KNOWLEDGE STRUCTURES IN ENGINEERING DESIGN: INTEGRATING MULTIPLE ‘WAYS OF KNOWING’

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Abstract - In this paper I discuss the different ‘knowledges’ needed to design, and their implications on the nature of reasoning in design. Donald Schön [1] and Herbert Simon [2] offer useful models of design that privilege different knowledge types, both needed to design. Schön describes a form of case-based reasoning built on material examples. Simon’s focus is on abstract reasoning, defined within academic disciplines by formal rational relations between theoretical concepts. Andrew Abbott’s [3] modalities of diagnosis, treatment, and inference help to show what underpins the different ways of knowing, but his modalities fail to account explicitly for translation between the various knowledge structures.

A focus on knowledge shows challenges students may face transitioning from sciences to design. It suggests ways that design project briefs constrain the way in which students work with, and between, different knowledge structures. It also potentially offers ways to think about introducing design reasoning into engineering science courses.

Keywords: engineering design, knowledge structures, professional reasoning

1. INTRODUCTION

One of the defining features of professions has always been the specialized disciplinary knowledge that their practitioners recruit to solve problems. Professional education has traditionally been aimed at transmitting this knowledge [4]. In engineering, specialized knowledge has been predominantly science based, although there has been a concern for the complementary disciplines of economics and the humanities throughout the history of engineering education [see for example 5, 6]. In traditional engineering curricula, disciplinary subjects (whether science or complementary) are taught in self-contained courses, with engineering design as the curriculum space in which students are exposed to both the integration of disciplines, and the relations between this specialized knowledge and ‘real world’ problems (as opposed to the idealized

problems pervasive in textbooks and exams). As a result, ‘design’ has become the subject most closely associated with professional practice and professional reasoning, and therefore a subject of central concern in engineering curricula.

Without going into the many critiques of design as the defining feature of engineering practice [see for example 7] it does offer a useful way to look at the nature of professional reasoning. In this paper I discuss some insights into what it means to reason between ‘theory’ and ‘the world’ through theoretical models of professional practice. Although the paper is largely theoretical, the argument was built on an empirical study of 17 engineering design projects in two engineering degree programs [8].

2. DESIGN PARADIGMS

The discussion that follows draws on two key design thinking theorists, Herbert Simon [2] and Donald Schön [1]. Although there has been a proliferation of design process models and descriptions of design thinking activities Simon and Schön’s models serve to highlight issues of knowledge that are particularly pertinent to this paper. In some senses they have been set up in opposition with one another [9]. Simon’s model has been described as ‘first generation’, founded on ‘technical rationality’, and relatively constrained, linear and restricted to well-defined problems. Schön’s model of reflective-practice on the other hand is described as a more cyclical model of parallel problem-framing and solution-generation. Each potential solution raises a new set of problems, with in turn offer new possibilities for solutions.

Most contemporary design thinking commentators tend to be attracted to Schön’s fluid and responsive model of design, and the influence of ‘reflection-in-action’ is evident in many models of design. It is a model amenable to the development of the generic outcomes defined by modern engineering program accreditation requirements. On the other hand, Simon’s model has been relegated to the ‘traditional’ model of science-led engineering that has proved to be inadequate to prepare engineers for

professional practice. Meng [10] offers one of the few critiques of this caricature of Simon's model. He points out that a careful reading of Simon [2] indicates that his model has far more in common with the open-ended, goal shifting model that Schön [1] offers. While Simon privileges the power of technical knowledge that can describe the performance of design artifacts, Meng [10] argues that he is also open to shifting goals and intuitive leaps:

Making complex designs ... has much in common with painting in oil. In oil painting every new spot of pigment laid on the canvas creates some kind of pattern that provides a source of new ideas to the painter. The painting process is a process of cyclical interaction between painter and canvas in which current goals lead to new applications of paint, while the gradually changing pattern suggests new goals. [2, p. 178]

While Schön [1] privileges material examples and the intuitive, he does acknowledge that :

Although it [engineering design] cannot be reduced to the application of general rules and theories, on the model of applied research, some of its main features are constant and amenable to description. [1, p. 10]

My focus in this paper is less on the process of design and more on the knowledge work that occurs in design. What sorts of knowledge do student engineering designers need to work with in order to propose a design solution, and how do they need to work between these different types of knowledge?

Andrew Abbott [3] is a less well known scholar in design thinking research but, like Schön and Simon, he is concerned with the nature of professional reasoning. Abbott's three modalities of professional action offer a useful way to both distinguish between the knowledge types privileged by Simon and Schön and a way to reconcile them. Abbot introduces what he calls three distinct modalities of professional action, each with a different knowledge structure and for a different purpose. Abbott's modalities are based on a medical metaphor, but he argues that they are transferable across professions.

Diagnosis serves the purpose of identifying the problem. Stripping the extraneous contextual details of the world from which the problem emerges and identifying only those details relevant to the problem itself (colligation) and categorizing it as a type of problem from a repertoire of professional problems (classification). Treatment serves the purpose of generating a solution/s. A solution is selected from a repertoire of past solutions (prescription) and is repackaged in response to the specifics of the problem (brokering). Both diagnosis and treatment rely on case-based knowledge, experience or knowledge of actual problems and solutions. Both rely on a classification

system of cases, organized in order of prevalence for diagnosis and efficacy for treatment. Abbott suggests that most professional work involves matching a problem type to a solution type, much like Schön's model of design. Like Schön, Abbott is clear that diagnosis and treatment can occur in either order (treatment is used to help diagnose), can occur in multiple cycles, (diagnoses might not respond to the prescribed treatment and a new diagnosis or treatment might be required), and that diagnostic cases and treatment regimens might be constructed from parts of different cases within each repertoire.

There are two aspects of diagnosis and treatment that are useful for understanding knowledge in design. The first relates to the nature of the knowledge, case knowledge, based on an understanding of what something is and how it works, not necessarily the science that describes it. I refer to this as knowledge of the material world. Schön describes the practitioner as having

... built up a repertoire of examples, images, understandings, and action. It includes sites he has seen, buildings he has known, design problems he has encountered, and solutions he has devised for them. The supervisor's repertoire includes patients he has seen or read about, types of stories he has heard psychodynamic patterns associated with them, interventions he has tried, and patients' responses to them. A practitioner's repertoire includes the whole of his experience insofar as it is accessible to him. [1, p. 138]

The second relates to the processes of colligation and brokering. The process of colligation, of simplifying the complexity of context and artifact down to the bare essentials and the process of brokering, of specializing a generic solution type to the specifics of a particular problem. Simon provides a succinct description of colligation

Most of the complex structures found in the world are enormously redundant, and we can use this redundancy to simplify the system. But to use it, to achieve the simplification, *we must find the right simplification*. [2, p. 228, emphasis added]

Brokering is the reverse of colligation – from the simplifications made during design, details have to be added. In the first instance, both colligation and brokering might be limited to reasoning about the material world, however, as will be discussed below, they take on a more complex role when designers are forced into Abbott's third modality, inference.

Abbott [3] argues that it is only when case-based reasoning falls short, when a problem type cannot be identified or constructed out of a repertoire of past problems, and/or when existing solutions or parts/combinations of past solutions can't be found to adequately solve the problem that professionals resort to

inference. However, for engineering students, who typically have a very limited repertoire of problem/solution cases to draw on, inference becomes a significant part of design. Where diagnosis and treatment draw on typologies of cases with concrete external examples, inference draws on abstract academic knowledge.

A profession's formal knowledge system is ordered by abstractions alone. Like any knowledge it is organised into a classification system and an inferential system. The classification, however, is quite unlike the diagnostic and treatment classifications. It is not organised from common to esoteric or from treatable to recalcitrant. Rather it is organised along logically consistent, rationally conceptualized dimensions. ... While these resemble the dimensions of the diagnostic classification, they are in fact more formal and rationalised. ... The character of the abstract classification system is thus dictated by its custodians, the academics, whose criteria are not practical clarity and efficacy, but logical consistency and rationality. *Professional knowledge exists, in academia, in a peculiarly disassembled state that prevents its use.* [3, p. 53, emphasis added]

What Abbott is pointing out is the fundamentally different knowledge structure and logic of diagnosis and treatment on one hand and inference on the other. He also highlights the disjuncture between knowledge favored in the academy and the objects to which it is applied in design. Where Schön privileges a repertoire of familiar case examples, Simon privileges the logically coherent conceptual networks defined within knowledge specializations. Abbott helps to draw attention to what Simon tends to leave more implicit, namely the case-based reasoning so important to Schön. And Abbott elaborates more clearly than Schön the inferences based on abstract reasoning so important to Simon's model of design.

3. EXAMPLES OF DESIGN REASONING IN STUDENT PROJECTS

In the two brief examples that follow I will illustrate the usefulness of Abbott's modalities, how they bring Schön and Simon together, but also their limitations for engineering design projects encountered by students. The intension is to show how the construction of a design brief directs student work into certain modalities and might neglect others, and consequently to provide a way to think about constructing engineering design projects.

The first example comes from a 4th year systems design course in mechanical engineering. Students used a number of prescribed systems thinking tools in the specification of a simplified coal fired power plant.

The following is an extract from the design brief:

The Republic of Rainbows plans an extensive expansion of its electricity supply network. It has decided to construct a number of single unit coal fired power plants at locations close to where the power is required. The generation capacity of each unit depends on its location, but all of them will be supplied by the same coal mine and will have similar site specifics.

In terms of Abbott's modalities of professional action, the problem has been diagnosed (a shortage of electricity) and the treatment prescribed (design a number of single unit coal fired power plants at locations close to where the power is required).

Students were provided with a process diagram of the prescribed artifact showing all the subsystems and their relation to each other, and showing the material paths (fuel, air and water/steam) through the prescribed plant. At no point did students need to work with identifying contextually emergent problems, test different potential solutions from any repertoire of possibilities, respond to the emergence of new problems as the overall solution type was refined. The process of design central to Schön's model was largely eliminated.

The context of operation was described in fixed, certain and invariable thermodynamic terms (ambient dry-bulb temperature, relative humidity, and atmospheric pressure). Implicit in the data is the focus on Abbott's mode of inference, a dependence on symbolic modeling defined by established conceptual relations. But what is significantly missing is the process of simplifying the context, identifying what matters and eliminating what does not, what Simon [2] refers to as making the *right* simplifications, and associated with colligation (the process of simplifying a problem by stripping extraneous contextual detail during diagnosis).

In this example, the idealization of the powerplant presented in the process diagram, the imaginary country and purpose, and the symbolic presentation of the context of operation all function to background the importance of making sense of the material world. The design brief constructs the problem as privileging theoretical knowledge over case knowledge. But more than that, by largely eliminating the material details students do not need to engage with the process of simplifying the material details and then translating them into symbolic form.

Among various system thinking techniques students were also required to model the performance of the system and subsystems as part of the process of quantifying key components. The modelling of the performance of the artifact (internal environment, subject to natural laws that can be described symbolically) within the context of operation (the external environment also subject to natural laws that can be described and modelled) forms an important part of engineering design. It is part of the process of specializing a general solution to the specifics

of the context, what Abbott calls the brokering process of treatment, and evident in different ways in both Schön and Simon.

What Abbott perhaps underestimates is the role of inference particularly in engineering design. While he associates routine professional action with matching cases or parts of cases in the development of the design, and inference only when cases are novel, Schön points out that designers are always facing novel situations. By implication then most professionals need to resort to some level of inference. This is particularly true for students who do not have a vast repertoire of past designs, successes and failures, from which to draw. The challenge is in making the shifts between case-knowledge located in the material world and theoretical knowledge located in academic rules of rational coherence.

The second example comes from a 4th year civil engineering design course. The project was far less idealized than the previous example presented. Done in conjunction with the City of Cape Town it represents a design project closely aligned with professional practice.

The design brief took the form of a question:

What should we do with the Foreshore?

And accompanying photographs, site visits and descriptions:

The north Foreshore precinct is a derelict part of the city characterized by neglected and unused open spaces and remnants of an older freeway-building era. Yet there is great potential to make use of this precinct to create a vibrant, mixed use area, open and attractive to all Capetonians, demonstrating principles of integration and sustainability, and possibly re-establishing the historical link between central Cape Town and the sea. Major new planned projects in this area and in relation to the Port make this task an urgent one.

In this example the problems are emergent from a real context, accessible to students, but initially presented without specialized disciplinary knowledge. The process of problem framing [1], making the right simplifications [2], or colligation [3] was left to the students.

Students needed to develop an overall precinct plan, a process of imagining possible ways to improve the precinct by the introduction, merging or removal of existing infrastructure. Reasoning, at least in the initial phases was very much located in the material: types of problems, types of solutions. Students were directed to look at precedent, other solutions implemented in other precincts, but still had to specialize their solution for the particular culture, history and existing environment. This stage of the design is well described by Abbott as 'routine professional action' and by the focus of Schön's model of reflective practice. Formal inferential reasoning or techno-rational decision making

after Simon would not be a necessity to develop a reasonable precinct plan.

But, as the technical design of various infrastructural elements progresses (the redesign of the incomplete overhead freeways, the introduction of canals linking the city and the harbor, mixed use buildings catering to a broad socio-economic spectrum and business possibilities, plans to improve and integrate the public transport systems in the city, etc) technical insights become more important. For example, much of the precinct is located on land reclaimed from the sea, offering particular geotechnical challenges. Identifying this and associated principled understanding that it provides earlier in the design process could avoid potential pitfalls only discovered in the technical design stages. I am suggesting that in engineering design there is a reliance on both case precedent and principled theoretical knowledge. One could argue that expert designers draw on theoretical insights intuitively and linked to case examples, but students are not expert designers and need a far more conscious use of disciplinary knowledge. For students this highlights the challenge of the process of identifying what is important in the process of simplification of both the material details and the theoretical principles.

Where in the first example the design brief framed the relevant theoretical concepts and relations required in the design tasks, the second example required students to make these judgements themselves. While recognizing the necessity of simplifying the problem by whatever terminology, Abbott, Schön, and Simon fail to make explicit the challenges of translating the material understanding of the context or artifact into symbolic language. While Abbott recognizes the difference in the nature and logic between case knowledge and academic knowledge he fails to articulate the translation between the two. Where Schön focuses on the importance of understanding the material details of the context and solution types, he underemphasizes the need to sometimes translate these material relations into symbolic academic relations.

I have not spent much of the discussion on the process of finalizing a design solution, adding details needed for the artifact to function in the complexity of the world, translating symbolic ideas into material artifacts. The process of reinserting the designed artifact into the complex realities of the world is associated with the 'brokering' of a 'prescription' (Abbott's mode of treatment). For engineering it involves re-describing the simplified analytical models into physical components, combining insights from individual analyses that were dislocated from one another for the purpose of inference onto an understanding of the whole. It's a process of adding the complexity back into the design following the simplifications needed for inference.

3.1. Summarizing the key ideas for designing design projects

There are two key insights that an analysis of this nature offers to engineering educators. Firstly, design requires students to work with two distinct ‘types’ of knowledge, both case knowledge of material things and theoretical knowledge of concepts and formal relations between concepts. And secondly, working between material cases and theoretical principles requires the ability to translate between the two.

In engineering curricula dominated by a focus on abstract theoretical concepts and the formal relations between them defined within disciplinary specializations, case-based reasoning tends to be neglected. While design type courses are often seen to fill the gap between ‘theory’ and ‘practice’, this takes the form of multiple expectations, most notably the role of design projects in the development and assessment of generic skills needed for accreditation purposes. The question is, to what extent do engineering curricula provided opportunities for students to engage with real things, embedded in the real world? To what extent is knowledge of things, what they are and how they work, valued in engineering curricula? As Schön [1] points out, design sinks into the messy world of the real, and making sense of that world in order to developing design solutions is a very complex task of iterative cycles of problems-solution-problem etc. This means finding spaces in the curriculum for students to start building a repertoire of case examples and knowledge of ‘things in the world’.

Both Schön [1] and Abbott [3] highlight the importance of building a repertoire of problem-solution case knowledge. In addition, Abbott suggests the importance of some sort of classification system for categorizing cases. This insight does raise questions about those design tasks that require students *only* to invent new solutions without at least some direction towards precedent – the requirement to research existing solutions to similar problems. It also raises the challenge of finding enough opportunities in overloaded curricula to build not just one or two examples, but to move towards building a repertoire of cases and their organization.

While Abbott sees most professional work as remaining within this case-based material reasoning, and Schön’s focus is almost exclusively on reasoning embedded in the material world, the examples presented in this paper show that even when typical solutions are matched to contextual problems that there is still a need to shift into a mode of inference. Design solution types need to be specialised to particular contexts, and in engineering that requires symbolic modelling to predict performance. But this requires the translation of case knowledge of material things into symbolic knowledge defined by abstract terms and established theoretical relations. As Abbott [3] points out, this is a shift between knowledge types with

completely different logics. But he does not offer how that translation happens.

To paraphrase Simon [2], students need to learn to read the material complexity and to make the *right* simplifications. What parts of an artifact of interest can be ignored and on what do they need to focus? How do they discern what parts of the context of operation are important, and which they can neglect? This is likely to be very unfamiliar to students who confront only those simplified and idealized objects stripped of meaningful interaction with their context of application presented in typical engineering science courses. Stripping material detail and isolating what can be isolated without distorting the system are important, but arguably overlooked, skills. I would suggest that not only do we need to consciously include student exposure to case-based reasoning, but we also need to find ways to help them to simplify and translate artifact and contexts into symbolic form amenable to inference.

When one considers how many of the engineering science examples students face in their degree programs end with a number, an abstract symbolic formulation far removed from the messiness of the world, one has to wonder how students learn to make sense of any analyses when they have to use them to make design decisions. By showing students how to interpret solutions to analyses in material terms, by using symbolic answers to make material decisions about symbolic solutions we could start to introduce students to the challenges of translating between the material world and symbolic models. Rather than leaving answers in simplified abstract form, teach and assess the process of translation, from the symbolic back into the material. It is perhaps here that design reasoning might be more explicitly built into engineering science courses by getting students more often to explicitly make sense of their symbolic answers in material terms.

4. CONCLUSION

One of the things that a comparison of Simon [2] and Schön [1] showed is that they privilege different ‘types’ of knowledge. Abbott [3] provided a useful comparison, including offering a suggestion that might help to account for why students have so much difficulty translating reasoning between ‘theory’ and ‘practice’ – knowledge is organized differently, and academic knowledge is constructed in a system that dislocates it from the world, making it difficult to ‘apply’ directly. Abbott’s position that most professional work is routine and located in reasoning in and about the material world may be valid in practice. But without substantial experience of this form of reasoning, engineering students may end up locked into obvious or naïve designs if they cannot rely on abstract theoretical reasoning.

As educators, we need to be careful of any glib suggestion of ‘applying’ theory learned in engineering

science courses to design problems. There are three things that need to happen first: the material problem needs to be understood in its own material terms so that it can be simplified; appropriate theory/concepts need to be identified from a vast canon of possible theory; and perhaps most challenging, knowledge of things needs to be translated into symbolic language amenable to analysis. Not only do students need to learn to simplify the material ‘things’ of the design, but also to find ways to describe them symbolically. This need to translate between the material and the symbolic seems to be largely left implicit in the models of design and professional reasoning I have presented in this paper. I would argue that it is also largely overlooked by engineering educators. Design briefs seem to either point students to the material world, or in some cases do the simplifications and remain in the symbolic world. Projects that explicitly focus on simplifying, categorizing and translating the material into the symbolic would be useful scaffolds to learning to design. And engineering science tasks that require students to translate symbolic answers into implications in the world would help to build links between the science and the world.

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