leading innovation benchmarks. Digital, physical, visual, and written data gathered showed that design education can add meaningful value to students and industry, so they create new means of production and social progress through leading knowledge and design-driven innovation. However, there were also a number of issues brought into attention.

As per Urry (2005), the project reappraised modern learning challenges in an environment that simulated complex global contemporary contexts and promoted social knowledge construction, experimentation and participation. Its strength was that it ran opposite to typical expertise that focused on basic discipline's technical skill acquisition. Many students did not fit the traditional profile of those who excel in tertiary education and working life. They were prepared mainly to execute closed briefs given by academics who assumed end of value chain manufacturing scenarios. Consequentially, students lacked contextualisation, critical making, HCD and pivoting thinking competencies when they reached the unit. Benchmarking considered user needs and students' background and experience to open opportunities for a unique learning culture. Thereby, the project value-added to education and industry with its participatory and design-driven mediation. This showed that students were able to shift into transformational learning in one semester. They were better equipped for employment when connecting upbringing, talent, and skills with contextualised environments, needs and resources. Also, they increasingly realised they could apply their skills and competencies to wider and newer areas for design intervention at a time the discipline is being redefined as post-industrial design in this 21st century.

Auxiliary questions for this research were also shown as interconnected. Typical industrial design education was based on transmission models that were indifferent to students' background and experience. Design intelligence development was limited because of students' lack of identification with projects, tasks, their meaning and purpose. The capstone unit promoted transformative improvement when customising knowledge construction and learning through heuristics of play and experimentation. However, one unit at the end of a course was not enough to revert three years of skill reproduction and transmission. Real change would come from establishing a new culture of learning from intake into the course. This was a point that Australian participants noted; their curriculum was highly regulated, high-tech focused, expensive and delegated tasks to technical support (e.g. machinery use, 3D printing and modelling). Initially, they shied away from industry involvement, coaching and collaborative work with others locally and abroad. By contrast internationally, Chilean participants ideated, developed mental and conceptual models, and took design artefacts through failure testing and up to working model stage manually from discarded or recycled materials. 25 participants each season came from a waiting list of 278 (300 students in their course). Their IDS project was an extra unit outside curriculum required for graduation. Most students were not bilingual. Yet, they prepared lengthy for dissertations in English via live video conferencing. Similarly, the Canadian and German students were used to work in collaborative communities of learning and used flexible and mediated technologies.

Such examples show curriculum may set autopoiesis, ZPD and 3GCHAT mechanics. However, knowledge externalisation, internalisation and cognitive progression do not happen if individuals are passive and incapable of socialising, owning and modifying the structures that precondition them. Australian participants repeatedly said the capstone unit helped them changing from a 'ticking the box' mentality to realising the importance of querying activities and making them worthwhile to resolve user need through empathy, customization and social construction of knowledge. Design research was a mediating activity that allowed potential innovation when blurring and crossing boundaries (Rancière, 2006) among students, users, industry coaches, experts, media, physical and digital materialities. Solving wicked problems through making and WIL helped students to figure out user and technology obstacles represented by information access and overload, physical-digital divide, training and socialisation breakdowns (Jenkins, 2012; Jenkins, Purushotma, Weigel, Clinton, & Robison, 2009). Customisation was critical for mediating tools such as mental and conceptual modelling, PAR, DWR and CDIO within an emerging sense of openness, unpredictability of outcomes and multiple futures that shape physical, digital and non-linear relationships across time and space. Visualising that diversity assisted students to map from a minimum discipline progress they might achieve to the promise of a new frontier of transdisciplinary implementation for industrial design.

Each year, students made post-mortem recommendations freely. These were compiled as tipping points that may trigger transformational learning as long as academics, institutions and students show the same willingness that participants in this project had. The rewards would be invigorated design learning and innovation when traditional professional practice suffers of diminishing industrial age manufacturing application. Students' concerns were how to change education to benefit the next generations. Repeatedly, they suggested the transformational model would work best if implemented through the complete course. A new course was formulated by 2014 for a launch in 2016, after more than a decade that our university asked for course reformulation. The course introduces students to the current 4.0 industrial revolution of smart manufacturing, automation, data exchange, cyber-physical systems, decentralised decisions and internet of things that enables artificial intelligence, creates virtual copies of the physical world and also generates intelligent devices threatening to take over means of employment from traditional industrial designers (Bledowski, 2015; Kagermann, Helbig, Hellinger, & Wahlster, 2013; Shafiq, Sanin, Szczerbicki, & Toro, 2015).

The following 10 tipping points were compiled based on students critical making experience in the unit. Several suggestions coincided with recommendations coming from experts in modern theory of design that consider from individual background and experience to institutional policy and practice within a growing hyper-complexity of organisations, products, technologies and socialities:

1. Approach: To shift units from allopoietic and convergent teacher-centred transmission to student-centred transformation characterised by autopoiesis, critical making, pivoting and expansive learning
2. Boundary Crossing: To connect academics and students as participants within units and across courses to break away from skill silos
3. Curriculum: To apply the capstone model to the whole course. Students wished they had worked like that from first year since they only learnt design research methods and heuristics at the end of the course
4. HCD: To replace aggregated skill acquisition with solving wicked problems as design challenges emerge together instead of following one another (Lawson, 1980; Rittel & Webber, 1973)
5. Methodology: To implement meaningful agile development that is contextual, CDIO, empathetic, design research and participatory driven
6. Modelling (Mental): To model system's causality and simulate competing small-scale prototypes of reality to facilitate reasoning, foresee actions and trigger explanations (Craik, 1967)
7. Modelling (Conceptual): To design abstract, digital and physical system prototypes to make problems and solutions graspable to participants (student, users, other stakeholders), and assist modularity and scalability (Norman, 2013).
8. Participation: To implement PAR, DWR and WIL with dynamics of discussion, inquiry, iterative making and reflection among participants (students, users, other stakeholders),
9. Transformative Learning: To implement EL based on cognitive, social constructivism and constructionism that customises learning based on individual and group background and experience, and how students can connect with the larger reality of industry, society and technology.
10. Triggers: To implement series of empathy activities to trigger cultural, suspend pre-conceptions and uncover people's unspoken needs within activity systems (Leonard & Rayport, 1997; Leonard & Sensiper, 1998).

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References

Backer, E. (2012). Burnt at the Student Evaluation Stake-the penalty for failing students. *The E-Journal of Business Education & Scholarship of Teaching, 6*, 1-13.

Beyer, H., & Holzblatt, K. (1998). *Contextual Design: Defining Customer-Centered Systems*. San Francisco, CA: San Francisco, CA : Morgan Kaufmann Publishers.

Bledowski, K. (2015). The internet of things: Industrie 4.0 vs. the industrial internet | MAPI Foundation. *Manufacturers Alliance for Productivity and Innovation, USA*.

Boden, M. A. (2004). *The creative mind: Myths and mechanisms*: Psychology Press, Routledge.

Boden, M. A. (2009). Computer models of creativity. *AI Magazine, 30*(3), 23.

Buchanan, R. (2001). Design Research and the New Learning. *Design Issues, 17*(4), 3-23. doi:10.1162/07479360152681056

Centra, J. A. (2003). Will teachers receive higher student evaluations by giving higher grades and less course work? *Research in Higher Education, 44*, 495-518.

Cooper, R. (1996). Overhauling the new product process. *Industrial Marketing Management, 25*(6), 465-482.

Cooper, R. G. (2001). *Winning at New Products: Accelerating the Process from Idea to Launch*: Perseus.

Cooper, R. G. (2008). Perspective: The Stage-Gate® idea-to-launch process—Update, what's new, and NexGen systems. *Journal of Product Innovation Management, 25*(3), 213-232. doi:10.1111/j.1540-5885.2008.00296.x

Cooper, R. G. (2014). What's next? After stage-gate. *Research Technology Management, 57*(1), 20-31. doi:10.5437/08956308X5606963

Cormack. (2013 - 2015). Home | Cormack Innovation Awards. Retrieved from http://cormackia.com.au/?page_id=48

Crabtree, A. (2006). *Designing collaborative systems: A practical guide to ethnography*: Springer Science & Business Media.

Craik, K. (1967). *The nature of explanation*. Cambridge, England: Cambridge University Press.

Crawley, E., Malmqvist, J., Ostlund, S., & Brodeur, D. (2007). Rethinking engineering education. *The CDIO Approach, 302*, 60-62.

Crawley, E. F. (2001). *The CDIO Syllabus: A statement of goals for undergraduate engineering education*. Cambridge, MA: Massachusetts Institute of Technology.

Denson, N., Loveday, T., & Dalton, H. (2010). Student evaluation of courses: what predicts satisfaction? *Higher Education Research & Development, 29*(4), 339-356.

DiSalvo, C. (2009). Design and the Construction of Publics. *Design Issues, 25*(1), 48-63. doi:10.1162/desi.2009.25.1.48

Dunne, A. (2005). *Hertzian Tales: Electronic Products, Aesthetic Experience and Critical Design*: MIT Press.

Dunne, A., & Raby, F. (2001). *Design Noir: The secret life of electronic objects*: Springer Science & Business Media.

Egger, F. N. (2000). *Lo-Fi vs. Hi-Fi Prototyping: how real does the real thing have to be?* Paper presented at the Teaching HCI workshop, OzCHI.

Engeström, Y. (1995). Objects, contradictions and collaboration in medical cognition: an activity-theoretical perspective. *Artificial Intelligence In Medicine, 7*(5), 395-412. doi:10.1016/0933-3657(95)00012-U

Engeström, Y. (1999a). Activity theory and individual and social transformation. In R.-L. Punamäki, R. Miettinen, & Y. Engeström (Eds.), *Perspectives on activity theory* (Vol. 19, pp. 19-38). Cambridge: Cambridge University Press.

Engeström, Y. (1999b). Innovative learning in work teams: Analyzing cycles of knowledge creation in practice. *Perspectives on activity theory*, 377-404.

Engeström, Y. (2001). Expansive Learning at Work: Toward an activity theoretical reconceptualization. *Journal of Education and Work, 14*, 133-156. doi:10.1080/13639080020028747

Engeström, Y. (2005). *Developmental work research: Expanding activity theory in practice* (Vol. 12): Lehmanns Media.

Engeström, Y. (2014). *Learning by expanding*: Cambridge University Press.

Flanders, M. (2011). What is the biological basis of sensorimotor integration? *Biological cybernetics, 104*, 1-8.

Friedman, K. (2012). Models of Design: Envisioning a Future Design Education. *Visible language, 46*(1/2), 133-153.

Geertz, C. (1972). Deep play: Notes on the Balinese cockfight. *Daedalus, 101*(1), 1-37.

Geertz, C. (1973). *The interpretation of cultures*. New York, N.Y.: Basic Books.

Geertz, C. (1993). *The interpretation of cultures: Selected essays*. London: Fontana Press.

Greenwald, A. G., & Gillmore, G. M. (1997). Grading leniency is a removable contaminant of student ratings. *American psychologist, 52*(11), 1209.

Guilford, J. P. (1967). *The nature of human intelligence*. New York, N.Y.: McGraw-Hill.

Guyotte, K. W., Sochacka, N. W., Costantino, T. E., Kellam, N. N., & Walther, J. (2015). Collaborative creativity in STEAM: Narratives of art education students' experiences in transdisciplinary spaces. *International journal of education & the arts, 16*(15).

Guyotte, K. W., Sochacka, N. W., Costantino, T. E., Walther, J., & Kellam, N. N. (2014). STEAM as social practice: Cultivating creativity in transdisciplinary spaces. *Art Education, 67*(6), 12-19.

Harel, I. E., & Papert, S. E. (1991). *Constructionism*: Ablex Publishing.

Holtzblatt, K., Wendell, J. B., & Wood, S. (2004). *Rapid contextual design: A how-to guide to key techniques for user-centered design*: Elsevier/Morgan Kaufmann.

Jenkins, H. (2012). *Textual poachers: Television fans and participatory culture*: Routledge.

Jenkins, H., Purushotma, R., Weigel, M., Clinton, K., & Robison, A. J. (2009). *Confronting the challenges of participatory culture: Media education for the 21st century*: Mit Press.

Kagermann, H., Helbig, J., Hellinger, A., & Wahlster, W. (2013). *Securing the future of German manufacturing industry. Recommendations for implementing the strategic initiative INDUSTRIE 4.0 Working Group*. Retrieved from National Academy of Science and Engineering, Germany: https://www.acatech.de/Publikation/recommendations-for-implementing-the-strategic-initiative-industrie-4-0-final-report-of-the-industrie-4-0-working-group/

Koskinen, K. U. (2009). Project-based company's vital condition: structural coupling. An autopoietic view. *Knowledge and Process Management, 16*(1), 13-22.

Krippendorff, K. (1995). Redesigning Design; an invitation to a responsible future. In P. Tahkokallio & S. Vihma (Eds.), *Design - pleasure or responsibility*. Helsinki, Finland: University of Art and Design.

Kulik, J. A. (2001). Student ratings: Validity, utility, and controversy. *New directions for institutional research, 2001*(109), 9-25.

Lawson, B. (1980). *How designer think*: Architectural Press.

Leonard, D., & Rayport, J. F. (1997, 1997-11-01T05:00:00Z). Spark innovation through empathic design. *Harvard Business Review.*

Leonard, D., & Sensiper, S. (1998). The role of tacit knowledge in group innovation. *California management review, 40*(3), 112-132.

Lyon, P. (2004). Autopoiesis and knowing: reflections on Maturana's biogenic explanation of cognition. *Cybernetics & Human Knowing, 11*(4), 21-46.

Maeda, J. (2012). STEM to STEAM: Art in K-12 is key to building a strong economy. Retrieved from https://www.edutopia.org/blog/stem-to-steam-strengthens-economy-john-maeda

Marsh, H. W. (2007). Students' evaluations of university teaching: Dimensionality, reliability, validity, potential biases and usefulness. In R. P. Perry & J. C. Smart (Eds.), *The scholarship of teaching and learning in higher education: An evidence-based perspective* (pp. 319-383): Springer, Dordrecht.

Maturana, H., & Varela, F. (1973). De Máquinas y Seres Vivos: una caracterización de la organización biológica. *Santiago, Chile: Editorial Universitaria*.

Maturana, H., & Varela, F. J. (1980). *Autopoiesis and Cognition - The Realization of the Living*. Reidel, Dordrecht, Holland: Springer Netherlands.

McGann, J. J., Ortner, S. B., & Dirks, N. B. (1991). *The textual condition*. Princeton, New Jersey: Princeton University Press.

Mingers, J. (1997). Systems typologies in the light of autopoiesis: a reconceptualization of Boulding's hierarchy, and a typology of self-referential systems. *Systems Research and Behavioral Science, 14*, 303-313.

Norman, D. A. (2013). *The design of everyday things: Revised and expanded edition*. New York, N.Y.: Basic Books. A member of the Perseus Books Group.

Novoa, M. (2010). Improving Design Education by International Collaboration, Traditional Skillsets, Discovery and Ubiquitous Learning. *Design Principles & Practice: An International Journal, 4*.

Novoa, M. (2012). 2012, *Vision for Industrial Design Course: Presentation to Directors of Academics Program Panel*, Unpublished internal document.

Ory, J. C., & Ryan, K. (2001). How do student ratings measure up to a new validity framework? *New directions for institutional research, 2001*, 27-44.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*: Basic Books, Inc.

Papert, S. (1986). *Constructionism: A New Opportunity for Elementary Science Education*. Cambridge, MA: Massachusetts Institute of Technology, Media Laboratory, Epistemology and Learning Group.

Pegden, J.-A., & Tucker, B. (2012). Does the timing of evaluations matter? An investigation into online student feedback and whether timing has an impact. *Studies in Learning, Evaluation, Innovation and Development, 9*(1), 66-73.

Poggenpohl, S. H., & Sato, K. (2009). *Design integrations research and collaboration*. Chicago: Intellect, the University of Chicago Press.

Rancière, J. (2006). Thinking between disciplines: an aesthetics of knowledge. *Parrhesia, 1*(1), 1-12.

Ratto, M., Atkinson, P., Avital, M., Mau, B., Ramakers, R., & Hummels, C. (2011). Open Design and Critical Making. In B. van Abel, L. Evers, R. Klaassen, & P. Troxler (Eds.), Open Design Now: Why Design Cannot Remain Exclusive. Amsterdam: BIS Publishers. Retrieved from http://opendesignnow.org.

Ratto, M., & Hockema, S. (2009). Flwr Pwr: Tending the Walled Garden. *Walled Garden. Virtueel Platform Amsterdam, The Netherlands*, 51-60.

Rittel, H. W., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy sciences, 4*(2), 155-169.

Robinson, S., & Pallasmaa, J. (2015). *Mind in architecture : neuroscience, embodiment, and the future of design*. Cambridge, Massachusetts: The MIT Press.

Rouse, W. B., & Rouse, W. B. (1991). *Design for success: A human-centered approach to designing successful products and systems* (Vol. 2). New York: Wiley-Interscience.

Schar, M. (2015). *Pivot thinking: Predicting entrepreneurial intent among engineering students and faculty using problem solving style preference*. Paper presented at the 2015 IEEE Frontiers in Education Conference (FIE), Camino Real El Paso, El Paso, TX, USA.

Schar, M. F., Leifer, L. J., Hinds, P., & Shavelson, R. J. (2011). *Pivot Thinking and the Differential Sharing of Information Within New Product Development Teams*. Stanford University. Department of Mechanical Engineering: Stanford University.

Senge, P. (1990). The fifth discipline: The art and science of the learning organization. *New York: Currency Doubleday*.

Shafiq, S. I., Sanin, C., Szczerbicki, E., & Toro, C. (2015). Virtual engineering object/virtual engineering process: a specialized form of cyber physical system for Industrie 4.0. *Procedia Computer Science, 60*, 1146-1155.

Somerson, R., & Hermano, M. L. (2013). *The Art of Critical Making*. Hoboken, New Jersey.: Wiley.

Speaks, M. (2003). Design intelligence. Part 11: Winka Dubbeldam / Archi-Tectonics. *A+U: Architecture and Urbanism, 11*(398), 190 - 197.

Theall, M., & Franklin, J. (2001). Looking for bias in all the wrong places: a search for truth or a witch hunt in student ratings of instruction? *New directions for institutional research, 2001*(109), 45-56.

Universities Australia. (2016). Western Sydney University Profile. *Universities Australia.* 18 September 2016. Retrieved from https://www.universitiesaustralia.edu.au/australias-universities/university-profiles/Western-Sydney-University/Western-Sydney-University#.WDgp1JInZRI

Urry, J. (2005). The complexities of the global. *Theory, Culture & Society, 22*, 235-254.

Vygotsky, L. S. (1980). *Mind in society: The development of higher mental process*: Cambridge, MA: Harvard University Press.