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The need for new paradigms for complex projects

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This is a version of a paper which formed the opening session of a workshop on managing and modelling complex projects. In order to introduce the theme, it discusses what constitutes project complexity. It aims to be inclusive rather than exclusive. Highlighted are structural complexity, the number and interdependence of elements (following a paper by Baccarini) and uncertainty in goals and means (following a paper by Turner and Cochrane). The paper considers whether these aspects can be operationalised. It gives some ideas about why project complexity might be considered to be increasing, in particular the increasing complexity of products being developed, and moves towards shorter timescales. Finally, it notes some areas where new methods are needed.

Introduction

This paper is a slightly improved version of a paper which formed the opening session of the NATO Advanced Research Workshop *Managing and Modelling Complex Projects* held in Kiev at the end of 1996. The Workshop was based on a series of premises: that projects are becoming increasingly complex; that traditional project management methods are proving inadequate; and that new methods of analysis and management are needed. The aim of the Workshop was to look at new methods and new experiences, both in the West and the new economic environment in Co-operation Partner (i.e. Eastern Bloc) countries. In order to consider these premises, and to look at new methods, it was essential at the start to look at whether we could define complexity, to provide a framework for the succeeding discussion. That was the aim of this paper.

While many project managers use the term a *complex* project, there is no clear definition about what is meant—beyond the general acceptance that it is something more than simply a 'big' project. This paper does not aim to give a definitive definition of complexity. Instead, in order to facilitate rather than restrict the open discussions that were a feature of the Workshop, the paper explores a number of various aspects of the idea of project complexity. It aims to be inclusive rather than exclusive, to encourage discussion of all of the dimensions of complexity. The paper considers whether these aspects can be operationalised, and gives some ideas about why project complexity might be considered to be increasing. Finally, it notes some areas where new methods are needed; the structure of the Workshop programme then followed these areas as an agenda.

By a fortunate coincidence, a good review of project complexity was published in the *International Journal of Project Management* only 3 months before the Workshop by Baccarini,[1] and this provides a useful starting-point for this discussion. He stresses the importance of the concept of complexity to the project manager, and its role in the strategic management of projects. He also states as a given, referencing Morris and Hough,[2] that "complex projects demand an exceptional level of management, and that the application of conventional systems developed for ordinary projects have been found to be inappropriate for complex projects".

What is complexity?: structural complexity

Baccarini[1] proposes a definition of project complexity as "consisting of many varied interrelated parts", which he operationalises in terms of *differentiation*—the number of varied elements—and *interdependency*—the degree of interrelatedness between these elements (or connectivity). These measures are to be applied in respect to various project dimensions, and he discusses two of them:

(i) In terms of organisational complexity, 'differentiation' would mean the number of hierarchical levels, number of formal organisational units, division of tasks, number of specialisations etc; 'interdependency' would be the degree of operational interdependencies between organisational elements.

(ii) In terms of technological complexity, 'differentiation' would mean the number and diversity of inputs, outputs, tasks or specialities; 'interdependency' would be the interdependencies between tasks, teams, technologies or inputs.

This clearly defines an important element of project complexity, perhaps the element which we think of most often when we consider a 'complex' project: complexity is concerned with the underlying structure of the project. For this paper, we can call this 'Structural Complexity'.

For projects such as design-and-manufacture, or design-and build, a major source of *project* (structural) complexity is *product* (structural) complexity, where the product is the physical deliverable (the product being designed and manufactured, or the building being built etc). A project to develop a more complex product must normally be a more complex (in this sense) project, but it is useful to distinguish the cause and effect of product type of complexity first. Product (structural) complexity, in the Baccarini sense, is the number of subsystems of a product and their inter-relationships (where an inter-relationship can mean, for example, that changes in the design to one subsystem produces cross-impacts and affect the design of the other system). When modelling or analysing a project to produce such a product, measures of complexity can be propounded in order to quantify these inter-relationships. As an example, take the analysis of a large design and manufacture engineering project for a Channel Tunnel sub-contractor, undertaken as part of a Delay and Disruption litigation by a team led by Eden.[3] Here, the system (i.e. the product) was divided into around 50 subsystems, and a 'cross-impact matrix' P developed, giving the probability p_{ij} that a change in subsystem i will affect subsystem j. From this could be defined, for example,

- sequential (product) complexity: the likely length of a sequence of interactions (i.e. if subsystem i affects subsystem j which affects subsystem k, this is a length of 3);
- feedback (product) complexity (the probability that a change in system i eventually affects system i).

Having measured the product complexity, such measures can be used to investigate aspects of project complexity: for example, in order to evaluate the effect of client changes on a project, consideration has to be given to how many changes to other systems are likely to be required, or how many hitherto frozen systems will need to become 'un-frozen'; these latter are functions of the measure of product complexity outlined above.

Clearly, merely counting interdependencies is not sufficient, the nature of those interdependencies is also important (as Baccarini points out). In a well-known paper, Thompson[4] looked at interdependencies and identified three types: pooled (in which each element gives a discrete contribution to the project, each element proceeding irrespective of the other elements), sequential (one element's output becomes another's input) and reciprocal. In the last of these types, each element's output becomes inputs for other elements, so the actions of each must be modified to the actions of others. It is this last type of interdependency which particularly intensifies complexity. In particular, reciprocal interdependencies will produce the type of feedback effects found in the Channel Tunnel work, described in Williams *et al.*,[5] where client comments caused work to return to the designer, then causing changes to other elements which themselves return to be re-worked; such effects, of course, run counter to the assumptions of most first-generation tools (e.g. PERT), which assume a steady progress through a project. (Diehl and Sterman[6] show clearly how decision-making suffers under conditions of dynamic feedback.) These reciprocal effects can clearly and obviously be seen in the case of a set of designers designing a product subject to a cross-impact matrix as described above. But less easily modelled reciprocal interdependencies occur, for example when there are functional aspects affected by, and affecting, many activities (e.g. the weight of the product, electro-magnetic interactions, safety issues—in any of these, a significant occurrence in one activity can have major effects across all of a project), or when events occur which affect many project elements (e.g. loss of a prototype, change in regulations—the possible list is endless). Clearly, the more complex the type of interdependency, the greater the added complexity. While the above is a general managerial definition, one driver in the project-management domain causing an increase in reciprocal interdependencies is the rise in concurrent engineering, which is be discussed further below.

While these are the main aspects of structural complexity, concerned with the multiplicity of project elements, two other aspects should be noted:

- Virtually all projects are by definition multi-objective, with conflicting goals (either constraints or optimisation). This adds (structural) complexity, as the effects of activities on all goals has to be assessed, and trade-offs have to consider the balancing effects of other activities.
- Virtually all projects have a multiplicity of stakeholders, not only the obvious—client, project manager(s) and project team—but also owner, champion, the public, sometimes public bodies, and so on. This will add complexity in a similar manner to the multiplicity of goals.

Both of these add additional dimensions of structural complexity to the project, which require consideration but go beyond the scope of this paper.

What is complexity?: uncertainty

Jones,[7] in discussing the social psychology of conflict within project management, defines 'technical complexity' as a three-fold concept: the variety of tasks, the degree of interdependencies within these tasks, and "the instability of the assumptions upon which the tasks are based". The first two of these, of course, are the same as Baccarini's two aspects that we have termed Structural Complexity above. The third, however, is one example of *Uncertainty*, which brings a further element to the idea of complexity—although we can perhaps widen the scope beyond Jones' example.

(It is the contention of this paper that uncertainty adds to the complexity of a project so can be viewed as a constituent dimension of project complexity. It should be noted that, as discussed by the anonymous referee to this paper, there is a strong body of thought that views uncertainty and complexity as two separate concepts—see for example references 1, 15 and 16 of Baccarini's paper.[1] Indeed, the discussion of Shenhar's paper below appears to strengthen this view. However, this view can be equated to the statement in the present paper that uncertainty and *structural* complexity are indeed separate concepts, while both together produce the overall difficultness and messiness of the overall project, and it is this last idea which has been called overall project 'complexity' as a shorthand in this paper. Most previous definitions of 'complexity' simply report structural complexity, while we are seeking to define complexity in this over-arching sense).

The idea of Uncertainty is discussed in the paper by Turner and Cochran.[8] They classify projects by two parameters: how well defined the goals are, and how well-defined are the methods of achieving those goals—a classification arrived at by a number of authors. They then identify four distinct types of project, depending on whether the goals are well- or ill-defined, and whether the methods are well- or ill-defined, and suggest different management and particularly different project start-up methods for the four types. It is suggested in this present paper that these two types of uncertainty bring two dimensions of added complexity to projects.

Dealing with the second dimension first, uncertainty in the methods to carry out a project will add complexity to the project. Turner and Cochran[8] point out that, if methods are uncertain, the fundamental building-blocks of project management will not be known: the WBS, the tasks required to complete the job and their sequence, the Organisational Breakdown Structure, etc; and even when they are planned, the plan will be subject to change. Clearly, then, some of the characteristics of Structural Complexity will occur here: as the team structures the work and refines the methods, there will be considerable interdependencies between project sub-teams; as methods are tried and re-planned, feed-back loops naturally occur, and so on.

Uncertainty in methods is well known to be related to complexity. For example, Shenhar[9] undertook a field study to distinguish among good management styles and practices for different types of projects (for engineering projects). He classified projects by two parameters: system scope (assemblies, systems arrays—one component of our idea of Structural Complexity) and 'technological uncertainty' (the newness of the technology to be used—i.e. the uncertainty in the methods). We should note here that 'Uncertainty' is being used in the broad sense, including both those elements which are stochastic but also those resulting from a lack of knowledge (i.e. epistemic uncertainties); thus, a project where a body of knowledge exists (e.g. building an air-liner) is less complex than a State-of-the-Art project where there is no experience (e.g. building a HOTOL craft to go to the atmosphere edge).

But while uncertainty in the methods brings about one element of added complexity, even when the methods are known, another dimension of added complexity comes about when there is uncertainty in the goals. Turner and Cochran use Software Development projects as a typical of projects whose methods are known but whose goals are uncertain, since users' requirements are difficult to specify, and are often changed when initial prototypes are seen. The essential difficulty with such projects is that the requirements are not frozen, and uncertainty or changes in some requirements will mean that interfacing elements also need to change, and again we have cross-impacts, re-work, feedback-loops—an increase in the features of structural complexity. Indeed, the 'freezing' and 'un-freezing' of sub-systems formed a central part of the Channel Tunnel model described in Williams *et al.*[5] Many of these results in practice are called 'Delay and Disruption'. (Wozniek's[10] 'clarity of scope definition' is presumably similar to Goals Uncertainty.)

A key element of the added complexity brought about by the changes or modifications that results from uncertainty in goals, is that these changes often cause two separate increases in complexity:

- not only does the action of making the changes often increase the project (structural) complexity (e.g. by making the product more complex),
- but also the individual changes themselves often combine to increase the product complexity and thus the project complexity. For example, continuously adding elements will eventually mean that it is extremely difficult to put in any more cable-ways, or fit all the elements into a constrained space, or work out the pipe-work.

In evaluating such a project, then, not only does the product complexity have to be taken into account, but also the increase in product complexity throughout the life of the project,[3] remembering that the effect on the project of many changes is more than the sum of the effects of each change individually.[5]

Both of these uncertainty measures are probably difficult to operationalise into a quantifiable parameter. The vagueness of the goals might be measurable by how long it would take to establish whether the goals were satisfied; changes in goals could perhaps be measured in terms of contract changes. It is not obvious to this author how uncertainty in methods could be operationalised, beyond vague terms such as 'newness of technology'.

What is complexity?: summary

The conclusion of the above is that overall project complexity can be characterised by two dimensions, each of which have two sub-dimensions:

- Project complexity
  - Structural uncertainty
    - number of elements
    - interdependence of elements
  - Uncertainty
    - uncertainty in goals
    - uncertainty in methods

Increasing complexity

It appears to be an accepted fact that the complexity of projects is increasing (even if complexity has not often been defined), and this is part of the *raison d'etre* of the NATO Workshop. Baccarini's review begins with the words "Construction projects are invariably complex and since World War II have become progressively more so". Helbrough[11] states as a given that "increased complexity of projects and the project environment have meant that despite improved methods, many projects still fail to meet expectations".

Williams[12] points to two compounding causes for projects increasing in (structural) complexity. The first derives from the relationship between product complexity and project complexity discussed above. As new products are developed which extend, or improve upon, previous generations of product, those products become more (structurally) complex, because of extra functionality, or reduction in physical size, or closer intra-connectivity, or similar reasons. This means that the projects developing those products are appearing to increase in Structural complexity, with a larger number of project elements and, in particular, a greater degree of inter-element connectivity. It should perhaps be said that this view is supported by anecdotal evidence only: without a clear definition of complexity, the author is aware of no quantitative evidence collected to investigate this; furthermore, the author's view is based on design-and-manufacture and software projects, and it isn't clear whether this applies also to, say, the civil engineering domain.

The second cause compounds this increasing structural complexity. Projects have tended to become more time-constrained,[13] and the ability to deliver a project quickly is becoming an increasingly important element in winning a bid. Furthermore, there is an increasing emphasis on tight contracts, using prime contractorship to pass time-risk onto the contractor, frequently with heavy liquidated damages for lateness. As projects become shorter in duration, this enforces parallelism and concurrency, which by definition increases project complexity further. The increasing desire to reduce 'time to market' times, and the subsequent development of the field of Concurrent Engineering (which aims to support the integrated, concurrent design of products and their related processes, including manufacture and support) is well-described in textbooks such as Syan and Menon.[14]

It is not obvious that there has been any significant increase in Goal Uncertainty—indeed, the tendency towards fixed-cost, prime contracts, with a tightly-written (perhaps performance-based) specification. suggests that, at least in the early 1990s, there was perhaps a general reduction in Goal Uncertainty. But many writers point to the increasing rate of change in technology (classically Toffler[15]), suggesting that uncertainty in Methods may well be increasing. But this is speculation that requires proper study.

Covering all of the above, Laufer[16] characterised the last 4 decades of project management by an evolution of models appropriate to changing dominant project characteristics: he characterises the 1960s by scheduling (control), for simple, certain projects; the 1970s by teamwork (integration) and the 1980s for reducing uncertainty (flexibility), both for complex, uncertain projects, and the 1990s by simultaneity (dynamism) for complex, uncertain and quick projects—in other words, the very elements that we have defined as 'Complexity'.

Methods

Having made a tentative definition of complexity, it is clear that classical project management techniques are unsuitable for dealing with such projects. For structural uncertainty, decomposition models do not account for the compounding effects when individual perturbations accumulate in a project;[5] they cannot deal with feed-back loops;[3] they do not account for the systemic, holistic effects that are present in structurally complex projects;[12] they are not able to deal with goal- or method-uncertainty.[8]

What are needed, then, are new ways of looking at modern, complex projects, new models and techniques for analysing them, new methods for managing them—in fact, new paradigms to underlie our approach to them. A number of such approaches have been taken, but it is difficult to take a view as to the most promising approach, nor has much synthesis been attempted (either between the approaches or with lower-level operational methods). This paper notes some of these areas in which work is on-going, but it is not the purpose of this paper to investigate such approaches—indeed, it was the aim of the NATO Workshop to do this, by bringing together workers from different backgrounds and with different agendas, hence the emphasis on round-table open discussions; the results of these discussions will be published soon.

In order to support the management function, in particular planning, forecasting, monitoring and control, analysts must be able to model complex projects.

- Models can improve on classical methods, retaining the bottom-up decomposition into project elements. Network models can be improved to include stochastic effects, or the effects of management decisions. Models of time and cost risk can be developed by modelling the combination of many risk elements. Simulation models can be built that simulate the behaviour of many project elements of different types in combination.
- Alternatively, top-down holistic models can be built—perhaps the most successful technique being System Dynamics. While such models usually fail to capture the detail desired by operational management, they allow a strategic overview, and allow modelling of systemic effects that bottom-up methods miss out.
- Traditional methods capture only 'hard' quantitative data. It has become clear that 'softer' ideas must also be included in project models, if they are to be a useful representation of the real project. Soft systems methods, and 'soft' Operational Research methods have proved useful. Some of this data can be used in some holistic modelling techniques, particularly System Dynamics.

Management techniques must similarly adapt to the new environment. Jones[7] explains how an increase in project complexity leads to an increase in internal conflicts within the project, so management methods and style must adapt to deal with such conflict. Changes need to be made to the internal management structures within projects; in particular, the use of multi-disciplinary teams is becoming more widespread. Laufer's study,[16] discussed above, concludes that for the new type of project, that we have defined by a wide definition of complexity, you should have a project management style based on elements such as integration, systemic management, simultaneous management, the use of teams, and managing functional plans simultaneously and interdependently *inter al*. Looking wider than one project, new views have to be taken of the multi-project environment, programme management. Complexity finally needs to be considered in the establishment of joint ventures and other inter-corporate arrangements. [At a conference during the period that this paper was being refereed, Hetland and Fevang[17] gave a paper giving a broad discussion of complexity and identifying implications for contracting mechanisms (such as the use of alliances etc.)].

Conclusion

Dalchar[18] claims that "Contemporary project management practise is characterised by: late delivery, exceeded budgets, reduced functionality and questioned quality. As the complexity and scale of attempted projects increases, the ability to bring these projects to a successful completion dramatically decreases". We need to take up this challenge, and look to see how, differently, we should tackle complex projects. As the first small step, this paper has tried to ask what constitutes complexity. In particular, it has highlighted structural complexity, the number and interdependence of elements (following Baccarini) and uncertainty in goals and means (following Turner and Cochrane). Complexity is increasing as all of these elements increase, exacerbated by simultaneity resulting from tightening project deadlines.

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