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Introduction

It is often argued that 'design' is an (perhaps the) essential characteristic of engineering practice (Schubert, Jacobitz, & Kim, 2012); that, "Design requires unique knowledge, skills, and attitudes common to all engineering disciplines, and it is these attributes that distinguish engineering as a profession." (Atman, Kilgore, & McKenna, 2008, p. 309) Hence, it is not surprising to see engineering design identified as a key element of engineering education (Davis, Gentili, Trevisan, & Calkins, 2002). For example:

> *"Engineering design is a critical element of engineering education and a competency that students need to acquire." (Atman et al., 2007, p. 359); and*
>
> *"… the purpose of engineering education is to graduate engineers who can design, and that design thinking is complex." (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 103)*

There is a range of pedagogical models, badged with a variety of names, that are suggested as approaches to the teaching of engineering design, for example:

- project-based learning (Agouridas, 2007);
- problem-based learning (PBL) (Atman, Chimka, Bursic, & Nachtmann, 1999);
- design-based learning (Gómez Puente, van Eijck, & Jochems, 2011);
- conceive-design-implement-operate (CDIO) (Cárdenas, 2009; Dym et al., 2005);
- problem-oriented project-based learning (Gómez Puente et al., 2011; Kolmos, 2002);
- social design based learning (Cárdenas, 2009); and
- project-oriented, design-based learning (Chandrasekaran, Stojcevski, Littlefair, & Joordens, 2013).

Gómez Puente, Eijck, and Jochems (2012) noted the practical difficulty in drawing precise distinctions between engineering design education pedagogies. Hereafter, for simplicity, we will refer collectively to pedagogical models for teaching aspects of engineering design as 'design-based learning' (DBL). Rather than providing a limiting definition, we note the following observed characteristics of DBL:

- a focus on the intellectual content of engineering design (Dym et al., 2005);
- "… grounded in the processes of inquiry and reasoning towards generating innovative artifacts, systems and solutions." (Gómez Puente et al., 2012, p. 717);
- "… emphasizes learning about design theory and methodologies … the cognitive and social models underlying design activities …" (Jessup & Sumner, 2005, p. 144);
- "… in addition to constructing and building, students engage in a design and planning process that follows engineering design." (Mehalik & Schunn, 2007, p. 519); and
- "… features such as professionalization, activation, co-operation, creativity, integration and multidisciplinarity …" (Perrenet, Aerts, & van der Woude, 2003, p. 1).

While significant literature on engineering design education generally exists, many authors note open questions regarding optimal pedagogical approaches, and opportunities for further evaluation and research (Atman et al., 2007; Atman, Cardella, Turns, & Adams, 2005; Atman et al., 2008; Cárdenas, 2009; Dym et al., 2005; Gómez Puente et al., 2011; Oman, Tumer, Wood, & Seepersad, 2013). In this paper we draw on the literature about design education and DBL in engineering education, and synthesise themes that present a potential research agenda for those educators/practitioners involved in DBL in engineering education.

Method

A search of the research literature was conducted using terms related to DBL in engineering education, including ‘Engineering Design’, ‘Design Education’, ‘Engineering + Project Based Learning’, ‘Engineering + Problem Based Learning’ and ‘Engineering + Design Based Learning’. The literature thus collected was expanded by inspecting the lists of references in the initially identified literature set for further potentially relevant literature. This process was repeated until no further related literature was identified, and resulted in 124 items. All collected literature was carefully reviewed for explicitly identified suggestions for future research. The authors also considered the literature set as a whole to identify additional research possibilities implied by aspects of DBL practice commonly addressed weakly, or not at all, in the available published research. From the results of this review, a set of themes was synthesised by grouping related research recommendations and possibilities. In the following section the identified research themes are presented and, for each, a summary of the supporting literature is given and a central research question is formulated by the authors.

Results

Theme 1 – Defining engineering design

Providing a precise definition of engineering design has proven elusive (Bucciarelli, 1988; Dym et al., 2005). Some authors claim a level of consensus on the elements of engineering design (Hubka & Eder, 1987), and a range of normative framings of engineering design can be found, for example, “… a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints.” (Dym et al., 2005, p. 104) However there are alternative perspectives on the nature of engineering design. Many common normative models of engineering design focus on technology and imply a well-defined process that proceeds in a linear way from concept to finished product (Lloyd, 2000). However, “… engineering design is not a mechanistic process which can be fully described in a manual, but a complex and elaborate socially-mediated activity of which much is tacit.” (Baird, Moore, & Jagodzinski, 2000, p. 333) Neither is it a natural process that is causal and deterministic, or one that can be mechanised or automated (Bucciarelli, 1988). Another factor that makes engineering design difficult to pin down is the language associated with it, and the shifting and variable meanings of certain key words. Hubka and Eder (1987) noted that words like ‘design’, ‘function’ and ‘process’ are often used in specific ways that are inconsistent between contexts. For example, design can be a noun (the design) or a verb (to design); function can refer to what something is intended to do, or to how it does it. Pragmatically, definitions and models of engineering design have to be agreed in local contexts to make progress, such as in teaching or in a design team working on a specific project. However it is important to acknowledge the contingent nature of engineering design and the re-framing of meanings that may be required moving between contexts and dealing with different people. Lloyd (2000) noted, “There are surely aspects of normative models that are important, but a normative model, by definition, does not cover the social reality of any particular design process. This reality is necessarily more complicated.” (p. 358)

How is engineering design effectively defined in the local context?

Theme 2 – Learning outcomes for engineering design education

Engineering design education is premised on clearly articulating a set of learning outcomes that students must achieve, which then provide an input for crafting curriculum, teaching, learning and assessment relating to engineering design. Hubka and Eder (1987) proposed that engineering design requires a large body of knowledge (‘design science’), and describe a complex hierarchy of general and technical design knowledge and methods. Drawing on workshops with engineering educators and practitioners in The United States of America, Davis et al. (2002) proposed a framework of engineering design learning objectives with eight criteria organised in three categories. In early work, Atman et al. (1999) identified eight design steps from a survey of seven first-year engineering design textbooks. In later work, Atman et al. (2008) identified 23 design activities drawn from the engineering design education literature. In another literature review, Mehalik and Schunn (2007) proposed 15 design process elements. Atman et al. (2008) suggested that, in engineering design education, there are likely to be aspects of both a relatively well-agreed body of knowledge, as well as local differences due to unique institutional priorities. There is a wide array of models and theories of engineering design, and such models can show the influence of the disciplinary origins of their authors (Mehalik & Schunn, 2007). As with the meaning of engineering design, we suggest that the learning outcomes for engineering design education are not wholly self-evident or fixed, but are, at least in part, dependent on the situational context. In undergraduate engineering programs, including those that are DBL-focussed, it is important to understand that the pedagogy is not the curriculum, and simply ‘doing design’ is not sufficient to ensure students will sufficiently develop all desired program learning outcomes.

How are the unique engineering design education learning outcomes for a program effectively developed?

Theme 3 – Integrating design education into the engineering curriculum

Design in the engineering undergraduate curriculum has always been an essential element of program accreditation requirements, and there is a range of models for the integration of design into the curriculum. Traditionally, exposure to aspects of design has been distributed throughout the curriculum (Davis et al., 2002), although this was often in later years following foundation units that focussed on knowledge and skills development. Another long-standing curriculum element has been the final-year/capstone engineering project, where students either individually or in a team tackle the major design of an engineering-related product or process (Dutson, Todd, Magleby, & Sorensen, 1997). A relatively recent development is the first-year/cornerstone design project – often premised on the idea that first-year design units enhance commencing student motivation and retention (Dym et al., 2005). However, a number of issues have been reported for cornerstone design units – commencing students may not have the technical knowledge to fully benefit from the early design experience, and running such units can be expensive (Dym et al., 2005). Schubert et al. (2012) conducted an evaluation of a cornerstone design unit and found wide variations in students’ interpretation of key design terminology, and significantly different understandings of the design process, even between members of the same student design group. More specialised undergraduate engineering curricula based on DBL exist – perhaps the most notable being the PBL model at Aalborg University (Kolmos, 2002). A Danish national review of civil engineering made observations about the Aalborg program, including that first-year student project work was limited by students’ technical knowledge, and that student capstone project work was comparable to other universities (Christophersen, Coupe, Lenschow, & Townson, 1994). In addition to exposure to just ‘doing design’, it is argued that engineering students need to develop metacognitive skills if they are to become reflective practitioners with the capacity to tackle challenging real design problems, and to operate independently as mature engineering professionals adept in both the art and science of design (Atman et al., 2008).

How are design studies and practice appropriately integrated, supported and evaluated in the undergraduate engineering curriculum?

Theme 4 – Scaffolding engineering design education

There is evidence that experienced engineers carry out design activities in qualitatively different ways to novice engineers. A similar growth in sophistication in engineering design output has been observed between junior and senior students. As part of a longitudinal investigation into undergraduate engineering student design performance, data were collected on how both freshmen (commencing) and senior students conducted design exercises (Atman et al., 2005; Atman et al., 1999). It was observed that senior student performance was better than freshman performance with respect to several design elements, with senior student design behaviour tending to be more sophisticated than freshmen, and seniors tending to produce higher quality design solutions. The authors noted a number of implications for appropriate teaching strategies to encourage students to iterate through all the steps in the design process, develop multiple alternatives and gather information. Lloyd and Scott (1994) conducted a study of the individual design processes of a number of engineering designers in the same firm, using the same structured design task that was typical of the work undertaken by the firm. They observed that more experienced designers more frequently articulated ‘generative utterances’ (statements that bring something new to the design) compared to ‘deductive utterances’ (statements that clarify the problem). Rather than simply the amount of general design experience being the differentiator in approaches between designers, they concluded that design engineers with previous experience in the specific design domain were more likely to perceive the design problem in terms of relevant, feasible solutions, rather than follow generic design processes. Engineering students are generally novices in development, and the skills and practices of experienced engineering designers suggest key competencies that should be part of the professional formation of engineering students.

How is engineering design capability appropriately scaffolded for development of sophistication across the duration of engineering studies?

Theme 5 – Real world engineering design

Brereton and McGarry (2000) noted that it is common for engineering project work to involve specific subsystems and/or significant constraints, such that the design task is focussed and limited, rather than open-ended in scope. Cross and Roozenburg (1992) discussed the limitations of a model of engineering design that is premised on the development of ‘new’ systems, whereas the reality of much engineering design is based on existing concepts or technology, focussing on the embodiment and details stages, where, “… the decisions to be taken in these phases are strongly interrelated, owing to the complexity of technical systems.” (p. 333) Lloyd (2000) noted that design and manufacturing organisations of a reasonable size will almost certainly have in-house procedures for the development of new products and designs, based on both accumulated organisational experience and the ubiquitous standards for quality systems (i.e. ISO 9000). At Rolls-Royce in The United Kingdom (UK), Baird et al. (2000) observed that typical engineering design tasks involved incremental innovation by extension of existing products, and that industry certification was the main driving force normally delimiting design solution spaces. Based on interviews across different divisions of Arup in the UK, Salter and Gann (2003) found that even in complex projects, much of the engineering design work was routine – “the same thing, with problems”. Their designers were involved in both creative and operational work, and argued that both forms of design could be a source of engineering innovation. However, operational design was the most common form – used for ensuring that designs met standards, safety and other regulatory requirements. Bucciarelli (2002) highlighted that engineering design often does not ‘succeed’ (for one or more reasons), so while a design failure may not be desirable, it is also not unexpected. Design education experiences that are based on sub-systems or elements of the full design lifecycle, or compliance with applicable industry standards, are likely to be just as useful and realistic for undergraduate students as more open-ended engineering design exercises.

How can engineering students be exposed to authentic design experiences in the presence of realistic constraints and standards compliance?

Theme 6 – Developing distinct engineering discipline identities

While design as a generic function might be a 'common core' of engineering practice, there are differences in the knowledge and practices between design engineers from different disciplines. As Atman et al. (2005) noted, "Mechanical, civil and electrical engineers attempt to solve very different types of problems, but they all design some solution to the problem at hand." (p. 325) In an ethnographic study of two multi-disciplinary engineering design teams, Bucciarelli (1988) used the term 'object worlds' to describe the instrumental norms that guide (and in some senses rule) the thoughts and actions of designers. He describes them thus:

> *"We can speak of 'object worlds'; worlds of technical specializations, with their own dialects, systems of symbols, metaphors and models, instruments and craft sensitivities. The mechanical engineer, designing a structure to hold the plates used to collimate an X-ray beam, moves within an object world of beams, of steel, of geometric constraints, of stress levels…The electrical engineer designing a photovoltaic module works in terms of voltage potentials, and of current flows…These are two different worlds." (p. 162)*

Different engineering disciplines have distinct knowledge, tools and language – collectively these create and influence the culture of any discipline. This means that an engineering design project with multi-disciplinary elements can have sub-groups working on their own distinct problems with their own distinct language, and that the complete details of all elements of the design may not be equally accessible to all members of the design project. It also suggests that an element of engineering design education should be the induction of student engineers into the language and culture of the major discipline area that they are pursuing.

How does engineering design education recognise and develop the unique knowledge, skills, language and identity of distinct engineering discipline groups?

Theme 7 – Assessing student performance in engineering design education

Three types of educational outcomes may be of interest in assessing student engineering design work: i) design knowledge; ii) the design process; and iii) the design outcome(s) (Davis et al., 2002). After-the-fact assessment of a final design output reveals little about the design processes from which it arose (Bucciarelli, 1988; Dym et al., 2005). So, in assessing engineering student design work, we are generally interested in (at least) both the quality (however defined) of the final design artefact, as well as the nature of the design processes used by students (Atman et al., 1999). Methods do exist for the collection of rich descriptions of engineering student design processes, but they are very time consuming, and more suited to research than practical student assessment (Atman & Bursic, 1998). Engineering design is, by its nature, creative and iterative, and potentially more difficult to assess than some other curriculum areas (Davis et al., 2002). While agreed marking criteria derived from the design specification and/or relevant engineering standards can be used to enhance the reliability of assessment of objective design performance criteria (Atman et al., 1999), the assessment of design 'creativity' is typically much more subjective, and potentially subject to issues with inter-rater reliability (Oman et al., 2013). In engineering practice, the quality and performance of design work may not be able to be fully judged until many years after the design activity (Baird et al., 2000). In an engineering education context, student design output will commonly have to be assessed at a point prior to implementation or extended service/performance. Engineering design projects commonly involve student group work. While there is a range of established methods for assessing group work generically, assessment that reflects a student's contribution as an effective team member was historically not well-developed in most engineering pedagogies, which typically focused on individual performance (Dym et al., 2005).

How is student design capability (including knowledge, process and output) effectively assessed in engineering design education?

Theme 8 – Off-campus engineering design education

In engineering, off-campus study is an essential element of access to education for those (often mature age) students in remote locations and/or seeking to upgrade their qualifications whilst employed, and it is also becoming increasingly important for some 'traditional' undergraduate students seeking to fund their studies with term-time work. Australian statistics for 2013 indicated that, of the 75,601 students enrolled in Engineering and Related Technology undergraduate programs, 4,579 where enrolled in external mode, and a further 1,923 were enrolled externally for at least part of their studies. A dedicated, physical design studio space is generally a key element of DBL curricula (Agouridas, 2007; Dym et al., 2005). There is significant existing research that highlights the social, situated and physical nature of engineering design. In a long-term observation of European engineering projects at Rolls-Royce, both single-site-based and distributed, Baird et al. (2000) observed the importance of the social and tacit aspects of engineering design, and noted that, "… as the design team project life cycle advances, engineers develop progressively stronger interpersonal 'permissions' … These permissions develop very much more slowly in distributed teams …" (p. 346-347). Based on interviews across different divisions of Arup in the UK, Salter and Gann (2003) confirmed previous research indicating that for engineering designers to be able to work successfully online, initial face-to-face meetings were required to build up the trust required to work collaboratively using communications technologies. In a multi-year study of students and professional designers, Brereton and McGarry (2000) found that engineering design thinking was heavily dependent on physical props and design prototypes. An engineering program with a significant off-campus enrolment must develop effective methods for off-campus students to authentically participate in engineering design and DBL activities.

What are the types of learning activities that will provide off-campus students (as well as on-campus students) with an authentic DBL environment?

Theme 9 – The staffing of engineering design education

Davis et al. (2002) identified four desirable abilities for staff that teach engineering design: "…

(a) understand teamwork, the engineering design process, and effective engineering design communication skills;
(b) define design education outcomes desired at different points in the curricula;
(c) employ classroom methods that develop desired student capabilities in design; and
(d) measure student achievement of design education learning outcomes." (p. 211)

It has been reported, both at the first-year/cornerstone level (Dym et al., 2005) and the final-year/capstone level (Dutson et al., 1997), that teaching duties for engineering design classes are not always popular, as the nature of the work is different and less predictable compared to a class in a specialised technical area, and the teaching workload may be significantly higher than other units with the same nominal credit weight. It is anecdotally reported that academic staff involved in teaching design may have a more difficult time with career advancement and other academic rewards (Dym et al., 2005). It is speculated that the relatively high workload in teaching design detracts from staff research efforts, and the general nature of generic design classes is unlikely to align with the specialist technical interests of teaching staff (Dutson et al., 1997). A systematic move to an entire undergraduate engineering curricula based on DBL requires most academic staff to engage with design teaching, so brings the issues related to staffing of engineering design teaching to the fore. The Aalborg PBL experience revealed that extensive staff development was a central element of the change. It was found that staff need not only training and experience with the new model (designing 'projects', student group supervision, reducing lectures, etc.), but also extended support over time to reflect on the change process to fully adopt the 'new' teaching methods as 'normal' (Kolmos, 2002).

How are staff adequately developed and rewarded to undertake the specialised requirements of teaching engineering design on a sustainable basis?

Theme 10 – Evaluation of the impact of engineering design education

DBL is often promoted as a superior engineering education pedagogy that improves a range of education outcomes (Dym et al., 2005). However, the evidence of long-term impact on engineering graduate outcomes from DBL, especially from DBL-focussed undergraduate university programs, is both limited and mixed (Christophersen et al., 1994; Gómez Puente et al., 2011). There is evidence that DBL pedagogies are more expensive than more traditional approaches (Agouridas, 2007), and cost/benefit analyses of DBL are often subjective at best (Dutson et al., 1997). If DBL is to be more than an alternative pedagogy in isolated units of study, or a whole-of-program brand offered by certain engineering schools, then meaningful evidence of long-term value and impact on student learning need to be collected (Atman & Bursic, 1998; Dutson et al., 1997). For both engineering program development and accreditation purposes, on-going program evaluation is essential.

How can the value and impact of engineering design education best evaluated?

Conclusions

In the engineering design education literature, many authors note open questions regarding optimal pedagogical approaches, as well as the need for further research. In this paper we draw on a literature review into DBL in engineering education, and synthesise a number of themes that present a potential research agenda for those educators involved in DBL. The themes presented here are not exhaustive. There are other issues that we suggest are important research topics in DBL. **Gender imbalance** remains a crucial issue in engineering education generally, yet it is infrequently mentioned in engineering design education literature. **Work integrated learning** is treated more or less formally in most engineering programs, and often includes engineering design elements that present valuable opportunities for learning. Historically, portfolios (and more recently **e-portfolios**) of student work have often been a central feature of design education, and could be more widely used in engineering education. **New modes of work**, such as tele-working, hot-desking and no-desking are entering professional design practice – how will they impact on engineering design education? Design professionals are using **social media** for marketing, professional networking, participatory social design projects, crowd sourcing and crowd funding – what is the role of social media in engineering design education? We acknowledge both the situational nature of many of the aspects relating to engineering design education, and the subjective aspects of this research project. We encourage those educators/practitioners involved in DBL in engineering education to engage with their own research agenda and contribute to advancing the research literature on, and especially the practice in, this area.

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