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The vicious circles of parallelism

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Manufacturing development projects are frequently highly parallel and time-constrained. The authors undertook a study of such a project as part of a Delay and Disruption (D&D) litigation to show the effect of delays and in-development product enhancements. The use of the "cognitive mapping" technique revealed some key vicious circles, in particular increasing cross-relations between concurrent activities increases activity durations, which under time constraints causes activities to become more parallel and hence increase cross-relations. System Dynamics was used to model these loops quantitatively, explaining the level of D&D experienced within the project, which was more than the sum of each individual causal effect as the effects compounded each other. The case study is used to analyse these effects, and discuss the wider implications for modelling projects for which project networks are the normal modelling medium, and possible ways in which the inadequacies of networks can be overcome.

INTRODUCTION

The issues and difficulties involved in managing large engineering projects have been the subject of much study, and project management is now a science in its own right[1,2]. This is often quoted as starting with the Polaris program, which essentially saw the birth of a fully developed network analysis methodology (although Morris[3] argues that it was used as a smokescreen rather than as a planning method). The key to the network methodology is its description of which activities must be carried out serially, and which can be carried out in parallel.

As the technology being developed by projects, and the economic environment within which projects are carried out, both develop, two trends can be seen, as described by Williams[4]

- As the technology and thus the products become more complex and more intra-connected, the projects developing the products become more parallel, and it is proposed that these projects are more difficult to manage, and more likely to escalate.
- Time-constraints on projects are becoming tighter, and time-based liquidated damages heavier, and it is proposed that this exacerbates the effect of the first trend.

This paper discusses these two proposals in the light of a recent major litigation in which the authors were involved, describes some of the key *vicious circles* (undesirable positive feedback loops) that cause problems in such projects, and describes and discusses the modelling used to quantify such effects. The paper concludes by arguing that classical network analysis cannot fully delineate the progress of a project, as it neglects the feedback loops inherent in parallelism, and describes improvements required to such analysis.

THE CASE STUDY

The project was the design and short-run manufacture of a specialised vehicle, involving considerable leading-edge development. The project was very time-constrained, and there was a highly parallel design stage, as well as a degree of concurrent engineering, with vehicles starting manufacture before the end of the design stage. The company concerned is one of the most successful in the world at this size of manufacture, but despite this the project had resulted in considerable overspend, and some lateness, and was by that time the subject of a formal claim. The bulk of the claim was for product changes requested by the purchaser (but not the subject of a formal Contract Change or Variation Order); this was termed the *Direct Claim*. The remainder was for delay and disruption, both that caused by the events that were the subject of the Direct Claim, and other delay and disruption felt to be caused by the purchaser, in particular delays in approving documentation. The authors were commissioned to discover the reasons for, and extent of, the delay and disruption, and to quantify the effects by an auditable model which could support the advocacy of a *Delay and Disruption* claim.

The key technique used to interview managers and subsequently model the explanations given for the various circumstances of the project was "cognitive mapping". There is insufficient scope here for a discussion of the methods, but Eden[5] gives a general description, and Ackermann and Tait[6] a discussion relating to this study. This technique structures the way in which humans construe and make sense of their experiences, and specialist computer software called "Graphics COPE"[*] was used to record and analyse the extensive maps developed. Each person's cognitive map was input, and these were then combined (through cross-relationships and the merging of identical ideas) into a single model which gave an overall representative view. This model was developed and validated working in a visual interactive mode with groups of senior members of the project team[7].

The analysis and clustering methods within the software were then used to locate all positive feedback loops which form the basis of understanding delay and disruption as it is generated by the dynamic impact of events. The critical feedback loops are described below. The overall feedback loop structure was complex (with over 90 feedback loops), as was the dynamics of the real situation; the overall behaviour of inter-connected and nested feedback loops is characteristically difficult to discern

[*] Graphics COPE is developed and supplied by the Department of Management Science, University of Strathclyde, Glasgow. It runs in the Windows environment.

subjectively.

LOOPS

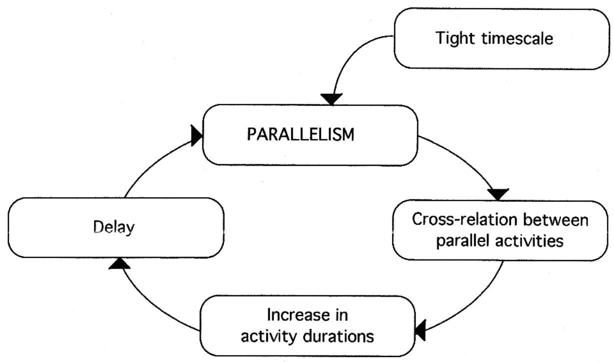

Figure 1: Key loop

The key loop is shown in Figure 1. In a design process where design of cross-related parts of the product is occurring in parallel, this causes the design activities to take longer, since each activity has to take cognisance of the other(s). This causes delay in the overall program. If there are tight timescale-constraints, so that the delay cannot be absorbed by extending the total project duration, this means that the project must become more parallel as delayed activities overlap more with succeeding non-delayed activities.

This deterministic effect is, of course, taken into account in the initial planning. However, the process becomes very non-robust, so that a small increase in one element causes a positive feedback loop to be set up, with each of the four elements in the loop in Figure 1 magnifying the next (a positive feedback loop which promotes undesirable effects, such as this, is generally called a vicious circle). This can (and in this case did) give rise to significant escalation. In particular, and of relevance to this case-study, an increase in delay (such as purchaser approval delays, or delays due to purchaser changes) will start up this feedback.

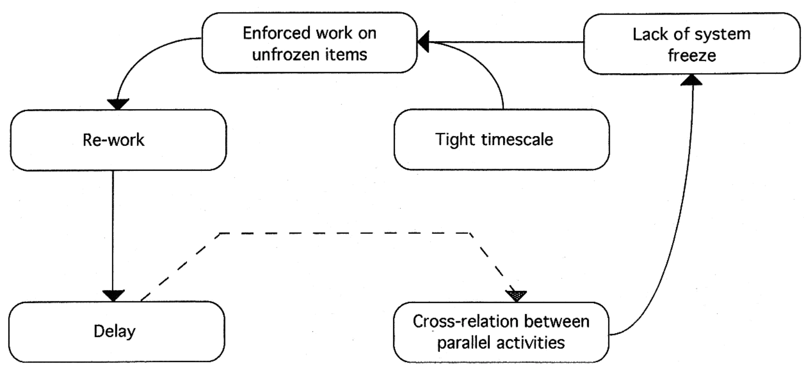

Figure 2: Additional loop

This key loop does not stand on its own, there are further loops accelerating it. One example is shown in Figure 2 (drawn retaining the topography of Figure 1). Where there are increasing cross-relations between parallel activities developing cross-related parts of the product, this implies increasing difficulty in providing a system freeze, since changes in one component will increasingly cross-impact other components, creating a ripple effect across the system. This lack of system freeze, when again combined with a rigorous timescale-constraint, forces design management to work on items for which the surrounding system is not yet frozen -items on which they would not normally wish to work. This has a number of effects, not least amongst them being disincentivising the design staff as they work with unclear or undefined parameters and with the knowledge that their work may turn out to be nugatory. The main effect of interest here, however, is that the design of such items will have to be re-worked if there are changes in the as-yet-unfrozen surrounding system. This causes delay, and contributes to the vicious circle in Figure 1.

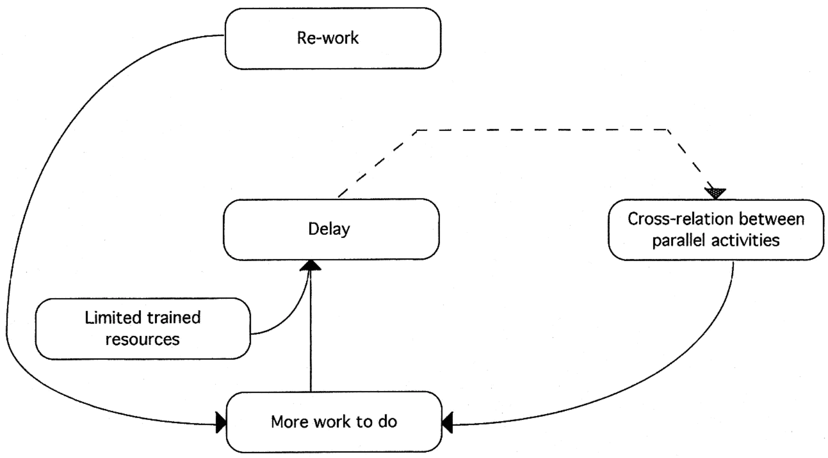

Figure 3: Further loop

A second example of additional exacerbating factors is shown in Figure 3 (again retaining the topography). Two of the factors identified above - the increasing use of parallel activities which are cross-related, and the increasing need for re-work - cause the absolute amount of work that is required to be done in the system to increase. In a situation where there are limited trained resources, this causes further delay, again adding to the positive feedback. In the case study, the supply of trained design manpower in the particular domain, either for direct recruitment or sub-contract, began to be exhausted in the whole of the geographic region.

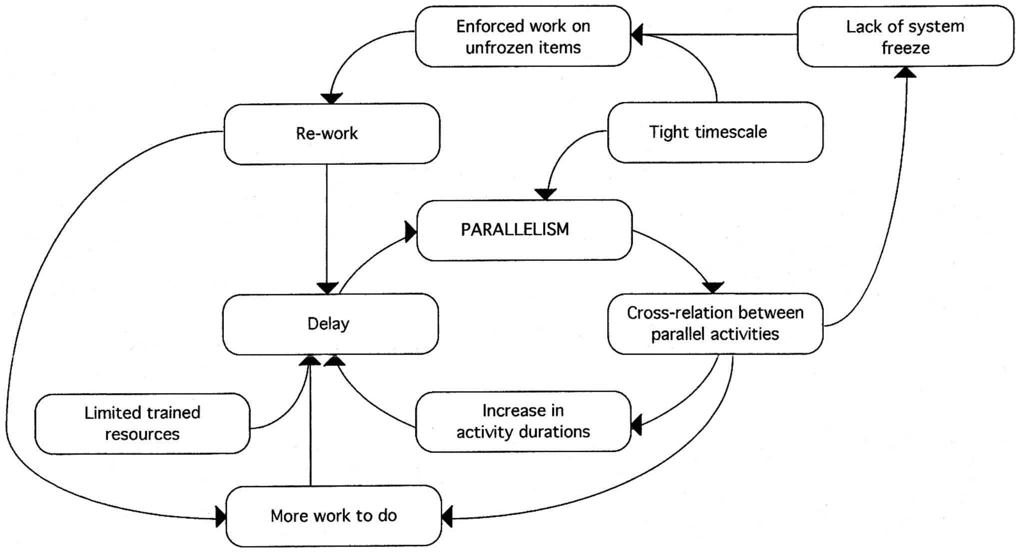

Figure 4: Loops combined

These three figures can be combined to give Figure 4: this shows a mutually reinforcing loop-structure which is already quite complex, with four positive feedback loops. However, even this only includes a few of the factors found in the case study. As one example, the limitation on trained design manpower means that less experienced personnel, perhaps temporary free-lancers, have to be brought in to meet the time-constraint; as well as taking longer over each job, exacerbating the effect, this also means that experienced personnel must be diverted to manage the new personnel, which can rapidly lead to a cliff-edge at which so many experienced design personnel are managing that the design process starts to fall apart.

Furthermore, the analysis above has covered only the Design phase. Further loops are set up when a concurrent Manufacturing phase is considered, both because design activities finish later and thus increase concurrency (and so on as above), but also because items begin manufacture and are then changed, which leads to retrofit, degradation of manufacture learning[8], increased load on production engineers etc.

Thus, the system becomes highly non-robust. It has been observed in practice that lateness in a project breeds more lateness, and these feedback loops show some of the reasons why. Small perturbations have an effect far greater than expected. Of particular relevance to this case study were two such perturbations. Firstly, design approval delays by the purchaser had an unexpected escalating effect. Secondly, purchaser changes which could not be allocated a Variation Order (either enhancements or simply changes to an equivalent but different component) led to increased cross-impacts and started up the positive feed-back loop, giving rise to further delay and disruption.

MODELLING

These feedback effects need to be quantified, to provide practical assistance to planners and analysts; in this case in particular, the effects needed to be quantified to support a legal claim. It can readily be seen from the arguments above that relying on standard network analysis alone is insufficient; indeed, it can be misleading because the analysis can incorrectly suggest satisfactory progress and adequate planning. As the feedback loops take effect, the network structure itself changes: activities become longer, and therefore become more and more concurrent, and the inter-relationships between activities change.

The approach taken in the case study was to use computer simulation methods. The methodology used and what it provides are described below, followed by a discussion of the implications for network analysis.

There are two relevant methodologies for constructing simulation models. The first is discrete event simulation, which is well known and used in a wide variety of fields. Models are constructed based on events at discrete points in time, with the attributes of the model entities, which describe the state of the entities, changing at the event-points. In order to avoid replicating the full detail, events are generated by using probabilistic variables, sampling from the whole to produce typical profiles of the system, and running the model many times to provide a good replication. of likely system behaviour patterns.

The second method is known as "System Dynamics" modelling and was originally developed in the 1960's at MIT (first described by Forrester[9]). Wolstenholme[10] gives a good overview of the current state of the art and should be referred to for more details of the technique. Such models are constructed by considering the way in which the <u>state</u> of the system changes with the <u>rate</u> of input and output of each variable which can be monitored. Changes in these rates depends upon an evaluation of the last monitoring of the system; this monitoring is modelled by the <u>auxiliary</u> variables which are the modelling of the information and decision-making procedures. When constructing such a model for a project, the <u>state</u> variables monitored would be those things that could be counted if the system stood still - for example, in a plant the number of people working on site can be counted, the extent of completion of a product can be evaluated, and this monitoring used to determine whether extra staff should be hired. If staff are to be hired or fired then staff levels will subsequently change depending upon the rate of hiring or firing. In this way the simulation model replicates movement over time. The modelling approach focuses upon an understanding of feedback and feedforward relationships, and the model construction requires the analyst to construct the relationships between the various state variables and rate variables (flows). The approach differs most crucially from discrete-event simulation in that it is a continuous modelling approach. This means that the detail of discrete-events are not included in the model. This makes it appear rather unnatural to the unfamiliar user (particularly so when modelling a past project forensically, as in this case), but it can be a powerful approximation technique when dealing with large numbers of objects (in this case, design documents). (The first author was most doubtful about the validity of the approximation at the start of the project, but was soundly converted when he tried modelling with the technique!)

System Dynamics modelling was designed for exploring feedback dynamics, which is the subject of this analysis. Given the use of cognitive mapping and "Graphics COPE" software in this case-study, a visual interactive modelling package known as "Stella"[**] was employed ("PowerSim"[***] is similar).

System Dynamics has been used to explain the process of re-work[11], and has contributed to litigation cases[12]. However, this study differs in two ways. Firstly, it varies from the current emphasis on the use of System Dynamics modelling. Such methods are often used in archetypical manner as part of organisational learning[13] where it is not particularly important that they are validated at the level of detailed output. They are used to demonstrate patterns of behaviour. In this case the model is required to report the quantum of behaviour under a variety of circumstances, for example replicating the project as originally anticipated, the project as completed and the various different profiles of client behaviour and liability. Secondly, this model analysed the combined effect of all the loops augmenting and exacerbating each other.

A model as described above gives a picture of the behaviour of a project over time, given the inputs to the project. In particular, given either probabilities or a temporal profile of purchaser changes, and probabilities or a temporal profile of documentation-approval delays, the model can show the flow of work through the system, and thus the spend-profile and completion-profile implied by the inputs. This overall aggregate modelling capability is essential as it shows the compounding effects of the various uncertainties: it is a clear result of the model that the aggregate effect of perturbations on the system is considerably greater than the sum of the individual effects, as they contribute to the positive feedback loops.

IMPLICATIONS FOR NETWORK PLANNING

The model has been used as a forensic tool, and as has been shown above it could be used as a overall strategic planning tool. However, such a model could not be used as it stands as a detailed planning tool, since the individual activities and Work Breakdown Structure elements are not distinguished within the model. What implications does this work have, then, for the normal network planning of a project?

[**] Stella is a registered trademark of High Performance Systems, Inc, Hanover NH, USA. The package ran only on Macintosh computers during the course of this study, but a PC/Windows version has recently been released.

[***] PowerSim v 1.0, developed 1993, is available from ModellData AS, Bergen, Norway. It runs in the Windows environment.

First of all, this work strengthens the growing evidence that network analysis on its own is not sufficient to model and manage the behaviour of projects. The effects described here, which were crucial to the project outcome, would not have been forecast, nor could have been explained, using a simple network model. It is not suggested that this might be a *replacement* for networks, but it is an important adjunct. Some synthesis of the methods might be even more powerful.

Secondly, the work shows the effects that need to be taken into account in modelling time-constrained parallel projects, centring around the effects of parallelism, and including the cross-relationships between parallel activities, time-constraints requiring design of unfrozen parts of the system to be started, and subsequent re-work.

Thirdly, the improvements required to network methodology can be seen. Fundamentally, there is a need for better modelling of activity inter-relationships. This has been known for some time, and work has been on-going to develop models of strongly inter-related activity-structures[14]. It can be seen firstly that this must be able to deal with feed-back loops, so that while Activity A affects Activity B, Activity B might also impact (directly or indirectly) on Activity A. Secondly, it can also be seen that these inter-relationships must not simply preserve the network structure, but also be able to change the network structure itself, increasing parallelism, for example, directly increasing the relationship between activities, thus delaying them and thus re-impacting the extent of parallelism. A tool such as RiskNet[14] provides the prototype flexibility to deal with such effects, and gives a useful pointer to the future developments required.

Fourthly, it points out what network modelling represents in practice. Extensions or adjustments to activities must not be seen in isolation. Network modelling is used as a management tool, and if an activity is extended, perhaps forming a new critical path, management take actions to keep the project on schedule. These actions can mean that the original project network is no longer valid. Any analysis method which still works on the original network is thus also invalidated; similarly, risk analysis methods which allow probabilistic effects but do not consider the actions of management in response to these effects are also invalid. (Thus traditional "Extension of Time" (EOT) claims methods[15], which only look at how activities have become extended, do not represent the full extent of the delay and disruption caused. Taking each activity or event separately and then carrying out an EOT analysis does not fully explain overspends, indeed will suggest time-extension has been slight where management has acted swiftly and effectively (albeit expensively) to keep a project on schedule.)

Finally, the work provides a prototype capability for the strategic modelling of projects. This is useful in itself, both as a planning tool and as a forensic post-mortem tool. It also, however, provides a vital check on the modified network analysis described above, since it is able to take into account the compounding effects as the perturbations and uncertainties combine.

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