THE POTENTIAL FOR APPLYING COMPLEX ADAPTIVE SYSTEMS THEORY TO THE PROCESS OF ESTIMATING IN THE CONSTRUCTION INDUSTRY

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Complex adaptive systems are networks consisting of large numbers of interacting agents: for example, genes in an organism; neurones in a brain; ants in a colony; people in an organisation; readymix concrete plants, trucks and construction sites in a city. Such systems are adaptive in the sense that they evolve in order to survive and as they evolve they produce emergent outcomes in a spontaneously self organising way. Theories of such systems are being developed, and their dynamic properties are being explored using computer simulations, in a number of research institutions, most notably at the Santa Fe Institute in New Mexico in the United States. There is a growing interest in this research on the part of industrial and commercial organisations: e.g. Cemento Mexicana in Mexico City has developed scheduling systems for its readymix concrete trucks based on complexity theory. This paper considers whether the theory of complex adaptive systems has any relevance to the process of estimating in the construction industry, concluding that it might have and suggesting a research agenda to develop applications.

Keywords: Complexity, emergence, estimating, genetic, algorithms.

INTRODUCTION

Complexity theory and the application of complex adaptive systems is the focus of growing interest in industry and commerce as a means problem solving. Problems where the network of influences involved lead to a range of dynamic solutions which can change over time. It is being applied to situations where the effects of demand, which are emergent from the complex networks of personnel intentions are interfaced with logistical problems. General Motors are scheduling truck painting sequences to meet demand and efficiency requirements and the Central Railway of Japan matching demand to train schedules. In the Construction Industry Cemento Mexicano have applied complexity theory to matching changing demand to supply and the unpredictability of the Mexico City traffic to improve the efficiency of their service (Katel 1997).

Complexity theory considers the behaviour of non-linear networks of interacting agents, such as, genes in an organism; neurones in a brain; ants in a colony or people in an organisation. In a complex adaptive system these agents interact with according to schema that require them to inspect each other’s behaviour and adjust their own behaviour in the light of that behaviour (Stacey 1996). The system will be non-linear when actions can generate multiple and non-proprtional outcomes. Such systems are adaptive in that they evolve in order to survive and as they evolve they produce emergent outcomes in a spontaneously self-organising way. The important point with complex adaptive systems is that the emergent effects of the system cannot by reduced to the single elements. Philosophically the whole is more than the sum of the parts

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(Mainzer 1996). Theories of such systems are being developed, and their dynamic properties are being explored using computer simulations, in a number of research institutions, most notably at the Santa Fe Institute in New Mexico in the USA.

Organisations are complex adaptive systems embedded within the wider complex adaptive system that is society as a whole (Mainzer 1996, Stacey 1996, Kaufmann 1995). Construction companies are complex adaptive systems which are embedded within that social system and the projects constructed result from the interaction of the agents concerned both within the company and the wider network comprising the client, designer and other interested bodies. The finished structure can be considered in terms of its emergence from the behaviour of that construction network. Estimating concentrates the construction processes involving the understanding and planning of the project and the determination of a tendered bid which evolves through interaction with the client, the designer, interested parties, suppliers, sub-contractors and the wider society.

This paper applies the theory of complex adaptive systems and the experience of the writers in the industry, to the understanding of estimating and tendering by contractors and considers how that could lead to a research agenda to develop its application. Firstly we must consider the nature of the construction process in complexity terms.

THE CONSTRUCTION PROCESS

Project management is viewed as a linear process of planning and control, starting with an intention that is then sequentially actualised (Woodward 1997). However, a more detailed examination displays many of the features of a non-linear complex adaptive system. Consider first how projects emerge within a large network of interacting agents.

A key feature of the construction process is its variability in a procedural sense and its fragmentation in terms of the number of different organisations involved in it. A construction project takes place within a network of relationships between all those who have an impact on the outcome of that project. The precise links vary with the type of project, as does the number of links which tend to be multifaceted: e.g. the influence of the Health and Safety Executive (HSE) on the main contractor covers such aspects as company policy, practical effects on working practice at site level, planning of operations and temporary works solutions. Relationships also differ in the immediacy of their effects on the project: those between main contractor, designer, client, subcontractors and suppliers have a direct influence on the progress and nature of the project; those between trades unions, regulatory bodies and the HSE can directly affect working practices on site but also have indirect effects through establishing standards, codes of practice, good working practice and quality criteria. The policies and procedures of banks determine the attitudes of many players toward risk, quality and overall policy with respect to progress. The UK Government and the European Union have an impact through their policies with regard to the HSE, regulatory bodies, trades unions and also through economic policies.

The links between the agents in the project network operate bi-laterally: the designer passes information on what is to be constructed to the contractor who will inform the him of the practical effects of that information. The suppliers inform the designer on developments in materials and technology gaining information themselves on what sort of product to develop. The effect of change and new information have knock-on impacts around the network. Information gained on site by the HSE informs general research into safety management; research informs the government in preparing safety legislation which in turn influences the designer, main contractor and subcontractor in the methods and materials used. In this way the reactions are non-linear and can have many outcomes.

This description of the network of agents involved in the realisation of a construction project resonates with descriptions of biological and social complex adaptive systems that are the focus of research at the Santa Fe Institute. One of the key points being made about such systems is that they do not operate according to an overall blueprint to realise a comprehensive prior intention. Rather, they produce unpredictable, emergent outcomes not intended collectively by the agents in the system. Whilst the agents have individual intentions relative to their own schema, the system as a whole will spontaneously self organise to produce emergent patterns. Thinking about construction projects as complex adaptive systems suggests a novel approach. So, in what sense is a construction project the realisation of comprehensive prior intention and in what sense can it be thought of as an emergent phenomenon?

INTENTION AND EMERGENCE

In one sense all construction projects are the realisation of some prior intention embodied in a design. Even in the simplest projects, where there may be no formal design, the builder has some idea of the nature and function of the structure. That idea may well change as the work proceeds and better solutions become apparent, but a design, or intention, is always present. In another sense, however, it is realistic to think of the structure, as well as its financial outcome, as emergent. Turning the virtual reality of a design into the actual reality of a structure involves an ongoing process of change (Hillebrandt 1990). Unforeseen circumstances may occur, ground conditions change, materials become unavailable, protesters and other interest groups may force a postponement or a rethink of the project (Tuman 1986) and the weather will almost certainly be different to that expected. As the structure takes shape, or emerges from the plans and their context, it will be viewed as a physical entity and opinions formed prompting further change. The context itself may change during the construction period and changes be made as work proceeds. The process is not a linear incremental one, as we may be inclined to think, but a non-linear adaptive one from which a structure emerges. Contracts recognise and make provision for the inevitability of such change.

CONSTRUCTION MANAGEMENT

The realisation of a construction project requires the management of a network of relationships which are in part governed by contracts rather than hierarchy. It involves the organisation, co-ordination and management of many resources to complete. The variable nature of the physical environment, the fragmentation of management relationships by contracts and the inevitable change that occurs all create difficulties. Projects rarely proceed according to the original plan and require considerable ingenuity and creativity to actualise (Hillebrandt 1990). At the centre of the process, for the construction firm, is the enhancement of production value through the balancing of three opposing objectives; the reduction of cost and time and the maintenance of quality (Woodward 1997). All three factors are influenced by external bodies which may be directly or indirectly involved in the product.

ESTIMATING

Whichever form of bid selection a construction company is involved in and whatever type of contract emerges from the process, an estimate has to be put together and tendered to compete for that work. The preferred bid, as assessed by the client, is the one that goes on to be converted into a contract. A contract then represents, for the bidding company, the opportunity for future cash flow and continued existence.

Those preparing an estimate need to understand the nature of the work, the methods of work to be applied, and the sequencing of that work. This process requires continual interaction with a wide network of agents concerned with the work including the client, sub-contractors and suppliers as well as related agencies such as utility companies and local authorities. Estimating can be considered, therefore, as a concentrated period of construction management involving many of the techniques, assumptions and influences applicable to the actual construction activity. The conventional way of thinking about an estimate is an essentially linear one; an analytical process of breaking down the work into its component parts. Each element is analysed to determine the materials, manpower and equipment necessary for its accomplishment (Parker 1984). The resultant cost is then tendered following an assessment of the risk and opportunity and possible financial effects of undertaking the project (McCaffer and Baldwin 1984).

We suggest that there is an alternative way of thinking about the estimating process and in the rest of this paper we explore how one might think about estimating, as a complex adaptive system. Our description of the construction process has brought out its complex adaptive system nature. Estimating's position within the same system provides a case for thinking of a bid as emerging from that network of non-linear relationships. We now need to be more specific about the nature of a complex adaptive system and to consider how it may relate to the creation of an estimate and its survival to form a contract.

THE ESTIMATING PROCESS AS A COMPLEX ADAPTIVE SYSTEM

The conventional view of estimating is a traditional systems approach; a designed system of decisions leading to the resolution of a problem. The design of such a system implies both a complete understanding of the behaviour of the system and a linear causality within the components of the system. As Simon (1977) points out; if the problem area is so hopelessly qualitative that it cannot be described even approximately in terms of such variables then the approach fails. A complex adaptive system is not a designed system and complexity theory addresses the behaviour of existing systems. The behaviour of the complex adaptive system, and any emergent phenomenon, is a factor of the nature of that system and not a designed intention. Whilst each agent within the system will have his or her (or its) own intention or schema the emergent outcome from the system will unpredictable and changing over time.

Experimentation with computer based complex adaptive systems has shown three characteristic dynamics which are dependent on a combination of the number of agents (N) in the network and the degree of connectivity (K). K relates to two factors: firstly the number of agents to which each individual is connected and secondly to the strength of that connection i.e. the probability of that change in one agent will bring about change in a connected neighbour (Stacey 1996). When both N and K are low then systems tend to stability, settling quickly into a fixed single pattern. For high values of N and K the system becomes randomly chaotic and unstable. On the boundary area between these conditions at the ‘edge of chaos’ the system adopts a stable dynamic state of emergent patterns of behaviour (Kauffman 1995).

The complex system from which an estimate emerges consists of a network of agents, individual contributors of prices, durations, methods and opinions, complex system sub-sets in their own right, who interact in non-linear ways according to their own schema. Whilst adding together component prices is a linear process, the decisions that lie behind those prices are non-linear. As with the tendered sum of the bid, an empirical assessment of future opportunity is made for each component price submitted by suppliers. Such assessments are the result of opinions, estimates or guesses about future out-turns, reflect the complex adaptive system which is the organisation supplying the price and the wider systems in which it is embedded. The rates offered by specialist sub-contractors are influenced by complex relationships, individual perceptions and schema of players in that market. In short, the estimate is the result of the interactions between agents operating within a complex adaptive system. An estimate evolves from and is also a part of a complex adaptive system. Its has the capacity to adapt to its surroundings, through the intention of the bidding company to secure work it has the objective of survival against competing estimates, to be the fittest, and accordingly be converted into a contract.

The conventional approach to estimating is reductionist with connections being made between elements in the reconstruction of the bid. A complex adaptive system approach would be to maintain the connectivity of the network seeking to position that network, through the strength of the connections, at the edge of chaos; a position where creative solutions can emerge. How, though, can we identify the best solution among all the possible emergent bids?

SEARCHING THE FITNESS LANDSCAPE OF ALL EMERGENT ESTIMATES.

The search for the best estimate can be conceptualised using the analogy of searching the space of all possible estimates on the fitness landscape of a given project. The fittest estimates will occupy the higher levels of the landscape and the less fit the lower levels. The assessment, by the client, of fitness is generally on the basis of lowest price for the completion of the work in accordance with the design and specification. However, other factors will be taken into account in the assessment, including the experience of the contractor relating to the type of work, management procedures, safety, quality, environmental policies and the financial stability of the bidding company. The effects of value engineering prior to acceptance of the bid can alter the assessment of fitness for a particular bid. The criteria determining fitness can, thus, be rather complicated. To make matters even more indeterminate competitors in a bid are not always aware of the relative weight placed by their clients on, say, price, quality and reputation for reliability.

We have seen that the dynamics of a complex adaptive system alter as K increases. Where K is very low the landscape of possible outcomes is characterised by a single or a small number of peaks. The dynamics here are those of stability and we are faced with simple optimising problems where linear approximations work. When K is very high the landscape is very rugged, there are many low fitness peaks and we have an intractable problem. At the boundary condition where connectivity is high but not too high, the landscape is rugged but not too rugged, novel solutions will emerge. As the system moves from a stable to a chaotic dynamic it passes through a phase transition at the 'edge of chaos'. It is when the system is richly connected enough so that it can operate near to this 'edge of chaos' that it can produce novel solutions. In this condition, though, a linear 'hill climbing' search algorithm will not identify the fittest solution. A wide ranging search mechanism is required, able to step across the landscape and test each location.

The larger and the more complicated a project becomes the more agents the system contains. Furthermore, the more the likely it is that changes to each component will have an impact on many others. For example, changes in a method of working can alter the nature of skills required to complete that item and with it the cost, duration or overall sequence; changes in the duration of an activity can alter the critical path, change the duration of the project, alter its cost and the level of risk involved. In other words, the connectivity between agents in the system increases dramatically as a project becomes larger and more complicated. As a result, smooth fitness landscapes can be expected to be exceptional in the construction industry, confined to small, simple projects. We will normally be dealing with rugged fitness landscapes: the space to be searched for any given project will contain an almost unlimited number of possibilities and the landscape will be continually changing, heaving about as competitors change their estimates.

In taking a complexity view of the estimating process we have established the nature of the network from which the novel solutions can emerge. How then do we create the network conditions at the edge of chaos and then search the landscape at that point to identify the fittest solution?

CREATING THE CONDITIONS AT THE EDGE OF CHAOS

As the number of agents in a system and the connectivity between them increases the number of points on the landscape, the peaks and the valleys, multiply. Finding a defined peak on this landscape becomes increasingly difficult and with it finding the optimum, or highest peak. The entire landscape would have to be searched and this becomes too time consuming and expensive. The problem then becomes one, not of optimisation, but of finding an excellent, or good enough, peak.

One way to deal with this problem of finding a good enough solution in a huge fitness landscape is suggested by Kauffman as follows:

"... take a hard, conflict-laden task in which many parts interact, and divide it into a quilt of non overlapping patches. Try to optimise each patch. As this occurs, the couplings ... across patch boundaries will mean that finding a "good" solution in one patch will change the problem to be solved by parts in the adjacent patches. Since changes in each patch will alter the problems confronted by neighbouring patches, and the adaptive moves by these patches in turn will alter the problem faced by yet other patches, the system ...[is]... co-evolving... Each patch climbs towards fitness peaks on its own landscape, but in doing so deforms the fitness landscapes of its partners." (Kauffman 1995: 253).

This process of mutual adjustment could spin out of control and never produce a solution, i.e. when the dynamic is chaotic, or the system might freeze up and get stuck on poor local peaks if it is operating the stable dynamic. However, the system can find good solutions if it operates near to the 'edge of chaos' and the possibility of this happening depends upon how many patches the system has been divided into. If the are too few patches the system exhibits stable dynamics and if the are too many patches it becomes chaotic. The number of patches required is also related to the connectivity of the whole system. Where K is low and the landscape smooth it is best to avoid patches or have a very small number. As K rises and the landscape gets more rugged it appears best to break the system into a number of patches such that it operates near the edge of chaos.

A complexity approach to estimating would require that the linkage between all parts of the network is maintained such that a change in one element is considered in terms of its effect on all other elements allowing patterns to emerge from the whole. The emphasis in a patched network process moves away from the simple costing of independent activities, to an understanding of how the changes in the approach to one activity, or patch, will affect related activities, or patches. Dividing the estimating system into patches in the pursuit of fitness within each patch while retaining linkages across patches will allow new patterns to develop within the system as a whole and challenge the assumptions made, moving the bid to a better overall fitness. One way of dividing the system into patches might be according to different component areas of the project. Another division might be determined by criteria such as quality, time, resource utility, cash flow, finance and investment return. For example, the whole system would be looked at from the point of view of improving cash flow with each change being measured against the overall objective of finding the lowest bid. Changes in the cash flow which reduce finance charges and therefore lower cost may, however, increase the overall duration. Hence, the patch that is concentrated on time may be adversely affected in terms of the overall objective of lowest cost. Here each patch pursues its own local advantage, but because they are linked to each other, they are affected by changes in other patches which they will then have to respond to in their attempts to improve fitness. In other words, they have to continually adapt to each other - they co-evolve. Patching the entire linked system in terms of different fitness criteria rather than component type means that each of these criteria can be pursued within a patch but in such a manner that they co-evolve simply because they are linked across their patch. This allows movement of the estimate around the fitness landscape, promotes the location of diverse solutions and the finding of higher fitness peaks for that estimate.

In viewing estimating as a complex adaptive system one sees that the drawback of approaching it in a linear approximating manner is the danger of being trapped on a local peak that does not constitute a good enough solution. This linear approximation assumes that the system has a very low K value and adopts a landscape search technique appropriate to a smooth landscape. If in fact the landscape is rugged this procedure will tend become trapped on a local peak. The need is for a landscape search technique that moves away from incremental hill climbing rules and which could possibly be combined with a patching approach. One possible approach is the use of a genetic algorithm.

GENETIC ALGORITHMS

The work of Holland (1995) at the University of Michigan on genetic algorithms has provided a form of random search technique which allows the search to move away from local optima by abandoning the linear incremental improvement philosophy (see also Kauffman 1995, Pet-Edwards 1996). Using a process of replication through random combination of algorithms the search gets away from incremental rules allowing for movement down hill as well as up and the opportunity of testing an alternative solution.

We might start off with a number of alternative bids, each represented by bit strings in a computer processor. The genetic programme, having tested each bid for fitness, would randomly recombine elements from the fittest to replace the less fit. Estimates survive only if they are able though 'breeding' reach higher levels of fitness. Algorithms that represented a bid in its entirety would be extremely complex requiring considerable computing power to handle. However, a combination of a patching logic and use of genetic algorithms to facilitate a landscape search process using ratios of variables may provide a practical solution. We now consider what such an approach may entail.

APPROACHING ESTIMATING FROM A COMPLEXITY PERSPECTIVE

The ever increasing power of computer modelling techniques is allowing models of projects to be constructed which are now very sophisticated in the number of variables included. Project modelling based on critical path analysis can provide a close, albeit still linear, approximation which is sensitive to change. The variable most commonly used to determine the model is time. This can be changed though to represent cost or resource levels and used to develop financial models representing cash flow, finance requirements or debt levels. Changes in quality specifications, technical requirements or environmental constraints can be reflected in the analysis of the model. To use the whole model in the process of search through genetic algorithms would involve bit strings of many megabytes in length and consequently large processing power to handle them. The values of N and K being very high the system would be operating far beyond the edge of chaos in a chaotic dynamic.

The ability to include multiple variables in the model also allows us to consider the technique of patching using these areas to define the patch criteria. Consider a patch that is defined by the objective of minimising the debt profile of the project. Whilst maintaining the connection throughout the model we can look at the effect of variations in pursuit of the lowest debt profile assessing each change for its effect on overall fitness. Changes in this patch will affect other patches that we may have defined. For example, another patch could be defined by the criteria of minimising the time period for the works. Changing the spread of work to minimise debt requirements may affect the time minimising patch either positively or negatively in terms of overall fitness. To pursue one patch criteria to the exclusion of others would take us on an incremental climb up one peak which may not be the highest. Having reduced K through the logic of patching to produce a system that is closer to the edge of chaos we still require a search mechanism that allows us to step across our patched landscape.

The use of weighted combinations of heuristics is an efficient search criterion in scheduling techniques. To follow a single heuristic is to incrementally scale the heights of one particular fitness peak. However if a combination is used then a number of peaks can be explored (Pet-Edwards 1996). In such a technique a number of heuristics can be applied with their weighting being varied by application of a genetic algorithm. In the estimating context that we have been considering the heuristics may be represented by the patches of quality, time, resource levels etc. If the influence of each criteria is taken as a variable we can then, by changing their relative influence, move around the landscape. Provided that the relative weight of the variable within the total can be represented by a mathematical algorithm then we can use a genetic technique to search the space of possible combinations. Rather than apply the technique to the algorithm representing the entire model we have simply applied it to the relative importance of each patch in determining the overall solution. Instead of randomly varying the base model in search of purely the highest point in the landscape we have produced a mechanism which randomly seeks alternative routes through the landscape testing them for fitness.

CONCLUSION

Estimating is traditionally seen as a de-constructive linear process. The work is taken apart priced up and then reassembled to make up the bid. Estimating though, as a concentration of the construction process, is subject to a complex network of relationships and feedback systems which constantly change the environment in which that estimate exists. This paper has suggested that it is conceptually useful to think about the estimating process as a complex adaptive system. Such thinking takes a holistic approach maintaining the complex nature of the model that represents the intended work.

To explore what this might mean in practice we suggest that further work be undertaken to model the process in terms of Kauffman's NK model using the logic of patching. We also suggest not only the exploration of the potential for applying genetic algorithms as a search procedure in this model but also that the consideration of the estimating process as being a complex adaptive system may promote a better understanding of the construction process as a whole. Further, a complexity view maintains the importance of context and recognises that a small change in detail may have a significant influence on the fitness of a bid. In a system that is kept responsive to change through its connectivity whilst bounded by defined criteria, i.e. through a system of patching, acting at the edge of chaos, novel solutions will emerge in response to that small change. We believe that applying an understanding of the nature of complex adaptive systems to the estimating process and the sort of model we have suggested will assist in the development of improved bids.

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