Engineering Design, why is it so difficult to teach and to learn?

Nicky Wolmarans
Department of Civil Engineering & CREE, University of Cape Town, South Africa.
nicky.wolmarans@uct.ac.za;

One of the challenges faced by education researchers, especially those of us working from fairly specialised educational or sociological theoretical frameworks, is to bring our research findings back to the practical realities of the curriculum and the classroom. The purpose of this paper is to take on that challenge, and to attempt to make the practical implications of theoretical research finding relevant to curriculum considerations. The theoretical background to this paper is a Bernsteinian analysis of knowledge progression through a sequence of engineering design projects. The discussion, focuses on the fundamental structural differences between organisation of knowledge in engineering sciences and in engineering design projects, and suggests a shift in organisation from that based on the conceptual rigour and norms of a particular disciplinary tradition, to coherence derived from the context of the design project requiring the integration of sometimes contradictory disciplinary traditions. The implications for learning to design (or more generally, to apply engineering sciences to open-ended, ill-defined project based problems) means a weakening of the boundaries around disciplinary knowledge in order that different 'knowledges' interact with one another in a way in which novel solutions can emerge from interaction between a problem context and the knowledge brought to bear on that context in the presence of other knowledge. There is also a requirement to specialise general abstract knowledge for application to a context. But perhaps most significantly, that this can only occur if the responsibility for selection of the relevant 'knowledges' required to solve a problem and the sequence in which they are applied to and integrated through the problem shifts from the lecturer to the student. This is one of the pedagogic challenges of sequencing design projects. What this paper attempts to offer is not a prescription for what to do, but rather a theoretical perspective on knowledge that allows lectures to make more informed decisions about one aspect of engineering design courses.

Introduction

One of the challenges faced by education researchers, especially those of us working from fairly specialised educational or sociological theoretical frameworks, is to bring our research findings back to the practical realities of the curriculum and the classroom. The purpose of this paper is to take on that challenge, and to attempt to make the practical implications of theoretical research finding relevant to teaching and learning. The theoretical background to this paper is a Bernsteinian analysis of knowledge progression through a sequence of engineering design projects. The discussion, though, focuses on the fundamental structural differences between organisation of knowledge in engineering sciences and in engineering design projects; the implications for learning to design (or more generally, to apply engineering sciences to open-ended, ill-defined project based problems); and the pedagogic challenge of sequencing design projects to facilitate student learning.

This paper reports on a pilot study for a broader PhD project. The larger project seeks to analyse the structure and progression of engineering design in two differently structured engineering programmes. In the first programme design is integrated into disciplinary streams and most disciplinary subjects include some sort of design project; while in the second programme design runs as its own stream through the curriculum and draws on the various disciplines in the programme. The research questions relate to the inherent structure and logic of engineering design knowledge. What is the logic of coherence in engineering design - or what holds the subject together? What is the logic of progression of design - or what progresses as students progress through the curriculum? In this pilot study only a sequence of 4 design tasks was analysed. All tasks were located in the structures stream of subjects in the civil engineering degree programme at the University of Cape Town. The design tasks were selected from a sequence of 4 semester courses in structural engineering spanning the second semester of second year through to the first semester of fourth year.

Literature review

Since the 1990s a strong theme in the engineering education literature has been the subject of engineering design. Harris et al (1994) attribute this interest to a response to the strengthening of the science and engineering science content of engineering curricula since the 1950s at the expense of engineering design and practice courses. More recent studies indicate “Although industry is generally satisfied with the current quality of graduate engineers it regards the ability to apply theoretical knowledge to real industrial problems as the single most desirable attribute in new recruits. But this ability has become rarer in recent years...” (Royal Academy of Engineering, 2007 p7). A common solution to this problem is seen to lie in the curriculum subject engineering design.

While design is seen as preparation for engineering practice Dym et al (2005) make the point that the intellectual requirement of design is significant; that technical analysis is insufficient for the creative process of design; and that the cognitive requirement of the design process is often underestimated. They argue that a different kind of thinking (generative and creative thinking) is required for design as opposed to the deep convergent reasoning required of analysis. Jonassen et al (2006) also point out the difference between convergent and divergent problem types, and associate the latter with ‘everyday workplace problems’. They highlight the problem of students facing only convergent, well-defined problems as deficient for application in professional engineering practice because workplace problems are “ill-structured and complex because they possess conflicting goals, multiple solution methods, non-engineering success standards non-engineering constraints, unanticipated problems, distributed knowledge, collaborative activity systems, the importance of experience, and multiple forms of problem representation.” (ibid p. 139) It was noted that these types of problems are most often limited to design courses.

Because of the conflation between engineering design and engineering practice, coupled with the association between design as the solution of open-ended problems, which are seen as multidisciplinary and socially situated, design has also become the site for the development and assessment of professional skills. Most notable of these are teamwork in the context of problem-based learning and communication in the form of documenting design solutions. For example the course most often mentioned in connection with students’ perception of their development of a range of graduate attributes is the final year design project (Martin, Maytham, Case, & Fraser, 2005). Shuman *et al* (2005) look into the teaching and assessing of the professional skills identified by ABET as accreditation criteria. Three of the four categories they discuss are associated with design courses as example of ways to teach the skills. This tendency to incorporate so-called ‘soft-skills’ into design further contributes to the devaluing of the intellectual content of design itself. The result is a subject with an ill-defined body of knowledge and an underestimated intellectual contribution to the curriculum.

A further consequence of an ill-defined body of knowledge that relies heavily on what individual lecturers deem to constitute design is evident at the pedagogic level. Kotta’s (2011) study clearly shows how students struggle to make sense of evaluative criteria that change between different courses. For example the lecturers in her study clearly hold different aspects of design as critical. In the first design course accurate modelling of a system was seen as critical (a focus on the analysis of the engineering science, aligned with the engineering science courses), whereas in the following course the modelling was seen to inform decisions, and the justification for decisions, coupled with an evaluation of the accuracy of the model was seen as critical (more aligned with engineering practice than with the disciplinary knowledge).

What is apparent in the literature is that what matters in design is not clearly defined and agreed upon. For example Pahl and Beitz (1996) and Ullman (1992) produce rigorous linear sets of steps through which the design progresses, although their steps are not the same. Bucciarelli (1994) argues that no clear process is evident in practice, design is rather a negotiation of meaning between participants; Cross (2006) identifies a problem and solution space with design occurring as a movement between the two, and Simon (1996) argues for the development of a process based on artificial intelligence models. Firstly, the body of knowledge, or the canon are ambiguous. Secondly, design relates to a wide range of diverse knowledge traditions, it is dependent on the integration of conceptual knowledge from a range of disciplines and requires the application of a range of skills. The principle of integration however is unclear. And finally, the progression in design is rarely if ever discussed. There appears to be an assumption that design skills result naturally once a student has an adequate knowledge of all the other 'stuff'. What matters in design is neither clearly defined nor agreed upon.

Theoretical Background

In this analysis I draw on two of Bernstein's (2000) fundamental analytical concepts in order to distinguish between different types of knowledge. The first relates to the structural aspects of systems of knowledge, or the disciplinary identity of the subject itself, the extent to which a subject is separated from other subjects, and the extent to which it has its own intellectual identity and rules of adequacy independent of other conceptual traditions. Bernstein called this classification. The core idea behind classification lies in the boundaries around categories (in this case subjects or disciplines) and the relations between different categories. Strong classification means that the category is strongly insulated from other categories, the boundary around it is strong, the influence from outside is minimal. Weak classification on the other hand means that a category may not have an entirely clear identity, that it is open to significant influence of categories outside of itself.

Within an engineering curriculum we immediately see a significant difference between the structure of science and engineering science subjects on the one hand, and engineering design on the other. The engineering sciences, like the natural sciences have their own disciplinary flavour; they deal with a specialised natural phenomenon, draw on coherent predictive laws, and follow consistent rules of truth and accuracy in each case. Coherence is based on a consistent conceptual system of abstract meaning in each discipline (Muller, 2009). Engineering design on the other hand is about integration of multiple disciplinary traditions. Here different 'knowledges' are brought together; coherence is achieved through the context provided by the specific design problem, not by the coherence of the conceptual meaning of the individual discipline, and the main criterion is one of adequacy or performance, rather than accuracy. But engineering design is not based on everyday concrete knowledge, it draws on multiple systems of abstract knowledge, each with its own conceptual coherence, which may conflict with other conceptual frameworks required to solve the problem.

The second of Bernstein's concepts that I use relates more to the processes of the transmission and acquisition of knowledge. In a pedagogic relationship there is a question of the extent to which the teacher defines what knowledge is relevant (selection), the sequence in which it is presented or used and the pace at which it is delivered or acquired, and what actually matters (evaluative criteria), or the extent to which the student has control over these things. Bernstein called this framing, where strong framing means that that the lecturer retains control of the various aspects, and weak framing means that the control is shifted to the student.

Again we see how different engineering design is to the other engineering sciences. Selection, sequence and evaluation are all fairly well defined by textbooks in the various disciplinary traditions in the engineering sciences, though pacing may vary. In design however, selection and sequencing of knowledge needed to solve a contextual problem is less well defined. Pacing may or may not be better defined based on submission dates and a defined design process, but evaluation of adequacy as opposed to accuracy is a particularly challenging problem for both lecturer and students to deal with in design.

Data

The data is drawn from four sequential design tasks, each located in a sequential semester course in structural engineering. The unit of analysis was an individual design task, the requirements of the task and the potential solutions to the design problem. For each task the design brief (the design task instructions provided to students at the beginning of the project) was the main data source; where available a marking memo for the desired solution was included, although because the nature of design tasks often tends to be divergent, a single solution memo is often inadequate to define the range of potential solutions. Therefore a selection of student submissions judged by the lecturer to be 'good' solutions was also analysed in each case. The student work was not viewed for a judgement of student learning, but rather as possible as one possible adequate solution to the design problem, or as a possible solution memo.

The first task (S1) required students to estimate the loads that would be exerted on each structural element of a given structure. Students needed to use loading codes of practice to estimate externally applied loads based on the function of the structure. They then developed loading diagrams (shear force diagrams and bending moment diagrams) and used structural engineering procedures (estimating tributary areas) in order to determine the load distribution on individual structural elements.

The second task (S2) required students to detail the various structural elements of a steel structure. Students were given the general layout of the structure and the location or distribution of various structural elements. They were taken through a sequence of eight tutorials in which they designed each aspect of the structure sequentially. The final tutorial involved the production of a full set of detail drawings for the structure.

The third task (S3) again began with the basic layout of a structure given to students. In this case students were required to detail the reinforcement design on one particular structural element. They were instructed to estimate potential dimensions for the element, determine the loading on the element based on this initial estimate, and analyse whether the estimated dimensions would carry the load or not. An iterative solution process was expected.

The fourth task (S4) required that students design a parking garage to be constructed under the UCT rugby fields. For the first time did not begin with any indication of the layout of the structure. Instead students were provided a location and a function for the structure along with quite specific construction constraints. Students were required to not only design the structure from scratch, but also to decide for themselves what knowledge would be relevant. Students were required to do an initial conceptual layout, which included reporting on the basis for their proposal and a justification of their decisions. This required them to draw on geotechnical engineering to give a sense of the foundations; transportation engineering to give a sense of the traffic access and volume to determine vehicle access and aspects of the loading on the structure. The concept design was submitted to grading before they proceeded with the detailing, which required aspects of S2 and S3, but without the explicit guidance of the lecturer. The project culminated in a report detailing the design decisions and including a set of detailed drawings as the final product.

Data analysis

The data was analysed based on classification and framing as discussed briefly above. One of the particularly useful things that Bernstein made explicit about the research process relates to the manner in which theoretical or conceptual tools need to be brought closer to the data before they can be used productively to analyse data. In the case of analysing the classification of each design task this means making explicit what counts as classification, and the various modes in which it can appear. Content analysis of the data suggested that the aspects of each design task that relate to their boundedness and relations to other knowledge include three main elements:

The relation between the task and the knowledge required in order to develop a solution to the design problem. This relates to the extent to which a particular design task is located within a single disciplinary discipline (in this case structures) or requires multiple disciplines for a solution. In the case of strong classification the task and the knowledge required are clearly related to only structures, the norms and values of structures are consistently applied to solve the design. For example in S1 the problem requires the use of the foundations of mechanics, principles of equilibrium, and shear and bending moment diagrams. In the case of weak classification, although the design problem is ostensibly a structural design, the knowledge required to adequately solve the problem comes from multiple (sometime conflicting) disciplinary traditions. For example in S4 students are required to design a 'structure as an integrated system ... work on all relevant aspects, such as operational safety; structural behaviour; safety and serviceability; construction methods; procedures and materials; cost, etc' (brief: S4)

The relation between the concrete nature of the design context set up by the design problem and the relative abstraction of the disciplinary knowledge used. This relates to the extent to which abstract knowledge needs to be elaborated or translated before it can be applied to the contextual problem, or whether there is a direct relation between the task and the knowledge marshalled. When the knowledge related quite directly to the problem without the need for significant translation the relation was considered strongly classified - this is often evident when codes of practice are used quite directly, for example in S2 and S3. When there was a relatively wider distance between the knowledge required and the concrete context of the problem, the task was considered weakly classified. Before abstract disciplinary knowledge can be applied it needs to be translated into a form appropriate for the design context. This was evident in S1 and S4, but in different ways. In S1, the design task required the application of basic principles of equilibrium, which needed to be translated into shear force and bending moment diagrams. In order to do this, a technique of assigning loads by an analogy of tributary areas was employed. In the case of S4, because the codes of practice required were not explicitly defined, students needed to identify which codes were appropriate to use, this requires a more fundamental appreciation of their underlying theoretical principles than when codes are prescribed and merely operationalised.

The boundedness of the solution itself, or the extent to which the design brief offered opportunities for solutions to emerge from it, or constrained the solution to a convergent problem. Convergent design problems were considered strongly classified and divergent problems were considered weakly classified. S1, S2 and S3 were all set up and controlled in a manner that restricted them to convergent solutions. This was really a function of prescribing the conceptual layout at the start of the design task, and further constrained by prescribing the knowledge to be used. Only S4 allowed scope for a truly divergent solution, the most obvious reason being because the conceptual layout had to be developed by the students themselves, but there were also framing issues that contributed to the potential divergence of the solutions.

A similar process was followed for the analysis of framing, although here the definition of framing as control over selection, sequence pacing and evaluative criteria was used more directly, each aspect of framing providing one element for the analysis. Therefore:

Framing of selection relates to the selection of the disciplinary knowledge required to solve the contextual design task. Strong framing over selection is defined when it is clear that the knowledge required to solve the problem is explicitly defined in the design brief. Weak framing over selection is defined when the student is required to select appropriate knowledge him/herself.

Framing of sequence relates to the order in which different knowledge bits are brought in to solve the design problem. Strong framing on sequence is defined when the sequence to be followed to solve the problem is explicitly defined in the design brief. Weak framing is defined when the student is required to sequence the design him/herself. In the case where students are expected to use the design process, or where framing on sequence is implicitly defined by the design process as used/interpreted by the student, this is considered weak framing.

Framing of pacing refers to the control over the temporal domain through the project. Strong framing on pacing is defined when the design brief sets out explicit interim tasks with tight time schedules associated with them. The lecturer defines when each part of the design task will be completed. Weak framing on pacing suggests limited or no guidance on progress until the final submission date.

Control over the evaluative criteria always lies with the lecturer, and thus the framing over what counts as a good or adequate solution is always strong, even though the students may experience it as implicit or tacit.

Each design task was analysed with respect to each of the elements of classification and framing developed and a relative strength of classification and framing was assigned to each task, based on an accumulation of the relative strengths and weakness of each element. It should be noted that this process is to some extent an attempt to quantify qualitative data. Care should however be taken when interpreting the results. Each element of classification cannot be considered equivalent to each of the other elements of classification. Therefore if all three elements of classification are strong in one task, and two elements of classification are strong with one weak in another, this does not make the first task three times more strongly classified than the second task. But it does indicate a relative weakening of classification as one shifts from the one task to the other. The results need to be read relative to one another, but not in absolute terms.

The relative values of classification and framing for each task were then plotted on a Cartesian plane to show some indication of the trajectory of design in this case study of engineering design projects in a civil engineering curriculum.

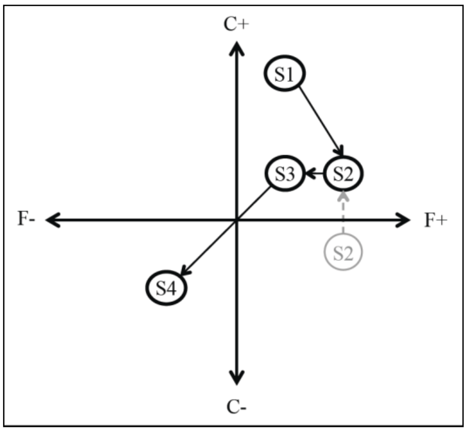

Figure 1: Trajectory of design tasks

Discussion

The trajectory of design tasks shown in figure 1 shows a general weakening of both classification and framing, although it is an uneven weakening. This can be seen as a shift from convergent type problems located firmly within disciplinary streams which define the theoretical knowledge to be drawn on, and where the lecturer determines the selection of knowledge and the sequence of its application to solve the design problem, towards divergent problems which draw on a range of disciplinary traditions, but perhaps more significantly, where the responsibility for selection of relevant knowledge, and the sequence in which it is used lies with the student not the lecturer. This shift is represented by crossing the boundary from the C+/F+ quadrant into the C-/F- quadrant.

S1, S2 and S3 all lie in the C+/F+ quadrant. In all three tasks the conceptual layout of the structure was prescribed. By comparison S4 is the only design task that lies in the C-/F- quadrant. It is also the only task that did not begin with a prescribed conceptual layout of the structure. For the first time students were required to consider alternative structural layouts for themselves. This is the first indication of expectations of divergent solutions. The other major distinction is that S1, S2 and S3 all restrict the knowledge required to knowledge within the field of structures. In many respects the design tasks are examples of the application of structures disciplinary knowledge to a context, but the coherence of the task lies more with the conceptual rigour of structural engineering theory. On the other hand S4 requires consideration of transportation planning, costing, and geotechnical engineering knowledge. Decisions made from a transportation modelling perspective impact on the conceptual layout, which in turn impacts on the structural loading. Consideration of costing and complex construction limitations, for the first time puts real constraints on the possible solutions. The design task provides a context in which multiple disciplines interact in an emergent manner. But in this case it is the context that holds the project together.

This raises the first implication for curriculum development: the shifting role of the design context set up by the design brief. Initially it is probably better to introduce design tasks that merely involve the application of disciplinary knowledge located within a single discipline to a design context, where the context is limited and fairly restrictive. However, there should be a shift towards contexts that allow scope for the generation of diverse and creative solutions, particularly through the interaction between multiple disciplines coming in contact with each other in the context set up by the design brief.

The second point relates to the implications of who determines the selection of relevant knowledge, the sequence in which it is applied, and the pacing of the design; the student or the lecturer. Here I draw particularly on a comparison between S2 and S4 in terms of framing.

S2 is the second design task in the structures stream. The task is located in the first semester of the third year, a point in most curricula where the majority of subjects could be categorised as engineering sciences. The students are therefore just starting to build up their engineering science knowledge and expertise, building on the pure sciences and some introductory engineering science in the previous two years. S4 is the final structures design task, located in the first semester of the final year, just prior to the capstone design and research courses. When students confront S4 they have had exposure to a diverse range of disciplinary subjects and are either attending or have completed the disciplinary basis of the undergraduate civil engineer program.

What figure 1 suggests is that S2 had the potential to be weakly classified, or the context had the potential to play a relatively generative role; but instead it was strongly classified, the knowledge drawn on was kept strictly in the structures discipline, the solution was forced to be relatively convergent, and the use of prescribed codes of practice in some ways did the job of translating the disciplinary knowledge for application in the context, and could potentially be applied mechanically, with limited appreciation for their theoretical underpinnings. This results from the strength of the framing of the task. S2 is sequenced by the lecturer through the allocation of sequential tutorials to specific parts of the design, which eliminates the possibility of the context allowing the sequence of decisions to play a role in generating alternative solutions. The selection of appropriate knowledge is defined by the lecturer for each sequential design task. The opportunity to resequence, or reselect as the design progresses in response to what is raised by the relation between previous solutions and the current one is eliminated by control over the pacing of the project in each tutorial. The naturally iterative nature of design is constrained. When the lecturer controls the sequence, selection of knowledge, and relative pacing of the process, the complex design becomes modularised and simplified into a sequence of independent and closed form solutions. The potential for divergent solutions emerging from interaction between knowledge and context is reduced. In Bernsteinian terms the strong framing strengthens the classification of the project. What is required in order to shift the problem to a weakly classified problem is to shift the responsibility for selection, sequence and pacing through the process from the lecturer to the student. It is exactly this aspect of S4 that contributes to its weaker classification.

In addition to allowing scope for alternative conceptual layouts of the structure, the fact that S4 required students to select for themselves what knowledge is appropriate from the range of disciplinary subjects they have seen in the curriculum and to apply it in the sequence that emerges as they progress, allows multiple 'knowledges' to interact with one another in emergent ways. Leaving the sequencing and to some extent the pacing to the student allows early decisions to impact on later decisions, and allows opportunities for reversals and iterations in solutions. This weakening of control over the design process is what allows the context to have generative powers in the solution.

Note that this discussion is not intended as a critique of S2. In terms of a trajectory of design knowledge, it is probably very appropriate to retain strong framing on the second design task. At the point in the curriculum when students confront S2 they are unlikely to have an adequate bank of disciplinary knowledge to draw on to make selection meaningful. Most third year students confronted with the uncertainty of a weakly framed design problem would not be able to appreciate the significance of selection and sequence on the process of design, rather it would serve to undermine their confidence in the power of the disciplinary knowledge that they are learning. However, if students only ever encounter strongly framed design tasks in the curriculum we should not be surprised when employers feel that students have strong theoretical foundations, but lack the ability to apply this knowledge to the messiness of the real world problems encountered in professional engineering practice (Royal Academy of Engineers, 2007). Rather this is a comment on the criteria for a certain type of design task, one where the context set by the brief and the knowledge required to develop a solution interact in a way that allows for the emergence of creative and divergent solutions. This is what is required of design tasks intended to align more directly with the world of engineering practice. In order to provide 'authentic' design problems, design contexts need to be sufficiently open that a student needs to select and sequence appropriate disciplinary knowledge himself or herself, directed not by the lecturer but rather by what emerges when multiple disciplinary 'knowledges' are applied and interact with each other in the design context.

In many respects the initial C+/F+ quadrant represents disciplinary knowledge, where coherence in the structure of the knowledge resides in the conceptual coherence of the discipline (Muller, 2009). This might be thought of as consistent with the ideals and logic of academic knowledge, where the principle evaluative criterion relates to using the knowledge and the knowledge relations in the ways of that particular discipline. The C-/F- quadrant on the other hand represents case based knowledge, where the coherence of the case is held by the context of the problem, what Muller (2009) called contextual coherence.

One of the problems with the dichotomy of contextual v conceptual coherence developed by Muller (2009) lies in the misrecognition of the role of context in holding together coherence. In a Bernsteinian tradition, context dependent knowledge is associated with a restricted form of meaning, where the knowledge gained is tied strongly to the context in which it is learned and possibilities of transferring the same knowledge to other contexts is seen as limited. The advantage of context independent knowledge is seen in its ability to transcend contexts. But in this case what is being seen is context playing a different role. In S4, context plays a generative rather than restrictive role in the problem. The knowledge is not learned in the context; rather it is applied to the context. There is a complex relation between theoretical knowledge from a wide range of disciplinary traditions, brought together, specialised to the context of application, and integrated in the context. In many ways the context can be seen as generative in that the context provides a catalyst for the emergence of something new as it allows for these multiple 'knowledges' to come together and interact in diverse and creative ways.

Conclusions

The study suggests that context set up by design tasks plays a critical role in the coherence of engineering design. Each design task has its own logic and coherence, which defines what knowledge is needed, that is, what holds the task together is the context set up by the design brief. This is not about knowledge being taught and learned in a context, rather it is about knowledge already learned being applied to a context, and in its application, in the presence of multiple disciplinary traditions the context functions in a generative manner, allowing new ideas to emerge.

It also suggests one aspect of the difficulty faced by students and teachers of design alike. What holds design together is not the same as what holds the engineering and pure sciences together. There is a different logic, not based on conceptual coherence of a discipline, but rather based on the specific case and its context.

The question of progression in design also relates to context, here progression is seen as a progression towards ever more open contexts that become increasingly generative as one progresses through the curriculum. However, even more than context, the aspect that allows contexts to become generative is the shift in selection of appropriate knowledge, sequence in the application of that knowledge and flexibility in the pacing of the project, a shift from lecturer to student.

An argument is made for a progression of projects beginning with more clearly defined projects located within single disciplines where the sequence of problem solving is controlled by the lecturer, through progressive stages to projects that require the student to define the boundaries of relevance (to select what knowledge is relevant, what must be considered and what is incidental to the project) and to take control of the problem solving sequence. However, there is a step-change necessary between where the lecturer selects the relevant knowledge and sequences the problem solving steps to where the responsibility is shifted to the student to make these decisions. This problem is compounded by the problem of evaluation or assessment, although the student needs to get to the point of defining the problem for her/himself and solving it to level judged adequate, the assessment is left firmly to the discretion of the lecturer. These are some of the challenges of teaching and learning engineering design.

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