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Detailed Analysis of an Engineering Design Project*

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To help meet the calls for more effective engineering design in practice better understanding of the engineering design process in industry is needed. Participant observation of engineering design projects and analysis of the field data collected is one possible approach for this. The participant observation of a two-year engineering design project involving 37 people and 2368 hours of work effort is summarized in this paper. The project is briefly described, and some of the quantitative and qualitative results are discussed with reference to a model.

INTRODUCTION

THE engineering design process is the means by which ideas and needs are converted into the information from which products and technical systems can be made. It is fundamental to all industry, and must continually respond to changing expectations and the effect of many indirect influences. Two critical issues are the quality of the final designs produced and the management of the design activities involved [1, 2, 3]. As the output from the engineering design process is information rather than a tangible product, and the concern is with both the quality of this output and the human activities which produce it, studies of the process are complex. The use of social science field research techniques is needed for gathering data, and practical engineering design experience for interpreting the results. From the literature it becomes evident that:

(i) Despite a long history of innovative engineering design in industry and the development of prescriptive methods and models, the engineering design process is still not completely understood.
(ii) The design process as it is currently modelled in theory does not accurately match what happens in practice.
(iii) Research is needed to gain a better understanding of the engineering design process in industry, and participant observation of real engineering projects is advocated.
(iv) Hybrid quantitative/qualitative approaches need to be developed for the analysis of empirical field data.
(v) Contingency models with multiple levels of resolution are needed to represent the activities and outputs of the engineering design process.

RESEARCH OBJECTIVES

The objectives for this particular research programme were:

(i) Detailed participant observation study of an engineering design project in industry.
(ii) Quantitative and qualitative analysis of the field data with reference to an appropriate model.

CONTEXT MODEL

When analysing the project it was necessary to differentiate between the overall project effort and that part of it regarded as the engineering design process, and to be able to classify the inputs to the project at different levels. To visualize this a model was developed, representing:

(i) The engineering design process in an industrial context;
(ii) Appropriate resolution levels within the context;
(iii) The human activities and outputs in engineering terms.

It comprised two diagrams, one representing the context within which engineering design takes place, and the other setting the engineering design process in this context (Fig. 1). Within an external environment are markets; within a specific market are competing companies; within a company is a management team controlling projects; and feeding

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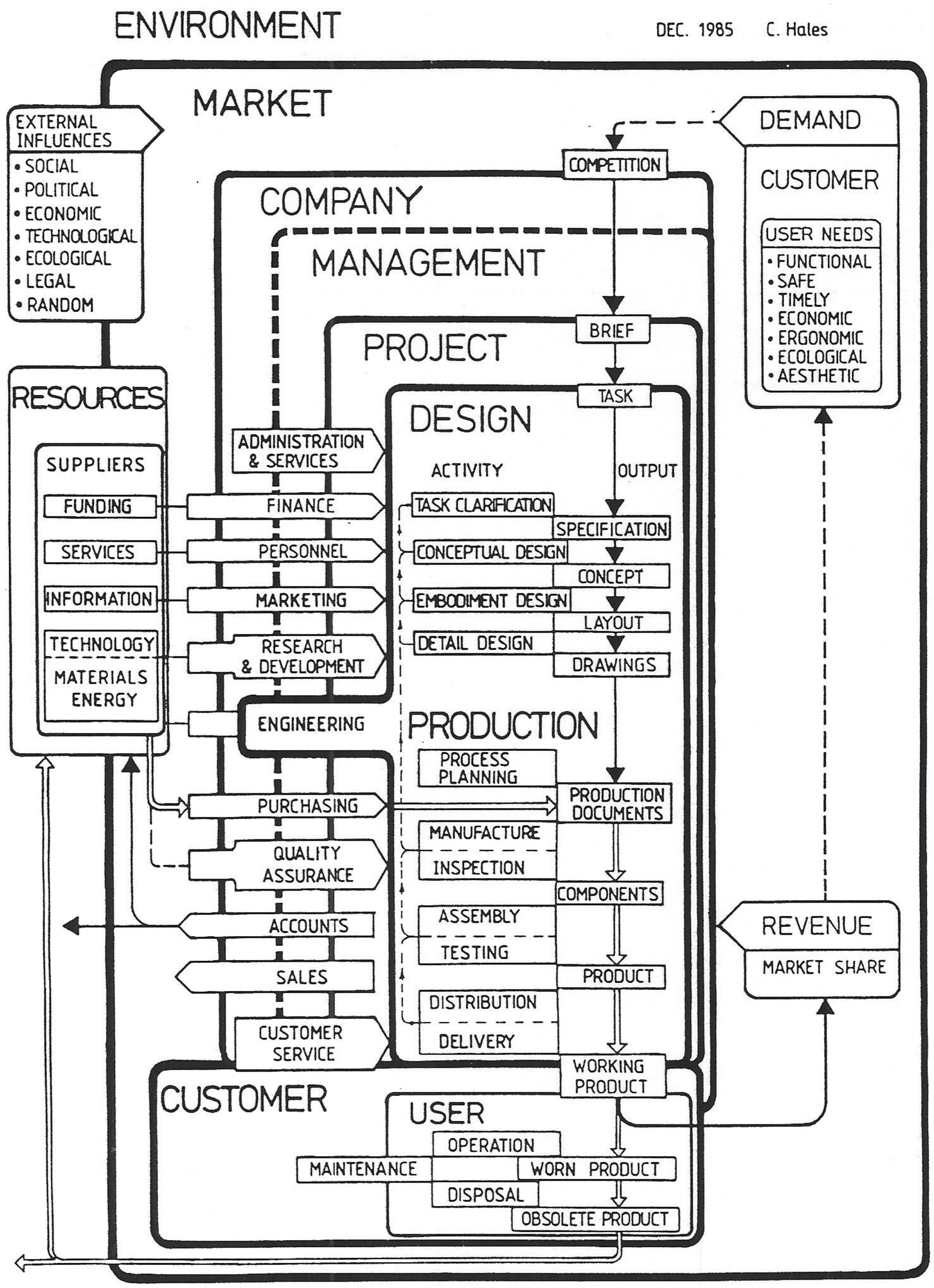

Fig. 1. Engineering Design Process Set in Context.

into a project are resources from the environment, the market, and the company. Customers and users generate revenue through exchange processes and the activities and outputs at all levels are affected by the impact of external influences. The concern was with the *engineering* input to the project, as distinct from marketing, finance or any other input. By highlighting the engineering input, with the design and production processes shown within the project, the phases of the engineering design process may be visualized in terms of the activities and outputs, and these phases may be described as:

(i) Through task clarification activities, the problem is defined. Output is a design specification.
(ii) Through conceptual design activities many solutions are generated, selected and evaluated. Output is a concept.
(iii) Through embodiment design activities the chosen concept is developed. Output is a definitive layout.
(iv) Through detail design activities every component is completely specified. Output is production information.

THE PROJECT

The project involved the design of a high-pressure and high-temperature system for evaluation of materials in a simulated slagging coal gasifier environment. The design task was seen by the company as challenging. Automatic control of temperature, gas flows, liquid flows and coal flows at high pressure for continuous periods of up to 1000 hours was required. The main difficulty, and the novel feature of the proposed system, lay in the handling of flowing coal on such a small scale under extreme pressures and temperatures. Although the need for such equipment had been identified by the company, the requirements had not been formally established and the ideas were vague, so in engineering design terms the problem was 'ill-defined'. The only unusual aspects from the company's viewpoint were, firstly that a systematic approach would be applied to the complete design effort, and secondly that every activity related to the project would be recorded in detail for analysis.

The project proposal, submitted to the materials research group within one division of the company, was accepted, a contract was signed and the design work started in October 1982. The design task was clarified by defining the problem more closely and compiling a 20-page design specification or requirements list. This document, listing 308 requirements, formalized the input of everyone involved and recorded what had been agreed. Conceptual design, which was completed during the next four months, presented few problems. Embodiment design, involving the development of the reactor concept, the subsystem layouts, the control system design and cost justification documents, took a further 17 months. Detail design of the 7 subsystems including the steelwork, was done during the final 14 months. Field data was collected from the time of the original proposal to the end of Month 34 when the drawings were almost finished.

QUANTITATIVE ANALYSIS OF THE PROJECT

The project was observed for 2.8 years, during which it passed through all phases of the design process to near completion of detail design. A systematic approach based on Pahl and Beitz [4] was used, providing a coherent structure which helped in categorizing the observational data and in making comparisons between theory and practice during the analysis. A total of 37 people were involved and 1373 interchanges, separately identifiable events, were recorded. This covered 2368 hours of work effort in time intervals down to 0.1 hour. The field data comprised 1180 pages of diary notes, 76 hours of audio tape-recordings, 116 weekly reports and 6 design reports. Data was reduced by colour-coding the notes according to participant, compiling a set of data sheets for each person and entering the 2488 records into a computer database for indexing, sorting and categorizing. Summary database files were then translated into spreadsheet files for final numerical and graphical analysis.

A graph of measured overall project effort by phase, Fig. 2, suggested the use of 'Ideal Phase Diagrams' for monitoring design projects. With reference to the example generated for this project, Fig. 3, the following conclusions were drawn:

(i) 'Ideal' engineering design projects may be classified and characterized by a series of

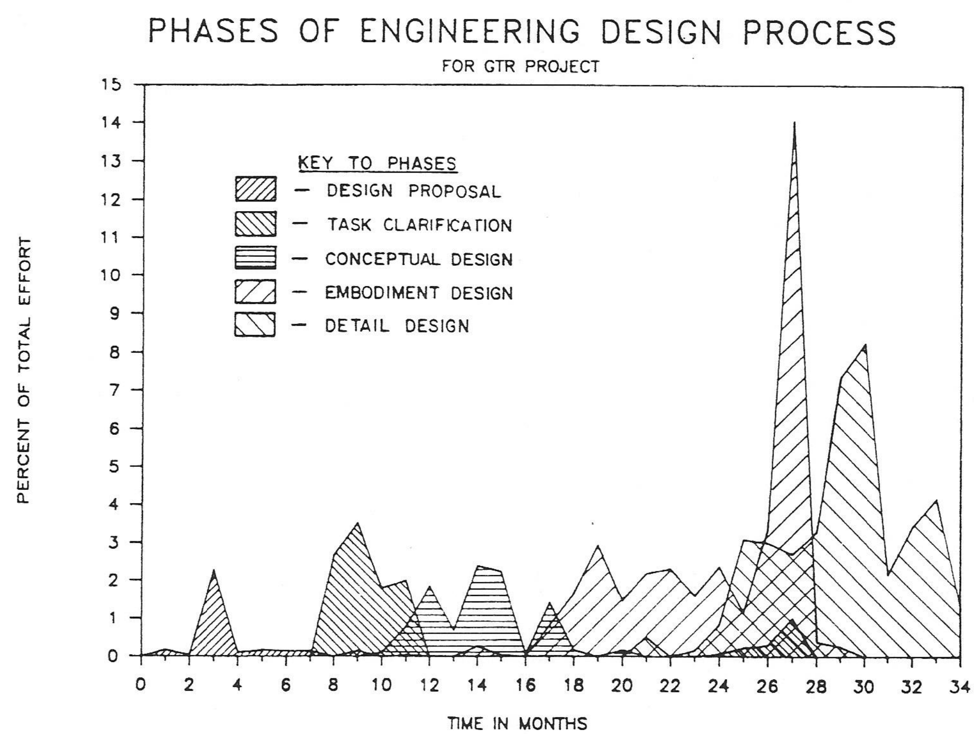

Fig. 2.

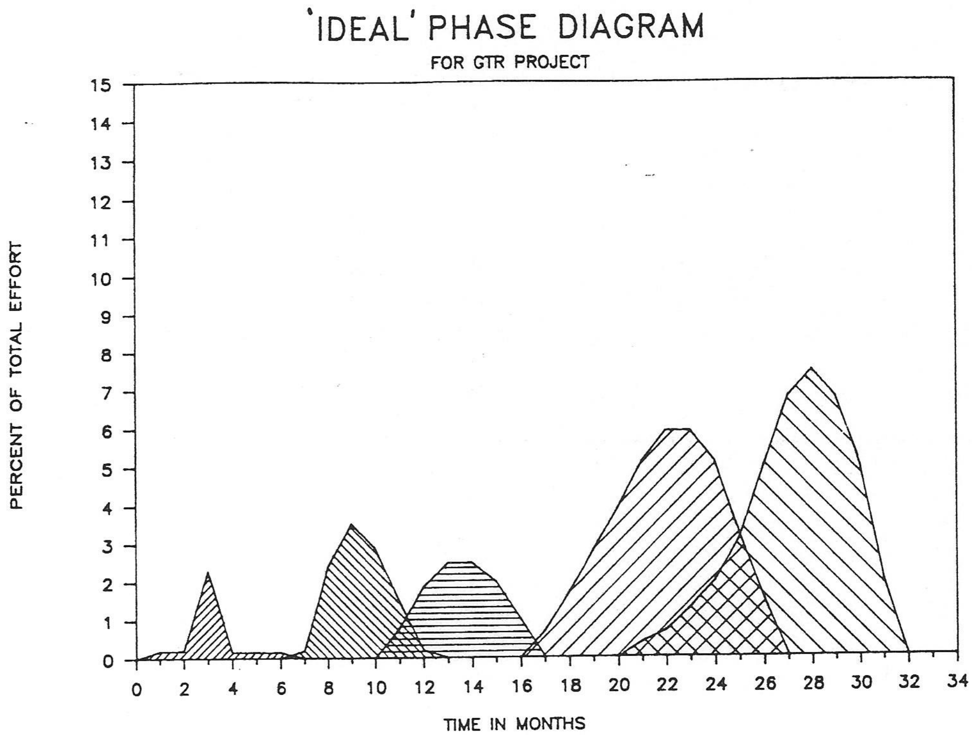

Fig. 3.

overlapping 'phase curves', each representing the work effort in a particular phase of the design process along a time-axis.

(ii) An 'ideal' graph of cumulative effort, based on an ideal phase diagram for a project, provides a model against which to measure actual performance.

(iii) Design work not completed within the envelope of the ideal phase curves for a particular project will have to be completed outside the envelope at a later time. This causes diversion of effort and thus increases the cost.

(iv) Changes to the design specification outside the ideal phase curve for Task Clarification cause increases in project effort and cost, and the later changes are made the greater the effect.

Other conclusions from the quantitative analysis were:

(i) Almost half the design team work effort was accounted for by the activities regarded as 'steps' of the design process in the literature. The other half was accounted for by a mix of the following six general activities:
- Personal day-by-day work planning
- Reviewing and reporting project progress
- Cost estimating
- Information retrieval and processing
- Social contact and interactions
- Informally helping on other projects.

(ii) The use of 'methods and aids' commonly described in the literature accounted for less than one-quarter of the observed engineering design effort and 13 categories of design-related working, communicating and motivating techniques were identified which accounted for the rest.

(iii) The activity which accounted for the highest proportion of the overall design effort was reviewing and reporting (22%) and the most used design-related technique was communicating by means of reviews and reports (15%).

(iv) The observed outputs of each engineering design process phase were assessed against what might be expected in theory. There was general agreement, except for the addition of cost justification documentation and the control system design in the Embodiment Design phase.

(v) Over 50% of the observed project effort involved people working alone or in pairs on specified tasks, 30% went on meetings involving 2, 3 or 4 people and 9% was spent on letter writing (or reading) and telephone calls.

(vi) Design work was carried out in a variety of locations ranging from specifically allocated personal space to more public areas within company premises, and remote locations such as in aircraft or at home. Over 50% took place in a personal office of one or other participant and only 17% took place in the 'design office'.

(vii) A preliminary way of reducing and quantifying subjective data collected on the 'mood' of participants during the course of the project was developed. The fluctuations in 'mean mood' were plotted by month for the participant groups, and for the project as a whole. The results did reflect the subjective assessments of team members.

QUALITATIVE ANALYSIS OF THE PROJECT

The quantitative analysis based on work hours characterized the project in terms of activities and outputs but did not explain why things happened the way they did. A complementary approach was needed for this. Instead of categorizing the activities and outputs for each project phase, 'influences' observed to have affected the project were identified at five levels of resolution [5, 6, 7] according to the context model. Influences may be defined as 'people or things having power', with power as 'the ability to affect outcomes' [8]. For the 'goal-orientated' engineering design process to be effective the balance of influence ('power in operation') must favour the attainment of project goals as distinct from goals at other levels. The Hughes Aircraft Company study [9] on productivity in technology-based organizations identified influences acting on R & D situations and most of these were found to apply also to this engineering design project. From the literature a list of 103 factors considered likely to influence the engineering design process was generated, divided into 20 categories of influence at 5 levels of resolution as summarized in Fig. 4. They may be categorized as continuously-changing or slowly-changing, and as favourable 'facilitators', or negative 'barriers', according to their effect on the project [10].

Attempts were made to 'profile' the project [11, 12, 13] according to the effect of influences but the levels and categories lacked a suitable structure at the time. With reference to appropriate

Level of resolution	Influence category	Contributing factors
Macroeconomic (Environment)	External Influences:	Social; Political; Economic; Legal; Technological; Ecological; Random.
Microeconomic (Market)	Market:	Demand; Competition; Financial Risk.
	Resource Availability:	Services (human); Finance; Information; Technology; Materials; Energy.
	Customer:	Clarity of need; Urgency of need; Expectations; Involvement.
Corporate (Company)	Corporate Structure:	Size; Span; Complexity; Flexibility; Centralization; Project Autonomy.
	Corporate Systems:	Integration; Information Use; Technical Complexity; Social Environment; Physical Environment; Pay & Benefits.
	Corporate Strategy:	Clarity of Objectives; Risk-taking; Innovation; Involvement.
	Shared Values:	Commitment; Enthusiasm.
	Management Style:	Autocratic Style; Benevolent Style; Consultative Style; Participative Style.
	Management Skills:	Planning; Organizing; Directing; Coordinating; Controlling; Communicating; Representing (champion); Resource Use.
	Management Staff:	Number; Awareness; Judgement (decision-making); Motivation; Morale; Confidence.
Project	Design Task:	Magnitude; Complexity; Novelty; Quantity; Technical Risk; Timing.
	Design Team:	Expertise; Experience; Role-balance; Cooperation; Commitment; Motivation; Morale; Negotiating Ability; Power-base; User Involvement.
	Design Techniques:	Systematic Approach; Formal Procedures; Working Methods; Communicating Methods; Motivating Methods; Computing; CAD; Standards & Codes.
	Design Output:	Productivity; Work Quality.
Personal	Personal Knowledge:	Knowledge-base; Knowledge Applicability.
	Personal Skills:	Judgement (perception); Competence; Communication; Creativity (imagination); Versatility; Negotiating Power.
	Personal Attitude:	Standards; Self-discipline (habits); Integrity; Role-compatibility.
	Personal Motivation:	Enthusiasm; Involvement; Tenacity (determination); Anxiety; Humour.
	Personal Output:	Productivity; Work Quality.

Fig. 4. A Checklist of Influences on the Engineering Design Process.

classifications such as used for the McKinsey 7-S Framework [14] the structure shown in Fig. 4 was developed, and the 103 contributing factors identified seem to form reasonably coherent sets within this. The output field data was analysed in terms of each contributing factor, within each influence category, at each level of resolution [15]. The influences which most affected this project were in the following categories: External Influences; Resource Availability; Corporate Systems; Management Style; Design Team and Design Techniques.

CONCLUSIONS

Participant observation data from an engineering design project in industry has been gathered and categorized according to a context model. The activities and outputs of the engineering design process have been analysed for the project, and based on this a possible approach to project monitoring is suggested. A list of 103 factors likely to influence the engineering design process has been drawn from the literature and categorized. An analysis of the project field data with respect to each factor identified those which most affected the project. Further work is needed to develop techniques for classifying and monitoring projects by 'phase diagram', and profiling projects according to 'influences'. The context model has proved helpful in the teaching of engineering design as a map to show how different topics relate to the engineering design process. Project monitoring by means of phase diagrams is currently being tried by several British companies keen to improve the effectiveness and efficiency of their design work.

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