3.7 COMPLEXITY, UNCERTAINTY AND RISK IN CONSTRUCTION AND CIVIL ENGINEERING PROJECTS

John M. Kelsey, University College London

Introduction

In order to understand the behaviour of those managing construction projects, one first has to understand construction outputs as consisting of economically, technically and environmentally complex products which both influence and are influenced by the non-construction environment. Following that the paper will explore the generic risk management processes used in construction and some recent developments in this area with a focus on schedule risk and procurement risk in particular.

The built environment as an economically complex product 1

The output of the construction industry is an economically complex product in the sense that it has a complex relationship with the rest of the economy given some direct relationship between the movements of general economic activity and the demand for constructed assets (Bon and Crosthwaite (2000), Ive and Gruneberg (2002)). The reason for this has to do with the life span of buildings which tend to be the longest of all produced goods and which, therefore, depreciate at the slowest total demand for buildings and the demand for changes in the stock. A simple example (see Table 1) will suffice:

Table 1: Capital Stock Adjustment

Current stock	**Depreciation**	**Change in total demand**	**Change in current demand**
100	5	+10	+15
100	5	+5	+10
100	5	0	+5
100	5	-5	0
100	5	-10	-5

Source: Adapted from Ive and Gruneberg, 2002

Thus an industry which sets its output capacity at 10 for replacement of current stock plus an anticipated growth rate of 5 per cent could face a 50 per cent increase or decrease from a 5 per cent change in total demand. Now such potentially large fluctuations are dampened in practice, not least because it takes some considerable time between the expression of increased demand and the delivery of new buildings. In the negative case, of course, the change in demand cannot be realised short of actually demolishing buildings. However, in recessions, this is instead manifested by the existence of empty property to let or unsold houses.

The recent and relatively long, prosperous period for construction is a relatively rare phenomenon and most construction businesses have grown with the highly volatile market in mind. This has tended to focus the mind of firm managers on the avoidance of downside risk which has been managed in various ways.

One of the ways in limiting risk is to minimise fixed or overhead costs so that a firm can shed labour relatively quickly in a recession. The lower a firm's overhead, the less vulnerable it is to recession-induced insolvency. One way to do this is by minimising the scope and variety of activities carried out by a firm. In one sense low-overhead specialisation increases the risk that a firm will have to be terminated in a recession, but it also facilitates the ability to do so quickly with the minimal mount of financial pain. Another strategy is to join a construction firm with some other firm with a more stable demand for its output. A good example in the UK would be the firm Balfour Beatty which for many years was part of the BICC group whose core demand was from the electricity supply industry. Yet another is to have interlocking relationships both with other firms having relatively stable output demand and financial institutions which will support the construction firm during recession. This example has been followed in different ways in (for example) Germany, Japan and Korea. However even this support network can unravel as shown by the insolvency of Philipp Holzmann AG, Germany's second largest contractor, in 2002. A further strategy is for large firms to have powerful lobbies in government partly so that counter-cyclical increases in government contracts can offset falls in non-government demand. This influence is itself a problematic issue and a wide variety of capital goods producers show such behaviour (POGO 2004) for varying reasons.

The built environment as an economically complex product 2

There is another sense in which the built environment is a complex product. That is because the output of the construction industry is a joint product of a built output plus a piece of land with fixed location. The individual location is itself subject to a complex set of influences but that is not the concern here. Rather it is that the value of the land is effectively a residual arising from the difference between total development value and total non-land development cost (Lawrence 1974).

Table 2: Development Land Value as a Residual

Development Value	**Non-land development costs**	**Residual land value**	**Value as % of 20**
90	80	10	50%
95	80	15	75%
100	80	20	100%
110	80	25	125%
120	80	30	150%

Source: (Kelsey 2007)

In Table 2, if a developer purchases land at 20 in the expectation of a development value of 100 and non-land costs of 80 (which is assumed to include a normal element of developer's profit), then relatively small changes in total development value bring about large changes in land value. A similar relationship can be shown to exist with regard to changes in non-land development costs. Thus in a rising market, large profits may be made by buying land in anticipation of increases in construction output value. Similarly large losses can be made and the insolvency of Phillipp Holzmann AG referred to earlier was as much, if not more due to losses on property as in contracting.

It is similarly argued (Kallberg *et al.* 2002) that the Asian currency crisis of 1997 (followed by crashes in Russia and Latin America) was in part due to property speculation in Thai and Korean markets combined with the complexity and interrelationship of global financial markets. In property crashes, the downside risk often ends up with the providers of finance. The developers may become insolvent but may re-appear in other guises at a more favourable date. Not a few directors of UK developers who experienced insolvency in the 1970's re-appeared as directors of new development companies in the 1980's. The problem is that for individual decision makers, the downside risk is effectively capped by the limited liability status of a corporation whereas the upside opportunity is not so capped. So here is a potentially risky area where the production of new buildings may actually be a by-product of speculation in land prices. (Attempts to introduced special taxes on development gains have proved problematic in the UK – the last serious attempt being the short-lived Development Land Tax Act 1976.)

The built environment as an economically complex product 3

The third way in which the built environment is a complex product is the way in which it tends to be financed.

Table 3 shows a hypothetical building financed by different combinations of debt and equity with rents at three different levels (120 +/- 10 per cent). There is here a non-linear relationship which shows the highest rate of return for high debt to equity ratios. However, at these ratios there is considerable risk as the rent to interest ratio is relatively small which would render the project particularly vulnerable to interest rate rises.

Table 3: Gearing and Shareholder risk

			Profit with net rent at			Profit as % of Equity		
Debt	**Equity**	**Interest**	**A=108**	**B=120**	**C=132**	**A**	**B**	**C**
100	900	10	98	110	122	10.9	12.2	13.6
200	800	20	88	100	112	11.0	12.5	14.0
300	700	30	78	90	102	11.1	12.9	14.6
400	600	40	68	80	92	11.3	13.3	15.3
500	500	50	58	70	82	11.6	14.0	16.4
600	400	60	48	60	72	12.0	15.0	18.0
700	300	70	38	50	62	12.7	16.7	20.7
800	200	80	28	40	52	14.0	20.0	26.0
900	100	90	18	30	42	18.0	30.0	42.0

Source: Kelsey (2007)

Lenders, typically, are willing to lend high proportions of value in the case of many properties because they are generally considered as a relatively safe security in case of default by the borrower. So high risk behaviour by the borrower is not perceived as such a high risk to the lender (until the general level of values is compromised such as in the recent US sub-prime crisis). Indeed it is similar to margin trading in stock markets which carries similar risks and plays a significant role in market volatility.

So then in summary we have three important relationships which are complex in the sense that a relatively small change in initial conditions can generate non-linear and/or significant change elsewhere. Two of those relationships encourage risk-loving behaviour and the other encourages risk-averse behaviour. These relationships may also cause wider disruption to market stability and even democratic political processes. While most construction project supply chain actors are in the risk-averse category, developer-clients and certain types of property companies can appear in the risk-loving set.

Construction as complex technical and socio-technical outputs requiring complex organisations

Each construction project requires some innovation even in the re-use and re-configuration of existing technology. Fonseca (2002) describes two models of innovation. In one the classic individual hero strives against opposition and scepticism to get acceptance for his innovation (of new types of service core conduit pipes). However it is argued that the clues to his success lie more in the brokering he did with architects and engineers earlier in his career in project management for a city council. His many conversations allowed him to take an integrated approach to the problem the pipes were designed to solve.

In the second model there is no heroic individual, only a group of people working in a water utility developing a new information capture and deployment system to increase operational and maintenance efficiency. The process of innovation had to solve not only technical problems but also organise 'horizontal' communications across departments and overcome opposition from those who felt their vested interests threatened by the innovation. As much person management was required as technology management and it was a more or less self-organised process at a less than senior level of the utility.

Bonke (2000) looks at two processes within the Great Belt Fixed Link (Denmark-Sweden). The first is the 'social construction of the fixed link'. He recognises that the proposal of a very large new technical artefact will have social consequences and that the view of the project from all stakeholder viewpoints needs to be understood through the concept of the social construction of technology. He understands the choice of technology not as an engineering decision but as a political one with the expertise of engineers as but one of the inputs. The process did, however, take some considerable time. During this time there were shifts in balances of power and viewpoints. There was still not universal agreement and continuing opposition. But the discussions had enabled a much greater number of people to begin to see the problems through similar perspectives (or at least acknowledge the perspectives of other stakeholders).

Once approval in principle had been given there was then a process of competition among rival firms with a possibility of three different technologies: (1) a bored tunnel, (2) concrete immersed tunnel and (3) a steel immersed tunnel. Bonke describes the need for the competitors to form consortia in order to have privileged access to a wide range of expertise in order to mount a bid which was risky both in the complexity (and variety) of technologies as well as the tender process.

The examples by Fonseca and Bonke reveal processes requiring management of complex communication, decision-making and information processes both within and across organisations. That suggests an examination of the form of organisation. The influence of technology upon the form of organisation has long been recognised (Burns and Stalker 1961, Woodward 1965/1980).

A civil engineer once said to the author "engineers solve complex problems by breaking them down into a simple one". What he did not say was that the simple solutions require re-assembly and integration into a complex product. A building and many other technologically complex products require such integrated solutions to be delivered (Davies 2003).

Hobday (2000) argues that complex high value capital goods are part of a set of outputs called Complex Products and Systems (CoPS). He argues that these largely one-off outputs require re-configuration of structures and innovation for each client. The traditional hierarchical and functionally organised enterprise is inappropriate and a different form of organisation – the Project-Based Organisation (PBO) is required to meet the demands of delivering CoPS.

The projects are carried out by separate, integrated teams rather than from within functional departments. There can be various hybrid forms (generally referred to as matrix organisations) where individuals have both project and functional reponsibilities. The advantages lie particularly in team focus, cross-functional communication and flexibility. The PBO does have its dangers in that it become detached from the strategic outlook of the main organisation and it may be difficult to re-integrate or re-position team members when the project is completed. A modified form (the project-led organisation) can be developed where members still retain some functional (albeit secondary) departmental relationships and responsibilities.

However, Keegan and Turner (2002) suggest that rigid application of traditional project management controls can actually inhibit innovation in project-based firms and actually work against the many other features of project-based organisations which are conducive to innovation. Innovation needs a certain degree of slack resources and the availability of these can be inconsistent or non-existent. It was also found that there was a problematic attitude to innovation – particularly where it either did not show relatively short-term gains in profits and/or market share. Innovation was otherwise seen as an additional source of risk.

Keegan and Turner (2002) contains a telling quote from one interviewee :

> *"This industry [engineering and construction] is very conservative. We work within so many safety standards and we do not innovate unless a client specifically asks us to. This is not very often. We have lots of reasons. We blame the client, the public sector, public opinion. Our expertise and culture are not for taking risks".*

What they conclude is that project management takes priority over innovation management to the detriment of the latter.

The Piccadilly Underground Railway line was extended to London Heathrow Airport and the tunnelling method used was the New Austrian Tunnelling Method (NATM). In 1994, however, there was a tunnel collapse while using this method. This not only required revision of the technique in use on this project but it also affected the Jubilee Line Extension (JLE) requiring a more time-consuming and expensive technique (Field *et al* 2000 quoted in Winch 2002).

There was also a technology failure on the JLE. The original Moving Block System of signalling (MBS) designed to enable a throughput of 36tph (trains per hour) was never delivered and late in the day, a substitute Fixed Block System enabling only 24tph was approved but created its own further problems as trackside cabling had to be installed in areas not intended to receive it. Not least in the considerations for the switch was the near certainty that a Moving Block System could not have been delivered in time for the Millenium when the JLE was intended to service the Millenium Dome at North Greenwich. The passenger facilities and capacity of the stations was designed to handle 36tph and so part of the (expensive) capabilities of the JLE have never been used. The consequence of this was that in 1999 the Rail Regulator, Tom Winsor refused to ratify the budget for the West Coast Main Line (WCML) upgrade (which was also attempting to introduce MBS) until there was a review of its viability on that project and the proposal of an alternative scheme. In fact MBS was also abandoned on WCML. So adverse technology events do not only impact the projects that they occur on but also have knock-on effects for other projects.

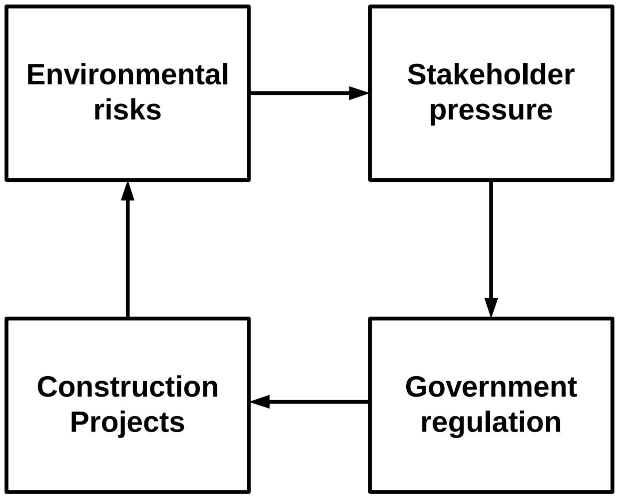
In a presentation on the management of the Channel Tunnel Rail Link (CTRL) one of the specific means of risk reduction was stated as 'minimise use of untried technology' (Jago, 2004). To be fair CTRL is part of a larger rail system using earlier technology and they opted for the basic French TGV systems which had been well-tried and tested. However it does suggest that the quote from Keegan and Turner is not an isolated viewpoint. Perhaps the bad experiences quoted from other projects may be seen to justify this approach. O'Connor and Yang (2003) however report some considerable success by US construction companies in employment of new technologies (notably integration and automation technologies) which apply to construction *processes* (rather than the final construction product). In general, however, these technologies are more successful in achieving schedule rather than cost targets.

So there is somewhat of a mixed verdict here. The project-based organisation (or a project-led organisation) does seem to be successful in delivering complex products and should in theory be the type of organisation that facilitates innovation. However, it is less obviously successful in delivering innovation (in construction products although more so in processes) and it is not always clear that those who run such organisations are motivated to take the risks which innovation requires.

Buildings as temporal-environmentally complex products

Construction projects create assets and infrastructure which give rise to environment risks and uncertainty. Stakeholder concerns bring pressure to bear on government which often but not invariably leads to regulation as shown in Figure 1.

Figure 1: Risk-regulation cycle



The main risk in terms of carbon emissions comes not from the embodied energy in materials and transport/process energy used in the construction process (although these provide significant matters for concern) but rather in the subsequent operation of the finished product. In the UK the government has responded to environmental concerns by introducing tighter regulations on new buildings (ODPM 2006) although the preparedness of the UK industry to implement them and the likely effectiveness of enforcement is open to question (Tshakilov 2006).

The international position is less clear cut. Perez (2002) argues that international construction contracts are almost oblivious to environmental risks posed by construction activities. As variations and contingent events emerge during the course of a large construction or infrastructure project, it is important that these are constrained by environmental considerations which may not have been addressed in the original (and extra-contractual) Environmental Impact Assessment. Therefore there may need to be some new forms of contract which allow for public engagement and/or intervention.

The governance of existing contracts lies with international professional bodies such as FIDIC (Fedération Internationale des Ingénieurs – Conseils) or centres for international arbitration. They are currently outside the realm of national governments. Regulatory governance is itself a problematic area in developing countries where imitation of models used in industrialised countries may not be appropriate (Minogue 2004). In addition, international bodies such as the World Bank (Palast *et al* 2003) and the World Trade Organisation (Brack 1999) may not favour government regulation of the environment where it conflicts with private sector interests. However in the older industrialised countries only a fraction of the built stock is replaced each year. Therefore the largest threat to the environment in these countries comes not from the newly built stock but from the existing stock. In other words it is *past* construction project management which poses the greater current (and future) environmental risk.

Even this is not quite the full picture – the energy used in the course of a building's operations is a complex function of structure and materials, building services, energy measurement, monitoring and regulatory equipment and finally (and most importantly) occupant behaviour (Young 2003). The combination of these factors produces emergent properties which render energy consumption difficult to predict. This is true not least because the ownership, type and manner of use may change through the life of the building. Derrida (1981) challenges the supremacy in European culture of the spoken word over the written text. This, he argues, ties thinking about the text too closely to its context of production and the original intention of the author. In the same way buildings develop a life of their own (Brand 1994) which may be independent of the intentions of the original client and the architect or the discussions between them.

Therefore, in the knowledge one aspect of failure of their predecessors and in the face of uncertainty both in the future of energy systems, the environment as well as of the building, construction project managers are required not only to look at the client's immediate requirements but the longer term adaptability of the constructed facility (a point made to some extent by Nutt 1993). This, however, requires the consent and co-operation of the client as well as their willingness to pay what may well be a significantly increased initial capital cost.

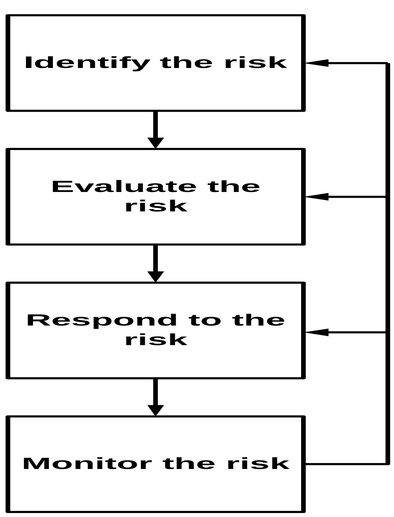
Buildings are currently only complex adaptive systems within rather narrow limits. If they are to adapt (Leung 2007) to what is now recognised as a changing environment, they need to be made more adaptable. Since buildings are normally constructed to last 60 years (and some are still being used after 900 or more years), they need to become "co-adaptive complex systems that adapt to systems that are simultaneously adapting to them" (Taylor 2001). Flexibility, however, comes at a price and may require more radical thinking by clients, architects, project managers and governments (since more external regulation may be required).

Risk management in construction

Risk and uncertainty

The generic model that is taught to construction (and other) project managers is the relatively simple one set out in Figure 2

Figure 2: The generic risk management process



Risk identification and evaluation

Not surprisingly risk identification and evaluation is actually the most difficult part. Various techniques are used including reviews of past projects, brainstorming, Delphi techniques and consultation of experienced construction (or design) managers. Intuitively one would expect those with considerable experience to be much better at identifying risks. However Edkins and Millán (2003) looked at the cognitive biases which were generally present in risk perception and Edkins et al (2003) suggested methods for investigating this. In a follow-up study Winch et al (2005) actually tested a sample of construction managers on their risk perceptions of an actual construction project (guided by the project manager). This involved interrogation by the managers of the interviewer about various aspects of the project. They found that the younger, less experienced but more educated managers tended to combine a linear approach (interrogation about one-off issues) with a much more feedback-based approach involving continuously monothematic sets of questions which pursued a connected line of enquiry as far as it would reasonably go. The older, more experienced and less educated managers tended to employ only the linear approach. There was a sense in which they were relatively complacent about their knowledge of risks and tended to proceed with a 'checklist' approach. Counter-intuitively the less experienced outperformed the more experienced in identifying significant project risks. It is ironic that the unwillingness to take innovation risks referred to earlier in the paper seems to reflects a conservative mentality which also results in a lesser ability to identify risks. Perhaps, however, the study also indicates that the mentality is changing.

Typically construction firms use risk logs or registers in the evaluation, prioritisation and management of risks (Figure 3).

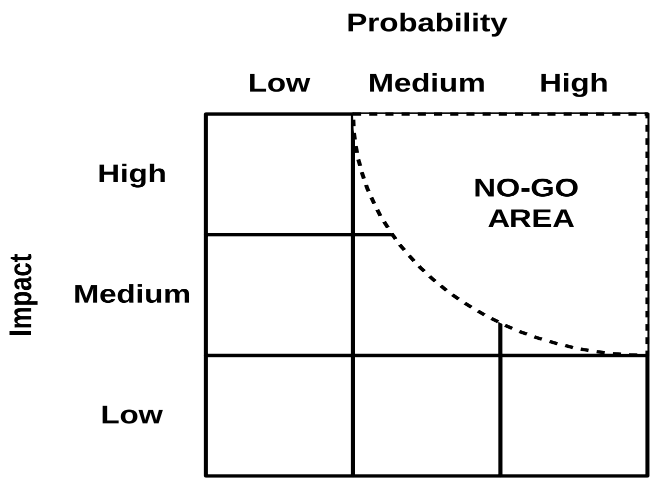
Figure 3: Risk log or register

PROJECT RISK LOG						
WHAT			HOW	WHO	WHEN	
Risk No	Probability	Impact	Method of managing	Responsible for managing	Timing of Risk	Action dates
Risk No						
Risk No						
Risk No						

Source Kelsey (2007)

The other way they might look at risk is through a probability-impact matrix (Figure 4) which shows both the likelihood of an adverse event and its impact upon the project. However as Chapman and Ward (2003) point out this is a rather crude 'first pass' and there is much potential for rather more sophisticated analysis. Typically certain risks will be treated on a traffic light basis and will not be entertained if they are in the 'no-go area'.

Figure 4: Probability-impact matrix



Source: Kelsey (2007)

Although the ability to evaluate risks to an acceptable degree of precision may be questioned, more serious is the willingness to do so. Flyvberg et al. (2003) point out that many projects are sponsored (not surprisingly) by those who stand to gain the most from them. Often such firms are likely to be included in the supply chain and have the technical expertise to press their case against which it may be difficult for those without such expertise to produce counter-arguments. The proponents can make a perfectly convincing technical case for estimates which appear to generate financially feasible projects. It sometimes turns out that such estimates are a combination of both deception and wishful thinking which ignores or underestimates downside risk.

This 'Optimism Bias' needs to be countered and following work done by Mott MacDonald (2002) the UK Treasury issued appropriate advice in a supplement to its Green Book (H.M. Treasury 2003). The bulk of this guidance is taken up with showing various degrees of bias that might occur in the estimation of both cost and schedule. However at the end of the guidance a whole set of sources of risk are shown which are:

- ***Procurement***
  - Complexity of contract structure
  - Late contractor involvement in design
  - Poor contractor capabilities
  - Government guidelines (lack of)
  - Disputes and claims
- ***Information management systems (inefficiently managed)***
  - Project specific
  - Design complexity

- Degree of innovation
    - Environmental impact
- ***Client specific***
    - Design complexity
    - Inadequacy of the business case
    - Large number of stakeholders
    - Funding availability
    - Project management team
    - Poor project intelligence
- ***Environment***
    - Public relations
    - Site characteristics
    - Permits/consents/approvals
- ***External influences***
    - Political
    - Economic
    - Legislation/Regulation
    - Technology

Now some elementary game theory would suggest that if project sponsors know that certain bias percentages will be added to their estimates (as has been done with the 2012 London Olympics) they will simply try and reduce the estimates further and that in 20 years the bias factors will have to be adjusted further.

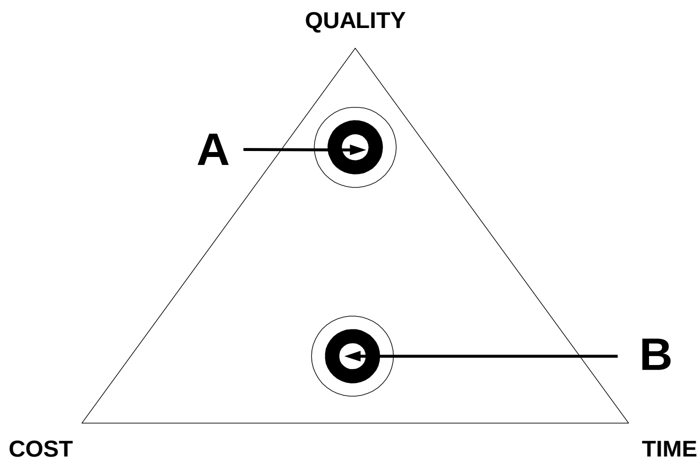
The list of factors above suggest that either those carrying out feasibility checks on behalf of other parties have some way to go in achieving 'due diligence' in their assessment of risks or all parties have actually got to be more open about the real degree of uncertainty and ignorance. This may also involve a greater degree of education of stakeholders. In project risk evaluation, the Emperor may not be in a situation of total nudity but may, nonetheless, be rather scantily clad.

Under the heading of monitoring risks, it needs to be stressed that risks must be reviewed throughout the project to assess whether the original assessment of risks needs adjustment, whether new risks have arisen or existing ones can be dispensed with. Continuous monitoring is desirable but in practice periodic reviews may be made. The UK Office of Government Commerce suggests a pattern of stage or 'Gateway Reviews' whereby this may be done. This is particularly true of construction projects where the stages of outline, detailed design, cost estimate and receipt of construction tenders (where separated construction procurement is used) reveals successively increased information on which to base decisions to continue, change or abandon. The process of deception does not always stop at the feasibility stage and the author has experience where final cost estimates were deliberately under-stated during construction in order to keep financial stakeholders supporting the project.

Risk response

Virtually all project managers are shown a diagram of conflicting objectives as shown in Figure 5.

Figure 5: The 'iron triangle'



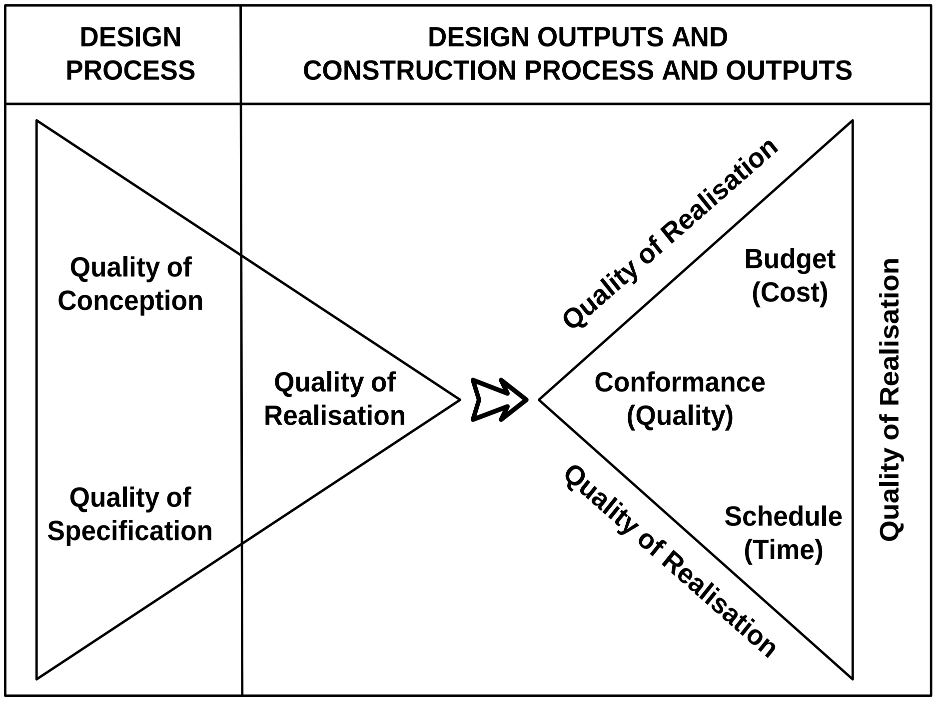
Source: Kelsey 2007

It is for the client and not the project manager or contractor to decide where the priorities are between the conflicting objectives – so points 'A' and 'B' are equally valid and the main objective of the project is to hit the client-specified target. However, this ignores a rather fundamental point made by Cooke-Davies (2002) who points out that even more important than doing the project right is doing the right project.

Spencer and Winch (2002) explain that the real conflicting objectives in a construction project are the quality of conception (in terms of the aesthetic and design values in the building), the quality of specification (in terms of how well the building fulfils its intended use) and the quality of realisation (in terms of the 'iron triangle' in Figure n). To this is added the quality of conformance (part of the quality of realisation) in the sense that the built product must not only conform in the technical sense but that the service quality in realisation must conform to client's expectations.

One of the risks that the supply chain faces is not that they do not deliver a technically correct product to the client, within time and budget (although clearly these are major risks). It is rather that they do so in a manner which is unacceptable in terms of the quality of process or service. A technically brilliant, timely and cheap building may not satisfy the client if 20 workers are killed during its construction or contractors cause trouble for surrounding property owners or residents. In this latter regard there are specific interventions in the UK in the form of the law such as the Construction, Design and Management regulations and other measures such as Codes of Construction Practice which a number of local authorities now impose on contractors in order to mitigate these risks. That such interventions have to be made suggests that the industry has been slow to adopt a customer-oriented service ethos rather than a production-oriented approach. (It should be said by way of caveat that interventions designed to increase the safety of one group may induce that group to act in a more risky manner thus increasing the risk of other groups – Adams 2000).

Figure 6: Quality, design and construction



Source: Adapted from Winch, 2002

In terms of managing the risks of conception/specification a well-managed briefing and design process is a key which may also need to embrace at the front end of the project a wide stakeholder engagement process – such as the London Heathrow Airport Terminal 5 project which provoked considerable local hostility. In particular, it needs to be mentioned that design processes are essentially 'wicked' problems (Rittel/Churchman 1967, Winch 2002) which require that a) the problem solution incorporates the problem definition, b) the solutions may be indeterminate, c) the solutions will be better or worse rather than right or wrong and d) the possibilities for improvement are open-ended. This requires a rather different mode of thinking than that normally employed by project managers.

The construction part of the industry embraced project management somewhat earlier than the design part in the UK (Touche 1992) – in the USA, there was a different approach but still rather more engineering functionally-oriented rather than aesthetically-oriented. Accordingly the objectives of construction project management were rather more production- than design-oriented. Winch's approach applies theconcept of product integrity developed in the Japanese automotive industry.

Risk responses – generic

Risks can be transferred to another party through subcontracting or insurance. Risks can be shared through, for instance, agreeing to do so contractually or by working with another company in joint venture Risks can also be mitigated by working to reduce the probability of an adverse event happening or the impact if it does. Risks can be accepted which is best done by those best able to manage them. Risks that cannot be transferred, shared or mitigate are referred to as *residual risk*.

Risk responses – schedule

Among those approaches to schedule risk management that have been prominent in recent years, two stand out: (1) the last planner and (2) the critical chain.

Last planner

Site management has sometimes relied too much on sanctions (contractual or employee-based) rather than pro-active management which seeks to understand why tasks are not completed and revise plans accordingly. In particular, borrowing from techniques of Japanese management, real control is seen as exercised by those relatively low in the employment/site hierarchy. Exercising control requires total site 'buy-in' rather than the site being a 'commitment-free zone' (Ballard and Howell 1998). These authors advocate a Last Planner (LP) system (recognising that the lowest level of supervisor is actually the 'last planner') which minimises sub-optimal and non value-adding activities. The system is related to critical path scheduling techniques and is specifically construction-oriented. LP asks the question 'what are *all* of the significant precedent conditions for a project task to take place?' Such precedent conditions being:

- Relevant designs are complete, approved and to hand,
- Relevant plant and materials are available or likely to be delivered in time,
- Relevant labour capacity is or likely to become available in time,
- Tasks are properly defined such that completeness can be determined,
- Tasks can be performed simultaneously with other planned tasks,
- Tasks are appropriate both to the constructability sequence and (where applicable) to client processes,
- The output of the tasks yield viable workloads for the succeeding production period,
- The reasons for failure to satisfactorily complete other tasks have been identified and addressed.

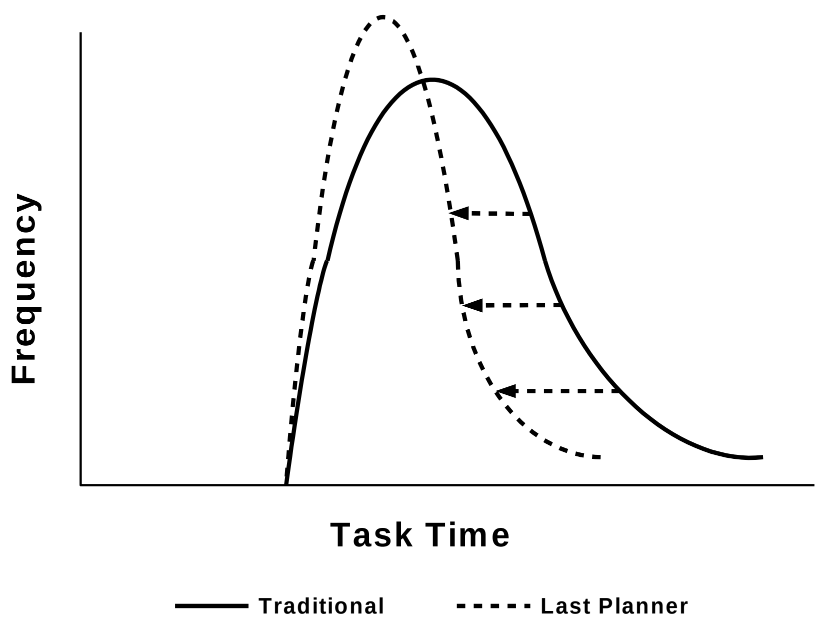
If those conditions are not met, the Last Planner approach suggests that the task should not be started. Failure to adhere to this, they observe, is responsible for all sorts of problems on construction sites. They call this approach 'shielding production'. Where all the precedent conditions have been met the task concerned is deemed to be a 'quality assignment'. It is suggested that a buffer of lower-priority quality assignments is maintained so that resources can be productively employed in the event of other quality assignments being unavailable.

Now the above may appear obvious but the precedent conditions are far more than appear on a Gantt chart – indeed a chart containing all these conditions would be both impossibly large and inappropriate since it is only much nearer the planned task date that it can be reasonably assessed whether all the conditions have or are likely to have been met. The arguments for the rule of performing only quality assignments are as follows:

- it reduces both the mean and variance of task duration (see Figure 7),
- it reduces workflow (and thus resource planning) uncertainty,
- it reduces additional problems caused by out-of-sequence working, gang multitasking and rework (or re-visits to complete work),
- any fundamental problems affecting production will be quickly brought to light.

The method uses the initial plan as a base, modifies the plan through multiple week 'lookahead' plans but only actually definitively assigns tasks through weekly 'commitment' plans. In motivation terms the site supervisor discusses with and obtains a commitment at ganger/foreman level to achieve the planned tasks for the following week and to investigate root causes where tasks fail to be achieved.

Figure 7: Task duration under last planner



Source: Kelsey (2002)

Criticisms of last planner

There is the argument that shielding production is unnecessary because work flow is sufficiently reliable to allow the master schedule to dictate assignment priorities. Ballard and Howell (1998) counter that research in process and commercial construction which suggest that assignments are not always well defined to allow ascertainment of completion. There is a lack of research in other types of construction and civil engineering, which need to be investigated

It is also argued that shielding is impossible. Ballard and Howell (1998) concede that there may be situations where a task simply cannot wait and that too often productivity is sacrificed for the sake of the schedule without in the end yielding the schedule benefits anticipated.

Finally, some construction managers [no reference necessary – this is an argument in the Ballard and Howell paper] claim that they are already shielding but without using the formal methods suggested by Ballard and Howell who are decidedly sceptical. Ballard and Howell argue however that the methods are a good checklist on making absolutely sure that the performance of assignments against plan and evaluation of the reasons for failure to carry out planned assignments are being properly monitored.

The theory of constraints (TOC)

This set of ideas contained in the theory of constraints (Goldratt and Cox 1993) addresses the constraints on production. It suggests the following steps for dealing with constraints:

- Identify the constraint – 'Identify what the limiting resource is.'
- Exploit the constraints – 'Make the best use of it.'
- Subordinate to the constraint – 'Do not run any part of the production process faster than the constrained resource can handle.'
- Elevate the constraint – 'Prioritise the supply of more of this resource.'
- Identify the new constraint – 'Identify the new bottleneck' and return to step ii.

Traditional project schedule management – the problem

'Old-style' critical path management uses the following assumptions:

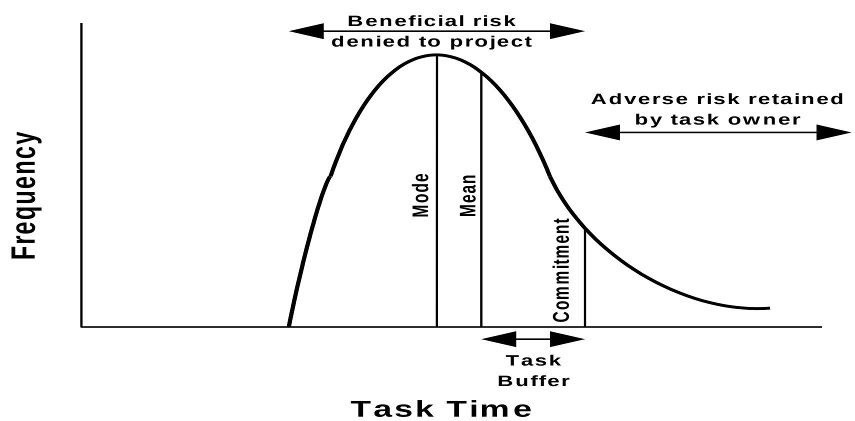
- The time taken to execute a project is comprised of the time taken to execute a number of tasks, which have to be performed in a certain sequence.
- Those tasks whose time cannot be lengthened without lengthening the time taken by the project are critical tasks.
- Therefore the key to controlling the time taken by the project is to control the individual times taken by each of the critical tasks.

The Critical Chain approach argues as follows: The time taken to execute a task is probabilistic NOT deterministic. This is particularly so in tasks such as design or software development (Brooks 1995). In everyday life we are actually pretty bad at forecasting task times. We tend (using faulty case-based reasoning) to use as an heuristic the *modal* time for estimating task execution times. In other words we take the most likely task time as our estimate instead of the *mean* task time, which is generally greater than the mode (because more things tend to go wrong than right in task execution). Students are notorious for handing in assignments late for precisely this reason.

When, however, we have to make a commitment to perform a task, we tend to be very conservative – particularly if a substantial penalty or risk to our reputation is involved. Then we tend to add a substantial buffer to our estimate of task time in order to cover our backside. However if (as is likely) we then complete a task early, we then either have to pretend that we have achieved something exceptional or (which is more generally the case) appear 'busy' for the remaining time in order to hide the fact that we overestimated the task time in the first place. (The task expands to fill the time available – Parkinson's Law.)

In order to plan a project (in the old way) we have to extract timed commitments from all those responsible for performing the component project tasks. Each of those task 'owners' will build in a buffer to protect either their finances (if subcontractors or suppliers) or their jobs (if employees). There is, therefore, in practice a substantial buffer built into each task and thus into the whole project. (The 'true' buffers for each task are the difference between the actual committed task time and the *mean* task time. This may not be the same as the task owner's view of the buffer. If the task owner uses the *mode* as the base point it will generally work to the project's advantage) (see Figure 8.) Typically project managers will also then add an extra safety buffer to cover their backsides. Therefore within each project there are a series of buffers each under separate ownership. We project manage in such a way that project managers are liable for punishment if individual projects are late and they, in turn, may punish individual task owners if an individual task is late. We, therefore, only have ourselves to blame if projects take more time than they should! (While the more recent PERT techniques recognise task duration variability, they do not address the relationship between the task owner and the project owner and the problem of reward-punishment systems, which attach to *individual* tasks.)

Figure 8: Task durations under traditional project schedule management

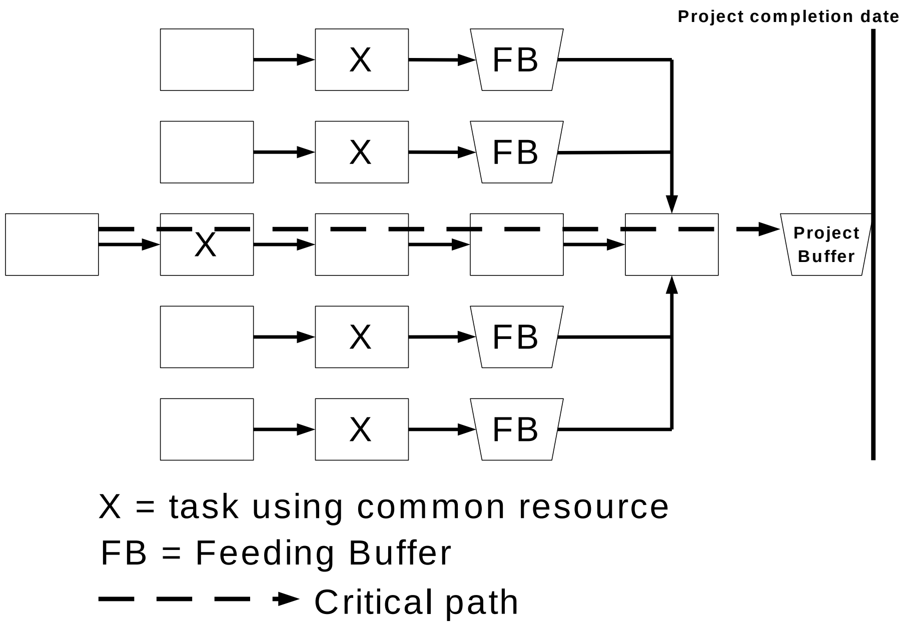


Source: **Kelsey (2002) adapted from Newbold (1998)*Critical chain management (CCM)***

The CCM approach (Goldratt, 1997) argues that in order to shorten *project* time durations, the project manager has to control all the *task* time buffers in the project. However, the task owners will only 'release' their individual task buffers if they in turn are 'released' from the threat of punishment against *individual* task time commitments. (Nonetheless, it is also assumed that they accept the principle of sanction if their *mean* task times are excessive measured over a series of tasks.)

The focus of project schedule management then becomes the overall *project* buffer (rather than task completion dates or milestones). A new critical path can then be created based on mean task times without individual protective task buffers (ie with a 50 per cent confidence interval). Resources are kept in place sufficiently early (using *resource* buffers) to take advantage of early task finishes. Non-critical tasks which feed critical tasks are scheduled to finish sufficiently early (using *feeding* buffers) both to take advantage of earlier than expected progress on the critical path and avoid delays owing to unexpected late finishes on the non-critical task. This may not, however, be good enough since there may be significant resource use clashes. While traditional critical path methods allow for resource levelling, they do not usually allow for resource constraining.

Figure 9: Sequence with no *critical* task buffers under traditional scheduling



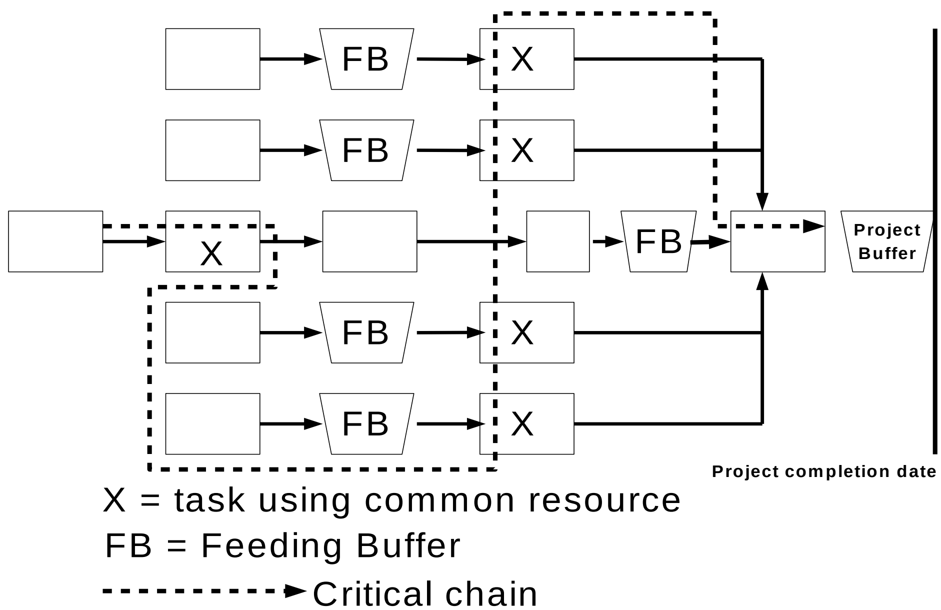
Source: Adapted from Winch, 2002

The critical chain is the *longest resource*-constrained path through the project task precedence logic sequence (Figure 10). It may be *longer* than the traditional critical path but then highlights the problems to which TOC is the suggested answer. Adopting the Theory of Constraints approach, project schedulers then have to get to work to both exploit and subordinate to constrained resources so that the project keeps within the resource constraints, prioritises the use of the critical resource on critical tasks and staggers the non-critical tasks which use the scarce resource (but without producing an unnecessarily large volume of work-in-progress on the one hand or putting the critical tasks at risk on the other). CCM does not promise to find all the answers to scheduling each project – rather it claims to provide the most sensible framework in which such answers may be found. The point of CCM is twofold:-

- it does not merely acknowledge task duration variability (as PERT does) but builds it specifically into the management of the entire project rather than having the focus on individual task durations. It does so a) by using the mean task time as the norm and not the 'protected' task time and b) having an overall flexible time buffer, which can be used for any unexpected problem. This allows the possibility of beneficial task duration risk reducing the overall project duration.

- It takes seriously the problem of resource constraints and builds those into the project management system as well (while accepting that sometimes such constraints are not always a big issue in projects).

Figure 10: Task/buffer sequence under critical chain scheduling



Source: Adapted from Winch, 2002

Criticisms of critical chain

Herroelen and Leus (2000) agree with much that is proposed under CCM but they do have the following reservations. Firstly, they argue that CCM relies on the amendment of deterministic baseline task times in order to create buffers and (ultimately) the critical chain. However, the correct mathematical problem is that of finding a minimum time spanning tree over a timed network with stochastic speed-constraints – with different mean speeds representing resource constraints (or a Resource Constrained Project Scheduling Problem – RCPSP). Research on this is only just emerging (for a later review see Demeulemeester and Herroelen 2002, for another approach to resource-constrained scheduling see Neumann *et al.* 2002). It suggests that heuristics such as latest start time (LST) and latest finish time (LFT) perform better than most but may still be on average more than 5 per cent above the optimum. The commercial software tested did not perform that well – +4.39 per cent to +9.76 per cent over the optimum time – and deteriorated in performance with increased complexity. So it remains questionable where the 'optimum' resource constrained schedule is coming from under CCM.

The secondly claim that CCM method omits NPV calculations when measuring the interaction of resource constraints on project schedule variation (ie is the Net Present

Cost of investing in more production resources justified by the Net Present Value of earlier project completion). In addition the NPV approach is itself open to the criticism of applying Real Option theory (Pindyck and Dixit 1994), which assigns an additional (negative) value to the decision to invest given that a more favourable opportunity might be revealed by a decision to wait for more information. Clearly real options theory is applicable to projects but CCM has nothing to say about it.

They thirdly argue that the CCM method's choice of the right-skewed task duration frequency distribution (see Figures 1 and 4) is arbitrary and ignores the 'linear programming' type alternatives where the same output may be achieved with differing combinations of resources at differing costs. The are resource types other than that which CCM concentrates on (ie human beings) whose constraint patterns differ from that of human beings (eg space or money).

Herroelen and Leus (2000) agree that multitasking is generally to be avoided but point out that this is not a new argument. They point out that problems of task quality and potential long-term stress on employees are not addressed. They also take issue with one CCM author (Newbold 1998) who advises against frequent project re-scheduling. If the project changes substantially, then failure to reschedule may leave the project manager watching over an inaccurate Critical Chain and associated Project Buffer. They further criticise the calculation and use of buffers, which seem somewhat arbitrary and, at times, inconsistent. Although recommending the minimisation of work in progress, CCM seems at the same time to advocate the 'roadrunner mentality' whereby a new activity should be started as soon as precedent tasks have been finished.

Discussion of schedule risk

Although vastly improved mathematical and computing methods are now available, one almost needs a degree in mathematics to understand and implement alternative project optimisation techniques. (There are, in fact, a whole raft of other dynamic programming and latterly AI-based techniques for looking at these problems and the literature on them is vast.) Trying to implement this in real projects requires a further period of up-rating the capabilities of project planners, which is some way off (particularly in the UK if the current proportion of students taking advanced level mathematics at school continues to decline). CCM's heuristics may be a bit crude but they may represent the 'second best' solution of what is currently achievable. For instance, the use of the right-skewed distribution (or a triangular approximation) may be arbitrary but it seems to do the job and is used by most of the larger contractors in the UK. The problem is that the further one passes down the supply chain the less the problem is even recognised let alone modelled. The criticism of neglect of the constraint nature of differing resource types is better founded although this does not affect many of the basic arguments. The use of sophisticated financial techniques for project evaluation applies more to the client or project owner than to the project manager (where the two are separate as they tend to be in construction).

The criticism of CCM regarding quality is more justified. However, Ballard and Howell (1998) explicitly address the tactical end of quality. Neither they nor the CCM authors address strategic quality issues, but those require a different kind of analysis. Project rescheduling is necessary – particularly on large, complex construction projects.

Schedule uncertainty is as important a problem as individual task uncertainty and has to be addressed. (This especially true in refurbishment projects where entire sets of tasks and resources that were never in the original plan may be called for)

There is one key problem that TOC (Theory of Constraints) does not seem to address – elevating a constraint does not necessarily increase productivity and then not always in a linear fashion (Brooks 1995, Horner and Talhouni 1995, Thomas 2000). This is even more the case when dealing with construction subcontractors (O'Brien and Fischer 2000).

The UK construction industry

A fundamental problem with both CCM and Last Planner concerns the current structure of the UK construction industry. Both of these methods require co-operative behaviour and the explicit recognition of task duration variability within a no-blame culture. They require that subcontractors either start work before or delay work until after the contractually stated date. The legal structure is one of adversarial contractual relations. As far as the law is concerned task duration variability does not exist. If a contractor promises to deliver product x within a period of y weeks then that is what has to be done. In construction, legal practice allows for the use of deterministic CPM-based argument to back up claims by and against contractors and subcontractors (Carnell 2000).

Both CCM and to a lesser extent Last Planner were developed in an environment whereby the Project Manager controlled the project resources. Ballard and Howell's work acknowledges the need for a learning period and close co-operation with subcontractors. The problem is that large parts of the UK construction industry are not like this. While at the top end many large contractors have rather more enlightened dealings with their subcontractors than they used to, there are still many more who pursue the adversarial road.

The problem is that sub-contractors have many masters and that unless all (or at least the vast majority) of them subscribe to the CCM and Last Planner methods (or some form of partnering), subcontractors will find it very difficult to juggle those who adopt these methods expecting co-operative behaviour and those who apply sanctions at the first indication of a subcontractors' minor failure.

Last Planner is used in the UK (a good example is Mace at Stansted, c.2005) and is known about and used elsewhere. Critical chain is less widely known but has been used successfully by Balfour Beatty (Winch, 2002). Interestingly although Balfours have a champion for CCM, they have been remarkably slow to introduce it on a company-wide basis. This suggests that adoption of such methods requires a widespread and radical change in attitudes, which while capable of happening in some parts of some major companies, has yet to make a critical breakthrough. The methods require trust and co-operation, which in turn require longer term and reasonably stable business relationships.

One very recent example of the successful central ownership of the schedule contingency by the client has been the execution of the London Heathrow Airport Terminal 5 project. This success on a very public and major project suggests that diffusion of the approach may in future become more widespread. However, it should be noted that this involved a very experienced and powerful client in the British Airports Authority (BAA). Some of these new methods came out of ideas inspired by Japanese management practices. However the relationship of Japanese super-companies with their subcontractors was a paternal relationship determined by emergency wartime planning whereby small firms were assigned to *zaibatsu*, which oversaw their technological development (Aoki, 1996). Most of the subcontractors only had a relationship with a single large company. In the UK industry there is a very different culture and it remains to be seen if and how the culture can change to take advantage of the opportunities offered by co-operative efficiency.

Risk response – integrated procurement

The most obviously visible form of procurement that has come to dominate large public sector procurement is that of total integration (see Figure 11). The failure of contractors to always be able to identify and manage risk has been matched by great success in negotiating away responsibility for risk in settling final accounts or in completing a project at all.

The first problem is one of *principal and agent* whereby the client (principal) cannot properly observe what the contractor (agent) is doing and even if that were possible, the balance of knowledge and expertise is generally skewed in favour of the contractor. The second problem is that, once a contract has been signed, a certain degree of negotiating power switches to the contractor in that the cost of terminating the contract and replacing the contractor with another can be an expensive process which outweighs the cost of giving into the existing contractor's post-contract demands (or not punishing failure to perform to client requirements). The contract has an *asset specificity* which renders one party vulnerable to opportunistic behaviour by the other.

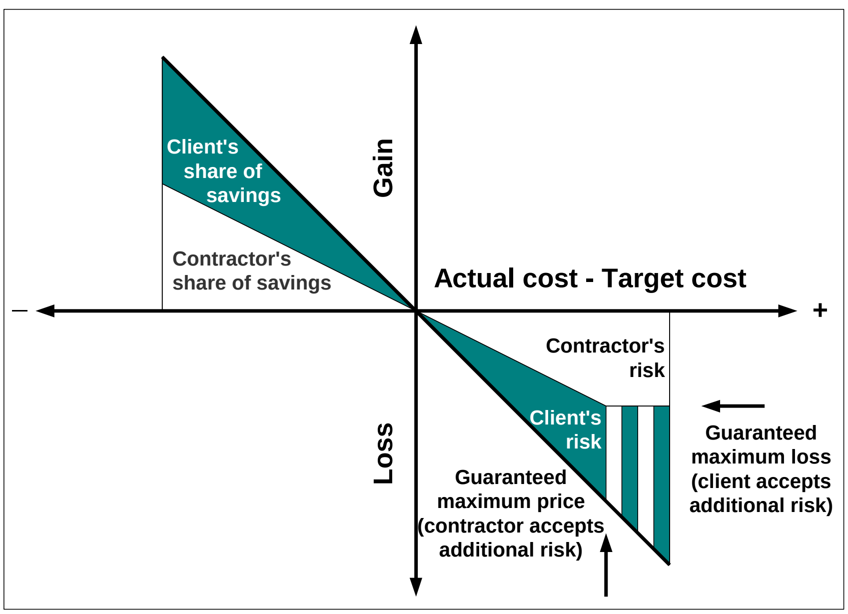
The third problem is that contractors need to be motivated to do their best to prevent adverse risk events from happening and to mitigate their impact if they do. Where that motivation is absent, there is a problem of *moral hazard*, whereby the contractor may act against the interest of the client. The fourth problem is that unproven and unreliable contractors may offer to carry out work at a cheaper price than their rivals. Regardless of whether they intend to carry out the contract, there is a competence problem which means they represent a risk to the client with a greater probability of failure than their rivals. In this situation the client resembles an insurance company which has unknowingly sold car insurance to a driver with a poor accident record. They have bought a bad risk and are in a situation of *adverse selection*. Indeed the terms moral hazard and adverse selection originate in the field of insurance.

These problems give rise to transaction costs and this area was originally explored by Coase (1937) and Williamson (1975). It is applied to construction in Gruneberg and Ive (2002) as well as Winch (2002). The principal and agent problem is to some extent dealt with through additional and expensive third party certification. The client buys in another expert to judge the work carried out by the contractor. In addition there are provisions in the contract for defects liability and a more general legal provision for latent defects. However, schedule/cost risks are more problematic, particularly if the client requires design changes. The asset specificity problem is dealt with through performance bonds, milestone payments and retentions. However, these are still not always able to prevent opportunistic behaviour and they cost money as the cost of these measures to the contractor will be included in the contract price.

The adverse selection problem is dealt with by pre-tender qualification and certification. However, while that may decrease the overall probability of selection of an incompetent contractor, it does not guarantee the quality of the contractor's team on an individual project, or the contractors' subcontractors and suppliers. (In two-stage tendering which seeks to weed out unsuitable contractors at the first stage the team issue is addressed up to a point.) The moral hazard problem can be addressed through incentivisation such as agreement of a target cost with sharing of profit or loss. The risk of the contractor may be capped with a Guaranteed Maximum Loss and that of the client with a Guaranteed Maximum Price. Thus both parties have incentives to minimise the occurrence of adverse events and co-operate in resolving them if they happen. Unfortunately there can be much haggling over the target cost and pressure for its adjustment if any event (such as variations) arises which the contractor feels was not in the baseline assumptions.

Given the fragmentation of the construction industry and the maxim that risks should be borne by those most able to manage them, risk ends up being widely distributed between a large group of separate firms. This group can be described as a project coalition and the interfaces between them are traditionally managed by contracts. These might be described as 'complex contracts'. These which are hybrids of pure market transactions and an employment hierarchies whereby the contracts give rights to the client (who is normally referred to as 'the employer') not only to specify what is procured but the right to intervene in certain ways should conditions be varied or other events occur.

Figure 11: Joint incentivisation of client and contractor



Source: Adapted from Winch (2002**)**

To some extent these contracts help deal with some of the problems described. But, it seems, they are not in themselves enough. In particular, the one-off or inexperienced client is at the greatest risk. Consider some basic construction project risks.

- The design of the building fails to understand the client's requirements
- The design of the building fails to achieve the client's purpose
- There are late design changes which increase the costs of both design and construction
- There is a building failure which cannot clearly be ascribed to design failure or construction failure
- There is a construction failure resulting in schedule and cost delay
- There is a construction failure in meeting the technical specification
- The facility is delivered late and is being financed by the client
- The facility is not fit for its intended purpose
- The operation/maintenance of the facility is unduly expensive because of either design or construction failure

The picture should be clear. The separation of responsibility for ownership, finance, operation/maintenance, design/construction creates risks which pose moral hazard in that different parties are not fully affected by the impact of their own failures. Accordingly, a new type of procurement has emerged variously referred to as the Private Finance Initiative (PFI) or Public-Private Partnerships (PPP) Design-Build-Finance-Operate (DBFO) in the UK and Build Own Operate (BOO) and/or Build Own Operate and Transfer (BOOT) elsewhere.

Essentially it consists either in the case of a revenue-earning facility handing (or selling) the entire set of risks and rewards over to a private sector entity (concession contracting) or paying that entity for the services of an adequate and available facility for an agreed period with provision for eventual return (in reasonable condition) to the client. In the latter case it may consist of operation of the entire facility (such as prisons) or it may consist purely in the provision and management of the facility alone (such as in hospitals).

Fundamentally all the risks are bundled up and sold off to the contracting body. If the building is late, or costs too much to build or maintain, is not fit for purpose or is otherwise defective, it is the contracting body that suffers and not the client. This sounds like a panacea but it comes at a price. Firstly, the design is strictly functional since there is no incentive to invest it with any aesthetic value other than that required to obtain planning consent. Secondly, technology risk is not encouraged by bankers who finance the project. One of the supposed benefits of the system was that the client gave the contractor an output specification of what the facility was supposed to achieve and it was up to the contractor to decide how to deliver it. Therefore, it was argued, innovation would be encouraged. However, not only is innovation problematic (as in the earlier discussion on technology risk) but it creates an asset which has potential for large gains (from the contractor's viewpoint) if things go well and large losses if they do not. Unfortunately, with debt finance, the banks are only likely to suffer in adverse conditions and only the contractor's equity holders will benefit in good conditions. Therefore banks are not motivated to encourage such risk.

On the issue of finance, it needs to be stressed that the finance is secured on the contract and not the facility (except possiby in a full concession contract). This means that the banks only security is the project revenue streams although they do normally have rights to intervene if the contractor fails in their duties to the client. Necessarily this increases the risk (and cost) of a loan compared with normal mortgage finance.

In evaluation, there is (in UK public sector procurement) comparison with a hypothetical cost of traditional procurement – the public sector comparator. Given the estimating failures referred to earlier, it is not clear how worthwhile such an exercise can be. One could argue that both the bidder and the public sector estimators are likely to make the same mistakes but it is not particularly good evidence *per se* that the public sector comparator study shows that the PPP route is best value.

Finally in certain types of buildings such as hospitals, flexibility will be essential because of rapidly changing technology and/or new medical risks. The PPP type of arrangement is fundamentally inflexible and costs a lot to change which renders the client vulnerable should radical change be required. One other point is that the bidding cost for such arrangements is very high and therefore restricts the supply of bidders to very large companies and/or joint ventures.

So the verdict on these integrated routes is mixed and the procurement route has only had relatively recent adoption which makes it difficult to evaluate its long-term effectiveness. Clearly there are some good points in removing certain types of risk from the client, but the risk removal is expensive and may be problematic if operational requirements change.

It may be a surprise to find that trust is a possible risk response. However it became clear as far back as Latham (1994) that the adversarial culture between client and contractor as well as contractor and sub-contractor was damaging to the industry costly and inefficient. Various larger contractors and clients have tried various forms of arrangement whereby trust is made an explicit or implicit part of the process. Various forms of co-operation, alliancing and partnering have emerged as well as client procurement arrangements involving longer-term procurement covering a number of contracts which allows a relationship to be developed and managed with the contractor.

Conclusions

In looking at the relationship between risk, uncertainty, complexity and constructed assets, we may conclude that small changes in initial conditions give rise to large fluctuations elsewhere, constructed assets have a complex nature:

- as joint commodities with development land,
- as long-lived products where the secondhand market dominates the value of new output,
- as products whose demand has an amplified but delayed reaction to changes in the overall level of economic activity
- as products of development projects with complex financing arrangements such that different providers of finance may experience a greater range of risk than that applying to the whole project

- as products whose total output and financing can themselves be the cause of economic instability

In that constructed products are themselves technologically varied and complex, the bringing of them into existence entails organisational and technological risks requiring complex organisations and systems to manage such risks. The long-term nature of constructed assets makes them economically and technologically vulnerable to long-range uncertainty as to the demand for their use, their relative competitiveness and their suitability for adaptation to other purposes. In that the totality of constructed products is a highly significant source of carbon emissions through the operational responses of occupants to the environment, constructed products are collectively a potential cause of and individually vulnerable to significant environmental change. Consideration, therefore, needs to be given not only to reducing their carbon footprint under existing environmental conditions, but designing in adaptability to a range of future such conditions. Large international construction projects are governed by supra-governmental regimes of international trade in services on the one hand and private international contract law on the other both of which (for different reasons) may militate against external (particularly environmental) costs having to be borne (and therefore taken into account) either by project sponsors or by their supply chains. Such projects do, therefore, represent potentially exceptional environmental risks.

Individual members of construction project coalitions have generically recognisable processes for the identification, evaluation, treatment and monitoring of project risk. However the necessarily fragmented nature of the project coalition offers possibilities for individually asymmetric rewards in risk allocation or pricing through opportunistic or highly risk-averse behaviour which may be individually rational at the level of the coalition member but which may be deleterious to the project as a whole. Various means to overcome the gaps between individual and total project optimisation include:

- Better systems of project governance, accountability and evaluation (including the countering of ‘optimism bias’)
- Changes of practice to more collaborative project and site planning
- Reclaiming of the total project risk ‘buffer’ by the project manager/sponsor through changes in incentivisation regimes
- New forms of procurement involving the re-integration and transfer of asset finance, design, operation and management risks for the whole or a significant part of the building life-cycle
- The cultivation of trust and long-term relationships among coalition partners through multi-party or multi-project procurement arrangements

However, many of the theoretical benefits from these new arrangements have yet to be fully captured and some methods bring new problems and risks with them.

References

Adams, J. (2000) *Risk*, UCL Press, London.

Aoki, M. (1996) 'Unintended fit: organisational evolution and government design of institutions,' in Japan, in Aoki M, Kim H -K and Okuno-Fujiwara M (Eds), *The role of government in East Asian economic development: comparative institutional analysis,* Clarendon Press, Oxford.

Ballard, G. and Howell. G. (1998) 'Shielding production: essential step in production control,' *Journal of Construction Engineering and Management*, **124** No 1, 11–17.

Bon, R. and Crosthwaite, D. (2000) *The future of international construction* Thomas Telford, London

Bonke, S. (2000) *Technology management on large construction projects*, Le Groupe Bagnolet, London.

Brack, D. (1999) 'Trade and the environment,' in Hocking B. and McGuire S. (eds), *Trade politics*, Routledge, London.

Brand, S. (1994) *How buildings learn: what happens to them after they're built*, Orion, London.

Brooks, F.R. Jr (1995) *The mythical man-month* (2nd edition, original 1975) Boston MA, Addison-Wesley Longman.

Burns, T. and Stalker, G.M. (1961) *The management of innovation*, OUP, Oxford.

Carnell, N.J. (2000) *Causation and delay in construction disputes*, Blackwell Science, Oxford.

Chapman, C. and Ward, S. (2003) *Project risk management: processes, techniques and insights* (2nd edition), John Wiley, Chichester.

Churchman, C.W. (1967) Wicked problems *Management Science*, **4 B** 141–142.

Cooke-Davies, T. (2002) 'Critical success factors in projects,' *International Journal of Project Management* **20/3** 185–190.

Davies, A. (2003) 'Integrated solutions: the changing business of systems integration,' in Prencipe, A., Davies, A. and Hobday, M. (eds), *The business of systems integration,* OUP, Oxford.

Demeulemeester, E.L. and Herroelen, W.S. (2002) *Project scheduling: a research handbook* Dordrecht, Kluwer.

Derrida, J. (1981) *Dissemination*, Athlone Press, London.

Dixit, A.K. and Pindyck, R.S. (1994) *Investment under uncertainty* Princeton NJ, University Press, Princeton.

Edkins, A. and Millán, G. (2003) *Construction risk identification: a review of the literature on cognitive understanding of risk perception* Bartlett Research Paper No. 16, London: Bartlett School of Graduate Studies, UCL.

Edkins, A., Millán, G., Maytorena, E. (2003) *Construction risk identification: a methodological proposal.* Bartlett Research Paper No. 17, London: Bartlett School of Graduate Studies, UCL.

Field, C., Gamble, M. and Karakashian, M. (2000) 'Design and construction of London Bridge Station on the Jubilee Line Extension,' *Civil Engineering,* **138**, 26–39.

Flyvbjerg, B., Bruzelius, N. and Rothengatter, W. (2003) *Megaprojects and risk: an anatomy of ambition*, CUP, Cambridge.

Fonseca, J. (2002) *Complexity and innovation in organisations*, Routledge, London.

Goldratt, E.M. (1997) *Critical chain,* North River Press, Great Barrington MA.

H.M. Treasury (2003) *Supplementary Green Book guidance on the treatment of optimism Bias*http://www.hm-treasury.gov.uk/media/D/B/GreenBook_optimism_bias.pdf Accessed 11/12/07.

Herroelen, W. and Leus, R. (2000) 'On the merits and pitfalls of critical chain scheduling,' *Proceedings of PMI Research Conference 2000,* PE Project Management Institute, Newtown Square.

Hobday, M. (2000) 'The project-based organisation: an ideal form for managing complex products and systems?,' *Research Policy,* **29,** 871–893.

Horner, R.W.M. and Talhouni, B.T. (1995) *Effects of accelerated working, delays and disruption on labour productivity*, CIOB, Ascot.

Ive, G.J. and Gruneberg, S.L. (2002) *The economics of the modern construction sector,* Macmillan, Basingstoke.

Jago, C. (2004) *How CTRL Section 1 was delivered on time and on budget,* Presentation to Strategic and Contract Risk Conference 16/04/04.

Kallberg, J.G., Liu, C.H. and Pasquariello, P. (2002) Regime shifts in Asian equity and real estate markets *Real Estate Economics* **20/2** 263-291

Keegan, A. and Turner, J.R. (2002) 'The management of innovation in project-based firms,' *Long Range Planning,* **35,** 367–388.

Kelsey, J.M. (2002) *Introduction to Critical Chain project schedule management and last planner* UCL, unpublished teaching paper

Kelsey, J.M. (2007) *Lecture Notes on Project Management* UCL, Unpublished

Lawrence, D. (1974) *Modern Methods of Valuation* The Estates Gazette, London

Leung, C. (2007) *Dynamic Environmental Control By Passive Environment Emulation,* Eng D research programme, UCL, London.

http://www.homepages.ucl.ac.uk/~ucfteic/projects.htm accessed 13/12/07.

Minogue, M. (2004) 'Public management and regulatory governance: problems of policy transfer to developing countries,' in Cook, P., Kirkpatrick, C., Minogue, M. and Parker, D. (eds), *Leading issues in competition, regulation and development,* Edward Elgar, Cheltenham.

Mott MacDonald (2002) *Review of large public procurement in the UK*, H.M. Treasury, London.

Neumann, K., Schwindt, C. and Zimmermann, J. (2002) *Project scheduling with time windows and scarce resources: temporal and resource-constrained project scheduling with regular and nonregular objective functions* Berlin, Springer-Verlag.

Newbold, R.C. (1998) *Project management in the fast lane*, St Lucie Pres, Boca Raton FL.

Nutt, B. (1993) 'The strategic brief,' *Facilities,* **11,** 28–32.

O'Brien, W.J. and Fischer, M.A. (2000) 'Importance of capacity constraints to construction cost and schedule,' *Journal of Construction Engineering and Management*, **126** No 5, 366-373.

ODPM (2006) *The Building Regulations 2006 Part L*, The Stationery Office, London.

O'Connor, J.T. and Yang, K.R. (2003) 'Project performance and use of technologies at project and phase level,' *Journal of Construction Engineering and Management*, **130** No 3, 322–329.

Palast, G., Oppenheim, J. and MacGregor, T. (2003) *Democracy and regulation: how the public can govern essential services*, Pluto Press, London.

Perez, O. (2002) 'Using private-public linkages to regulate environmental conflicts: the case of international construction contracts,' *Journal of Law and Society*, **29** No 1**,** 77–110, reprinted in Picciotto, S. and Campbell, D. (Eds) (2002), *New directions in regulatory theory*, Blackwell, Oxford.

POGO (2004) *The politics of contracting* Washington DC, Project on government oversight http://www.pogo.org/p/contracts/c/PoliticsOfContracting-2004.pdfaccessed 29/01/08.

Spencer, N.C. and Winch, G.M. (2002) *How buildings add value for clients*, Thomas Telford, London.

Taylor, M.C. (2001) *The moment of complexity: emerging network culture*, University of Chicago Press, Chicago.

Thomas, H.R. (2000) 'Schedule acceleration, work flow and labor productivity,' *Journal of Construction Engineering and Management*, **126** No 4.

Touche Group (1992) *Report on the Architectural Profession*, Touche Ross, London.

Tshakilov, R. (2006) *Energy Conservation in UK Housing: Investigation into the 2006 Edition of Part L, Building Regulations*, The Bartlett School UCL, London, unpublished BSc dissertation.

Winch, G.M. (2002) *Managing the construction project: an information processing approach*, Blackwell, Oxford.

Winch, G.M., Maytorena, E. and Keily, T. (2005) *Making sense of the uncertain: does experience matter in project risk identification?*, Paper presented at EURAM (European Academy of Management) Conference, Munich, May 2005.

Woodward, J. (1965/1980) *Industrial organisation: theory and practice*, OUP, Oxford.

Young, A. (2003) *Lecture notes on case studies of environmentally efficient buildings*, The Bartlett School UCL, unpublished.