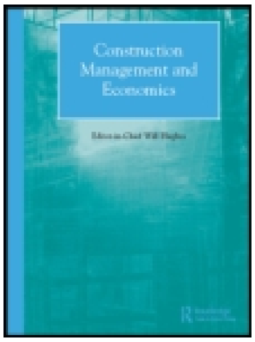

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Project complexity: The focal point of construction production planning

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Construction production planning is a paramount preoccupation of contractors and the process is rapidly increasing in difficulty with a continuous loss in confidence by clients. Today, one of the difficult issues facing practitioners in planning is that of a continuous increase in the complexity of construction projects. There seems to be no available tool or technique for assessing project complexity; consequently practitioners tend to neglect or subjectively assume its effect on project managerial objectives. This paper proposes an approach that measures the complexity of the production process in construction. The approach enables the construction practitioner to focus his or her attention on the issue of project complexity from the beginning through to the end of a project. By using a literature search and structured interviewing of practitioners, the paper has defined project complexity and identified the factors that influence its effect on project success in relation to estimated production time and cost.

Keywords: Project complexity, work flow, production time and cost, disaggregate systems.

Introduction

Among the managerial functions in construction, planning is considered as the most important function that brings success for any given process (but only if it is done well and at the right time). With the advent of computing in the construction industry, practitioners around the world have begun to invest more in the planning of construction projects. This has speeded up the planning process within the limited time allocated for the submission of tender for construction jobs. A lot though is still to be done in the area of construction computing, with many construction planning and programming techniques yet to be computerized and put in the ever-growing market. The planning of the production process in construction is mainly made up of the development of method and sequence and organizational factors. It is to do with the setting up of strategies, policies, methods and procedures and foreseeing trouble points. Research has indicated that tools and techniques that aid the planning of most construction jobs are available to construction practitioners that have good knowledge and experience. However, recent economic and technological developments have brought to the forefront the issue of project complexity. The lack of suitable tools or techniques that specifically address this issue has made it almost impossible for practitioners to assess its effect on project success objectively. This has been exacerbated by the variety of definitions of the term 'project complexity' and consequential use of highly subjective methods that hinge only on cost.

This paper is aimed at developing an approach that measures the complexity of construction production process. The developed approach is to aid construction practitioners to focus their attention on the effect of project complexity during planning in order to produce more reliable contract time and cost estimates. Firstly, the paper defines the term project complexity, by deriving a general consensus from the views and opinions of construction experts. Secondly, it identifies the factors that influence the effect of project[1] complexity on production time and cost. Thirdly, it proposes a concept of project complexity in relation to construction programming. Based upon these three objectives, a method of measuring project complexity has been developed and recommendations have been suggested.

[1] Project is here regarded as starting from the day the contractor mobilizes to site through to the hand-over date.

Project complexity

The continuous demands for speed in construction, cost and quality control, safety in the work place and avoidance of disputes, together with technological advances, economic liberalization and globalization, environmental issues and fragmentation of the construction industry have resulted in a spiral and rapid increase in the complexity of construction processes. It has today reached a level where construction managers must consider its influence on project success very seriously. It is unfortunate though that subjective methods are currently being used in the industry to measure its influence on managerial objectives. This has resulted from a lack of research in the area and the variety of definitions of the term 'project complexity'. Consequently, the ideal starting point for this paper must be the dictionary, through a literature review of experts' definitions, to obtaining the views and opinions of construction practitioners on the issue of complexity. This elaborates the subjectivity and assists in deriving a consensus of the definition of project complexity in construction.

The Oxford and Collins dictionaries define 'complex' as 'that made up of many parts; complicated or difficult to understand or carry out' and 'intricate, compound, involved' ('complexity' is a noun). Scientists and mathematicians consider a system 'complex' only when it consists of a multitude of interacting elements. The construction process is always made up of a multitude of interacting parts. Therefore, in simple terms, this may suggest that construction is generally complex in nature. However, the dictionary definition adds another interesting property, i.e. 'being difficult to understand or carry out, intricate, involved'. Since not all construction production processes satisfy this property, it may then be acceptable to consider it as a meaningful cut-off point that makes a distinction between a 'complex' construction process and a simple or 'non-complex' one.

A number of experts and researchers have defined a complex process in quite a number of specific ways. Perrow (1965) defined the complexity of a task as the degree of difficulty of the search process in performing the task, the amount of thinking time required to solve work-related problems and the body of knowledge that may provide guidelines for performing the task. Burns and Stalker (1965) considered managing a process which comprises of unfamiliar activities and/or conducted in an unfamiliar environment as 'complex'. They argued that an unfamiliar condition is an impediment to prediction of the measure of output or productivity of a gang of men. It is deduced from the work of Woodward (1965) that processes having a multitude of inherent technically difficult parts are 'complex', and it is arduous to predict the result of the works in terms of cost or time. Mohr (1971) considered processes that include the execution of tasks that are not very well understood by the present state of advances in science and technology as 'complex' processes. Van-de-Ven and Delbecq (1974) referred to a similar definition but considered it as a factor of complexity which they called 'task difficulty'. Thompson (1981) considered complexity as the measure of the difficulty of coordinating a production process comprising of activities that lack uniformity of work. That is, when resources employed for the activities vary with place and time. Gray (1983) defined a technically difficult task, referred to by Woodward (1965), as that with a known method or procedure of doing the work, but the implementation of the method and procedure requires all the skills, knowledge and attention of the person concerned with the task to produce the required finished product. Malzio *et al.* (1988) suggested that a complex process is that which comprises of operations that are innovative and conducted in an uncertain situation or that which involves operations that are not clearly defined or lack a complete specification. They argued that such conditions often result in variations which are demonstrated to increase production time and cost.

The above reviewed literature seems to suggest that the complexity of a process is the measure of the difficulty of executing the individual tasks that make up the process. However, other research, such as that of Bennett and Fine (1980), sees 'the complexity' of a process as the nature of the combination of a number of operations involved in the process or the incidence of roles requiring different kinds of work identified as work packages. Hill (1991) seemed to suggest that the size and diversity of tasks involved in a production process and the implications of decisions in terms of investment, costs, time and people required for the overall process are what make the process 'complex'.

The views and opinions of practitioners on the issue of project complexity have been collected by using structured interviews with selected experts in the building industry. The interviewed experts consider project complexity in a number of ways. They see a complex project as follows.

1. That having a large number of different systems that need to be put together and/or that with a large number of interfaces between elements.
2. When a project involves construction work on a confined site with access difficulty and requiring many trades to work in close proximity and at the same time.
3. That with a great deal of intricacy which is difficult to specify clearly how to achieve a desired goal or how long it would take.
4. That which requires a lot of details about how it should be executed.
5. That which requires efficient coordinating, control and monitoring from start to finish.

6. That which requires a logical link because a complex project usually encounters a series of revisions during construction and without interrelationships between activities it becomes very difficult to successfully update the programme in the most effective manner.

These definitions seem to suggest that there are basically two perspectives of complexity to heed in the industry.

1. The managerial perspective, which involves the planning of bringing together numerous pieces of work to form a work flow.[2]
2. The operative and technological perspective, which involves the technical intricacies or difficulties of executing individual pieces of work. This may originate from the resources used and the environment in which the work is conducted.

There seems to be an overall general consensus that a construction production process is 'complex' only if the difficulty of producing individual parts and/or bringing these parts together influence one or a number of or all of the set managerial objectives focused towards project success. Usually, these managerial objectives are the control of cost, time, quality, avoidance of conflict and functionality of the finished product. A 'complex production process' can therefore be regarded as that having a number of complicated individual parts brought together in an intricate operational network to form a work flow that is to be completed within a stipulated production time, cost and quality and to achieve a required function without unnecessary conflict between the numerous parties involved in the process. 'Complicated individual parts'[3] are those operations that are inherently difficult and/or comprised of operational uncertainties. This implies that 'project complexity' is the measure of the difficulty of executing a 'complex production process' or it can simply be defined as the measure of the difficulty of implementing a planned production work flow in relation to any one or a number of quantifiable objectives.

The components of project complexity

The review of the literature and the conducted structured interviews seem to suggest that complexity factors influencing the managerial objectives in construction originate from a number of sources, namely the employed resources, the environment, the level of scientific and technological knowledge required and the number and interaction of different parts in the work flow. For clarity, these sources have been put into two categories as follows.

1. Category A: this deals with the components that are inherent in the operation of individual tasks and originate from the resources employed or the environment.
   Category B: this deals with those that originate from bringing different parts together to form a work flow.

Although these two categories may intersect one another, each category has been initially isolated by approaching the overall system in a disaggregate view. This enables individual components that originate from each category to be clearly established.

The components in category A

By concentrating on the operations involved in an isolated task with regard to the required resources necessary to complete the task and the environment in which it is executed, the primary constraints affecting the process towards achieving a desired goal are inherent complexity and uncertainty factors. These primary components can influence project complexity in the managerial, technological and operational perspectives. Ultimately, they hinder progress of work by directly affecting individual tasks resulting in interferences in the sequence of the work flow.

Inherent complexity

The inherent complexity in production refers to the inherent difficulty or complication involved in conducting individual roles in a system of work flow. Inherent complexity may originate from science and technological advances, physical ability, availability of skills required and environmental sources (including the topographical, geological and chemical condition of the site surface and subsurface). In relation to the effect on the managerial objectives of achieving a planned production time and cost, inherent complexity factors within individual tasks can be sorted into three intersecting divisions.

1. That which is understood by current advances in construction technology, but requires all the skills, knowledge and attention of those involved.[4] This may arise by using a form of construction that is new to the local construction industry (Bennett, 1985).

[2] The term 'work flow' means the overall workshop process of producing the output (i.e. completed building). Based upon the Input–Conversion–Output model (Katz and Kahn, 1978).
[3] These kinds of operations are henceforth referred to in this paper as 'complex activities or roles'.

[4] Henceforth referred to as 'technical complexity' (TC).

2. That which is not understood by current advances in construction technology and requires all the skills, knowledge and attention of those involved.[5] It refers to the degree of difficulty of the search process in performing the task, the amount of thinking time required to solve work-related problems and the body of knowledge that may provide new or original guidelines for performing the task.
3. That which is understood by current advances in construction technology and does not require special skills or knowledge, but it requires the use of unusual processes due to environmental constraints.[6] From experience in the building industries of developing countries, where construction is labour intensive, this factor surely has a significant influence on the effect of project complexity on project success.

Each of these three intersecting divisions directly affect the standard time and/or cost.[7]

Uncertainty factors

The uncertainty factors also originate from within the task, the environment and the resources employed (manpower, materials, plant and machinery and information). This classification of the origin of delays in a work flow refers to the unknown in both the design and production. It basically refers to natural systems that are still not clearly understood by science.

The uncertainty factors can be subclassified into four intersecting divisions.

1. Lack of complete specification for the activities to be executed (CS).
2. Unfamiliarity of the inputs and/or environment by management (UF).[8]
3. Lack of uniformity of work (UN), i.e. when material to be worked with varies with place and time or teams working together vary with place and time or the role of the teams keeps varying with place and time.
4. Unpredictability of the environment (UP), e.g. the effect of weather in the UK and refurbishing of very old buildings having no record drawings.

The seven inherent complexity and uncertainty factors in category A may intersect with one another and at the same time interrelate with the environment in which they exist. This intersection is illustrated by the simple aggregated hard system model shown in Figure 1. The illustration shows the complication of the system. In order to simplify the above framework for application in practice, a disaggregate system approach has been used. This provided a means by which each component can be isolated in order to enable this work to concentrate initially on their individual influences originating from the environment and the resources employed. Once these are understood, the components can then be brought together to study any intersections. To achieve this goal, each subsystem in Figure 1 has been broken down or subdivided into sub-subsystems. This provided more practical composition and specific definitions of the subsystems as an elaboration of those already discussed. The subdivision is illustrated in Figure 2.

The components in category B

This category deals with the complication that lies in the sequencing of various operations in a work flow which arises from bringing together different parts to form a work flow. Managers can change the sequencing of operations in a work flow and therefore have some influence on the effect of project complexity. The manager's influence may depend upon the number of technologies or trades or activities, the size of the activities involved or repetition of roles within each activity or trade, the nature of interdependences between the various roles and the rigidity or flexibility of sequencing operations or packages in the work flow. Gidado (1992) has shown that the overlapping of elemental programmes by managers may also have an effect on the project complexity. He indicated that the programming of most new-build production processes is often carried out in three or more independent elemental subprogrammes (e.g. the substructure, superstructure and

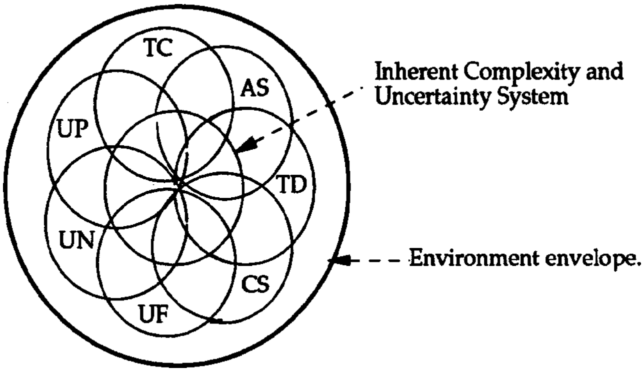

Figure 1 Aggregated model of inherent complexity and uncertainty factors

[5] Henceforth referred to as 'analysability' (AS).
[6] Henceforth referred to as 'task difficulty' (TD).
[7] 'Standard time' is defined as the total estimated cost or time to complete an individual task, including elapsed period.
[8] Unfamiliarity does not mean that the process is technically complex (TC) nor unanalysable (AS). It is a case where methods and procedures exist locally, but the management is unfamiliar with the local resources and/or environment. The unfamiliarity (UF) factor specifically relates to the management, technical complexity (TC) relates to the operative manpower resource and analysability (AS) may relate to both.

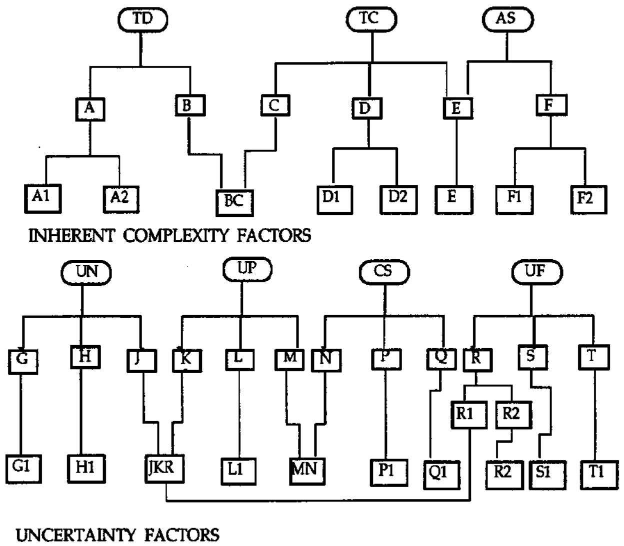

Figure 2 The subdivided definition of the category A factors. A, physically difficult task that requires simple or no equipment; B, physically difficult task that requires the use of complex or sophisticated equipment; C, technically complex task as a result of the sophistication of the required equipment or method used; D, technically complex task that requires locally available special skills; E, technically complex task that requires available special skills, knowledge and complex equipment; F, task that has no known procedure; G, lack of uniformity due to lack of working space and or access; H, lack of uniformity due to continuous change in material or other resources; J, lack of uniformity due to the direct influence of the environment; K, the effect of weather or climatic conditions; L, unpredictable subsurface (e.g. excavation in ancient city grounds); M, unpredictable work in a defined new structure (e.g. as in new work added to old buildings without record drawings); N, due to undefined structure or poor initial buildability assessment (e.g. as in refurbishing works of old buildings); P, due to lack of working drawings (e.g. installation of mechanical and electrical services in new building); Q, as a result of overlap of design and construction; R, due to environmental influence – cultural/social environmental layer (e.g. a similar project in a new geographical environment) and technical core environmental layer (e.g. underwater construction); S, due to lack of experienced local work-force; T, conducting or managing such a project for the first time.

finishes and services elements), depending upon whether the project is of generalist or specialist composition. The independent elemental subprogrammes are then integrated or simply overlapped with one another to produce the overall production programme without due consideration of its actual implications.

The category B components can be classified into three divisions.

1. The number of technologies involved in a task, repetition of their roles and their interdependences.
2. The rigidity of sequence between the various main operations.
3. The overlap of stages or elements of construction.

These variable intersecting divisions are individually listed and described as follows.

Interdependences of different kinds of technologies with or without repetitive roles (TRI)

In construction production processes, there are numerous kinds of technologies or trades using varying methods and tools. Each requires access, space and time to carry out its objective and often occurs within the same period. The number of roles involved in each of the different technologies may vary and are quite often interdependent with one another in a number of ways depending upon the time and location in which they are carried out on site, the access provided, size of available working space, working surface (vertical top to bottom, vertical bottom to top, horizontal top or horizontal bottom) and technical requirement (e.g. curing time). The varying nature of the interdependencesor interfaces of roles may bring about the occurrence of any one or a number of the inherent complexity and uncertainty factors. In a case where one already exists in the system, the nature of interfacing may increase its effect on the production time or cost.

Based upon the learning curve concept, the repetition of roles of teams in construction may influence the effect of some, if not all, of the complexity components in category A. It is human nature to learn from experience and improve in future similar processes; therefore, when roles are repeated over and over by the same team, it is quite possible that the effect of a category A complexity factor on standard time or cost may decrease.

Rigidity of sequence (RS)

Construction production process often involve a large number of specialist packages working within a specific area with each package having a structured number of roles to accomplish. It is always complicated to devise an effective work flow and once this is established, the sequence of work between the specialist packages tends to be structured as a standard sequence of work flow. Depending upon the nature of the structured sequence, the occurrence of interference in any one role in the sequence may result in an increase in production time or cost. The flexibility of the structured sequence of work flow varies from case to case. This is indicated by the availability of various kinds of floats or 'slack', e.g. free float, interfering float, independent float and total float. The nature of the variability may also influence the individual effect of any one of the category A factors on the production time and/or cost. In a flexible sequence of work flow, it is possible for one specialist's work to be extended or reduced in time without affecting the durations of other specialists' works or the overall process duration. However, in a rigid sequence of work flow, time or duration change in any specialist's work may affect the durations of others or even the overall production process duration. This sort of knock-on effect may also affect the production cost.

Overlap of construction elements (OV)

The overlapping of major elements of production is used by practitioners simply to compress or shorten the production time. In practice, this process is dictated by a number of resource-dependent factors.[9] Even by considering these factors, overlapping may change the interdependences of activities (or trades in particular) within individual elements and also create a new structure of interdependences between the roles of the overlapping elements. These changes may increase the effect of inherent complexity and uncertainty factors on project complexity. The additional effect may cause delays which often affect succeeding elements. These delays accumulate throughout the project and cost dearly in both time and cost to the contractor. The resulting accumulated increase in time may even exceed the time thought to have been saved by the compression. Gidado (1993) indicated that such consequences may not be detected on a simple outline programme, but that a detailed diagnosis of the new condition created by the overlapping of the elements must be undertaken.

The concept of project complexity

Project complexity has been defined as the measure of the difficulty of implementing a planned production work flow in relation to any one or a number of quantifiable managerial objectives. An efficient implementation of managerial functions (planning through to controlling) can influence the effect of project complexity on project success. It has been shown from the discussion on category B components that managers can influence the effect of project complexity on project failure by using appropriate planning and controlling adjustments. If project success is hinged only on project duration and cost and managers provide an inadequate planning and control effort, the resulting project failure (by exceeding the estimated production time and or cost) may not be evaded. This kind of failure is henceforth referred to as a positive (+ ve) failure where the measure of project complexity outweighs the amount of managerial effort invested. Again, where excessive planning through to controlling effort is provided, failure may

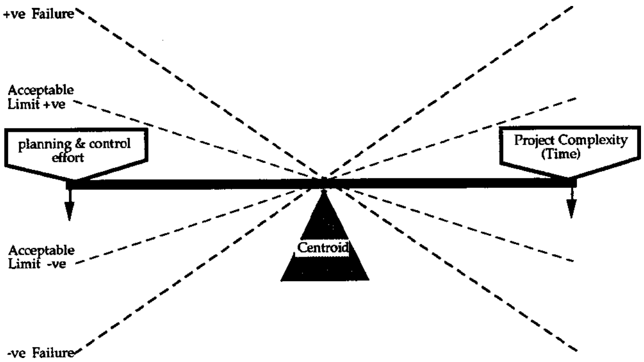

Figure 3 Balance of project success (effort versus project complexity)

still not be evaded but it may occur in a different form. Such a consequence is often seen as a decrease in the profit margin due to unnecessary overhead costs. This kind of failure is henceforth referred to as a negative (− ve) failure where lack of knowledge of the required effort to achieve success results in an unnecessary waste of managerial resources. The whole concept is illustrated as a balance of project success in Figure 3, which shows that if project complexity can be measured and managers can establish a corresponding planning and control effort to be invested to counter its effect, then project success can be predicted within a tolerable or acceptable margin.

Once project complexity become measurable, the acceptable limits can be established as the threshold of complexity and converted into what is referred to as contingency[10] sum or contingency time.

With a particular consideration to production time and cost, it seems realistic to claim that each of the category A components have a direct influence on the measure of project complexity. Similarly, it is also possible to claim that the category B components have an indirect effect on the measure of project complexity through their resulting influence on the effect of category A components. Considering the established definition of project complexity and its identified components, this simple theory can be transformed into numerical relationships between project complexity and production time and/or cost. Since the effect of the category A components is directly on the standard time of individual activities and the relationship between production time and standard times can be obtained by using a network analysis, all that is required therefore is to develop a numerical relationship between the components in category A with standard time. The direct relationship with the production time produces a linking point between the relative influence of the components in category B on the effect of category A components on

[9] These factors are discussed in Gidado (1992).

[10] Contingency is a measure of the net effect on a project cost or time of expected but uncertain variation.

the measure of project complexity. This again can be achieved by using existing systems such as network techniques (critical path method or project evaluation and reviewing technique and cost or bar chart construction planning system). The above theoretical claims have been justified by using simple logic in a later section.

Measuring project complexity

One of the first to draw attention to the issue of complexity was the mathematician von Neumann. He essentially made two points regarding the measurement and threshold of complexity: (1) complexity could be numerically measured, like any other system observable, if it was to be related to such things as the dimension of a state space, the length of a programme or the magnitude of a 'cost' in money or time and (2) there is a threshold of complexity, below which systems behave in some simple sense, Rosen (1987).

This paper is based on these principles and takes mainly the same position as von Neumann that complexity is of a purely technical character within accepted universal canons of system description. The non-linear component of complexity lies within the established category A factors which has been assumed to be linear and simply regarded as 'delay' or 'interference'. The substitution of non-linearity may be justifiable because the majority of the category A factors are mainly governed by natural systems which are still not fully understood by science. Based on current knowledge, this sort of effect can only be measured from experience, probably aided by using systems such as computer-based reasoning (CBR) database systems.

Project complexity has been defined in relation to any one or a number of quantifiable managerial objectives. However, the primary aim of this paper has been the relationships between project complexity, the length of a programme (production time) and cost in money terms. The work did not consider other managerial objectives, such as quality, due to the current lack of an objective means by which they can be quantified. Bennett (1985) and Langford and Shoesmith (1991) indicated that building contractors regard the control of time and cost during the production process as the two most important objectives. They also indicated that intensive research investigations have failed to reveal a suitable method of measurement of quality which would truly represent its influence on the success of a building production process. Other research such as that of Ireland (1984), Kendall (1986) and Rowlinson (1988) has had problems in trying to measure quality and had to resolve them by relying on subjective measures.

In construction planning, cost and time intersect each other, i.e. an increase or decrease in time may or may not increase or decrease cost and vice versa. In order to simplify the approach, disaggregate hard system theory can be used to isolate one from the other. This enables the independent relationships between time and complexity and between cost and complexity to be established. From these two relationships, it may then be possible to directly relate production cost and production time.

Project complexity versus time

The measure of the effect of any one of the category A complexity components on the standard time of an activity in a serial sequence of work flow varies directly with the duration over which the component is affecting the activity (based on the assumption that the magnitude of the effect is constant). In other words, complexity is directly proportional to the duration of any category A component affecting an activity. This can be represented in the following relationship:

$$C \propto t_{i\text{complex}}$$

$$\text{therefore } C = k\ (t_{i\text{complex}})$$

where C is the complexity, k is the unknown complexity component coefficient and $t_{i\text{complex}}$ is the duration that a complexity component affects a complex activity or role.

Figure 4(A) illustrates a simple project work flow made up of a number of activities in a serial sequence, having the first activity being affected by a category A component of complexity. The measure of project complexity (resulting from the effect of the complexity component) will vary inversely with the increase in the production time of the work flow. This is because of the fact that the relative effect of a delay or interference on production time will be reduced if the production time is simply increased. In other words project complexity is inversely proportional to production time, i.e.

$$C \propto 1/T_p$$

Combining the two relationships will imply that the project complexity (due to a category A component) is the multiple of an unknown coefficient (k) and the ratio of the duration that the complexity component affects an activity or role (t_{complex}) to the overall work flow production time (T_p). This is represented in the following relationship:

$$C = k\ (t_{\text{complex}}/T_p) \qquad (1)$$

where T_p is the work flow production time.

Where more than one complex role arises due to the occurrence of a number of complexity components, Equation 1 can be modified as follows:

$$C = \Sigma\ (k_i t_{i\text{complex}})/T_p \qquad (2a)$$

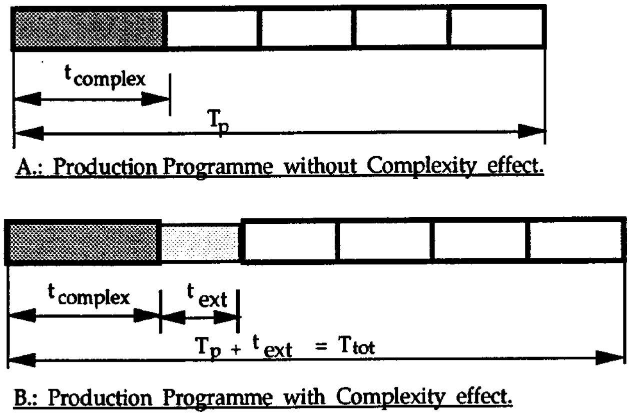

Figure 4 Sample element with roles in serial sequence

In the above relationships indicated in Equations 1 and 2a, the value of the coefficient k is the only value not obtainable from a simple work flow. This coefficient though can be defined and numerically established by using simple logic. The way in which this has been achieved is described below.

With reference to Figure 4.

1. Let the standard duration of a complexity component affecting a role be t_{complex}.
2. Let the total duration of the activity including that which originates from the effect of the complexity component be t_x
3. Let the ratio of the two durations be equal to a factor, K, therefore $K = t_x/t_{\text{complex}}$ or $t_x = t_{\text{complex}} \times K$

The extension of duration due to the effect of complexity is t_{ext}, therefore $t_{\text{ext}} = t_x - t_{\text{complex}}$ and $t_{\text{ext}} = (t_{\text{complex}} \times K) - t_{\text{complex}}$ or

$$t_{\text{ext}} = t_{\text{complex}}\,(K-1) \tag{2b}$$

The total production duration including that added due to the effect of complexity is given as

$$T_{\text{tot}} = T_p \times t_{\text{ext}}$$

From Equation 2b

$$T_{\text{tot}} = T_p \times t_{\text{complex}}\,(K-1)$$

Dividing both sides of the equation by T_p

$$(T_{\text{tot}}/T_p) = (T_p/T_p) + ((t_{\text{complex}}\,(K-1))/T_p) \tag{2c}$$

$$\text{Let } C_o = (t_{\text{complex}}\,(K-1))/T_p. \tag{2d}$$

Therefore, from Equation 2c:

$$(T_{\text{tot}}/T_p) = 1 + C_o$$

$$T_{\text{tot}} = T_p\,(1 + C_o) \text{ or } T_{\text{tot}} = \mathrm{T}_p + T_p + T_pC_o \tag{3}$$

From the following come the real conditions.

1. The total production duration (T_{tot}) of a project is the summation of the initially planned production time (T_p) and the extension of the standard duration due to any effect, i.e. $T_{\text{tot}} = T_p + t_{\text{ext}}$
2. The multiple of the initial duration and the effect coefficient is equal to the extension time, i.e. $T_p \times C_o = t_{\text{ext}}$

Therefore C_o is the complexity coefficient.

From Equations 1 and 2d

$$(t_{\text{complex}}\,(K-1))/T_p = kt_{\text{complex}}/T_p$$

therefore

$$k = K-1 \tag{4}$$

From Equations 2a and 4, the complexity equation can then be modified as

$$C = \Sigma\ (t_{\text{complex}}(K_i - 1))/T_p \tag{5}$$

Considering a project with more than one element in serial sequence, from Equation 3, the overall total project duration can be calculated as

$$T_{\text{tot}} = \Sigma\ (T_i(C_i + 1)) \tag{6}$$

therefore project extension due to complexity $= T_{\text{tot}} - \Sigma T_i$

where

$$\Sigma T_i = T_p = T_1 + T_2 + T_3 + \ldots T_n \tag{7}$$

Again from Equations 3, 6 and 7, the complexity of a project with more than one element or stage in serial sequence can be calculated from the following equation:

$$C_p = (C_1T_1 + C_2T_2 + C_3T_3 + \ldots C_nT_n)/T_p \tag{8}$$

where C_p is the measure of overall project complexity.

It is important to consider the main problem noted by experts that use network systems that the process sometimes ignores network routes other than the critical path when evaluating the probability of completion time. This has resulted in over optimistic assessment of the probability of completion. Klingel (1966) observed that forecasts tended to underestimate actual completions by one-third of the total period. Gray (1983) identified this cause and said it was due to what he referred to as 'merge event bias'. He identified that it occurs when or where several paths converge on a single network event, i.e. one of the paths will be the longest net path but in practice may not necessarily be the earliest start time of the single event because variability in the completion of other paths may exceed the original critical path. Since the effect of complexity components in category A on the duration of activities is often the cause of the variability in the completion time of non-critical path activities, it is important to consider all activities in the network including those with 'slack' or 'total float'.

Slack or total float represents the available spare time for which an activity can be delayed without extending the production time. This is governed by the rigidity of sequence (RS) in the work flow. It can be concluded that the effect of any complex activity can only increase the duration of an element or the overall project if the following condition is satisfied:

$$t_{i\text{complex}}\,(K_i - 1) - F.F_i > 0 \qquad (9)$$

where $F.F_i$ is the available total float of activity (i).

This means that the complexity formula, given in Equation 5, for the calculation of element or stage complexity must take into account the total float value of the complex activity and thus be modified by summing along all the individual possible routes in a network including the critical path and written as

$$C_n = \Sigma\,((t_{i\text{complex}}(K_i - 1)) - F.F_i)/T_n \qquad (10)$$

where C_n is a complexity of element (n), $F.F_i = L.F_i - E.S_i - t_i$, $L.F$ is the latest finish time of the activity in a work flow, $E.S$ is the earliest start time of the activity in a work flow, t is the overall standard duration of the activity and T_n is the production duration of the element.

From Equations 8 and 10, the total complexity for a project with elements in serial sequence can be calculated as

$$C_p = \Sigma C_n T_n / \Sigma T_n \qquad (11)$$

Thus far, the measure of complexity of a project, having elements in a serial sequence of work flow, depends upon the standard time of complex roles ($t_{i\text{complex}}$), duration of elements (T_n) and the K values of the affecting complexity components in category A. However, when other forms of interdependences of sequencing are considered, the measure of complexity will in addition depend upon the nature of the interdependencesbetween roles (TRI) and the rigidity of sequence of work flow of elements (RS). By changing the interdependencesbetween elements in a serial sequence to other forms of interdependences, the value of the project production time (T_p) may change. Again, it may also generate new values of total floats ($F.F$) in the complex roles.

To consider the issue of overlapping of major elements of construction (OV), Figure 5 illustrates a simple case of a project made up of three overlapping elements. If the influence of overlap is disregarded, the project complexity can simply be calculated by using Equation 8 with a modified formula for calculating the value of T_p as follows:

$$C_p = (C_1T_1 + C_2T_2 + C_3T_3 + \ \ldots\ C_nT_n)/T_p$$

where

$$T_p = (T_1 + T_2 + T_3 + \ldots\ T_n) - \Sigma T1_p \text{ and}$$

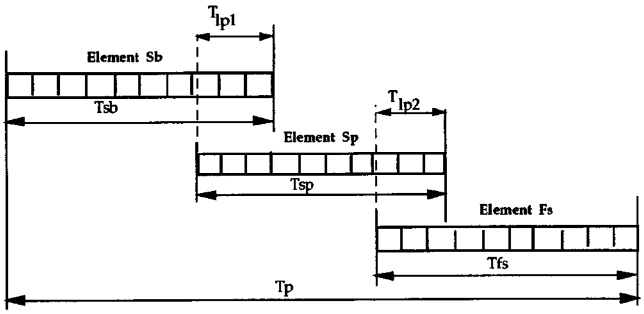

Figure 5 Project with three overlapping elements

$$\Sigma T1_p = T1_p1 + T1_p2$$

The results obtained in the above case could be misleading because the three elements are considered almost independent of one another. The start date of each element is simply fixed based upon the constraints that prevent further overlapping of construction elements. This represents what happens in practice[11] and elaborates how practitioners underestimate the implications of simple overlap of major construction elements in programming practice. The use of these results in the balance of project success (shown in Figure 3) may result in a −ve failure.

However, by considering the effect of overlap and the critical path principle, the project case can be modified as shown in Figure 6. The critical path of the project can pass through a portion or whole of any of the elements or through the whole of the roles in the project. This means that the longest of the following routes is the critical path.

Route 1 – through blocks 1–2–4–5–7: $T_{sb1} + T_{1p1} + T_{sp1} + T_{1p2} + T_{fs1} = T_p$

Route 2 – through blocks 1–3–4–5–7: $T_{sb1} + T_{1p1} + T_{sp1} + T_{1p2} + T_{fs1} = T_p$

Route 3 – through blocks 1–2–4–6–7: $T_{sb1} + T_{1p1} + T_{sp1} + T_{1p2} + T_{fs1} = T_p$

Route 4 – through blocks 1–3–4–6–7: $T_{sb1} + T_{1p1} + T_{sp1} + T_{1p2} + T_{fs1} = T_p$

[11] As indicated by the structured interviews discussed in Gidado (1992).

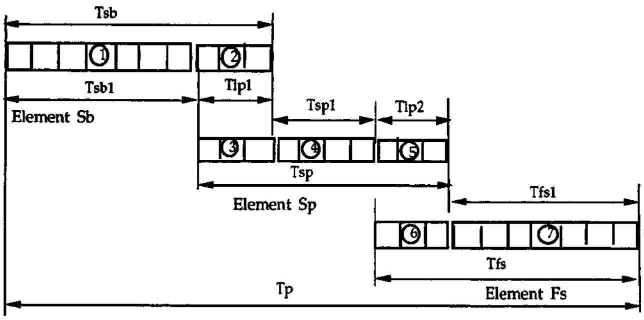

Figure 6 Schematic block programme (three overlapping elements)

The extension of any of the blocks in Figure 6 may change the critical path route.

Assuming each block in Figure 6 is independent of the other blocks, the measure of complexity in this case can be calculated by using Equation 10. Therefore, by using Equation 11 and routes 1–4, the project complexity C_{Ti} will then be the greater value of the following equations.

$$C_{T1} = (C_{sb}T_{sb} + C_4T_{sp1} + C_5T_{spl2} + C_7T_{fs1})/T_p$$
$$C_{T2} = (C_1T_{sb1} + C_{sp}T_{sp} + C_7T_{fs1})/T_p$$
$$C_{T3} = (C_{sb}T_{sb} + C_4T_{sp1} + C_{fs}T_{fs})/T_p$$
$$C_{T4} = (C_1T_{sb1} + C_3T_{spl1} + C_4T_{sp1} + C_6T_{fs1} + C_7T_{fs1})/T_p$$

where C_i is the complexity coefficient of block i in Figure 6, C_{sb} is the complexity of element Sb, C_{sp} is the complexity of element Sp and C_{fs} is the complexity of element Fs.

The computation of the complexity values for the four identified routes can provide managers with important information at the planning stage of a project by identifying the available room for manoeuvre should the need to vary or review the sequence of work flow arise. It will also arrest the problem expressed by Klingel (1966), Gray (1983) and experts that use network systems.

The numerical relationships between project complexity and production time can be summarized as

$$C_t = (T_{tot}/T_p) - 1 \qquad (12)$$

where C_t is the measure of project complexity in relation to time, $T_{tot} = T_p + et$, T_p is the original estimated or stipulated production time and et is the additional production time as the result of the effect of project complexity without change in the initial corresponding planned effort (contingency time) (refer to the acceptable limit in Figure 1).

Project complexity versus cost

Production cost is often made up of two parts: the direct cost and indirect cost. The direct relationship between complexity and direct cost is to some extent similar to that between project complexity and time. Inherent complexity and uncertainty may be reduced to an extent by expenditure on additional information, special resources and so on, e.g. better definition of requirements, site investigation, mock trials, off-site fabrication and importation of foreign skilled labour. However, there may be a distinct difference in the manner in which the complexity K values are obtained. Unlike the increase in time (e.g. from the effect of technical complexity) which often depends upon productivity rates of manpower and/or plant and machinery, the increase in cost may, in addition, result from the increase in wastage of valuable resources including materials. Again, the issue of floats in the network is not considered in the complexity direct cost relationship.

Indirect cost involves not only the cost for prelims, including overheads, but also items such as penalty wage rates and incentives. These costs are directly related to the number and duration of interruptions and the increased time resulting from the effect of complexity.

From the above descriptions, it is clear that the relationship between project complexity and cost be best considered initially in two parts: the direct cost and indirect cost relationships. It means that the two costs must be separated in the network analysis so that the planned total project cost (V) can simply be

$$V = V_p + V_o$$

where V_p is the total direct production cost and V_o is the total indirect cost.

The project complexity relating to the direct production cost (C_c) of a process having activities in a serial sequence can similarly be calculated as

$$C_c = \Sigma(v_{i\text{complex}}(K_{ic} - 1))/V_p \qquad (13)$$

where $v_{i\text{complex}}$ is the activity's direct cost affected by complexity component i and K_{ic} is the direct cost complexity factor of component i.

Using a similar relationship as in Equation 12, the actual production direct cost (V_{tot1}) is

$$V_{tot1} = V_p(C_c + 1) \qquad (14)$$

while the actual production indirect cost (V_{tot2}) is calculated as

$$V_{tot2} = \{(T_{tot} - T_p)(T_p/V_o)\} + V_o \qquad (15)$$

where T_p is the planned production time and T_{tot} is the total production time including the effect of complexity.

Equation 15 is based upon the assumption that the rate of increase in indirect cost is constant throughout the production period.

Equations 13–15 imply that the total actual project cost (V_{tot}) can be calculated as

$$V_{tot} = V_{tot1} + V_{tot2} \qquad (16)$$

and, therefore, as in Equation 12, the project complexity (C_v) that relates to production cost can be obtained as

$$C_v = (V_{tot}/V) - 1 \qquad (17)$$

and the contingency sum as

$$ec = V_{tot} - V$$

Relating project complexity, time and cost

Using the established equations, project complexity, production time and cost can be related to provide valuable information for construction managers.

Starting from Equation 17

$$C_v = (V_{tot}/V) - 1 = ((V_{tot1} + V_{tot2})/V) - 1$$

using Equation 15 to substitute $V_{\text{tot2}} = \{[((T_{\text{tot}} - T_p)(T_p/V_o)) + V_o + V_{\text{tot1}}]/V\} - 1$

using Equation 12 to substitute T_{tot}

$$+ \{[((C_t T_p)\ (T_p/V_o)) + V_o + V_{\text{tot1}}]/V\} - 1$$

and using Equation 14 to substitute V_{tot1}, therefore

$$C_v = \{[((C_t T_p)\ (T_p/V_o)) + V_o + V_p + V_p C_c]/V\} - 1 \quad (18)$$

The starting point of using Equations 12, 17 and 18 in practice must be the contractors establishing the threshold of project complexity for their individual organizations, below which they can consider projects as systems that behave in a simple sense. As an additional aid to construction management practice, the derived equations can be used to predict, right from the early stage of planning, the variability of project complexity with project progress. This variability can be plotted in a linear graph (an example is shown as Appendix 1) and used as a guide to planning the managerial effort required to create a balance of project success (Figure 1) as the project progresses.

Conclusions

Based upon current knowledge on the issue of complexity, this paper has defined project complexity and identified the factors that affect its influence on project success. The paper has developed a numerical approach of measuring the effect of project complexity on project success with a particular consideration to production time and cost. The approach provides a simple and straightforward numerical model by which project complexity can be assessed and used as valuable information by practising managers in the building industry. The application of the model in practice would bring to the forefront the issue of project complexity during planning and thus provide a better in-depth understanding of the project at a much earlier stage. It must be recognized that where standard times of activities are established by using the conventional approach in practice (i.e. by using trial and error or intuition developed from experience) there may be a problem of double counting of the effect of some of the category A components of complexity which may be inherent in the approach. This problem can only be evaded if construction planning practitioners adopt the use of scientifically established productivity rates of output to estimate standard times.

It can be deduced that the use of the developed approach in practice to obtain a reliable measure of project complexity depends mainly upon how practitioners understand the concept of project complexity and how they can identify activities affected by the category A components, the reliability or accuracy of their established *K* values and the quality of the available project data and information (i.e. the more the production process becomes defined and the standard times being established by using realistic productivity rates of output, the more accurate will be the results of the assessment). There may not be a single universal solution for the *K* values, but every contractor will have to gear up to establish their own applicable and realistic values in line with their experience and capabilities. This can be established by using the tested procedure included as Appendix 2 or by using other probabilistic modelling of data and information collected through work studies. It is important to state here that Gidado (1993) tested the application of the developed numerical concept in practice by using plausible *K* values. His results have shown that practitioners understand the developed concept and valuable information necessary for conducting an objective prediction of project success can be obtained by using the equations developed.

Recommendations

Each of the identified complexity components is complex in its own right, let alone the complication that develops when these components are brought together. The subdivisions illustrated in Figure 2 provide some disaggregation of the category A components (i.e. the inherent complexity and uncertainty factors). The third tier or tertiary level (in Figure 2) clearly indicates that there may still be further intersections in the subdefinitions, e.g. BC, the use of sophisticated equipment. This may suggest the need for furtherance beyond the tertiary level. The further fragmentation may contribute to a clearer understanding of the intersections that exist between the various components. Again it may provide a more defined base on which complexity subcomponent *K* values can be established that may be more accurate than the plausible values used by Gidado (1993). However, this furtherance may still not provide universal *K* values because of the chaotic or anti-chaotic phenomena of natural systems, but it may result in the avoidance of excessive intersections between the seven category A components. The developed concept could be computerized and interfaced with existing planning packages or built-in to enhance the sophistication of the existing planning packages. This may be achieved through the cost–time–resource (CTR) catalogue of activities. Firstly the user must load their organization's *K* values into the computer's database. Then the activity CTR catalogue must be designed in such a way that it displays all the category A complexity factors to enable a quick selection of those that affect the activity. These improvements would enable managers to obtain 'on-the-spot' project appraisals.

References

Bennett, J. (1985) *Construction Project Management*. Butterworths, University Press, Cambridge.

Bennett J. and Fine, B. (1980) *Measurement of Complexity in Construction Projects*. Department of Construction Management, University of Reading.

Burns, T. and Stalker, G.M. (1961) *The Management of Innovation*. Tavistock, London.

Cohenca, D., Laufer, A. and Ledbetter, W.B. (1989) Factors affecting construction planning efforts, *Journal of Construction Engineering and Management*, **155**(1).

Gidado, K.I. (1992) The effect of simple overlap of the stages or elements of construction on project complexity and production time. *Proceedings of the 8th Annual Conference of the ARCOM*. Douglas, Isle of Man. September, 307–17

Gidado, K.I. (1993) Numerical index of complexity in building construction with a particular consideration to its effect on production time. PhD thesis, University of Brighton.

Gray, C. (1983) *Buildability – the Construction Contribution*. The Chartered Institute Of Building.

Hill, T. (1991) *Production/Operations Management – Text and Cases* (2nd edn). Prentice Hall, University Press, Cambridge.

Ireland, V. (1984) Virtually meaningless distinctions between nominally different procurement forms. *Proceedings of Fourth International Symposium on Organisation and Management of Construction*, Vol. 1. Waterloo, Ontario, Canada, 203–312.

Katz, D. and Kahn, R.L. (1978) *The Social Psychology of Organisations*. Wiley, New York.

Kendall, R.E.H. (1986) The integration of subcontractors into construction project systems. Dissertation in partial fulfilment of MSc, Brunel University.

Klingel, A.R. (1966) Bias in PERT project completion time. Calculations of real networks, *Management Science Journal*, December.

Langford, D.A. and Shoesmith, D.R. (1991) Research into specialist building services procurement and its impact on project performance. *Proceedings of the Seventh Annual ARCOM Conference*, University of Bath, September, 132–43.

Malzio, P., Moselhi, O., Theberg, P. and Revay, S. (1988) Design impact of construction fast-track, *Construction Management and Economics*, **5**, 195–208.

Mohr, L.B. (1971) Organisational technology and organisational structure, *Administrative Science Quarterly*, **16**, 444–59.

Perrow, C. (1965) *Hospitals, Technology, Structure and Goals. Handbook of Organisations*. Rand McNally, Chicago.

Rosen, R. (1987) On complex systems, *European Journal of Operational Research*, **30**, 129–34.

Rowlinson, S.M. (1988) An analysis of factors affecting performance in industrialised buildings. PhD thesis, Brunel University.

Thompson, P. (1981) *Organisation and Economics of Construction*. McGraw-Hill, UK.

Van der Ven, A.H. and Delbecq, A.L. (1974) A task contingent model of work unit structures, *Administrative Science Quarterly*, **19**, 183–97.

Woodward, J. (1965) *Industrial Organisation Theory and Practice*. Oxford University Press, Oxford.

Appendix 1: prediction of the variability of project complexity with progress of work

Two case study projects are labelled here as project 1 and project 2.

Project 1 was a high rise hospital building project using the traditional procurement system with a planned production time of 55 weeks. Project 2 was a sports and leisure complex using a design and build procurement system having production time of 55 weeks. Both were built in the South East of England in the traditionalist approach (i.e. a main contractor with the project in three elements). Ten equally spanned intermittent times were selected for the assessment of the future measure of project complexity as shown in Figure 7. The individual assessments were carried out on the assumption that all activities before the selected time have been completed as planned.

By using the developed equations, the various project complexities have been assessed and plotted in a linear graph for each project. The corresponding required contingency times were also calculated and plotted. The results are illustrated in Figure 8. The results seem to support Cohenca *et al.* (1989), that the level of complexity varies with progress in a manner that cannot simply be predicted from an outline programme and that the required managerial effort must be adjusted accordingly. The results have provided a prudent means by which managers can measure this variability. Although plausible values of K were used, the real outcome of these two case studies have been compared with the prediction, and the comparisons were found to be interestingly close.

Appendix 2: procedure used for the determination of K values for category A complexity factors

1. Identify the complex activities (e.g. install air-conditioning ducts).
2. Identify the complex factor that may separately affect the complex activity (e.g. technical complexity, TC).
3. Identify the project stage or element (e.g. substructure).
4. Determine the original time allocated to the identified complex activity from the construction programme and record it as t_0

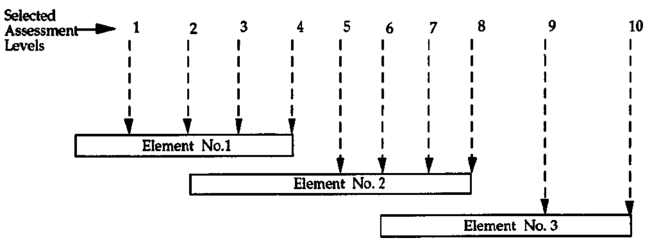

Figure 7 The 10 selected points of assessment

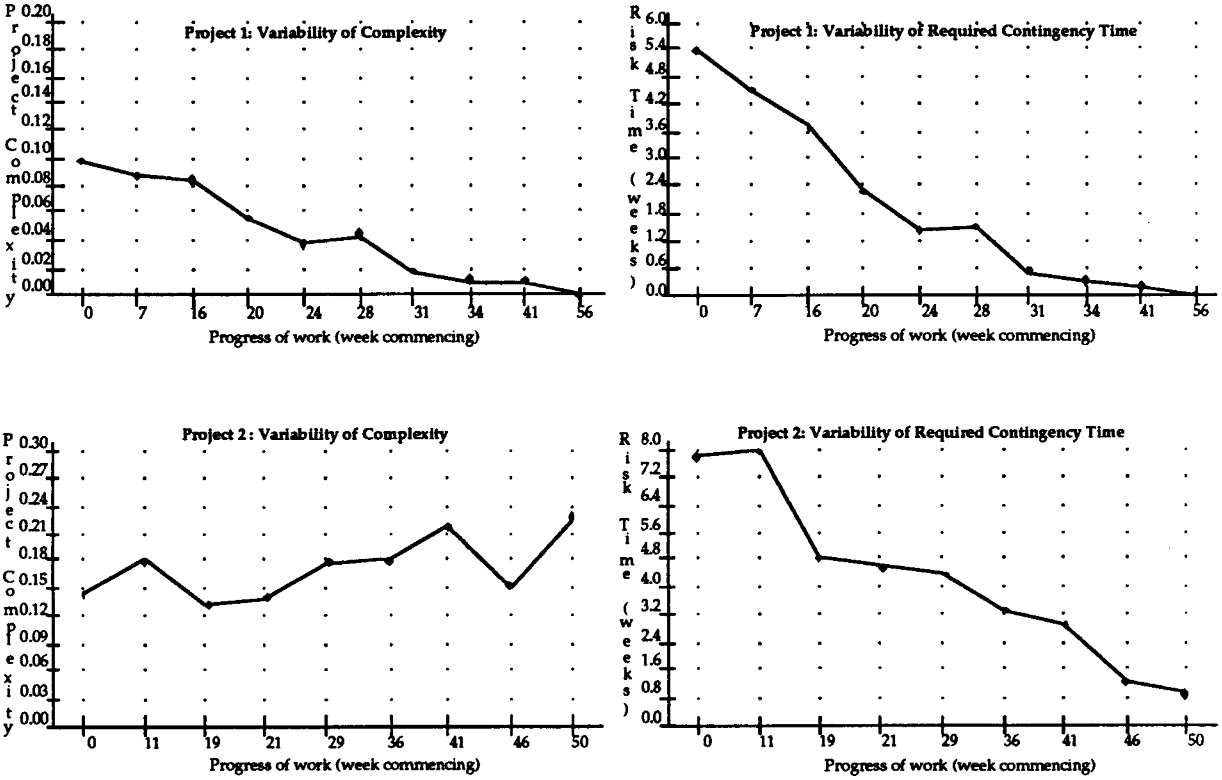

Figure 8 The prediction of the variability of project complexity and contingency time with progress of work

5. If the activity is to be executed by a single trade, compute the planned output rate from the method statement and the construction programme.
6. Determine the actual duration of the complex portion of the identified complex activity and record the duration as $t_{complex0}$.
7. If the activity is done by a single trade, monitor the actual output rate during the $t_{complex0}$ duration and compare with planned output.
8. From the case study, determine the actual time taken to complete the complex portion of the activity and record the duration as $t_{complex1}$.
9. Compute the value of K by using Equation 2b:

$$\text{text} = \{K(t_{complex0})\} - t_{complex0} = t_{complex0}(K - 1)$$

where

$$t_{ext} = t_{complex1} - t_{complex0}$$

therefore

$$K = \{(t_{complex1} - t_{complex0})/(t_{complex0})\} + 1$$

10. If more than one same factor in the same project stage was monitored, compute the arithmetic mean value of K, i.e. $K = \Sigma K_i/_n$ where n is the number of monitored cases of the same factor in the same stage and similar activities.

NB: with reference to item 10 above, the ideal statistical approach should be as follows.

K is a discrete random variable capable of having n values, x_i, where i ranges from 1 to n. It implies that the probability mass function (PMF) can be obtained as

$$p_x(x_i) = P[K = x]$$

i.e. the probability that $K = x$ where

$$P[K = x] = (\text{number of occurrences of } K = x)/n$$

The PMF must obviously satisfy the following laws of probability:

$$0 \leqslant p_x(x) \leqslant 1 \text{ for all values of } x$$

$$\Sigma p_x(x) = 1 \text{ with the summation taken for all possible values of } x$$

From the obtained PMF values, the expected value of K, with a range of possible values from x_1 to x_n can be calculated as

$$E[K] = \Sigma_i n_{=1}\, x_i P[K = x_i] = \Sigma x p_x(x)$$

Where there is a limited range of i (i.e. the number of sample values), the $E[K]$ can be substituted by the arithmetic mean value as discussed in item 10. The data collection can be done by using the standard Forman–Delay survey sheet currently being used in practice.