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PROJECT STRUCTURE: AN IMPORTANT FACTOR IN DESIGN PLANNING?

Tomas Flanagan, Claudia Eckert and P. John Clarkson
Cambridge EDC

ABSTRACT
Planning large-scale design projects is difficult due to a combination of structural variations in terms of task-connectivity patters and uncertainties concerning task durations, rework behaviour, requirements changes and resource availability. This paper uses generated, hypothetical models to explore how variations in design project structure – in terms of rework cycle duration and task connectivity level – are likely to impact plannability, and evaluates the findings against those for models of real industrial projects.
Results show how the size and number of iteration loops impact the number of alternative task configurations that must be considered during planning. They also show that increasing connectivity between tasks is likely to adversely affect project schedules, particularly in the context of high-rework levels. In line with these and other insights obtained from the simulation analyses, heuristics for design planning are proposed.

Keywords: planning and scheduling, risk management, design process improvement, design connectivity, process structure

1 INTRODUCTION

Companies often find it difficult to predict which projects are likely to succeed because a myriad of diverse project outcomes are plausible due to the complex interaction of different uncertainties. Satisfying cost and schedule targets necessitates the construction of plans that remain robust as different scenarios unfold [1].
Managers in industry can often think of examples of previous plans that did not work properly and expect that similar problems will arise with current plans. By clarifying appropriate expectations for different plans at a structural level, some of this scepticism could be reduced and different plans could be handled appropriately. Planners and managers then hence be better placed to recognise opportunities for risk mitigation based on structural similarity with previous projects. In reality, however, designers and design managers spend little time reflecting over the quality of their plans after the end of projects. Retrospective examination of plans can prove a difficult activity, as plans are not always updated throughout the project, so that as the project accumulates uncertainty, the plans bare little resemblance to the actual events that unfolds.
While much of the information about the project can be attributed to the characteristics of the individual tasks, project structure is the back-drop upon which these tasks interact together. The structure determines which tasks can be performed in parallel and how the effects of task failures/delays are likely to be amplified or attenuated by other tasks which comprise the project. Project structure varies in terms of the degree of connectivity between tasks and the nature of the feedback loops which drive iteration. As product development times decrease despite rising product complexity, concurrent engineering initiatives lead to a greater need for information exchange between tasks and hence drive increased connectivity.
In addition to feed-forward dependencies between tasks, which can limit the degree to which tasks can be parallelised, design processes are also subject to feedback dependencies which drive iteration [2]. The size of such iteration loops (in terms of number of tasks), as well as their timing within the project, varies from project to project but the implications for the planner are not always clear. While iteration is widely recognised as an inherent characteristic of design processes, the impact of structural characteristics of iteration such as timing and duration on project plannability are poorly understood.

This paper will argue that understanding the implications of project structure on plannability would be useful to industry (Section 2) before outlining how simulation analysis of hypothetical models can provide such understanding in Section 3. In line with results from the simulation analysis in Section 4 and the implications of this work for industry are discussed in Section 5. The results are evaluated against case-study observations in Section 6 prior to the closing summary.

2 FROM CASE STUDY OBSERVATIONS TO RESEARCH REQUIREMENTS

This work is motivated by findings from an extensive case study undertaken with a diesel engine design company. Data from 46 one-hour interviews, company documentation, industrial project plans and process documents were analysed to obtain a good understanding of planning practice. A four-week on-site ethnographic study was also undertaken to investigate how the company really plans and manages projects. While the observations reported here focus largely on a single study, other studies aimed at modelling and improving design processes [3][4][5] and at predicting the impact of engineering changes [6] testify towards the generality of the case study observations.

The initial interviewees were selected by a senior manager within the company; subsequent candidates were selected based on interviewee recommendations. All interviews were semi-structured: while the authors had a detailed catalogue of questions, interviewees were encouraged to speak freely. In many cases, later informal conversations were used to clarify issues arising from the interviews. Most interviews (33 of 46) were recorded and interview transcripts were analysed by the authors.

Interview data from different participants were compared and contrasted. Interviewees discussed their work situation and provided descriptions of their typical actions. In so far as possible, hypotheses given by interviewees were validated through discussion with their colleagues and comparison with data from other sources (e.g. documents, observation). Throughout the analysis phase, a continuous dialogue was maintained with the company. The findings were presented back to interview participants and to other company personnel to discuss questions arising from the analysis and assess the practical applicability of findings. Case study observations concerning project structure are discussed below.

2.1 Case study observations concerning project structure

Case study data showed that project planning challenges due to uncertainty associated with task properties such as duration, cost, resource requirements and rework likelihood were aggravated by variations due to process structure. Some tasks were tightly connected in task-clusters while others had few information dependencies. Also, the size and timing of these task clusters varied for different components within the design. For example, the engine block is typically designed early in the project and resulting information is used to inform subsequent downstream tasks such as the oil-and-cooling system design. In this case, the block is designed early, because it as a long lead time item, it needs to be frozen early. Being also a highly-connected component, it can not accommodate changes later in the processes, thus passing them on to other components and in turn increasing the pressure on those components that are frozen late [6]

Likewise, project structure can vary due to social and technical differences between different products: an aero-engine takes roughly 4 years to develop and requires 2,500 people thus equating to approximately 20 million man-hours, an order of magnitude greater than that associated with the design of a diesel engine. The jet engine is developed mainly in parallel streams for each major component and structured through explicitly planned convergence interaction loops. In contrast, the diesel engines is developed by engineers who have a far greater overview over the product and who are able to resolve many potential problems through targeted negotiation [7]. However, the manner in which structural variations affect project plannability is poorly understood.

The interdependence between task connectivity level and iteration may also present planning challenges. The degree of connectivity may influence the number of tasks that require rework in the event of a given task-failure: highly connected processes are likely to suffer more severely. Also, the time taken to discover rework may be influenced by the structure of the project: in simple projects, a single designer may be responsible for all of the design tasks and thus quickly identify mistakes; in a complex, interconnected project, a wide range of issues (complexity, cultural differences, lack of design overview) may cause mistakes to go unnoticed. Finally, the structure of the project, particularly in terms of connectivity, may provide clues towards its robustness in terms of its ability to absorb rework.

Figure 1. EDC case studies concerning: diesel engine, aero engine and helicopter design planning highlighted the importance associated with task connectivity structure

Other studies performed by the Cambridge Engineering Design Centre indicate the generality of planning problems in the aerospace [3] and automotive industries [4] (Figure 1). The importance of task connectivity structure was also highlighted by previous case studies data, which underscored the difficulty associated with managing engineering change, and concluded that many change projects have a better chance of succeeding if treated like small scale NPD projects [8][9].

3 USING SIMILATION TO ANALYSE CONNECTIVITY STRUCTURE

Simulation analysis was seen as an appropriate technique for exploring project sensitivity to structural variations. Simulation is a powerful approach for analysing the dynamic behaviour of some complex systems [10]. Its merits include good scalability, control over project variables and richness of output results available. These results, in turn, are easier to access, analyse and interpret than actual project data and are more easily reduced to visual summaries.

The value of simulation in project management has been recognised for over forty years in the context of CPM, the Critical Path Method, developed by DuPont in 1957 [11] and PERT, the Process Evaluation and Review Technique [12], both of which are instances of the Precedence Diagramming Method (PDM). In CPM, the critical path is the longest sequence of consecutive tasks that establishes the minimum length of time for project-completion; any delays to these tasks will result in project overrun [13]. In both PERT and CPM, activities are typically shown as nodes and arrows between activities represent information or material flow (although Gantt charts are also commonly used to represent the schedules which emanate from PDM models). One major difference between both approaches is that CPM uses a modal estimate for task duration, while PERT uses a weighted average of lowest, highest and most likely duration.

Haga and O'Keefe [14] discuss the development of PERT/CPM and associated simulation analyses for exploring the effects of task duration uncertainty. Some of the limitations of PERT/CPM methods, such as failure to model iteration, were addressed by Pritsker and Happ [15] through the Graphical Evaluation and Review Technique (GERT). Nonetheless, GERT and the later extension, Q-GERT [16], have not achieved the same acceptance among practitioners as the original PERT/CPM approach.

While simulation has been successfully applied to many project planning challenges, its application to the analysis of structural variations between projects is hindered by the dearth of suitable models and because variations in the degree and type of uncertainty obscure the impact of structural differences.

Challenges also arise during the abstraction, modelling, representation and comparison of real-world projects [17][18]. Every modelling activity by humans is carried out from a specific perspective and with a certain bias (e.g. [19]), which will highlight some tasks and connections and not others. The structure of a process depends on the connectivity between its elements and the nature of iteration, both can be obscured at certain levels of detail. For example, when a task-cluster is expressed as a single task, the associated project risk may become obscured.

Despite these difficulties, some authors – particularly those in the DSM (Design Structure Matrix) community – have explored how re-sequencing tasks can improve project performance [20][21][22][23] but such authors typically ignore the impact of factors such as task alternatives (which allow modelling of alternative process routes during iteration). Also, much of this work is based on models that are specific to a single design process and the generality of result is not always clear.

Our approach, in contrast, was to generate models with specific structural characteristics but randomly generated details and to explore how these hypothetical models could provide practical insights for real-world projects [1]. The use of hypothetical models allows the separation of the structural problems from specific 'what-if' questions. Such models can be used to explore a wide range of processes with different characteristics while typical case study data usually focuses on a very small number of processes (Nonetheless, industrial case study data was used to inform generation of hypothetical models). The approach also avoids the problems of establishing how well a model characterises a real project - it avoids the issue of separating modelling errors from simulation errors while acknowledging that both can lead to erroneous results.

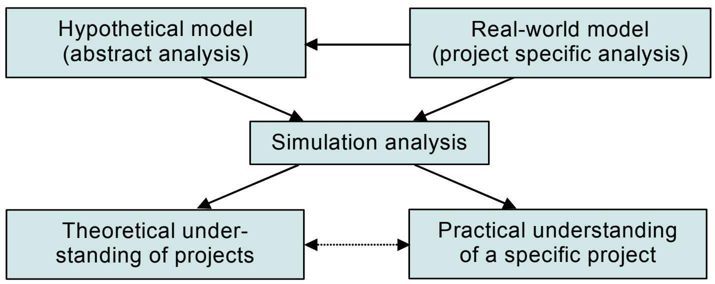

Figure 2. Simulation of both real-world and hypothetical models can lead to insights into project behaviour

3.1 Generating hypothetical models

Hypothetical models were generated and simulated using the Signposting tool [1]. Signposting is a task-based parameter-driven process modelling framework which can be used for project planning and simulation [3]. The technique also supports optimum task ordering for the entire project by selecting the most appropriate option from a list of available tasks [7]. Signposting is extremely versatile and can model project specific constraints, as well as alternative routes through the design process.

In order to generate such models, the following information must be specified: the number of tasks in the model, the number of parameters in the models and the level of task-connectivity (average number of connections per task). Once this information has been provided, several task instances are created. Costs, durations, and resources requirements are randomly assigned. These tasks are then linking together through parameter dependencies assigned at random according to a preset filling grade. Next, task properties such as cost, duration and precedence relations are assigned randomly but constraints can be applied by the researcher to reflect a particular industrial context. Alternative task outcomes, which reflect the uncertainty associated with high-risk tasks, are created by cloning the task output state and changing output characteristics such as the degree of rework required. Typically, multiple outcomes are defined only for a subset of the model's tasks. A DSM representation of an example hypothetical model is shown in Figure 3.

4 SIMULATION ANALYSES

Having argued for the theoretical benefit of hypothetical models in the previous section, this paper now proceeds to demonstrate how hypothetical models can be used to explore structural variations in terms of task connectivity-level and iteration characteristics. The simulation analyses described below build on a previous work by the authors described in [1] and [24]. Hence, this paper describes only a comparatively small number of models but is nonetheless illustrative of the arguments which we wish to present here and is supported by findings discussed in the other publications.

4.1 Variations in task connectivity structure

Hypothetical models were generated which varied in terms of the number and size of the task clusters involved in the iteration loops (Figure 3). Both models consisted of 30 tasks and had identical feed-forward dependencies between tasks. However, the first model shown on the l.h.s. of Figure 3 had six potential feedback loops which concerned clusters of 6 tasks or less while the second model (r.h.s. of Figure 3) consisted of 2 large iteration loops which affected 11 and 16 task respectively. Simulation analyses were then undertaken to explore how the number and size of the iteration loops affected project plannability and performance.

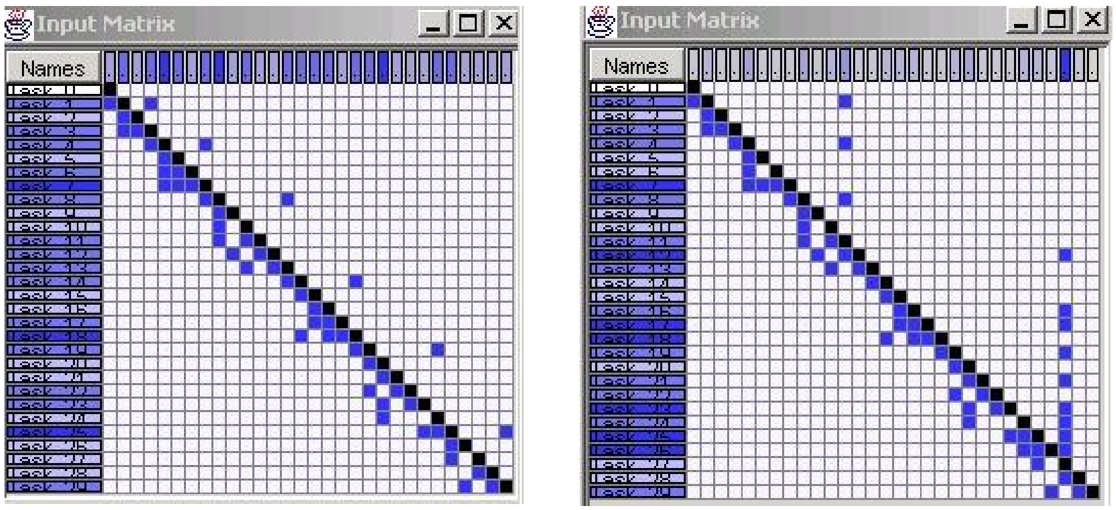

Figure 3. Hypothetical models were constructed to explore how the number and size of feedback loops within a project affect plannability.

Results show that variations in task connectivity structure are likely to have a major impact on the mean and standard deviation of project duration (Figure 4). However, the likely project duration variations obscure the true difficulty of design planning, particularly in the case of multiple small iteration loops. This happens because numerous different task orders can result in highly similar project durations. The resulting planning challenges are especially relevant when information- and resource-dependencies between tasks are sufficiently sparse to allow numerous alternative task sequences in different simulation runs. Simulation results also show that indirect dependencies between tasks mean that the number of direct dependencies can be a poor indicator of task order flexibility: although the above matrices are sparse, the task order for the project is nonetheless highly constrained.

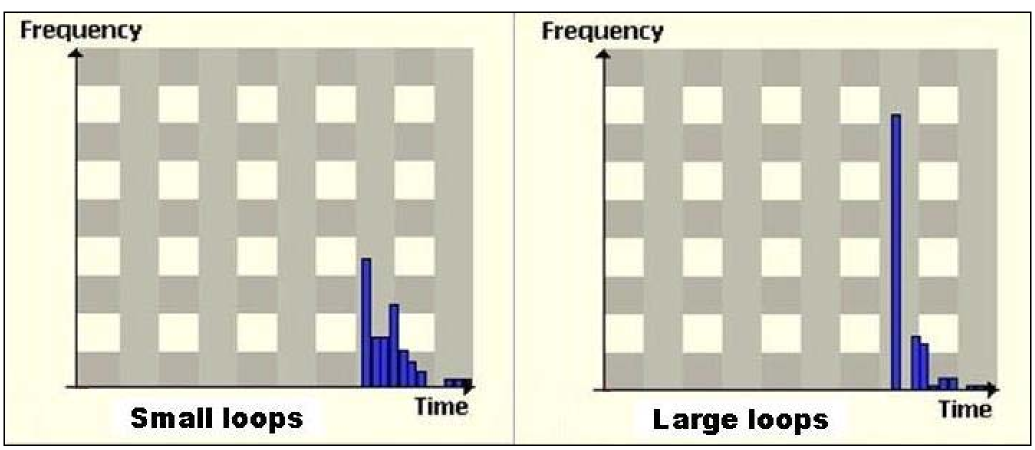

Figure 4. Simulation results show how the size and number of the iteration loops affects likely project duration

4.2 Variations in connectivity level

This section explores the impact of changing connectivity level on process performance. To this end, the connectivity-level between tasks (the filling grade for a DSM) was varied from 5% to 30% in steps of 5% and 1200 simulations were executed on a 100-task model. (Levels of connectivity greater than 30% were not analyzed because such model-characteristics were not common in the literature of case-study process models).

Overall, the results show that as the connectivity level rises, both the mean and the standard deviation for the process increase (Figure 5). The analysis showed that increasing the connectivity level restricted the number of tasks that could be executed concurrently (Figure 10) and increased the impact of task-failures (a greater number of dependencies means that more tasks must be reworked in the event of failure). Both of these factors impact project duration, although the influence of concurrency-level declines as models reach a saturation point in terms of connectivity-level – as the connectivity level rises the task-order be-comes increasingly constrained until a point is reached when the introduction of further dependencies has little or no effect. For example, if task C depends on task B and task B depends on tasks A, then there exists an indirect dependency between C and A and the addition of a direct dependency between these tasks is immaterial. Before reaching the saturation point, however, tasks that had previously been performed in parallel to slower, critical tasks are increasingly performed in series, increasing the total number of critical tasks. As a result, the process displays higher variance.

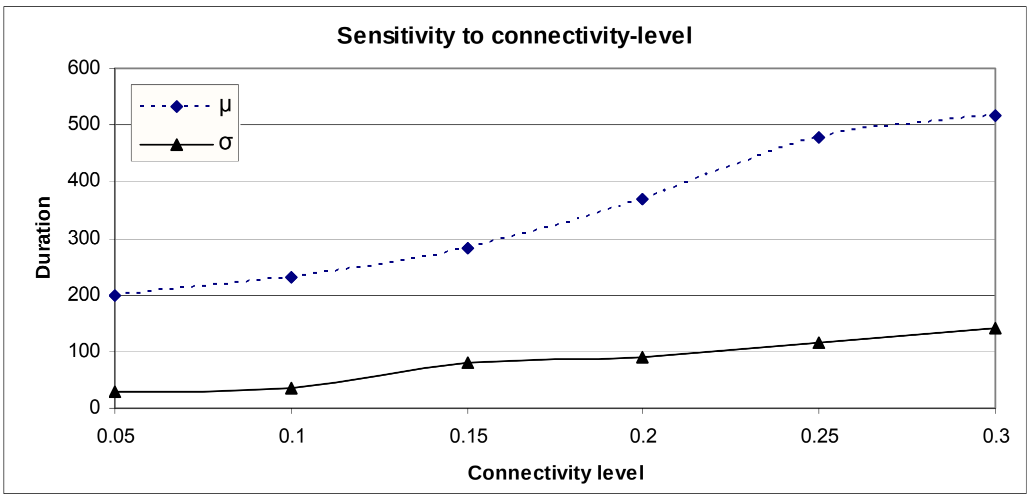

Figure 5. Increasing duration mean and standard deviation with increased connectivity

5 IMPLICATIONS FOR PRACTICE

In section 2 of this paper, it was noted that the impact of connectivity and task-connectivity structure is poorly understood in industry even though insights into this issue could lead to improved project planning. Simulation analyses of hypothetical models showed how model structure serves to amplify or attenuate the uncertainty associated with events such as task failures. The implications for practice are discussed below and heuristics for planning are defined.

The scale and number of iteration loops should be reflected in the planning approach: The structure of task connectivity affects the way in which the project is likely to behave. Even when the level of feed-forward task-connectivity is constant, the frequency and size of the iteration loops impacts the plannability of the project. This factor should be taken into account during the project planning phase. For example, re-ordering tasks to reduce the size of iteration loops can reduce the risk of large delays. Alternatively, contingency can be included in plans to allow the process to get back on track in the event of delays or task failures. Sensible setting of gateways can also reduce the project uncertainty by localising the effects of rework.

Robust planning is critical for highly connected projects: Increasing connectivity is likely to increase project duration and reduce plan robustness by placing an increased percentage of tasks on the critical path. In this context, it is important that the process is made robust because 1) failed tasks are likely to be critical and 2) rework of several tasks is likely in the event of a single task-failure since tasks are highly connected. This can be achieved by adding rework discovery tasks, defining non-critical process-recovery tasks or by restructuring the project to remove information dependencies.

Project connectivity is often caused by product connectivity. Through more modular product architectures or increased re-use of components it might also be possible to reduce the number of task dependencies and thus reduce project risk.

6 EVALUATION AND LIMITATIONS

Evaluation of the simulation results was performed based on observations from several real-world projects and from interviews with project managers. During simulation analysis, it is easy to explore the sensitivity to a single factor by fixing all other project variables at constant values and perturbing the factor of interest. In real-world projects, however, obtaining a clear view of sensitivity to a single variable is more difficult as controlling other project variables is usually impossible or impractical.

Nonetheless, it was possible to investigate whether the trends observed from simulation were reflected in industrial projects. Increased project duration mean and variance in response to rising task connectivity was predicted by the simulation analyses. This echoed strongly with comments from experienced managers that highly connected components were most susceptible to delays, particularly when engineering changes are taken into account.

The simulation results showed that a fundamental problem with rework is not only that it delays projects but also that, particularly in the case of several small iteration loops, the task order during project execution is likely to deviate considerable from the plan. Engineers and managers confirmed that reshuffling of tasks in order to meet hard deadlines is commonplace in response to rework but that such reshuffling causes people to “lose faith” in the plan. These problems are particularly acute when task reshuffling is performed in an informal ad-hoc manner because the transparency of the project is often reduced as a result. Conversely, large iteration loops are less amenable to reshuffling and hence more likely to result in project delays if they occurred.

6.1 Limitations

The results reported in this paper suffer from the intrinsic limitations of all simulation analyses. Such analyses are limited by the accuracy and detail of the underlying models – poor models will lead to poor results. As hypothetical models do not correspond directly to real processes, validation of such models is problematic. Even when real models are used, however, it is inherently difficult to validate simulation results concerning socio-technical systems [10].

In addition to variations in connectivity level, process structure can vary in terms of connectivity patterns. For example, some processes have clusters of highly connected tasks while other tasks are relatively unconnected. The hypothetical models considered above assume random levels of connectivity between tasks – it would be interesting to generate hypothetical models which vary in terms of the connectivity patterns, rather than solely the degree of connectivity. While it would be beneficial to examine more models, however, we believe that our observational concerning the impact of structural patterns on project plannability would not fundamentally change as a result.

Likewise, the nature of rework in projects differs not only in terms of task failure probability and task rework duration but also in terms of the number of tasks which must be reworked and the timing of task failures. Such variations in process structure were not reflected in the hypothetical models. Analyses to explore the impact of different degrees of rework – number of tasks affected and the size of iterations – and timing of task failures would be useful.

7 CONCLUSIONS

Project risk associated with complex engineering products is a multifaceted issue and resulting problems are a concern in industry. Our research used a combination of case study data and simulation analysis to explore how structural variations between projects affect plannability and performance.

The case study showed that design project planning is particularly difficult and that companies struggle to separate uncertainties associated with individual tasks from structural variations between projects. Managers can frequently think of examples of previous “problem-projects” and find it difficult to assess how the structural properties of these projects – particularly in terms of task-connectivity level and iteration characteristics – affect plannability. As a result, they struggle to forecast whether current and future plans are likely to prove accurate.

Simulation results show that understanding task connectivity structure is valuable in design project planning. Even when specific project details are unknown, some inferences about likely project behaviour are possible. By simulating variations in task connectivity patterns, this research provided insight into why many industrial projects overrun. In particular, it showed how the size and number of iteration loops are likely to cause project delays. For projects with several small iteration loops, the actual project duration is likely to be close to the mean duration determined from a number of simulation runs although the actual task order which unfolds during the project is difficult to predict. In contrast, the task order for projects with a small number of large iteration loops is easier to predict but the actual project duration is likely to deviate from the mean simulated duration.

Future work will focus on the analysis of a more extensive range of structural variations between models (e.g. project scale, task rework duration, resource profiling) and the development of further heuristics for design project planning and management. In addition, it is hope that the interaction between different structural parameters can be analysed.

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Contact: Claudia Eckert,
EDC Cambridge,
Department of Engineering,
Trumpington Street,
CB2 1PZ,
Cambridge, UK
Phone: 0044 1223 765107
Fax: 0044 1223 332662
e-mail: cme26@cam.ac.uk
URL: http://www-edc.eng.cam.ac.uk/people/cme26.html