

# Towards characterising design-based learning in engineering education : a review of the literature

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## Towards characterising design-based learning in engineering education: a review of the literature

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Design-based learning is a teaching approach akin to problem-based learning but one to which the design of artefacts, systems and solutions in project-based settings is central. Although design-based learning has been employed in the practice of higher engineering education, it has hardly been theorised at this educational level. The aim of this study is to characterise design-based learning from existing empirical research literature on engineering education. Drawing on a perspective that accounts for domain-specific, idiosyncratic and learner-centred aspects of design problems in the context of engineering education, 50 empirical studies on project-based and problem-based engineering education, to which the design of artefacts is central, were reviewed. Based on the findings, design-based learning is characterised with regard to domain-specificity, learner expertise and task authenticity. The implications of this study for the practice of engineering education are discussed.

**Keywords:** design-based learning; problem-based learning; project-based learning; design tasks

### 1. Introduction

Design-based learning (DBL) is an instructional learning approach, which students in engineering design embark upon (Mehalik and Schunn 2006). Taking the design of artefacts as being central, it borrows features from problem-based learning (PBL) (Gijssels 1996) and from problem-oriented project-based learning (Kolmos 2002). In both secondary and tertiary education, DBL has been coined as a fruitful approach to learning engineering design (e.g. Wijnen 2000, Mehalik *et al.* 2008).

Research has yielded empirical specifications for setting up and conducting DBL at the level of secondary science and technology education (e.g. Apedoe *et al.* 2008). However, in higher education DBL has been hardly investigated empirically and little is known of its characteristics at this level. Hence, the aim of this study is to characterise DBL as an approach to higher engineering education.

In what follows, this paper first provides an overview of the practical and theoretical background of the state of the art of DBL in higher education. This background shapes theoretical perspective, which accounts for domain-specific, idiosyncratic and learner-focused aspects of engineering education. Next, by drawing on this perspective, 50 journal articles on project-based

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and problem-based engineering education, to which the design of artefacts and solutions is central, were reviewed. Based on the findings, DBL is characterised in both domain-specific and generic ways, thereby pointing out critical similarities and differences with the professional practice of engineering design itself. Finally, this characterisation is explained in light of educational considerations underpinning engineering education and the implications of this study for the practice of engineering education are discussed.

## 2. Background

This section sketches the practical and theoretical background of the review study. The practical educational context underlying this study concerns the introduction of DBL as a leading principle for engineering education at Eindhoven University of Technology, now more than 10 years ago. This introduction not only yielded some preliminary characterising principles of DBL but also induced a need for further theoretical clarification of the concept and hence this literature study. This section ends by pointing out the theoretical considerations underpinning this literature study.

### 2.1. Practical context

The transition towards more learner-centred (constructivist) curricula in higher education can be taken as a particular of a worldwide recognition that the amalgam of skills and knowledge required for complex activities such as design can best be learned by doing. In technology-oriented universities in particular, this resulted in an increased interest in both PBL and project-organised learning. DBL has been coined from these two active approaches, borrowing learner-centred educational principles as well. Consequently, the aim of this concept is to motivate students as creative professionals to collectively apply knowledge and skills in newly designed systems, thereby highlighting six features, such as professionalisation, activation, cooperation, authenticity, creativity, integration and multidisciplines (Wijnen 2000).

DBL was introduced in 1997 at the Eindhoven University of Technology and it has adopted specifics from the PBL model from Maastricht University (Gijsselaers 1996) and from the Aalborg University model of problem-oriented, project-based learning (Kolmos 2002). Initially, DBL had been developed as the university's central educational concept. The educational form that DBL took at the beginning in the different study programmes was based on discussions with directors of studies from the different departments (Wijnen 1999). Likewise, study tours with groups of students and teaching staff were organised to learn from the project work model of Aalborg and Roskilde universities in Denmark (Perrenet and Pleijers 2000). As a result of these experiences, DBL resembled project-like characteristics in each department. The introduction of DBL was initiated, therefore, to build experiences upon practices. This was taken as an initial step to create a platform for further innovation (Perrenet *et al.* 2000). In this way, the six DBL-characteristics were typified and worked out to give direction for further development and integration of DBL in the study programmes (Wijnen *et al.* 2000). For some programmes, the implementation of DBL led to the introduction of projects into the curriculum; whereas for others, it implied the incorporation of some educational elements in the existing projects (i.e. tutoring at the Mechanical Engineering Department). Another representation of the project work was the competence-based curriculum at the Industrial Design Department, which, as a very innovative model, has students and teachers work as junior-senior employees in realistic contexts.

DBL has been implemented for over the past 10 years but it is a concept that still needs further development. The aim of this study, therefore, is to characterise DBL as an educational concept in higher engineering education.

## 2.2. Design-based learning in higher engineering education

Approaches centred on design problems in project-based settings are widely employed in higher engineering education. Some researchers even more strongly suggest that design exercises traditionally shape the core of design education (e.g. Dorst and Reymen 2004). Nevertheless, DBL is not always explicitly attributed to such 'DBL-like' exercises. For the purpose of this study, therefore, DBL is broadly defined to include both the concept of DBL as it has been introduced at the university as well as the many 'DBL-like approaches' described in the literature. Hence, DBL is taken as a teaching approach akin to PBL and to which the design of artefacts, systems or solutions in project-based settings is central.

In the empirical research literature, DBL has been studied mostly in the context of secondary science education (e.g. Roth 2001, Ellefson *et al.* 2008). Here, DBL has been employed as a vehicle for the learning of science rather than explicitly preparing for the professional practice of engineering design. This orientation does not account for epistemologies inherent to technology (van Eijck and Claxton 2009). Consequently, empirical studies on DBL in the context of secondary education often do not account for the idiosyncratic and domain-specific nature of the practice of engineering design. Hence, the outcomes of these studies cannot be transferred straightforwardly to the practice of higher engineering education.

In the context of DBL in higher education, one theoretical framework has been developed in which a more integrated, meta-perspective on design points out ways by which design can be used as an effective vehicle for learning (Mehalik and Schunn 2006). Drawing on 40 empirical studies on the nature of engineering design processes, this classification comprised both a taxonomy of engineering design elements and an indication of the frequency that these elements were reported to (potentially) constitute good design. The result is a classification of 15 design elements associated with (potentially) good design, which are reported with high, moderate or low frequency in the literature (Table 1). Particularly, the different reporting frequencies of the elements account for the idiosyncrasy.

Although the classification of Mehalik and Schunn (2006) provides some detail of possible objectives and activities inherent to DBL, it also induces problems for further research. For instance, whereas this classification focuses on the professional practice of engineering design, it is yet unknown which activities support students' preparation for such a practice and what this implies

Table 1. Database of reviewed journals

<i>International Journal of Engineering Education</i>	11
<i>European Journal of Engineering Education</i>	7
<i>International Journal of Mechanical Engineering Education</i>	3
<i>Journal of Engineering Technology</i>	1
<i>American Journal of Physics</i>	1
<i>Design Studies (Elsevier)</i>	1
<i>Chemical Engineering Education</i>	2
<i>Biochemistry and Molecular Biology Education</i>	1
<i>Computer Applications in Engineering Education</i>	1
<i>Progress in Robotics, Communications in Computer and Information Science</i>	1
<i>IEEE Transactions of Education</i>	16
<i>Journal of Information Technology Education: Innovations in Practice</i>	1
<i>Computer Science Education</i>	1
<i>Journal of Learning Sciences</i>	1
<i>Journal of Professional Issues in Engineering Education</i>	1
<i>Interactive Learning Environments</i>	1
Total	50

for the nature of DBL-based curricula in higher engineering education. Inherently, there is a need to better understand the student expertise required for particular design activities. Furthermore, given that educational practices, as compared to professional practices, are constrained in several ways, more empirical detail is required to understand in what respect the professional practice of engineering design can function as a model for engineering design curricula. In addition to the practical aim to contribute to a better foundation of the concept of DBL in this university, this characterisation of DBL is oriented towards these gaps in the empirical literature to provide insights for educational practitioners.

### 2.3. Theoretical considerations

Given the foregoing, particular theoretical considerations are drawn on to further characterise DBL from the empirical literature. The first consideration follows from the given that the professional design enterprise is idiosyncratic in nature. On the one hand, it is recognised that characterisation of the practice of engineering design into elements such as those from Mehalik and Schunn (2006) is arbitrary. Inherently, such a classification renders design practices to particular generics that ultimately do not account for its idiosyncratic nature (Latour 1987, Dorst and van Overveld 2009). However, a classification system of design elements may be helpful to identify whether and how design elements common to professional engineering design play a role in DBL in higher engineering education. Because of its fine-grained typology of design elements, the instrument of Mehalik and Schunn (2006) is adopted. Yet, in using this instrument, it is recognised that these elements (see Table 2) in the professional practice of engineering design do not necessarily need to be sequenced one after another in time and may be present in various constellations in different forms of DBL.

Second, related to the intrinsic nature of design is its domain-specific nature. The present authors are committed to the overwhelming empirical evidence from the past 40 years that the learning

Table 2. Design elements constituting good design and their reporting frequency in engineering design studies\*

Explore problem representation
Use interactive/iterative design methodology
Search the space (explore alternatives)
Use functional decomposition
Explore graphic representation
Redefine constraints
Explore scope of constraints
Validate assumptions and constraints
Examine existing designs
Explore user perspective
Build normative model
Explore engineering facts
Explore issues of measurement
Conduct failure analysis
Encourage reflection on process

Dark grey = high reporting frequency; light grey = moderate reporting frequency; white = low reporting frequency.

\*According to Mehalik and Schunn (2006).

of techno-scientific knowledge and skills is highly domain-specific (e.g. Duit 2009). Therefore, in the characterization of DBL the differences between domains regarding the nature of design problems, as well as the relevance of particular design activities for solving these problems, are taken into account.

Third, the given that engineering design education is akin but certainly not identical to the professional practice of engineering design is drawn on. On the one hand, learning, especially in the context of preparation for complex practices such as design, can be taken as a form of participation in this practice (cf. Lave and Wenger 1990). Accordingly, DBL may include activities akin to those in professional engineering practices, eventually being fully authentic and taking place in these practices. Indeed, the six DBL characteristics is an attempt to model DBL authentically according to professional engineering practices. On the other hand, newcomers, because of their underdeveloped professional expertise, conduct particular activities in order to become experts themselves. They are not employed by experts but help to develop that expertise gradually (Atman *et al.* 2007). Hence, it is recognised that higher engineering curricula employing DBL-like activities are simultaneously akin to and different from professional engineering practices and exhibit different levels of authenticity.

#### **2.4. Research questions**

Given the theoretical considerations, the aim herein is to answer the following questions in characterising current DBL as described in the empirical literature:

- (1) Which design elements of the professional practice of engineering design are common in DBL and which are not?
- (2) In what respect is DBL either domain-specific or generic?
- (3) In what respect does DBL account for developing the expertise of learners?
- (4) Which elements of the professional practice of engineering design are common to DBL in authentic settings?

### **3. Review approach**

This section explains how the journals and articles were selected for the review. The analytical approach yielding the review of the literature is then illustrated.

#### **3.1. Selection of journal articles**

To obtain articles for review, journals were selected that are likely to publish on educational engineering design practices indexed in the ISI Web of Science and the Education Resources Information Centre databases. A list of accepted journals of The Interuniversity Centre for Educational Research<sup>1</sup> was also obtained. To obtain a selection of potential useful articles, the 16 selected journals were screened by using the following keywords: ‘problem-based learning’; ‘project-based learning’; ‘design-based learning’; ‘engineering design process’; ‘design education’; ‘design tasks’; ‘engineering education’. In the selection of the articles emphasis has been made to cover a representation of engineering disciplines, such as mechanical engineering, electrical engineering, civil and environmental engineering, mining engineering, computer science, chemical, biomedical engineering and physics, among other subjects. In accordance with the definition of DBL, articles were finally selected that described problem-based, project-based learning or comparable instructional active learning methods (e.g. scenario assignments) to which the construction of artefacts or systems was central. The preliminary selection was limited to 50 articles.

### 3.2. Classification of articles

Drawing on the theoretical considerations, several characteristics potentially relevant to DBL were determined for each article. First, to get an understanding of elements of professional design processes common to the practice of design considered significant for DBL, the reporting frequency of design elements over all articles was counted. Here, the classification of design elements of Mehalik and Schunn (2006) were followed. Since this classification consisted of precise coding of design activities reported in the articles, a second researcher independently recoded dubious cases identified by the first researcher. Yielding an initial agreement of 84%, all disagreements were resolved through discussion. Furthermore, to allow comparison with the practice of professional design, the reporting frequency of design elements in the study were counted and they were compared with the design elements classified in the taxonomy of Mehalik and Schunn (2006). An element was included in the 'high reporting' category if it was focused on in more than 50% of the articles. The element was considered to be in the 'moderate reporting' category if it was focused on in 25–50% of the articles. Finally, elements that were reported in fewer than 25% of the articles were included in the 'low reporting' category.

Second, to get an understanding of the domain-specificity of DBL, the articles were organised into three main areas according to a classification of engineering adapted from the university library. These are mechanical engineering, electrical engineering and the cluster of biomedical, chemistry and environmental engineering. Under electrical engineering, both electrical and computer engineering (hardware) and computer sciences and telecommunications engineering (software) have been clustered. One final category included the rest of the domains, such as physics, civil engineering, architecture or industrial design and graphics.

Third, to account for the level of expertise, the articles were classified according to whether they concerned courses in either graduate or undergraduate programmes or in both.

Finally, to provide detail about the authenticity of design tasks, artificial design activities were distinguished from authentic design activities. The former activities were defined as being fully carried out in educational institutions without any involvement of experts in professional engineering practice.

## 4. Findings

The results are presented in Table 2. For each design element, its frequency in the articles is given, as well as how its frequency is divided over: (a) different engineering domains; (b) educational levels; (c) authentic and artificial design activities. In the remainder of this section, these findings are briefly sketched in light of the research questions.

### 4.1. DBL compared to studies on engineering design

To gain an overview of the design elements the classification of Mehalik and Schunn (2006) were compared (Table 1), emphasising engineering design, with the results of this study (Table 2), emphasising DBL-like engineering education.

The present findings reveal differences in reporting frequencies of design elements between DBL and the professional practice of engineering design. Several design elements are reported with high frequency in engineering education (see Table 3) and with low or moderate frequency in professional engineering design (see Table 2): Build normative model; Explore issues of measurement; Validate assumptions and constraints; Explore graphic representation. Conversely, several design elements are reported with low or moderate frequency in the literature on DBL and with high

Table 3. Design elements constituting good design and their reporting frequency in empirical studies on DBL in higher engineering education categorised according to domain, educational level and authenticity

Design stages	Domain (%)				Level (%)			Authenticity (%)		Total (%) (n = 50)
	ME (n = 6)	EE (n = 25)	BCEE (n = 7)	Other (n = 12)	UnGr (n = 38)	Gr (n = 9)	Both (n = 3)	Artif* (n = 39)	**Auth <sup>†</sup> (n = 11)	
Explore problem representation	50	72	100	92	74	89	100	79	64	78
Use interactive/iterative design methodology	17	24	29	42	29	22	33	28	27	28
Search the space (explore alternatives)	50	36	57	33	42	11	100	38	45	40
Use functional decomposition	17	36	29	17	29	22	0	31	0	28
Explore graphic representation	83	80	71	75	79	78	33	85	36	78
Redefine constraints	33	16	29	8	18	0	67	15	18	18
Explore scope of constraints	33	32	29	8	26	11	67	26	18	26
Validate assumptions and constraints	67	80	100	92	89	78	67	92	55	86
Examine existing designs	17	0	29	0	5	11	0	8	0	6
Explore user perspective	17	28	14	33	21	33	67	21	45	26
Build normative model	100	92	100	92	95	100	100	100	55	96
Explore engineering facts	33	36	14	17	26	22	33	28	9	28
Explore issues of measurement	33	68	57	42	61	33	67	56	36	56
Conduct failure analysis	17	8	14	0	5	0	33	8	0	6
Encourage reflection on process	17	8	29	25	16	0	33	10	27	16

DBL = design-based learning; ME = mechanical engineering; EE = electrical engineering; BCEE = biochemical, chemical and environmental engineering; UnGr = undergraduate; Gr = graduate; Artif = artificial activities; Auth = authentic activities.

Shading indicates a classification of reporting frequencies according to Mehalik and Schunn (2006): dark grey = high reporting frequency (100–50%); light grey = moderate reporting frequency (50–25%); blank = low reporting frequency (25–0%). See also Table 2.

\*Artificial refers to design project activities conducted within the educational context (i.e. university).

<sup>†</sup>Authentic refers to design project activities that are conducted in closely cooperation with the industry (e.g. students conduct a research within companies, industry staff makes part of the examination committee, etc.).



frequency in the literature on professional engineering design: Use interactive/iterative design methodology; Search the space (explore alternatives); Use functional decomposition. All these cases point to differences between the professional practice of engineering and DBL. Reported frequencies in the literature on both the professional practice of design and DBL are comparable only for the design elements 'Explore problem representation', 'Explore scope of constraints', 'Explore user perspective', 'Conduct failure analysis' and 'Encourage reflection on process'.

#### **4.2. Domain-specificity**

For particular design elements, some domains reveal reporting frequencies that deviate substantially from the other domains. For instance, the design element 'Explore problem representation' is reported with a lower frequency in mechanical engineering in comparison with the other domains. The difference in frequency among disciplines is also to be found in, for instance, 'Explore issues of measurement', which is remarkably lower in mechanical engineering than in the other disciplines, such as in electrical engineering. Interestingly, the design element 'Build normative model' does not differ substantially between all domains.

#### **4.3. Learner expertise**

Regarding the level of expertise, the differences between undergraduate and graduate level in reported frequencies of design elements are generally low. Exceptions are found in the design elements 'Search the space (explore alternatives)', 'Redefine constraints', 'Explore scope of constraints', 'Explore issues of measurement' and 'Encourage reflection on process', which are reported less frequently in articles concerning DBL in graduate programmes. In addition to this, there are some other design elements such as 'Examine existing designs', 'Explore problem representation', 'Explore user perspective', 'Build normative model', which are reported more frequently in articles focusing on the graduate level.

#### **4.4. Authenticity**

Finally, some substantial differences between authentic and artificial forms of DBL are observable. Particularly, the design elements 'Use functional decomposition', 'Explore graphic representation', 'Validate assumptions and constraints', 'Build normative model', 'Explore engineering facts' and 'Explore issues of measurement' are reported more frequently in articles on artificial courses than in articles on authentic courses. Conversely, counts for 'Explore user perspective' and 'Encourage reflection on process' are reported more frequently in articles on authentic courses than in articles on artificial courses.

### **5. Conclusions and implications**

This section summarises the findings of the review and sketches some implications for both higher engineering design education and further research on DBL.

#### **5.1. Characteristics of current DBL in higher engineering education**

Regarding the reporting frequency of design elements, the characterisation of DBL reveals some critical differences with professional practice of engineering design. Most design elements are

reported with either a substantial higher or lower frequency in the literature on DBL than in the literature of design studies. Furthermore, some design elements were found, which were reported in every article on DBL and in association with every domain, whereas others were reported in differing frequencies over different domains. Hence, DBL exhibits domain-specific elements as well as generic aspects. Strikingly, current DBL does not account substantially for developing expertise of learners with regard to either graduates or undergraduates. Regarding the reporting frequency of design elements in articles on DBL, only moderate differences were found between undergraduate and graduate courses. With regard to authenticity, some striking differences were found in reporting frequencies of design elements. That is, in articles on DBL in authentic settings, some design elements were reported substantially more frequently than in articles on DBL in artificial contexts.

Finally, in this study, several differences were found between DBL on the one hand, and good design as reported by Mehalik and Schunn (2006) on the other hand. Based on this, it is concluded that DBL is not necessarily equivalent to good design practice. Rather, DBL comprises a set of activities that prepare students for good design practices. Although DBL and good design may share many characteristics, a better understanding of DBL in educational settings implies, among other issues, considerations of how to adapt and adjust characteristics of good design practices to educational activities that support and prepare students for such a practice. This requires further research in curriculum design and in instructional approaches.

## **5.2. Implications for higher engineering design education**

The substantial differences in reporting frequencies of design elements between the literature on professional design and current DBL induces the question of in what respect the latter can be considered either preparatory for the practice of design or a vehicle for learning specific design elements, such as 'Building a normative model' or 'Exploring graphic representations'. On the other hand, since such design elements are relatively easily assessable as products, the high reporting frequency in DBL may also be caused by specific constraints of education in undergraduate courses in particular, such as efficiency, testability and accountability. Nonetheless, these findings imply that engineering educators should consider the precise pedagogical function of DBL in their educational programmes. The pertinence of this implication also follows from the substantial differences in reporting frequencies of design elements between either professional design practices or DBL, as well as between either authentic or less authentic contexts. Especially, the latter finding induces the question of in what respect is DBL in artificial settings preparatory for the professional practice of designers. This is not necessarily the case. For instance, DBL in artificial settings in undergraduate courses may be predominantly used as a vehicle to learn particular engineering skills more generally. If this is the case, such courses may be appropriate vehicles to learn skills associated with more generic design elements in DBL, such as 'Building a normative model', 'Exploring problem representation', 'Exploring graphic representations' and 'Validate assumptions and constraints'. On the other hand, if expert participation in the professional practice of design is the ultimate aim of DBL, the developing expertise in the route from novice to expert through undergraduate and graduate courses should imply careful consideration. Particularly relevant are the nature of both the design activities to be practised and the authenticity of the context wherein these activities are conducted. Such considerations may support educators to develop curricula that reflect more substantial differences between undergraduate and graduate forms of DBL. Related to this implication is the consideration of the domain-specificity of design courses. Given that DBL is domain-specific, every course should be developed accordingly. Nevertheless, educators should also be aware of more generic elements of DBL in the design of curricula, from novice to professional expertise.

### 5.3. Implications for further research on DBL in higher engineering design education

The outcomes point out a need for further research in several directions. One avenue for further explorations concerns the question of in what respect DBL can be considered either as preparatory for the practice of design or as a vehicle for learning specific design elements. This requires empirical research in association with educators who employ forms of DBL that are comparable to the ones reported in the literature. Of critical importance is the question of how the learning outcomes of these forms of DBL are considered and how these relate to levels of authenticity and learner expertise. Also relevant is the question of to what respect goals reported as relevant to DBL educators are either generic aims or specific to their domain. Another avenue for further research concerns the substantial differences in reporting frequencies of design elements in the literature on DBL either in itself or as related to the professional literature. This opens up the question of which design elements are considered relevant to educators for what particular reasons, as related to the domain they are working in, the outcomes of their courses and, related to the former implication, the authenticity and domain-specificity of the setting of their courses. Again, this requires empirical research in collaboration with professional educators developing and conducting DBL-like courses in higher engineering education. It also requires further research to gain insights from the literature in curriculum and instructional approaches related to the practice of engineering design education.

#### Note

1. The Interuniversity Centre for Educational Research is the Dutch PhD research school for educational sciences formally recognised by the Royal Netherlands Academy of Arts and Sciences. The academic board of the organisation maintains a list of non-ISI journals of acceptable academic quality in which its members can publish (<http://www.ou.nl/eCache/DEF/1/93/759.html>).

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## Appendix 1: Reviewed journal articles

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