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DEVELOPING SKILLS FOR SOLVING COMPLEX DESIGN PROBLEMS

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Abstract

A study has been conducted of novice designer responses to problems of intermediate complexity. Responses were collected by means of a detailed questionnaire concerning the use of design thinking tools, the rate of information assimilation, the adequateness of educational preparation, the effectiveness of experience gained, and the areas in which substantial learning outcomes were achieved. Response data was obtained for two different groups of design teams (121 designers in all) working on two distinct projects: a Wind Farm overview design and a large-scale Gearbox design. A comparison is made between responses to these two sample projects, and possible reasons for differences are explored. Contrasts between the approaches taken by novice and expert designers are noted, and implications discussed. Criteria are proposed for assessing the suitability of candidate projects for developing the skills of novice designers in solving moderately complex design problems.

Keywords: complexity, information management, knowledge representation, design learning, problem solving skills

1. Introduction

One of the recurring themes of engineering design practice and research is the inherent complexity of design problems and the consequent heavy mental loads imposed on designers during the problem solving process. Complexity is here considered as an attribute of design problem solving, arising from the nature of the solutions proposed by the designer and the methods used to generate and evaluate these proposals. It is manifest in the quantity of information handled by the designer, the knowledge domains traversed, the arrays of decisions made and the numbers of variables entering into these decisions [1]. Experienced designers approach complex problems in diverse ways, calling on formal strategies and systematic procedures as well as on unstructured insights derived from their experience [2]. They have acquired the skill of developing representational structures for complex problems that simplify them to manageable proportions.

How do novice designers acquire this facility for processing complex problems? As in all learning, the acquisition of skill in engineering design proceeds by a process of grafting the unfamiliar onto the familiar [3, 4]. In this paper we explore the outcomes of procedures in which novice designers are presented with problems at hitherto unprecedented (for them) levels of complexity, and nurtured through the experience of managing such problems to solution. In finding their way through this challenge the designers in question are faced with an inchoate, amorphous mass of information, and must impose their own simplifying structure upon it as a means to pursuing an optimal solution. Yet this learning experience needs to avoid negative outcomes such as technically overwhelming the novice designers or presenting them with apparently intractable problems.

Engineering design educators exercise their judgement in devising effective learning experiences which challenge students to extend themselves and to develop beyond the level already reached. They create graduated programmes of progressively more complex projects in which the completion of one level is judged to be adequate preparation for attempting the next. But how successful are educators in making these judgements? Are students adequately prepared at one level to proceed to the next? To what extent do they rely on the formal methods or "design tools" seen by professionals as essential aids to managing complexity? What are the learning outcomes? Do they gain the desired skills and confidence in managing and solving complex problems at or near a professional level of competence? In this paper methods of addressing these and related questions are described, and the results of a subsequent investigation incorporating these methods are presented and their significance for engineering design education assessed.

2. Background

2.1 Experienced designers: management of complexity

Skill in managing design complexity rests on the successful application of methods and procedures — acquired either by experience on the job or by formal learning. For examples of such methods and procedures we instance the following, taken from research papers and reports of descriptions of professional practice.

- Decomposition of complex problems into manageable sub-problems that are more or less independent of each other. (See discussion of quasi-decomposable systems in [5].)
- Identification of tasks and/or major decision areas and the interconnections between them, as a basis for elimination of infeasible combinations of sub-solutions and systematic examination of the remainder [6].
- Incremental assault on a complex problem, working through tractable sub-problems stage by stage until eventually the complete design problem is solved, see [2, 7] for examples.
- Iconic representations to capture the essentials of candidate design configurations, discarding inessentials [2].
- Networks and flow charts for keeping track of design variables and the interactions between them [8, 9].
- Initial trialling, "having a go", to discover key aspects of the design problem [10].
- Systematically addressing problem via an "Initial Appreciation", a procedure abstracted from observations of large numbers of engineering design presentations [11].

2.2 Novice designers: experiential learning

The undergraduate programme in Engineering Design at the University of Melbourne culminates in a capstone project in Year 4, the final year of the four year course. Work of professional standard is expected for external clients in industry, on projects with complex patterns of information to be unravelled and designer-client relations as an additional source of complexity [12]. In this paper we are concerned with Year 3, the pre-capstone year, and the selection and conduct of projects chosen to represent intermediate levels of complexity. For experiential learning in Year 3 projects, students work as novice designers in teams of four, over 5 weeks, with two hours each week set aside for consultation with and reporting to staff tutors. The tutors ensure that the design briefs are understood, offer advice on tricky technical issues, and generally guide and mentor the student teams. Students keep design diaries to record their progress and ensure there is written documentation supporting all major decisions. There are four projects scheduled to be evenly spread over the academic year.

Guidelines adopted for the selection of project topics suited to developing skills in the management of design complexity at an intermediate level are as follows.

Design phase: Embodiment design, design concept(s) already chosen, design schemes now to be worked out and key decision made on configurations and materials. (Other projects and case studies in the Year 3 programme deal with conceptual design and detail design).

Problem structure: Projects are open-ended to the extent that there is no immediately obvious path from the starting point in the design brief to the final, desired outcome.

Information content: Projects to contain manageable sets of design problems and variables, enough to challenge the students but not so much as to overburden or discourage them.

Social relevance: Projects either to be in the field of environmentally responsible engineering design or to be clearly associated with it.

2.3 Subject problems of intermediate complexity level

We now focus on the two projects selected in accordance with these guidelines in the academic year 2001. The topics were as follows. (Full design briefs are given in [13].)

A. A feasibility study for a 150 MW wind farm at a site on the southeast coast of Australia about 200 km west of Melbourne. The use of two commercially available wind turbines was to be investigated together with analysis of land usage and the design and costing of support towers and associated infrastructure over the working life of the installation.

B. The design of a compact gearbox to suit the drive from the turbine to the generator in one of the wind farm turbines, to transmit 1.3 MWe, step-up speed ratio of 1:78 to an output speed of 1,500 r.p.m. The number of stages of gearing was left open (the optimum turns out to be 3 with an epicyclic first stage for compactness), adding considerably to the challenge and complexity of the problem.

3. Investigation

In the year 2001 the opportunity arose to prepare and administer a questionnaire devised to elicit answers to the questions posed at the end of Section 1, a questionnaire in which the students would comment on their preparedness for the projects, list the design aids they made use of, and state what they saw as the learning outcomes and the substantial benefits gained.

There were nine questions, a deliberate mix of multiple-choice and open-ended formats. In the interests of brevity, and to concentrate on the most important results educationally, only six are considered here [13]. Regarding format, consecutive questions required different types of answer in an attempt to prevent students developing a mindset in which the answer to one question would carry over and influence the answer to the next. It was administered to students at the end of the semester in which these two projects constituted the practical work in the engineering design subject, providing the opportunity for guided experiential learning. Half the class were asked to reply on the basis of the Wind Farm project, and half on the Gearbox project. Participation was voluntary although an incentive was offered to attract a high rate of reply. 59 useable replies were received for the Wind Farm project and 62 for the Gearbox project, an overall participation rate of 83.5%. The six questions covered the following matters.

1. Design Thinking Tools. What tools assisted you or your team recognise the scope of the problem, and plan your attack on it?
2. Problem Complexity. At what stage of the project did you find you had organised the large amount of information available into useable form? — 12 stages nominated, students to circle one. The stages nominated are listed in the next section, under the presentation of results for Question 2.
3. Background Experience. Did your previous experiences in your course adequately prepare you for this project? If answering "No", please identify the knowledge and skills that would have assisted you.
4. Experience Gained. Following this project how prepared are you to tackle other problems with large numbers of unknowns or variables? Students to circle one of: much less prepared, less prepared, no change, better prepared, much better prepared.
5. Challenging Experience. To what extent did the project provide an adequate challenge for you? Students to circle one of: far too little challenge, slightly too little challenge, adequate challenge, slightly too much challenge, far too much challenge.
6. Learning Outcomes. What do you consider to be your substantial learning outcomes from this project apart from now being able to design a wind farm or gearbox?

4. Results

We adopt a convenient shorthand and in what follows denote the Wind Farm project as "A" and the Gearbox project as "B". The numbers in brackets denote the numbers of students making a particular response, project A followed by project B.

Question 1. — Design thinking tools to apprehend scope of problem

For both projects far and away the most frequently mentioned design thinking tools were:

(1) flow charts showing the flows of information through each project, often in the form of a strategic information-flow network or SIN (see [9] for example) (A: 29, B: 23);

(2) problem enformulations and sub-goaling via an "initial appreciation" of the project or some equivalent method, as explained in [11] (A: 30, B: 29).

Fifteen other design tools were mentioned, those mentioned by more than two students in at least one of the projects were: (3) trials and iterations, successive modifications based on feedback of results from previous trial (A: 6, B: 3); (4) spreadsheets (A: 3, B: 9); (5) failure mode analysis (A: 5, B: 4); (6) decision tables (A: 0, B: 5); (7) the discipline of weekly reporting sessions (A: 3, B: 1); and (8) compilation of design diaries (A: 3, B: 1).

We suggest that there are some generally applicable mental disciplines (in the form of design tools) in which all students and professionals should be proficient. Flow charting and problem enformulation are two of these. Thus we would argue that it is not possible to understand any process, including the design process, unless you can construct a flow chart demonstrating the transformation of available inputs into desired outputs. Moreover, we argue that this process must begin with some systematic consideration of design objectives and the resources needed to achieve those objectives.

Further than this, opinions may vary. At the least it would appear that engineering designers — student or professional — should be familiar with a variety of tools with which they feel comfortable and which they can bring to bear on the problem at hand.

It should also be recorded that 3 students replied “no design tool” for project B, while none did this for project A. This is one of several pieces of evidence that the information content of project B was significantly greater than that for project A, to the point that some students felt overwhelmed by the project and could not find a way of getting on top of it. This point will recur in later analyses for questions 2, 3 and 5.

Question 2. — Problem complexity and organisation of information

Designers nominated the stage of the project at which they felt they had organised all information pertaining to the problem into useful form. This was an indicator of the stage at which they had come to grips with the complexity of the problem. The twelve stages in problem solving were given as (a) Definition of problem — establishment of objectives, criteria; (b) Sub-goaling — decomposition of project into manageable tasks; (c) Completion of task description — identifying of interdependence of tasks, and constructing schedule for their completion; (d) Evaluation of background information in design brief; (e) Development of algorithms for optimisation; (f) Execution of sample calculations; (g) Development of system for computer-based analysis; (h) Obtaining results from computer; (i) Interpretation of results of analysis; (j) Further iterations; (k) Compilation of written report; (l) No stage. Examples of designer actions corresponding to these stages are provided in Appendix I of [14] (on-line). Frequency plots of student responses to Question 2 are shown in Figure 1.

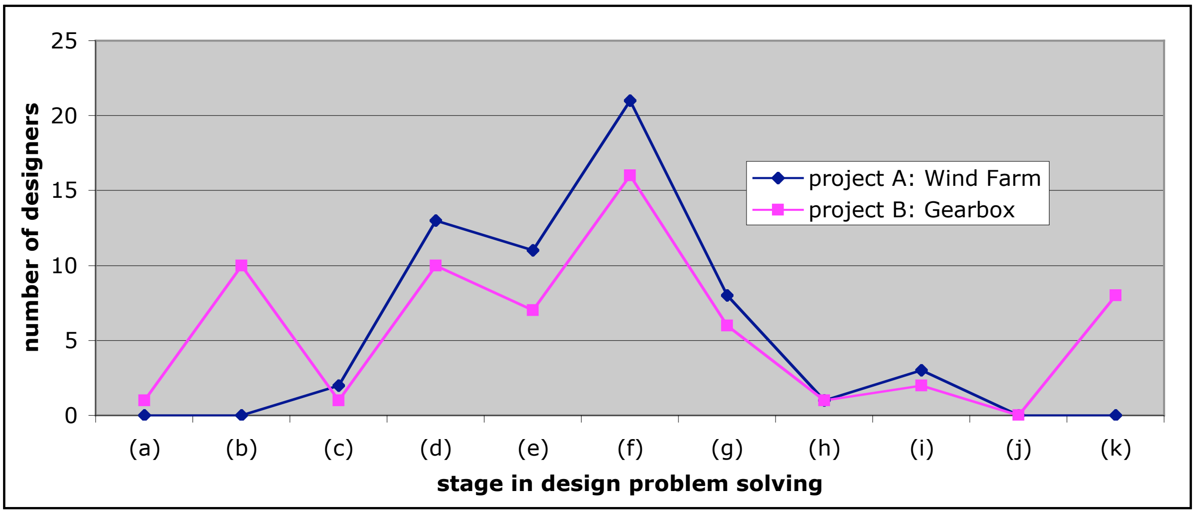

Figure 1. Designer responses to question 2 — projects A and B.

In project A, the Wind Farm, 80% of students gave an answer lying in the first six stages (a) to (f). In project B, the Gearbox, this ratio had fallen to 73%. Nevertheless, there is a general similarity between the two sets of results.

The major difference lies in the greater spread of stages nominated by the students in the case of project B. Reasons for the earlier selection of stages (a) and (b) are not clear. However, the eight students who answered (k) are in effect saying that there was so much information to be handled they really didn’t sees how everything fitted together until the final stage of the design when the report was written and submitted. This result is in accordance with an observation made in the analysis of the answers to question 1, as noted above.

Question 3. — Adequacy of Preparation for Project

The responses of students to question 3 may be summarised as follows in Table 1. Interestingly, the two students with unclassifiable responses to this question for project B replied that they had not been adequately prepared by their previous studies, but for them this was a good feature of the project as it forced them to be independent, and learn how to learn. “It was good for us to learn to do things for ourselves”, commented one of them.

Table 1. Replies to question 3 (“Did previous course experience prepare you adequately for this project?”)

	A: Wind Farm	B: Gearbox
“Yes” (sometimes with comments or qualifications)	83%	53%
“No” (stating matters of concern, sometimes implicit)	15%	44%
nil response or unclassifiable	2%	3%

In the “No” responses, students raised matters of concern regarding their level of preparation. For project A, various matters were raised by the nine students, covering better grounding in mechanical engineering science, more guidance on relatively new material in statistics and boundary layer mechanics, more training in 3D visualisation and practical engineering, also worries about crossing boundaries between subject areas previously regarded as separate.

For project B, the 27 students raised a total of 50 matters, distributed as follows: Report writing to professional standard (14 times); Mechanical engineering science, gear theory (11 times); Project management and teamwork (7 times); Engineering design education (18 times). This last grouping covers particular matters concerning bearings, seals and practical details of construction and assembly; and also general concerns about information overload, “I think this project is too big a jump from previous projects”.

Overall, while there were many positive responses to both projects, one is forced to the conclusion that project B (Gearbox) in the form it was presented to students was overly ambitious. On educational grounds it is a good thing for students to have to seek out new information for themselves and in the process “learn how to learn”, but in this case more time should have been provided for this relatively uncontrolled learning process to take place. Academic staff have taken to heart the demonstrated need for more careful pre-planning of potentially large projects in Year 3 of the programme.

Question 4. — Experience gained, transferability to other multi-variable projects

The responses to question 4 are shown in Table 2 for students saying how prepared they were following this project to tackle other problems with large numbers of unknowns or variables.

Table 2. Replies to question 4

Project:	A	B
(1) Much less prepared	0	0
(2) Less prepared	1	0
(3) No change	6	6
(4) Better prepared	43	48
(5) Much better prepared	9	8
% replies stating (4) or (5)	88%	90%

Table 3. Replies to question 5

Project:	A	B
(1) Far too little challenge	0	0
(2) Slightly too little challenge	2	1
(3) Adequate challenge	45	19
(4) Slightly too much challenge	8	34
(5) Far too much challenge	4	8
% replies stating (4) or (5)	20%	68%

A high percentage of students consider they have made significant educational gains as a result of these projects, a nice validation of the efforts of the responsible academic staff.

Question 5. — Challenge of the educational experience

Students' replies on the adequacy of the challenge experienced working on these projects are shown in Table 3, above. Note that students answering (2) did so because they wanted more innovative projects where there was more scope for creative initiatives. The answers to this question reinforced the message that the gearbox project tended to overload students with information which they found difficult to organise in a coherent manner.

Around 20% of the students considered the Wind Farm project too challenging. There always comes a time when educators have to make responsible judgements, and for the authors this was one of them. The figure of 20% is one we can live with, but anything over 30% we regard as needing remedial action in the planning of future projects in engineering design.

Question 6. — Substantial learning outcomes

This question was open-ended, deliberately so, to allow students to give their own, considered replies. In the event, a great variety of responses was received. An indication of this is given by the summary of the responses covering the Wind Farm project summarised in Appendix II of [14], available on-line. (Replies for the gearbox project were generally similar, and are therefore not included here.) The wide range of matters covered by these responses is noteworthy, an indication if one were needed that educators should not limit themselves to overly constrained or *a priori* statements of educational objectives.

Analysis of the responses to question 6 showed that they fell into three main categories, namely: (A) engineering design problem solving; (B) project management and teamwork; and (C) generic and attitudinal matters. The listing in Appendix II of [14] (on-line) follows these groupings. Category (C) covers generic high level learning, confidence in approaching new problems, and insights gained into professional standards and professional practice.

The numbers of students giving replies in these categories is shown in Table 4, together with the corresponding percentages of the total number replying. It should be noted that the contents of some students' replies covered more than one category.

Table 4. Replies to question 6.

Category	project A: Wind Farm	project B: Gearbox
(A) Design problem solving	35 (59.3%)	42 (67.7%)
(B) Project management and teamwork	32 (54.2%)	40 (64.5%)
(C) Generic and attitudinal matters	19 (32.2%)	15 (24.2%)
Number of students covering both (A) and (B)	16 (27.1%)	22 (35.5%)

The data in Table 4 provides a benchmark for assessment of the educational outcomes of future projects. As management and teamwork are often stated as important objectives in engineering education, it was gratifying to find so many students responding in this category.

To illustrate the student responses to the Wind Farm project we draw attention to what educators might describe as the "best" and from their point of view the "worst". At one end of the educational spectrum there were two students who responded in terms of high level learning thus, "improved ability to find out how to do something without being taught (self-learning)", and learning to set priorities, "learning what is important to be included, what should be left out". At the other end of the pedagogic scale, two students replies that "nothing much" had been learnt from the project.

5. Discussion

5.1 Review of significance of results reported in Section 4

The construction of a questionnaire which gives meaningful results regarding students coming to grips with and managing complex problems in engineering design has been demonstrated. The questionnaire contained both multiple-choice questions and open-ended questions. The multiple-choice questions could be analysed quickly — within a day or two of the completion of a project if desired. This in turn enabled quick evaluations of the validity and effectiveness of the project, either confirming current educational practice or pointing to desirable changes. It is suggested that this information — or data from other similar questionnaires — usefully supports but does not replace the exercise of pedagogic judgement, particularly with respect to decisions on the allocation of resources to constructively engage with small numbers of "under-challenged" or "under-prepared" students.

Open-ended questions will inevitably elicit a great variety of answers. This variety is in itself a stimulus to engineering academics to rethink their priorities and educational objectives. To take one example: in the authors' experience, skills in mathematical modelling (see data from the Wind Farm project in Appendix II of [14], available on-line) can easily be overlooked by the engineering design community on the one hand and the engineering science on the other — to the ultimate disadvantage of students and graduates when they are inevitably exposed to serious professional problem solving.

5.2 Student progress in professional problem solving

An evaluation is made of students' progress towards the successful management of complex design problems at a professional level. For this purpose we review relevant evidence from the questionnaires for the Wind Farm project. The performance of professionals on this project is exemplified by the efforts of two of the authors (JGW and WPL) who worked through the project in parallel with the students. Comparisons of interest are set out in Table 5 below, in which entries for the students attempt to characterise the group as a whole, and data for outliers whose responses are at the extremes are discarded. Characteristics of professional problem solving have been extracted from [13].

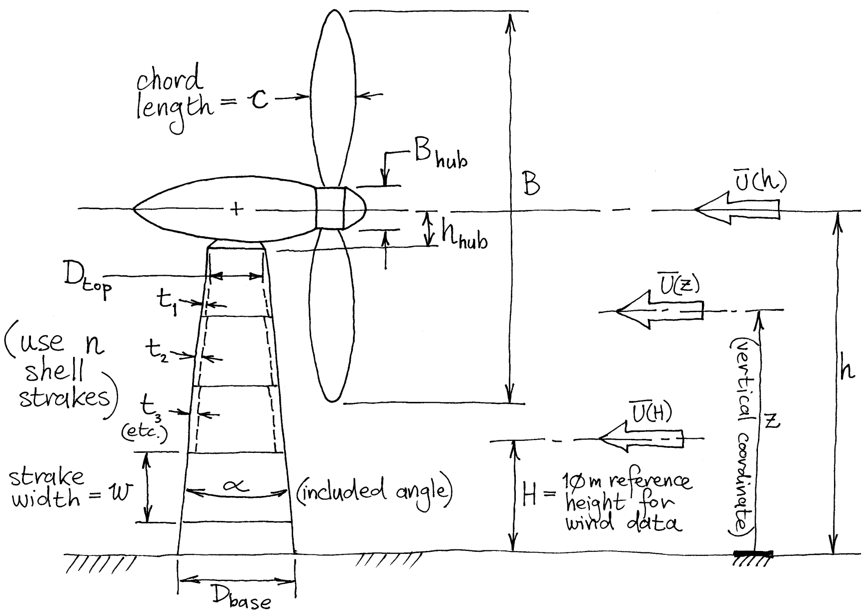

Figure 2. Focus diagram produced by experienced designer (JGW) to apprehend problem scope

Table 5. Comparisons of professionals and students in design problem solving — Wind Farm Project

Characteristics of Professionals, Engineering Design of Wind Farm	*Quality of Student Performance at Equivalent Stage of Design Process*
Early use of sketches to assist visualisation of problem, define variables of interest, and focus on key issues. (refer Figure 2)	Poor, use of sketches mentioned by only one student, few examples in reports.
Use of systematic aids to problem definition, e.g. an initial appreciation.	Good, mentioned by many students, used in their reports.
Use of flow charts to illustrate and control overall design strategy, and/or the detailed process of optimisation. (refer Figure 3)	Variable, mentioned by many students, but not always followed up in reports.
Construction of spreadsheets.	Good, adopted by nearly all design teams.
Identification of comprehensive set of modes of failure, failure analysis.	Poor, vibrations and fatigue overlooked by many students.
Capacity for self-learning.	Insufficient evidence from Wind Farm project. However, some positive evidence from Gearbox project.

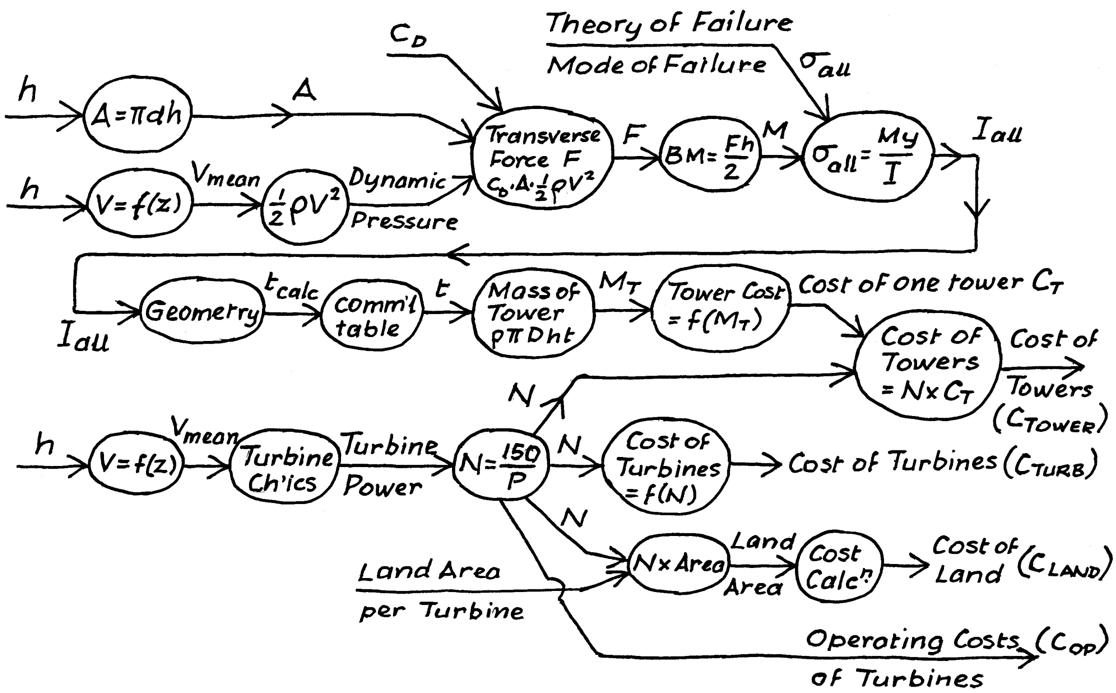

Figure 3. Flowchart constructed by experienced designer (WPL) to summarise Wind Farm design process

6. Conclusion

This paper has investigated an educational and problem solving environment which challenges novice designers but does not overwhelm them, one in which students learn to deal with complexity by processes of guided mentoring, independent action, and self-learning. Two problems at an intermediate level of complexity in engineering design have been exhibited, and attempts made to assess the challenges presented to students in the light of their previous experiences as well as the educational benefits accruing to them. It is hoped that the paper will assist engineering design educators to exercise their pedagogic skills in creating and managing supportive learning environments for novice designers.

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