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ENGINEERING MANAGEMENT THEORIES AND METHODOLOGIES

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Whole-life Thinking and Engineering the Future

Abstract Whole-life thinking for engineers working on the built environment has become more important in a fast changing world. Whole-life thinking is not new, every project attempts to balance the initial capital cost with the operating and maintenance cost of an asset. Engineers are increasingly concerned with complex systems, in which the parts interact with each other and with the outside world in many ways — the relationships between the parts determine how the system behaves. Systems thinking provides one approach to developing a more robust whole-life approach. Systems thinking is a process of understanding how things influence one another within a wider perspective. Complexity, chaos, and risk are endemic in all major projects. New approaches are needed to produce more reliable whole-life predictions. Best value, rather than lowest cost, can be achieved by using whole-life appraisal as a part of the design and delivery strategy.

Keywords: whole-life thinking, systems thinking, complexity, chaos, risk management through life

1 Introduction

Many built environment facilities, such as bridges, dams, airports, roads and hospitals can have a design life of many hundreds of years, although the requirements placed on them are changing rapidly in time horizons which are short. During its lifetime, a facility must be operated, maintained and made fit for purpose to cope with new legislation on such issues as safety and health, sustainability, climate change, security, and environmental impact. Facilities, such as hospitals, can consume up to five or six times their initial capital cost in operating and maintenance costs through their life.

Projects have become larger with mega projects now commonly over US$1 billion capital cost; they are more complex as new technologies change the nature of the product. The engineering challenge is that each project is unique, it is not possible to build a prototype and test it before use, although computer systems and visualisation are improving the task. The widening of the Panama Canal has a capital cost of US$5.25 billion, it is a huge infrastructure project that will enable mega tankers to use the existing 100-year-old waterway between the Atlantic and the Pacific Oceans. It has been designed to take the Canal into the next century and involves new technologies and new standards of materials and design. Over its life it will need to be maintained, and upgraded; it will cost many times its initial capital construction in the running and operational cost. Similarly, buildings can consume up to five times their initial capital cost in heating, cooling, cleaning, maintaining, securing, and retrofitting. Decision makers are therefore making investment decisions not just about the initial capital cost, but on a whole-life basis.

Whole-life appraisal is the systematic consideration of all relevant costs, revenues and performance associated with the acquisition and ownership of an asset over its physical/economic/functional/service/design life (Flanagan & Jewell, 2005). The balance between capital cost, whole-life cost, and whole-life performance is complex because of the factors influencing facilities in use. There has been a gradual shift away from a focus on lowest initial capital cost to the consideration of whole-life value (Boussabaine & Kirkham, 2008), especially with the advent of long-term project investment such as build-operate-transfer (BOT), and public-private partnership (PPP) projects where a private sector entity designs, finances, builds and operates a facility over a time horizon. Increases in energy prices and running costs have caused both public and private clients to demand better value for money over the long-term. Whilst there is less suspicion about whole-life estimates being inaccurate or based only on guesswork, there is still concern over the need for better cost and performance data, how this will be collected, and how much it will cost (Kirkham et al., 2004). Technology is an enabler as it can monitor facilities in real-time and feedback performance information to a central repository system.

New issues are constantly appearing that must be incor-

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porated into the whole-life appraisal:

(1) Allowances for advances in technology where a facility needs to be upgraded through its life. This is particularly true of health care buildings, airports, rail, and commercial office buildings.

(2) Environmental and sustainability pressures to cope with the "green" agenda and the need to recycle materials, minimize waste, minimize pollution, and reduce carbon emissions. Ecologically sustainable design requires that service life considerations be integrated in the design process to reduce the environmental impact by encouraging the conservation of finite resources and the selection of appropriate materials and construction methods.

(3) Ensuring the use of renewable and green energy whenever possible.

(4) Future proofing projects for the impact of climate change.

(5) Incorporating security and cyber-security measures over the whole-life.

(6) Understanding the concept of a suitable period of analysis for whole-life considerations. Design life, service life, and functional life are not the same as the physical life of the asset.

These are set in a context of increasing bureaucracy and governance procedures where governments are introducing legislation and targets to ensure compliance. Globalization has led to global competition with greater connectivity which exploits technology and, in turn, creating "more complex products, systems and capabilities that operate across national boundaries" (The Royal Academy of Engineering, 2007).

Whole-life appraisal must consider the cost, performance, different user requirements, running costs for energy, annual, cyclical, and periodic maintenance, insurances, cleaning, security, facility management, as well as considering how the project can be green and comply with all the changing standards. An important objective, "will be to ensure that the most advantageous combination of capital, maintenance and operational costs is achieved over the life of the facility." (ISO, 2000). Hence, it is not just design and production, but engineering for the future and ensuring the project is "future proofed," and can be retrofitted and upgraded when new legislation is introduced.

2 The changing project delivery environment

Increasing urbanisation is leading to larger, more complex projects becoming more prevalent, particularly infrastructure. This has led to innovative forms of procurement to achieve the necessary public/private funding. PPP projects involve one party taking responsibility for the design, engineering, financing, and operation and maintenance of a built facility over a time horizon. Many of the multi-national aid agencies are placing a greater emphasis on PPP projects involving whole life appraisal. For example, under the *Asia Development Bank's Long-Term Strategic Framework for 2008—2020* (ADB, 2008), their infrastructure operations emphasize PPPs and private sector engagement. Support for private sector development and related operations are to account for 50% of ADB's operations by 2020. Similarly, under China's Twelfth Five-year Plan, greater emphasis has been placed on private investment for public infrastructure. The move from public to private financing for infrastructure is happening all over the world. The World Bank (2011) states that the sustainable financing of municipal infrastructure investment will require greater involvement of capital markets and the private sector. All PPP projects have the need for the engineer to design and project that takes whole-life perspective into consideration from concept to demolition.

The OECD (2007) estimated that around 3.5% of global GDP (approx. US$2 trillion) needs to be invested in electricity distribution, road and rail transportation, telecommunications, and water infrastructure annually. Adding in sectors such as ports and airports pushes the figure even higher: including another US$11trn makes the annual requirement US$3trn plus per annum, some of which will have to come from the private sector (PWC, 2013). Larger long-term projects mean greater complexity and involve greater uncertainty, and more risk.

"Engineers are increasingly concerned with complex systems, in which the parts interact with each other and with the outside world in many ways—the relationships between the parts determine how the system behaves." The Royal Academy of Engineering, 2007

Complexity is reflected in designing for a sustainable future, as shown in *Figure 1*. Engineers must consider environmental, economic and social issues in the design, production and operation of facilities.

The emphasis on sustainability means that the need to understand whole-life issues has never been more important. The principal concern is to ensure the balance between capital costs and whole-life costs and performance over a time horizon. Forecasts must be made of the future operating and maintenance costs over the time horizon, taking into account inflation; not an easy task looking 25 years into the future. The mathematics are simple, the forecasting is much harder because of uncertainty in such areas as the price of fossil fuels, the impact of new government legislation, changing client expectations, and climate change issues.

Forecasting the future involves many unknowns, many assumptions, and managing risk. It is humans that forecast the future, and they are subject to bias in many forms. Engineers are frequently blinded by illusions of certainty and over optimism by over-estimating the abilities and under-estimating what can go wrong. Optimism bias involves organisations and individuals being over optimistic, as often happens in construction work. Optimistic bias is commonly defined as the mistaken belief that one's chances of experiencing a negative event are lower (or a positive event higher) than that of one's peers—it is self-deception (Flyvbjerg, 2008). Other terms representing the same construct include "unrealistic

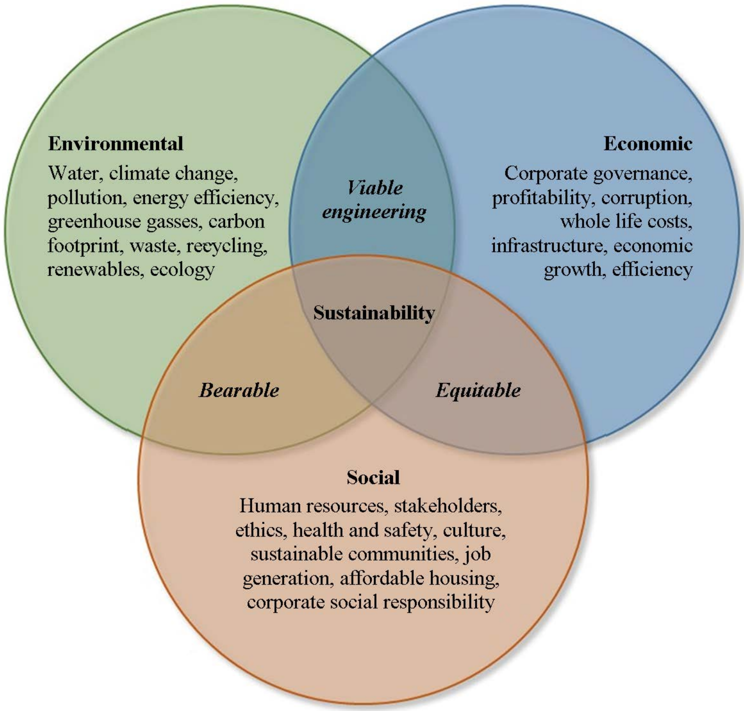

Figure 1. Sustainable engineering.

optimism" , "illusion of invulnerability", "illusion of unique invulnerability", and"personal fable".

A system is needed to structure all the key issues in balancing costs, performance, environmental, economic, and social issues using systems thinking theory, to manage complexity and chaos, and risk management to deal with uncertainty and perceptions about the future.

3 Systems thinking

The world of engineering is complex, inter-connected and fast-changing. Systems thinking is particularly useful in looking at complex systems and so highly relevant to large construction projects. Systems thinking research began in the 1950s when it was used to solve management problems. Developed from systems analysis and systems engineering it was mainly used in the defence and aerospace sectors (Yeo, 1993). These "hard" systems are still well used with well-established tried and tested quantitative methods used by construction engineers and project managers such as project planning, scheduling and control (Yeo, 1993). In the 1980s there was a shift to "soft" systems thinking which involves people and consists of actions, reactions and intentions (Blockley and Godfrey, 2000). This was a reaction to need for a solution to projects tending to run over time and over budget. Soft systems have the ability to cope with uncertainty and other problems such as management competency, human perceptions/judgement, bias, and differences in culture and value systems (Yeo, 1993).

Systems thinking is a process of understanding how things influence one another within a wider perspective. It is an approach to resolve any problems by understanding them as a part of the system, rather than responding to particular parts, results or activities and, potentially, contributing to further developments (Sherwood, 2002). Systems thinking allows the engineer to take a holistic view of the project from concept through to demolition. Projects have become so large that the cost of demolition can be very significant, for example, the demolition of the Burj Khalifa in Dubai at 830 metres high will pose many technological challenges as no one has ever attempted such a task so high. Hence, engineers must think about de-construction as well as construction.

Complexity

Complexity theory is not one theory but a number of different ideas and concepts emanating from different disciplines such as the sciences, mathematics and computer science (Mitleton-Kelly, 2003). The theory emanates from earlier work on the chaos theory which helped to explain, in construction, the lack of predictability in cost estimation, long range planning, etc. Langton (1992) suggested that projects are a mix of ordered and chaotic behaviour which he called on the "edge of chaos". "The coexistence of order and chaos enables companies to deal with heterogeneous demands in the same period of time, such as flexibility and efficiency" (Geraldi, 2008).

Complexity is not easily defined with little agreement among scientists. There are two main approaches to complexity (Schlindwein & Ison, 2005): descriptive complexity and perceived complexity (Vidal & Marle, 2008). Descriptive complexity is considered as a property of a system. Baccarini (1996) researched descriptive complexity, looking in particular at project complexity which he suggested could be divided into technological complexity and organisational complexity. Perceived complexity is more subjective as it relates to the complexity as seen through the eyes of an observer. This paper is concerned with project complexity.

Lebcir and Choudrie (2011) identified a number of project complexity factors in their research into complex construction projects:

• Infrastructure size — size of the project and number of elements.

• Infrastructure inter-connectivity — the level of linkages within the project.

• Infrastructure newness — the level/number of elements/processes new/unique to the project.

• Project uncertainty — the gap between the competencies needed and the competencies available.

They devised a project complexity framework driven by the above factors. The framework combines decisions made at strategic and operational levels as well as project policies such as human resource management.

Systems thinking can help to make sense of a complex system and to identify the risks at the outset before the project turns “chaotic”. This is why where risk management is so important. It is not about forecasting the future, but about identifying different scenarios in which uncertainties/risks can be identified and managed.

4 Managing risk in whole life appraisal

There are numerous definitions and many standards for risk management. “Risk is measurable uncertainty; uncertainty is unmeasurable risk” (Hillson, 2003). In its simplest form a “risk” can be described as an uncertain event, or set of circumstances, that should it occur will have an effect on an outcome (the effect can either be positive or negative) to a greater or lesser degree. Uncertainty is about ambiguity and variability (Chapman, 2006). Variability occurs when an event is defined which can take on a range of outcomes, ambiguity is prevalent in opinion-based “scores” for the probability/likelihood of an event. Risk management is a process that involves logical and systematic methods of identifying, analysing, mitigating, monitoring and communicating risks in a way that will allow the project to minimise the potential for losses (through delays to the programme or increases in cost) and to maximise opportunities for improving performance.

Risk is inherent in everything that we do. Risk management is helping to run projects in the “real” world. Too often project plans and budgets are formulated on the basis of an ideal situation where everything goes according to plan. This may be a result of naivety, optimism or just plain wishful thinking, without taking adequate account of the risks involved. Risk management is simply helping the project team to make better decisions and to be better informed on how to deal with the risk, whether to retain it, avoid it, reduce it or transfer it. Risk management should be an integral part of the whole-life management process and should inform project decisions and forecasts by including (Maughan, 2006):

• Acceptable levels of risk should be agreed at all major decision points.

• Risk information, in conjunction with project data, should be used to generate the 10%, 50% and 90% confidence figures for time, cost, performance, energy usage, maintenance requirements, etc.

• Risk ownership should be assigned to the party best able to manage the risk.

The widely-accepted steps in risk management, to identify, analyse, plan, track and control, are focused on individual risks, not a “risk collection”. Furthermore, the identification and analysis phase depends heavily on the risk attitude of individuals or the firm. A firm with a risk-loving attitude will not include risks that have a low likelihood of occurring even if they are high impact and, conversely will not include low-impact risks even if they have a high likelihood (Han et al., 2010). Introducing a risk management system to whole life appraisal is new, historically, risk management systems have been restricted to managing the cost and time at the design and production stages of projects.

By managing risks, a business can reassure shareholders, customers and employees that it is being effectively managed and confirms its compliance with corporate governance requirements. A governance risk management and compliance strategy at the corporate level, that keeps pace with new legislation and the expectations of stakeholders is important in remaining competitive (PWC, 2013). By managing project risks, all the stakeholders are made aware of the risks being faced. Risk management and assessment is necessary across many business processes, not just areas such as health and safety. There is no shortages of standards, ISO 31000 is a standard for the process of risk management providing principles, a framework and a process for managing risk. It was not devised for construction and is equally applicable across every industry.

Risk in construction design, procurement and delivery

Construction projects have an abundance of risk, contractors cope with it and owners pay for it, and when things go badly wrong the insurers and bond issuers also pay. Traditionally:

• The client/owner is responsible for the investment/finance risk and operating and maintenance risk.

• The design team is responsible for the design risk and sometimes the performance risk, they identify the risk and endeavour to control it, recognising that some risks are uncontrollable, such as the weather.

• The contractor and specialist contractors are responsible for all aspects of the construction risk, including financial, health and safety, performance, and time.

• The suppliers and manufacturers are responsible for the performance risk of their components, and materials through life.

• The insurance industry carries the risk of failure by any of the parties through negligence, accident or force majeure throughout the whole life of the project.

• Government agencies are responsible for ensuring their codes and regulations set the minimum acceptable standards and the risk of failure of the standards.

• Maintenance teams and facilities managers take the risk of ensuring the project performs effectively in use.

5 Whole-life appraisal — the impact of time on complexity and risk

Systems thinking and risk management for large construction projects can provide a framework for understanding the complexity of construction and engineering today. Placing this framework in the context of whole-life appraisal, highlights the important concept of time. Over the life of a facility time will impact risk perceptions and it will add to the complexities within the system.

The construction sector works on long time horizons. Inception through to occupation can be up to ten years on major projects. *Figure 2* shows the different time horizons within the life cycle of a building. The facility then has to be in use for two years before any meaningful data can be fed back to the design team. This means that the feedback process also has a long time horizon. The defence sector has addressed this issue by establishing a process called Integrated Logistic Support (ILS).

The use of ILS in the defence sector has demonstrated that there is potential for significant savings through the use of a structured approach to whole-life support. Preferably, this should be addressed at the early design stages, where impact of change is most significant. In the context of engineering, support means the maintenance/repair/refurbishment and the way in which a facility or component is kept at optimum performance, including breakdown, failure and service life.

Data and feedback

Making forecasts about the future requires data and information about the present. Collecting and using data and information about a facility in use has been beset with difficulties because of the lack of structured feedback systems. But that is changing as sensors are more responsive and dynamic to providing data and information about performance and cost, thus allowing whole-life thinking to be embodied in the process. Technology is an enabler to cope with huge amounts of information over the life cycle of a facility. Data collection is costly, complex and changes over time. Technology is changing the way of working, ten years ago data collection would have involved mounds of paperwork; automated data collection with sensors has speeded up the task and made it more cost effective.

Whole-life appraisal can fail because of the lack of data and information about the performance and cost of owning and operating facilities in use. This is a major risk in large projects. For example, equipment is becoming more complex and high-tech. The expected patterns of equipment failure used twenty years ago are no longer always applicable. Studies of the aircraft industry showed that 93% of the equipment tested does not conform to the expected pattern of failure with the older the equipment, the more likely it is to fail (Moubray, 1997)(see *Figure 3*).

Hence, forecasts on failure should use risk analysis to consider probabilities of failure patterns.

6 Conclusions

Engineers have always designed and produced functional projects that satisfy the functional, economic, social, and technological requirements. New ways of procuring projects and pressure from clients for best value have introduced new pressures for the engineer to incorporate and justify whole-life issues. Whole-life appraisal involves thinking about the future. Any forecast of the future involves uncertainty, risk, and complexity. The fundamental assumption is that the future can be extrapolated from the past; yet in the world of ac-

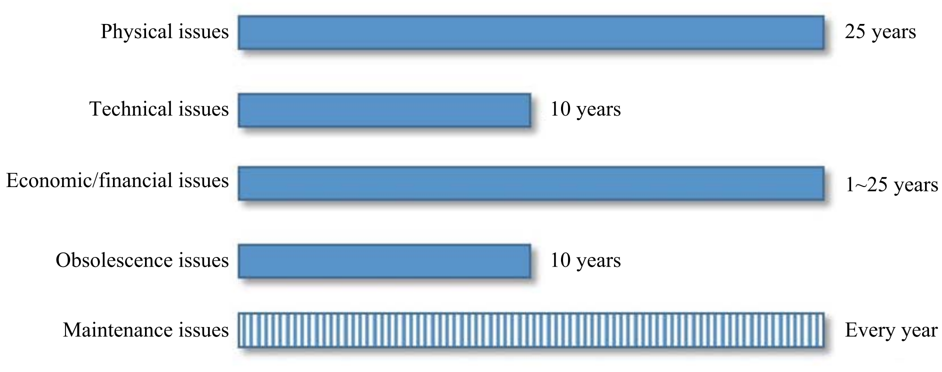

Figure 2. Time horizons in a facility's life cycle.

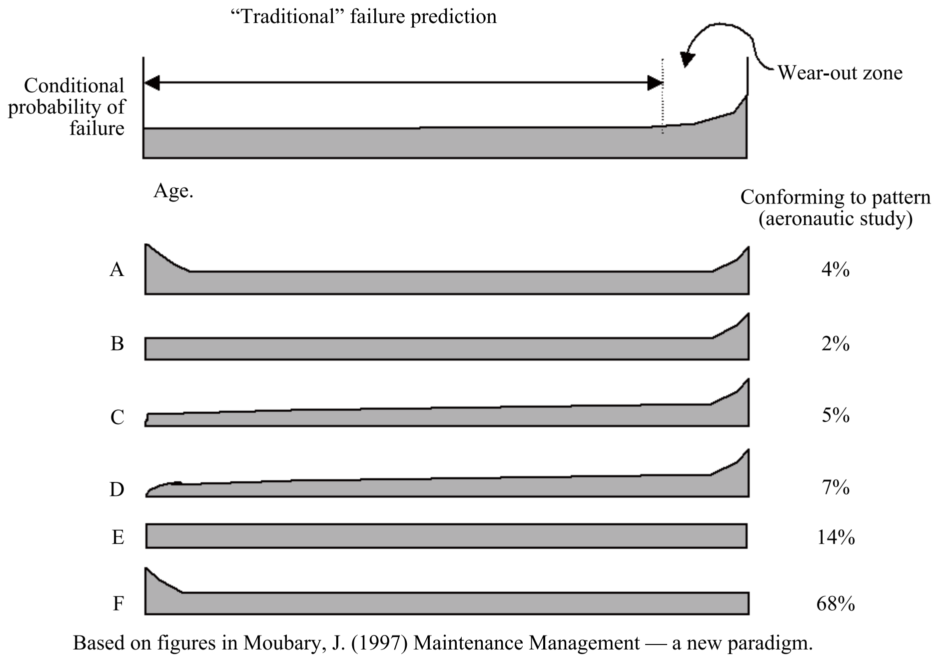

Figure 3. The probability of component failure.

celerating change, the past is no longer a good proxy for the future. Uncertainty abounds and engineering design involve people who use facilities, and they often do not behave as expected. There is no ideal or perfect solution,but there are many possible solutions and the skill of the engineer lies in producing the best or optimal solution. Value for money is the most important issue for every client and business. The cheapest initial cost may not remain the cheapest in the long run. Best value, rather than lowest cost can be achieved by using whole-life appraisal as a part of the design and delivery strategy.

Whole-life appraisal is challenging because of the vast area that needs to be taken into account, but nobody should ignore the future and how the built environment can perform and be adapted for future generations. Better tools are needed to manage risk and uncertainty and to develop more rigorous system thinking approaches.

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