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Integrated Design: What Knowledge Is of Most Worth in Engineering Design Education?*

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This paper is based on the premise that the design ideas and methods that cut across most fields of engineering, herein called integrated design, have grown rapidly in the last two or three decades and that integrated design now has the status of cumulative knowledge. This is old news for many, but a rather limited approach to teaching design knowledge is still common in the United States and perhaps elsewhere. In many engineering departments in the United States, students are only required to have a motivational and experiential introductory design course that is followed several years later by an experiential and discipline-specific capstone course [1]. Some limitations of the capstone approach, such as too little and too late, have been noted [2]. In some departments, and for some students, another experiential design course may be taken as an elective. A few non-design courses have an experiential design project added following a design across the curriculum approach. However, design education may often be only 5–10% of the required engineering undergraduate curriculum. We identify several issues. First, experience alone is not enough, and we suggest the need for re-organizing the design curriculum to include more design knowledge. Second, 5–10% of the curriculum may not be enough time devoted to what 30% of the students will be doing upon graduation or adequate to cover what now constitutes design knowledge (unpublished alumni data from Penn State University and the University of Michigan). Third, design research and design education are not well connected, although some new subjects appear to run counter to this pattern. Working from a modified version of the categorization of design research by Finger and Dixon [3, 4], we attempt to sketch the universe of engineering design scholarship. We then discuss the content of about 15 leading design texts that we have examined as an indication of what design educators may be teaching. Further, we quantitatively review some disparate models of design education in Europe and the United States to help reveal the scope of what is possible. The authors are members of a new international consortium, Prestige, which is designed to prepare students to work in the global economy by developing learning opportunities in global product design such as: web resources; virtual, cross-national, design teams; and global internship experiences in projects and industries (http://cede.psu.edu/Prestige/). Activities such as creating web resources in design make the present paper a useful endeavor, as do the new design programs that are emerging at two partner institutions (http://www.leeds.ac.uk/product-design/, http://cede.psu.edu/ed/).

INTRODUCTION: DESIGN KNOWLEDGE

DESIGN IS a domain that is difficult to circumscribe, much less to understand. Most of the literature we examined has its roots in mechanical and industrial engineering. When exploring the world of engineering design, the first complication arises because not everyone makes a distinction between industrial and mechanical engineering. In the US they usually do, in Europe they usually do not. The next issue is the distinction between industrial design and industrial engineering. In the US, this usually means separate institutions that are different in nature as well as in subject matter. In Europe, they may be separate programs but in similar or even the same institutions. There are also a few successful programs that integrate both, such as the Faculty of Industrial Design Engineering at the Technical University of Delft. Integration of industrial design and industrial engineering is also the idea behind the new Product Design degree program authored by faculty in the Department of Mechanical Engineering at the University of Leeds (which is actually housed at the Keyworth Institute in Leeds). This new

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program is interesting, since, in its inaugural year 2003, its parent Department of Mechanical Engineering received the top (and rarely awarded) rating from the Research Council in the UK. Many industrial engineering departments in the US view industrial design as a liability to its research image, although one of the best texts we examined, and one which is widely used at Penn State, includes a chapter on industrial design [5].

All these complications arise even before considering commonalities in design across all fields of engineering, not to mention the world of aesthetic design, including and beyond industrial and architectural design. There are, in addition, over a hundred different terms to describe various approaches to design, from machine design to affective design. But, to understand what should be taught in the undergraduate curriculum, we need to understand engineering design and look at the options for organizing design knowledge. To do this, we begin with the seminal work of Finger and Dixon [3, 4], with three caveats. First, as broad as their coverage was, there were areas of design that they did not cover and areas that have emerged since their work. Second, while it is an enormously valuable categorization, it was not intended to be a theory, nor was it aimed at our present subject of design education. It was, and is, very useful for framing the unruly universe of engineering design. The third caveat is that we have restructured their typology, to capture our interests in education and theory, and named it Prestige after our consortium.

Finger and Dixon used six broad categories of design research [3]:

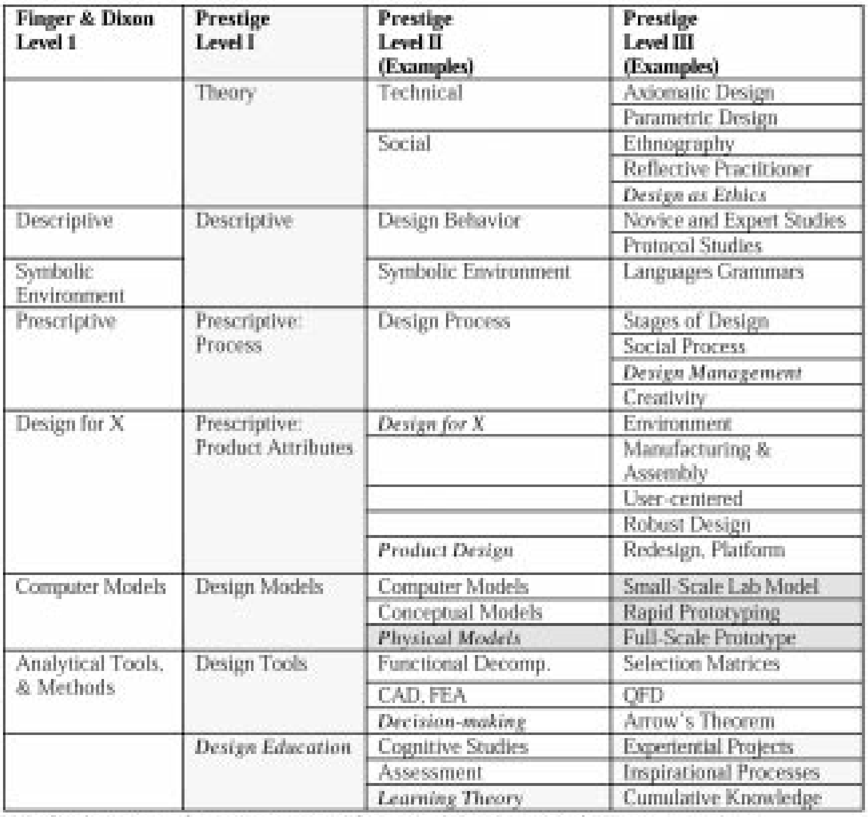
- Descriptive models of the processes
- Prescriptive models for design
- Computer-based models of design processes
- Languages, representations, and environments for design
- Analysis to support design decisions
- Design for manufacturing and other life cycle issues such as reliability, serviceability, etc.

We have reconfigured Finger and Dixon's categories in Table 1 by providing some vertical organization, two new categories, and some redefining of terms. This meets our own needs better. Unfortunately, the table permits comparisons only at the highest level, and lower levels are illustrated only with examples. One of our new categories, design models, will not be discussed in this paper, but it does not represent a major change from Finger and Dixon.

DESIGN TEXTS IN REVIEW

We have not included every text on design that has been published in the English language over the last 10 years, but we have included most we

Table 1. Finger & Dixon and Prestige design typologies compared



Finger & Dixon Level 1	**Prestige Level I**	**Prestige Level II (Examples)**	**Prestige Level III (Examples)**
	Theory	Technical	Axiomatic Design
			Parametric Design
		Social	Ethnography
			Reflective Practitioner
			Design as Ethics
Descriptive	Descriptive	Design Behavior	Novice and Expert Studies
			Protocol Studies
Symbolic Environment		Symbolic Environment	Languages Grammars
Prescriptive	Prescriptive: Process	Design Process	Stages of Design
			Social Process
			Design Management
			Creativity
Design for X	Prescriptive: Product Attributes	*Design for X*	Environment
			Manufacturing & Assembly
			User-centered
			Robust Design
		Product Design	Redesign, Platform
Computer Models	Design Models	Computer Models	Small-Scale Lab Model
		Conceptual Models	Rapid Prototyping
		Physical Models	Full-Scale Prototype
Analytical Tools, & Methods	Design Tools	Functional Decomp.	Selection Matrices
		CAD, FEA	QFD
		Decision-making	Arrow's Theorem
	Design Education	Cognitive Studies	Experiential Projects
		Assessment	Inspirational Processes
		Learning Theory	Cumulative Knowledge

N.B. Shading occurs for text content and for equivalent subjects in the Prestige typology.

found in the 15 reviewed and we welcome suggestions for good design texts in any language [6–19].

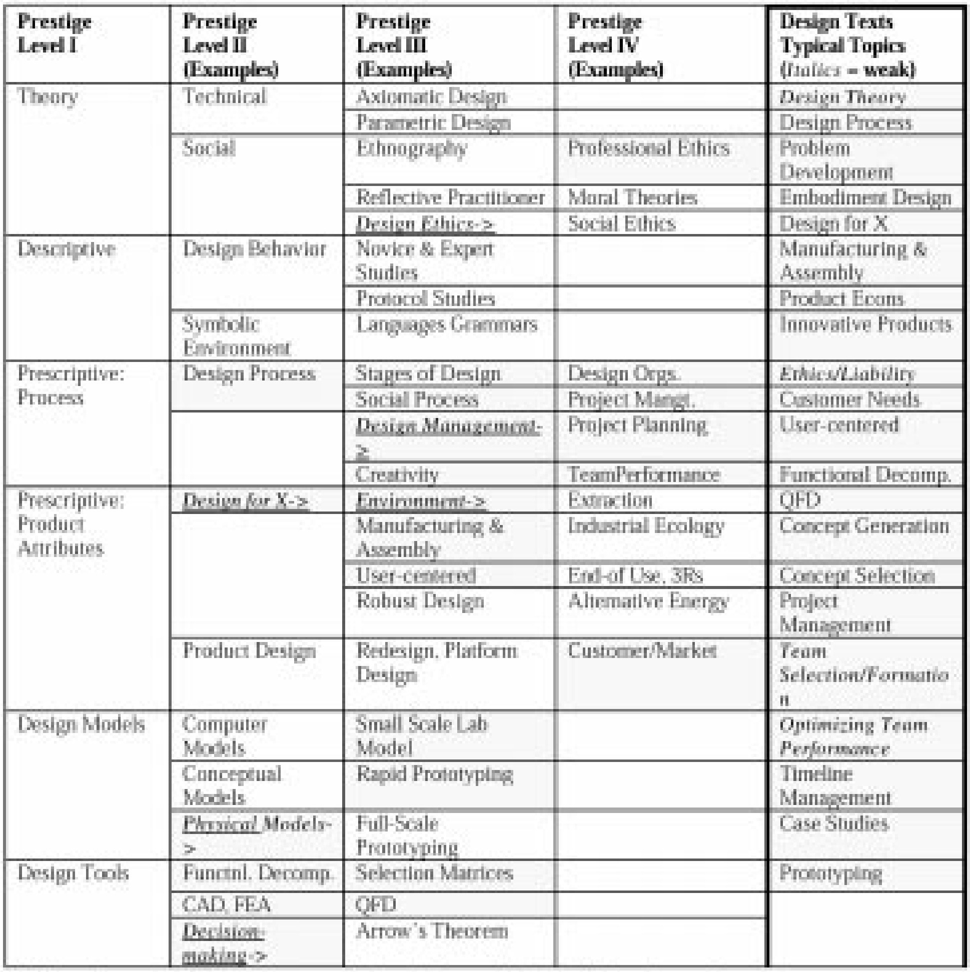
Although a number of very good design texts have emerged in recent years, an obvious finding in reviewing the texts is the rather weak connection between the content of the texts, all written after 1990, and the research reviewed by Finger and Dixon that was done before 1990. The best texts do have clear connections to the research on the topics they cover [e.g. 5, 15]; the disjuncture for them occurs in what they do and do not cover. However, most texts do not have very good research links. This suggests a disjuncture between those who do design research and those who do design teaching. Another important and very positive finding is that the work done in Germany, particularly by Pahl and Beitz [15], with help from Wallace at the University of Cambridge, has been very successful in popularizing the idea of process in design, and their model in particular. This has been the single most unifying factor in creating a general approach to design and it appears in some form or another in almost all of the texts we reviewed [20].

Table 2 shows a simplified content analysis of the texts in the last column, plus some assumptions about design education practice that few texts include. The first four columns in Table 2 show the Prestige typology for design, but levels two, three and four can only be shown with a few relevant examples. Design education is not covered in the texts and is omitted from this table.

Starting at the highest level, there is little coverage in the design texts of either design theory or descriptive design. Only the texts by Cross [7] and Birmingham [6] even recognize design theory as a topic worthy of inclusion, and their treatments are quite limited. Good sources for technical and social design theory include the Journals *Research in Engineering Design, Design Studies and scholarship in STS from Lewis Mumford to Langdon Winner.* We think an early introduction of students to design theory would enable students to understand the broader meanings of design and the alternatives pursued by various schools of thought. It would also make it easier to introduce design ethics, a new subject of particular interest in the US (ABET 2000) and one that is rarely covered in the texts we examined.

Similarly, a chapter on descriptive design, beyond the case studies that are quite widely used, could focus on such subjects as studies of

Table 2. Prestige categories vs. design text content



Prestige Level I	**Prestige Level II (Examples)**	**Prestige Level III (Examples)**	**Prestige Level IV (Examples)**	**Design Texts Typical Topics (*Italics* = weak)**
Theory	Technical	Axiomatic Design		*Design Theory*
		Parametric Design		Design Process
	Social	Ethnography	Professional Ethics	Problem Development
		Reflective Practitioner	Moral Theories	Embodiment Design
		Design Ethics->	Social Ethics	Design for X
Descriptive	Design Behavior	Novice & Expert Studies		Manufacturing & Assembly
		Protocol Studies		Product Econs
	Symbolic Environment	Languages Grammars		Innovative Products
Prescriptive: Process	Design Process	Stages of Design	Design Orgs.	*Ethics/Liability*
		Social Process	Project Mangt.	Customer Needs
		Design Management->	Project Planning	User-centered
		Creativity	TeamPerformance	Functional Decomp.
Prescriptive: Product Attributes	*Design for X->*	*Environment->*	Extraction	QFD
		Manufacturing & Assembly	Industrial Ecology	Concept Generation
		User-centered	End-of Use, 3Rs	Concept Selection
		Robust Design	Alternative Energy	Project Management
	Product Design	Redesign, Platform Design	Customer/Market	*Team Selection/Formation*
Design Models	Computer Models	Small Scale Lab Model		*Optimizing Team Performance*
	Conceptual Models	Rapid Prototyping		Timeline Management
	Physical Models->	Full-Scale Prototyping		Case Studies
Design Tools	Functnl. Decomp.	Selection Matrices		Prototyping
	CAD, FEA	QFD		
	Decision-making->	Arrow's Theorem		

N.B. Shading occurs for text content and for equivalent subjects in the Prestige typology.

the use of prescriptive approaches, expert vs. novice studies, ethnographic reports from the workplace, and design protocols. The research in these areas has grown steadily since the review by Finger and Dixon. Team behavior research was not covered by Finger and Dixon, but it is now a significant area of research and the subject is appearing in some of the texts [21]. Descriptive models of design also should have produced a rich area for teaching about design. Even in the 1980s, a number of studies of design behavior had recorded such things as 'solution lock' (single, unchanging, design concept strategy), the tendency to reuse familiar solutions, differences between experienced and naïve designers, and the role of '(stereo) types' in design thinking.

Prescriptive process topics tend to be very well covered in the design texts, although they do not usually have good links to the relevant research. The design process and several of its stages are almost universally included, albeit with different accounts of the process. Only one author treats the process itself as a variable to be designed [19]. Finger and Dixon were able to document a lot of work in creativity even pre-1990, and this topic is often present in the texts, albeit with a rather prescriptive pro forma treatment. Decision-making in design is an area not covered much by Finger and Dixon, but there is more research in this field now and it is typically included in design texts at an introductory level. Usually the topic is covered prescriptively in the texts using selection matrices.

Finger and Dixon noted that prescriptive models of the process had not been tested at the time of their review and, much more recently, Wallace and Blessing have noted that studies of the value of adopting a good process are still few, although positive [20]. Also, Finger and Dixon noted there had been too much focus on the individual and not enough on the social nature of the design process [3]. This has improved in the 1990s with the work done at Stanford (Leifer), MIT (Bucchiarelli), and elsewhere. There has been some commentary on the importance of the early stages of design (through to embodiment) and the need to develop our ideas and knowledge about it. The early stages may be the easiest to teach during the first years of a degree.

The social process topic of design management (project management, teamwork) was not included in the Finger and Dixon review, but now is clearly in the research and in the texts. Similarly, product design, innovative design, and customer needs assessment are all turning up, both in the texts and the research, particularly in the United States. This is an optimistic sign that the disjuncture between design research and design texts is weakening. However, it may only be occurring in instances where industry pressure is creating some commonalities in education and research and not more generally. Innovation, breakthrough products, and entrepreneurship are ideas that appear to have spun off from the economic boom of the 1990s, perhaps in the hope that these might go from outcomes (lessons learned) to causal factors for competitive advantage. Some texts offer good support for an upper-level course in innovative design [19, 22].

The other main prescriptive approach, looking at desirable attributes of design, has continued to be significant in research, particularly in robust design, but this topic involves fairly technical statistics and rarely appears in design texts. Design for X is arguably the theoretical parent of this approach and other aspects of Design for X are slowly finding their way into design texts. Design for X is still suffering from a surprising lack of development in the texts, although Pahl and Beitz do it well and there are many specialized books on design for this or that X, such as design for the environment [23]. Design for manufacturing and assembly are the most likely topics to be embraced and they are the best developed. Design for X, more generally, should become a significant aspect of the undergraduate engineering design curriculum, because it is so germane to broadening the minds of the students, letting them see the myriad trade-offs involved in design, and because it is so adaptable to so many topics, from design for the environment to inclusive design.

Design tools are active areas of research, but less so in the texts. This is to be expected, since many tools require sophisticated mathematics and others are based on the ever-changing software scene and come with their own documentation. Most texts use some sort of functional analysis to break the design problems down and tree structures also appear in decision-making methods, needs analysis, and risk assessment. Tabular tools appear in decision matrices and Quality Function Deployment. Spreadsheets are used for costing methods. Probabilistic statistics are used in some texts [8, 11]. An area that is not developed in the texts is the subject of design resources. There are good handbooks, good on-line resources, and good specialized texts, such as *Materials and Design* [24], *Inclusive Design* [25] and *Mechanism Design* [26].

DESIGN THEORY

Finger and Dixon note the incompatibility of many design theories. Dixon appeared to consider this a result of the 'pre-theoretical' stage of design at the time and he expected design ultimately to reach the standards of scientific theory, although science is usually viewed as advancing through theoretical debate as well as through the generation of empirical results. Dixon's stance is itself a theory about design that is contested by others who stress intuition, creativity and experience. Other authors have noted the need to develop synthetic reasoning methods that are more appropriate to design than the deductive and inductive methods of science [6], and this has become an area of design research [27], but it is not reflected in the design texts we reviewed. There are a number of well-known authors who have made distinctive contributions to design theory, but their work is not usually included in the texts we examined, such as Suh [28], Schön [29], and Bucchiarelli [30].

Another way to categorize design knowledge is to separate purpose-driven design, such as utilitarian market-driven and (other) value-driven design, like most Design for X, from the technology-driven or discipline-based nature of traditional design. This helps simplify the overall picture, at least, and it could be useful for organizing design knowledge in the curriculum, and the idea did inform our re-categorization of design. However, Finger and Dixon did not make this distinction, though they frequently note that this or that method is very domain-dependent. The difference between discipline-based design and generic design is the most important distinction in many schools of engineering in the United States.

An approach that might help unify design theories, at least to the extent of understanding their relative meanings, would be to consider what drives particular schools of thought in design. In this regard, there can be no question that the larger cultural context of design has had some influence. Indeed, the value of exploring the new perspectives from other cultures explains the cross-national nature of the present authorship.

For example, American schools of thought in design education are very reflective of the needs of industry, with much emphasis on customer needs, innovation, and product design, and also much stress on experience as the great teacher of design skills. In Germany, Pahl and Beitz, and others, have made an enormous contribution to design knowledge by pioneering prescriptive models of design, but they, too, reflect their own culture, which is known for its elevation of rational analysis and its deductive approach to reasoning. The great enthusiasm for design that is evident in the UK may well represent the strong historical role of empiricism and pragmatism in their culture.

However, while cultural variations may be explained by local influences, the reason why design research has not had strong links to design education may be because the drivers and incentive systems are quite different, even within the same institutions. As it was until the 1950s, design education is again responsive to what the employers of engineers wish to see when they employ them after the first or second degree. The focus is on the desirable qualities of the designers. On the other hand, design research is driven by publishing and funding. The funding may come from industry as well as from the government, but it is always focused on the future and on ways to gain a competitive edge at the corporate or national level. The focus is on products, tools, and the process.

DESIGN EDUCATION

In the United States, the appearance of some integration of teaching and research in design around such topics as innovative and entrepreneurial design may reflect a common source in industry's quest for the competitive edge, in both new products and new engineers, that can develop them. The National Science Foundation heavily funded six coalitions in the 1990s, including ECSEL, to which Penn State belonged. These coalitions were unevenly effective with respect to education reform, but they enhanced activity levels and interest in education research and publishing. There are now some good studies on research in engineering design education [31]. Atman and colleagues, for example, have produced a series of studies that document ways to measure design skills and which show at least three interventions that promote their acquisition: a first-year design course, reading a design text, and completion of an engineering degree [32–34].

However, our earlier conclusion that design research pre-1990 did not have much impact on the design education texts that are post-1990 is supported by a recent study that suggests that even design education research is not having an impact on design education. At the University of Washington, Martin, Adams, and Turns [35] used citation analysis to study the content of 12 journals and conference proceedings that address issues in engineering design education from 1995 to 2000 (they excluded *Research in Engineering Design*). From their examination of 274 articles, they concluded: 'most of the citations were publications by design educators, not design researchers. In particular, most of the journals, conferences, and periodicals were from the engineering design education community. In comparison, references to design research or education research sources, such as AERA [American Education Research Association] and *Research in Engineering Design*, were rare.' Presumably they found this result because design educators and design researchers tend to be different people, which is another variant of the disconnect problem. Martin *et al.* also noted 'that the average design educator is not consistently drawing from a wide variety of sources. The average paper has about ten citations, most of these being from similar sources (e.g. someone who cites books usually cites multiple books).'

Even more recently, Bucciarelli has added his commentary on what he sees as another disjuncture: that between design education and engineering practice (*Design Studies*, 2003).

INTEGRATED DESIGN

Originally, we sought a rubric for the general approaches to design that were of interest to us that would be the most useful and the least ambiguous. We have used the name 'integrated design' for the new approach, to distinguish it from discipline-based approaches to design such as the design of steel structures or machine design. We believe that, although it is an interdisciplinary approach, integrated design is more focused than the first term implies and in the United States interdisciplinarity is often marginalized in universities and treated with suspicion by many engineering faculty. Design is very purposeful, with a clear integrating goal, hence our preference for the term 'integrated design.' This name is not new and its use seems to be growing. For example, the Society for Design and Process Science (SDPS) now publishes the *Journal of Integrated Design and Process Science* (http://www.sdpsnet.org/publications.html). In Europe, the Center for Integrated Design (CID, Pôle Conception Intégrée) in Grenoble also follows this terminology. The meaning of integrated design varies with use, but we will not address that directly here.

We can now see a new meaning for this term. Clearly we need to integrate design research with design education—and both with design practice. From the perspective of cumulative knowledge, we need not only to define the knowledge base and its theoretical frameworks, we need to ensure that connections exist between the knowledge base and both the efforts to advance design knowledge through research and the way that we transfer that knowledge through teaching. The questions with which we began, of deciding what design knowledge is of most worth and how best to organize design knowledge in the curriculum, can now be seen to define a pathology in the literature in which we searched for an answer.

Interestingly, even within the design research community a similar use of 'integrated design' has appeared:

> *The need for an integrated design research methodology has been widely acknowledged in industry and the world-wide academic community. Currently, there is no consistent and agreed design research methodology, hence research results are often fragmented and the resulting design methods not validated. . . . We aim to bring together design research methods into a consistent practical design research methodology, integrated with a flexible and comprehensive software platform on which to build demonstrators.*

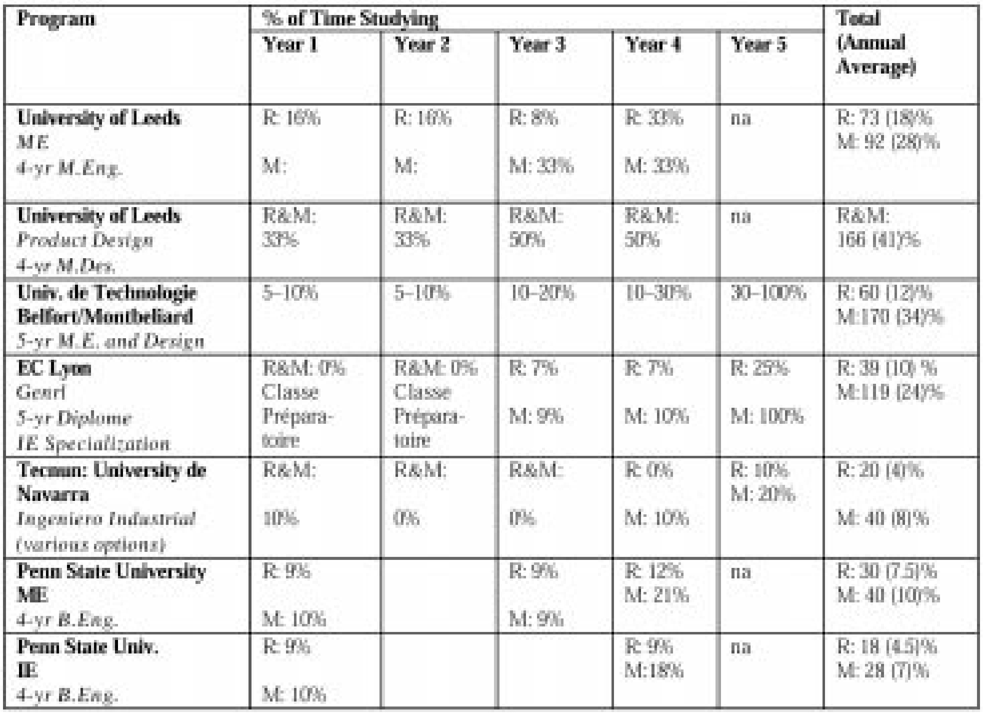
This is from the statement on 'Research Methodology' at the website of the Engineering Design Centre at the University of Cambridge (http://www-edc.eng.cam.ac.uk/researchmethodology/).

A GLIMPSE OF SELECTED DESIGN PROGRAMS

To study the options available in design education, we have quantified design education at our universities, and one other, in Table 3. We made these assessments using estimates provided by only one or two faculty. The numbers are only being used to explore the variations possible in design curricula formations and do not represent assessments of the models.

Several patterns emerge from Table 3. First, there are differences in the level of commitment to design that we could refer to simply as high and low levels. The special case of the new product design degree at the University of Leeds, which begins in 2003, obviously displays a higher level of

Table 3. Curricular commitment to engineering design at five universities



Program	% of Time Studying					Total (Annual Average)
	Year 1	Year 2	Year 3	Year 4	Year 5	
University of Leeds *M.E.* *4-yr M.Eng.*	R: 16% M:	R: 16% M:	R: 8% M: 33%	R: 33% M: 33%	na	R: 73 (18)% M: 92 (28)%
University of Leeds *Product Design* *4-yr M.Des.*	R&M: 33%	R&M: 33%	R&M: 50%	R&M: 50%	na	R&M: 166 (41)%
Univ. de Technologie Belfort/Montbeliard *5-yr M.E. and Design*	5–10%	5–10%	10–20%	10–30%	30–100%	R: 60 (12)% M:170 (34)%
EC Lyon Genri 5-yr *Diplome* *IE Specialization*	R&M: 0% Classe Prépara-toire	R&M: 0% Classe Prépara-toire	R: 7% M: 9%	R: 7% M: 10%	R: 25% M: 100%	R: 39 (10) % M:119 (24)%
Tecnun: University de Navarra *Ingeniero Industrial* *(various options)*	R&M: 10%	R&M: 0%	R&M: 0%	R: 0% M: 10%	R: 10% M: 20%	R: 20 (4)% M: 40 (8)%
Penn State University **ME** 4-yr *B.Eng.*	R: 9% M: 10%		R: 9% M: 9%	R: 12% M: 21%	na	R: 30 (7.5)% M: 40 (10)%
Penn State Univ. **IE** 4-yr *B.Eng.*	R: 9% M: 10%			R: 9% M:18%	na	R: 18 (4.5)% M: 28 (7)%

R = required minimum curricula exposure; M = maximum possible curricula exposure.

commitment than any other. Also, Professor Samuel Gomes at the Université de Technologie de Belfort-Montbéliard (UTBM) has offered data for their program in Mechanical Engineering and Design. This, too, has a high level of commitment, reflecting their specialization in design, but it is not higher than the ME program at Leeds, where students meet the requirements of the Engineering Council in the UK for design by the end of their second year. Although not in Table 3, Wallace has described the four-year degree in Mechanical Engineering at the University of Cambridge with commitment level to design similar to that at Leeds [36].

Second, the distribution of the commitment to design varies, from having a commitment every year, to a concentration in later years, to the pattern of design in the early and late years with nothing in the middle. This gives six possible patterns when combined with the two commitment levels, although we do not have examples of all six. Other patterns are not hard to imagine. The UTBM, for example, has a steady increase each year in the role of design.

Another important factor is the degree to which it is even possible to choose an emphasis in design. In our examples, low levels of commitment to design seem to restrict this option also. These universities are very highly ranked in their countries, yet they have made very different decisions about design education. Presumably they have made different decisions about other subjects also, but the variation in these patterns at least raises questions about the intent and impact of design education.

Further categorization of design curricula would need to explore the breakdown between knowledge and experientially-based modes of learning, and statements of curricula goals and expected learning outcomes.

Assessment tools are also important. If one were to take seriously the idea that success in the first job experience after graduation shapes success in the subsequent career path, then we could construct surveys to ascertain if more design education improves career success, particularly for the 30% or so that we think start their careers in product design and development. A related variable that could be studied at the same time would be the role of experience in industry for internships, coops and projects.

CONCLUSION

In summary, we think the Prestige typology offers some guidance for structuring design knowledge in the curriculum as well as showing the need for that knowledge. Further, choices need to be made about the level and the sequencing of design in the curriculum. The best guide to such choices would be assessments of the many different existing models. *A priori*, the least convincing model is the early and late model, because it has a low level of required and optional commitments to design and because of the long hiatus between the two main design experiences, which hinders the accumulation of design knowledge. However, assessment of design education programs must take into account both their objectives and how well these objectives are achieved in the context of each particular engineering school and its distinctive nature in the national and international scene.

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