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UNDERSTANDING GROUP DESIGN BEHAVIOUR IN ENGINEERING DESIGN EDUCATION

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ABSTRACT
Observations in industry show that engineers' perceptions of design activity tend towards positivistic, rational problem-solving, which is at odds with the nuanced, situated, constructivist nature of observed design behaviour. This paradigmatic mismatch appears to inhibit the ability of engineers to reflect 'on' reflecting 'in' action, and is apparently formed during engineering design education which, within the UK and commonly elsewhere, is heavily influenced by a positivistic 'engineering science' doctrine. In this research natural group design behaviour in engineering design education was explored through detailed observation of undergraduate group-project activity. An analytic framework was formed by three sensitising concepts: *design as the resolution of paradoxes, designerly ways of knowing*, and *design as talk*. Key findings conceptualise natural design activity in this setting as a form of constructivist inquiry akin to case study research. Five core activity themes emerged; *collecting data, analyzing and interpreting data, identifying themes, theory-building and testing,* and *telling the story*. Students engaged spontaneously in these core activities. Findings were sense-checked from an ontological and epistemological viewpoint, and found to be well-grounded *if* design is considered from a complexity perspective. Implications are that a radically different pedagogy may be appropriate for engineering design education. Students could significantly benefit from understanding their own design activity as constructivist inquiry, rather than rational problem-solving. Set within a broader education in the 'philosophy of design', rooted in a complexity paradigm, students could be better enabled to reflect on their own experiential learning of design. Thus resolving the paradigmatic conflict between perception and practice.

Keywords: Design paradigm, design behaviour, design pedagogy.

1 INTRODUCTION

Our world is changing. The major problems of today are manifestly different from those of the past. The dawn of the digital age and an explosion in 'smart' technologies means that the very fabric of our society has become complex and networked. Historically the focus of design has been on the physical artefact, but as our world continues to complexify we see "increasingly ambiguous boundaries between artefacts, structure, and process, increasingly large-scale social, economic, and industrial frames; a complex environment of needs, requirements, and constraints, and information content that often exceeds the value of the physical substance" [1]. These challenges require a different approach to engineering practice. Dorst [2] suggests that a "radically new species of problem" has emerged, and that they require a "radically different response". He describes these new problems as "open, complex, dynamic, and networked". For example, problems relating to issues of climate change, global food production, antibiotic resistance, sustainable energy and transport, health and an aging population. These problems are open because the system boundaries are not clear. They are complex, because the problem situation consists of many interconnected elements. You cannot divide or abstract the problem situation, it must be approached as a complex whole. They are dynamic, because the problem situation changes over time, with the addition of new elements and shifting connections, and networked, because the problem situation is spread across organisations, with multiple stakeholders, who unexpectedly influence the problem situation. Rational problem-solving practices are inadequate in the face of such challenges, practices that rely on isolating the problem, decomposing into simple sub-problems amenable to analysis, and generating a series of sub-solutions ready for recombining into an overall solution. When a problem cannot be isolated from its wider context, or decomposed without ignoring critical interdependencies, or analysed or abstracted using simplified models, then a different approach to problem-solving is needed.

It is not news that the rational problem-solving model of the design process has been found wanting in these respects. However, it remains the dominant problem-solving model within engineering design education, in the UK and elsewhere, as exemplified by systematic methods such as those described in Pahl and Beitz [3], amongst others. Rational problem-solving has its place within the wider engineering curriculum, particularly in relation to core engineering science subjects, but there is a need for additional problem-solving approaches that enable graduates to tackle the kind of open, complex, dynamic, and networked challenges described. The problem is not that these issues are not known, rather it seems that there is not a suitable alternative. The findings from design research are generally esoteric and subtle in their nature, meaning engineering design educators have little to grasp hold of in the way of effective new pedagogical approaches.

The positivistic culture engendered by a focus on this kind of problem-solving does not fit with natural design behaviour observed in practice [4]. These observations show that perceptions of engineering design activity in industry tend towards positivistic, rational problem-solving, which is at odds with the nuanced, situated, constructivist nature of their observed design behaviour. This paradigmatic mismatch appears to be inhibiting the ability of these design engineers to effectively reflect 'on' reflecting 'in' action. This ability to reflect is critical to learning in design [5], and a necessary modus operandi in the face of open, complex, dynamic and networked problems. This paradigm conflict appears to stem from engineering design education which, within the UK and commonly elsewhere, is heavily influenced by a positivistic 'engineering science' doctrine. This educational culture is ill-equipping engineering graduates for the realities of future industry. Many of the global issues of our time will require innovative design solutions. But innovative, conceptual design does not sit comfortably within the rational problem-solving paradigm Engineering design projects are also becoming increasingly complex, therefore new educational approaches to engineering design that embrace complexity are needed. All this suggests that future engineering graduates will need an additional set of problem-solving skills to those of current graduates. Our rapidly evolving understanding of design problems and processes "presents a formidable challenge to engineering educators striving to ensure that students not only become technically and scientifically knowledgeable but also are prepared to engage competently in the complexities of design processes. The time criticality of this challenge has been articulated by industry, engineering forums, and accrediting agencies" [6]. Perhaps we need to rethink some aspects of engineering design education.

2 METHODOLOGY

As part of a programme of doctoral research, two ethnomethodological case studies were undertaken, in the first and final (fifth) years of the academic programme in the dept. of Mechanical Engineering, at the University of Bristol. Findings from both studies support the conclusions of this paper, but only the first year case study will be presented here (see [7] for full details of both studies).

2.1 Research questions

Two key research questions were developed after consideration of the problem situation as outlined:

- *SRQ1: How can design activity within group projects in engineering design education be described and understood?*
- *SRQ2: What basis for alternative pedagogical approaches within engineering design education, if any, might lead to a resolution of the paradigm conflict?*

2.2 Analytic framework

Three key sensitising concepts were identified as highly linked and broadly relevant to the identified research problem. The first is 'design as the resolution of paradoxes', a constructivist theory developed by Dorst [8], in which design problems are conceived as paradoxes formed by conflicting discourses in the design situation, and creative design is the forging of connections between these discourses. The second concept is 'designerly ways of knowing', a set of ideas established primarily by Cross [9], outlining the specific set of abilities and knowledge required to design including; a solution-focused mode to problem-solving, using non-verbal media, and using 'abductive' thinking. The final concept is 'design as talk', the idea that talk is the crucial enactor of design, that design is a social process, and information exchanges between team members, in the form of talk, provide the fundamental basis for collaborative design activity. Design as talk encompasses ideas relating to storytelling, negotiation, shared understanding, and the productive force of language such as analogy and metonymy. These ‘sensitising’ concepts form a core theoretical tripod broadly outlining; a philosophical description of what design is, the unique abilities and knowledge that designers must have in order to go about design, and a key medium through which those abilities are enacted. The research questions are explored and answered with respect to this analytic framework.

2.3 Case study context

The educational context of the undergraduate degree programmes within the school of engineering is that of an integrated project-based learning (PBL) approach to design. A PBL type experience is a feature of almost every year within the various undergraduate programmes, with most culminating in a major design project in the final year. The university is also a member of the international CDIO initiative. At the time of this study (2013), undergraduate students in the first year of the MEng in Mechanical Engineering studied units in dynamics, materials, fluids, thermodynamics, computer-based modelling, electronics, engineering maths, and design and manufacture. They were also required to undertake a group design project in the second semester, over an 8 week period, with a further week spent building and testing prototype devices at the end of the academic year. The cohort of almost 150 students was divided into 18 design teams, containing 8 or 9 students in each. Students were allocated to teams in order to achieve a balanced spread of ability and gender, though female students represented a small minority within the cohort as a whole, numbering only one or two of the students per team. One design team from the cohort was randomly selected, containing 8 students of various nationalities and ethnicities, 6 male and 2 female. The timetabled studio slot for the design project was 3 hours a week, and the team had regular interactions with their supervisor. The main project objectives were; learning effective design strategies, using creativity and innovation, experience in selection and costing of materials and components, honing drawing skills, and improving team work. The design brief was for a new coffee vending machine that dispenses plastic cups from a stack, using a programmable controller, a 12V DC power supply, whilst keeping within a budget of £100. Basic materials were available from the workshop as well as access to simple tools and manufacturing processes. All other materials and components had to be bought in using the given budget.

2.4 Data collection and analysis

Primary data was collected through participant observation, over the 8 week design period (not the build week), in a small design studio within the school of engineering. This resulted in 21 hours of video recordings. Secondary data was also collected, in the form of a project course guide, student design report, presentation slides, informal interviews, Facebook group posts, final team marks and assessment feedback, and 36 pages of field notes. This secondary data was not formally analysed and coded, but served to triangulate data and provide background information about the wider study context. The primary data set was inductively analysed using a thematic analysis approach. According to Clarke & Braun [10] “thematic analysis is a method for identifying, analysing, and reporting patterns (themes) within data”. They outline six phases of thematic analysis, and the primary data set has been analysed in accordance with this procedure, using NVivo coding software.

3 ANALYSIS & FINDINGS

18 parent codes, and 21 sub-codes were established from the data (see [7] for full list). Having made some initial sense of the data, with reference to the analytic framework, I attempted to group the codes into higher level themes that would bring some coherence to these ideas, and give insights into the underlying mechanisms of paradox resolution, in terms of talk, and designerly ways of knowing. It was then that I began to notice the similarities between the students approach to designing, and my own approach to research. See figure 1. Five core activity themes emerged; *collecting data, analyzing and interpreting data, identifying themes, theory-building and testing,* and *telling the story*. An additional theme of *enablers* also emerged, encapsulating processes that support the five core activities. The students engaged spontaneously in these core activities, directly analogous to case-study research.

Figure 1. Map of parent codes grouped into themes

3.1 Collecting data

In case study research, the three most commonly used methods of data collection are; interview, document review, and observation. The students were seen to go about collecting data using all three of these methods. Interview was the method used most extensively. These interviews were almost always informal and spontaneous. The key interview subjects were the two studio supervisors, and the faculty technicians. They also interviewed students from other groups within their cohort, as well as previous cohorts, and also each other. Document review was the second most utilised method. Sometimes these documents were physical paper copies, but more often they were digital copies viewed online. The primary document was the project guide, written by the course director. Each guide contained information about aims and objectives, time-scales, resources, budget, assessment criteria and submission details. Other documentation included patents, catalogues, and technical specifications. Observation was the least used method of data collection. They observed the use of real vending machines in action, both in person and remotely via clips on YouTube. They also looked at Google images, using architecture for ‘inspiration’ for the outer casing of their coffee machine.

3.2 Analysing & interpreting data

Analysing and interpreting is all about how the students take the collected data and organise it, reduce it, transform it, and try to make sense of it. Simons [11] defines *analysis* as “those procedures, like coding, categorising, concept mapping […] which enable you to organise and make sense of the data”. The group did this for example by trying to establish functions, flows, and sequences etc. Both verbally and visually. They used methods and tools to help analyse the data e.g. functional analysis, concept mapping, and morphological analysis. They discussed and clarified functions, they developed the ‘operating sequence’, they wrote the specification, compared different concepts, advantages and disadvantages, and evaluated against criteria in a process of down-selection. Simons defines *interpretation* as “the understanding and insight you derive from a more holistic grasp of the data […] evoked through analogy, imaging, reflective thinking, puzzling over incidents and observations, exploring alternative interpretations”. The group frequently used sketching, group discussion, and analogy as methods of data interpretation, e.g. “*pinball”, “guillotine”, “castle drawbridge”, “shopping centre door”, “fingernail”, “pneumatic drill”, “car distributor cap”,* and “*chicken’s foot”.*

3.3 Identifying themes

Dorst [2] suggests that designers search the broader problem context for ‘themes that inform new frames’. The students could be seen to take this approach. The discourses on ‘design aspects’ within the project were; technology, manufacturing, economics, functionality, and aesthetics. The key themes that the students identified related directly to these discourses. One of the earliest themes the group identified was ‘cup separation as critical function’, which relates to the design discourse on ‘functionality. A second theme was ‘simplicity’, which relates to both the functionality and manufacture discourses. A third theme was ‘motor vs. solenoids’, which is related to the design discourse on technology. The students established motors were expensive, but could drive two subsystems. Solenoids were cheap, but the displacement small. The discourses on ‘stakeholder value’ within the project were; making-it-work, innovation, design-as-student-project, and design-as-commercial-product. Key themes identified by the students related to these discourses. A key stakeholder value theme was the conflict: student project vs. commercial product, as well as the conflict: make-it-work vs innovation. The final stakeholder value theme identified was that of ‘getting credit’, related to all four stakeholder value design discourses. It was not always clear to the students what would gain them most credit, and members of the group interpreted the evidence differently.

3.4 Theory-building & testing

In this context ‘theory’ means a proposed design concept. The students started theory-building i.e. suggesting solution ideas, almost from the beginning, and they used basic materials i.e. sketching, a stack of cups, and their own hands, to ‘test’ their ideas. More formal testing and planned prototyping came later in the project. The group also tested their theory through talk i.e. they discussed and debated their ideas at length, trying to find issues, or improved alternatives. They continued to refine their theory right up until the end of the project. They carried out theory-building and testing as simultaneous, highly linked activities. For example, in the first week the group had a productive episode of theory-building and testing for the cup separator subsystem. Using cups, hands, and sketching the group proposed and tested “*a little claw*”, *“a vacuum”*, “a *gear whose teeth goes into the stack”,* an inverted *“caterpillar track”*, “*a pinball style”,* upturning the stack, using gravity, tapping, squeezing, a *“spring mechanism”, “sideways options”,* and lining up the cups in a row.

3.5 Telling the story

During the project the group spent time planning how they would ‘tell the design story’ to their intended audience, as well as time presenting it in written and visual formats for the final design report. For example, the group discussed the format and scale of engineering drawings they needed to include, as well as the content of other sections on concept designs, electronics, the manufacturing, assembly, and test plan, and the business case, They also spent time discussing the report layout.

4 DISCUSSION & CONCLUSIONS

4.1 Constructivist inquiry & complexity

Constructivism is a theory in which learning is viewed as a *‘process of struggling with the conflict between existing personal models of the world and discrepant new insights, constructing new representations and models of reality as a human meaning-making venture’* [12]. Case study research is a form of constructivist inquiry focused on the “singular, the particular, and the unique” [11]. The specific case may be an individual, a group, an institution, a programme, or a system. The notion of a case as a system links to ideas proposed by Findelli [13] for an alternative epistemology of design practice based on complexity theory. He argues that “instead of a problem, we have state A of a system; instead of a solution, we have state B of the system; and the designer and the user are part of the system (stakeholders)”, and that “the designer’s task is to understand the dynamic morphology of the system”. He concludes that “a system, and especially a human or social system, is best understood from within, through a constructivist approach.” Wang [14] supports this view, claiming that “under this paradigm research is mainly concerned with constructivist understanding of the relationship among all the parts of the system”. Together these ideas support the notion of design as constructivist inquiry. The designers ‘research’ questions in this case would be of the form: ‘How can this system in state A be explored and understood’?, ‘Why does state A of the system lead to these particular emergent properties?’, ‘How can the system be moved to a state B, in order to generate preferred emergent properties?’ The design concepts are theories about possible states of the system that might lead to preferred emergent properties, theories which can then be investigated, tested, and evaluated. These investigations lead to a better understanding of the existing system state, through emerging themes, which in turn lead to additional or refined theories via an improved framing of the situation.

4.2 Implications for design education

If design can be considered from the viewpoint of complexity, then forms of constructivist inquiry such as case study research methodology make sense as an explanatory framework for natural design behaviour. Many of the constructivist methods of case study are already used by designers in practice i.e. data collection through participant observation (of users interacting with products), interviews (with users, clients, and stakeholders), document analysis (design briefs, technical specifications, user scenarios). But much of this data collection is considered to be part of 'market research', done by specialists, and therefore not part of doing design. The way the end user actually uses the final product, and how it impacts on their lives (sometimes negatively), is also usually far removed from the designer. But all this falls within the 'system' of interest that must be investigated and understood in order to design effectively. Complex constructivist inquiry helps bring these aspects into the world of the designer, and supports the notion that a designer has an ethical responsibility in what they design. Making this approach explicit through education could better enable graduates as reflective practitioners. The current gap in appropriate problem-solving skills seems to relate to a lack of ability to reflect on designing, blinkered by an unhelpful paradigm at odds with the way students naturally go about design. Case study research makes sense of design behaviour, potentially allowing students to access a deeper understanding of design, by supporting experiential learning. In this way they may come to *understand what* they do when they design, and not just learn to *do* it. The focus is also shifted away from the end product. If students are able to articulate their own individual and group approaches to design in terms of resolving conflicts through reframing, teachers can award credit for appropriate attempts at reflection and conflict resolution. Therefore, another implication of these findings is in the way group projects are assessed. A move away from assessment of the final product, to assessment of learning and reflective practice (as espoused by others) might be better enabled by a case study research pedagogy, part of a general education in the 'philosophy of design' which could help make visible the positivist paradigm within which the school of engineering operates.

In conclusion, case study research represents a good fit to the way that students, and practising designers, naturally go about design. It is not prescriptive, or linear, instead it embraces complexity and accounts for the uniqueness of every design situation. It includes the designer as part of the design situation, and acknowledges that the experience of designing actually changes the designer i.e. they are learning. This allows designers to reflect on and make-sense of their learning experience, enabling their design reasoning skills to mature. For all these reasons case study research seems a more appropriate basis for a pedagogy for engineering design education than the prevailing prescriptive process orientated pedagogy, rooted in a rational problem-solving paradigm.

REFERENCES

[1] Friedman, K., & Stolterman, E. (2015) Foreword in [2].
[2] Dorst, K. (2015). *Frame innovation.* MIT Press.
[3] Pahl, G., & Beitz, W. (2013). *Engineering design: a systematic approach*. Springer.
[4] Morgan, T., & Tryfonas, T. (2011). Adoption of a systematic design process: A study of cognitive and social influences on design. In *DS 68-7: Proceedings of the 18th International Conference on Engineering Design, Vol. 7*
[5] Schön, D. A. (1984). *The reflective practitioner: How professionals think in action*. Basic books.
[6] Atman, C., Eris, O., McDonnell, J., Cardella, M., & Borgford-Parnell, J. (2015). Chapter 11, in Cambridge Handbook of Engineering Education Research. CU Press.
[7] Morgan, T. (2017). *Understanding group design behaviour in engineering design education*. PhD
[8] Dorst, K. (2006). *Design problems and design paradoxes*. *Design issues*, *22*(3), 4-17.
[9] Cross, N. (2006). *Designerly ways of knowing*. Springer London.
[10] Clarke, V., & Braun, V. (2013). Teaching thematic analysis: Overcoming challenges and developing strategies for effective learning. *The psychologist*, *26*(2), 120-123.
[11] Simons, H. (2009). *Case study research in practice*. SAGE publications.
[12] Fosnot, C. T., & Perry, R. S. (1996). Constructivism: A psychological theory of learning. *Constructivism: Theory, perspectives, and practice*, *2*, 8-33.
[13] Findeli, A. (2001). Rethinking design education for the 21st century: Theoretical, methodological, and ethical discussion. *Design issues*, *17*(1), 5-17.
[14] Wang, T. (2010). A new paradigm for design studio education. *International Journal of Art & Design Education*, *29*(2), 173-183.