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Systemic Modelling of Design Error Causation in Social Infrastructure Projects

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Abstract

Design errors contribute significantly to cost and schedule growth in social infrastructure projects and to engineering failures, which can result in accidents and loss of life. Despite considerable research that has addressed their error causation they still remain prevalent in projects. This paper develops a conceptual model of the underlying conditions that contribute to design errors in social infrastructure projects. A systemic model of design error causation is then propagated. The research suggests that a multitude of strategies should be adopted in congruence to prevent design errors from occurring and so ensure that safety and project performance are ameliorated.

Keywords: Causal influence, contract documents, design error, social infrastructure.

1. INTRODUCTION

The prevalence of design errors and their resultant cumulative negative impact upon the structural integrity of social infrastructure (e.g., schools, hospitals, education, law and order) and the financial performance of organizations and projects is a *leitmotiv* within the construction industry (Wardhana and Hadipriono, 2003a,b). Design errors are the predominant cause of accidents and research has revealed that gross errors can cause 80 to 90% of the failures occurring on buildings, bridges and other civil engineering structures (Matousek and Schneider, 1976). Errors contained within contract documentation alone can contribute to a 5% increase in a project's contract value (Cusack, 1992). Such costs would be

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significantly higher in the event of an engineering failure and consequent loss of life. For example, Bijen (2003) identified that engineering failures account for as much 10% of the total investment in new social infrastructure. Importantly, these failures are not restricted to simple direct cost considerations because they are also inextricably linked to less tangible environmental and social costs. Against this contextual backdrop, a systemic model of design error causation is developed and then the key issues are examined using a infrastructure case study project.

2. CONCEPTUAL SYSTEMIC MODEL OF DESIGN ERROR

A conceptual causal model of design error causation is presented in Figure 1. The influence diagram shows explicitly the direction and type of causality among major variables and it is used to model the influences of inputs on outputs and vice-versa. For example, if variable *A* is causing a change in variable *B*, the direction of causality is from *A* to *B*. If an increase (decrease) in variable *A* leads to an increase (decrease) in variable *B*, then the type of causality is positive, otherwise it is negative. For conceptual models of this nature, it is appropriate to assume that there can be both positive and negative influences between variables. The variables external to the shaded area of Figure 1 provide the conditions for errors to arise. In the shaded area of Figure 1 the *rework cycle* is presented (Cooper, 1993), which is fundamental to understanding error generation and project behaviour (Williams, 2002). Work rate is determined by staff skills, productivity and availability, and as project time advances the amount of work remaining reduces. If the quality of work produced is not to the required standard then errors may occur, but these errors are often not immediately identifiable (latent), transpiring only after a period of incubation in the system (refer to Figure 1). When the errors are detected rework is identified, which increases the amount of work to be undertaken by staff. The degree of rework required is dependent on how long the latent error has remained undetected. For instance, a dimensional error or spatial conflict contained within the engineering design may not arise until the project is physically constructed on-site. If the error necessitates a major change to be undertaken, then all the perceived progress prior to the error occurring may be considered wasted. Addressing the error may generate more work for individuals and the possibility of more errors being generated. This is denoted by the main cycle loop in the model which is a reinforcing loop (indicated by *R*). Importantly, the balancing loops, denoted by *B*, should however counteract the accumulation of work remaining. The gap between perceived and actual progress may be difficult to close; it may appear that all work is nearly complete but the project can persistently remain at a frustrating 90% level of completion.

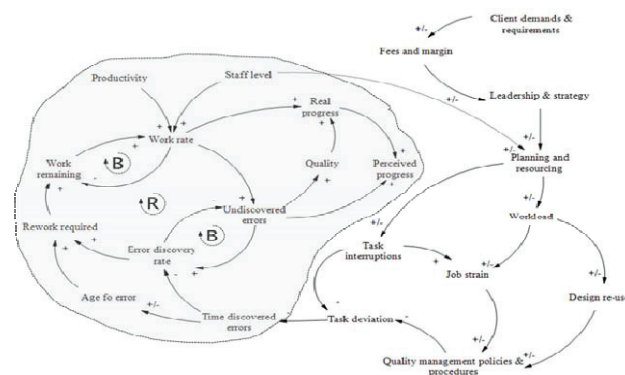


Figure 1. Conceptual systemic causal model of design error causation

Poor rates of progress occur mainly when staff involved with tasks either leave (staff turnover) or become unavailable and replacement staff are needed to complete the tasks. This problem may be further compounded by the prevailing skills shortages being experienced within the Australian construction industry. Discontinuity of design staff application significantly impacts upon design process performance (Rodrigues and Williams, 1998). This is because the inherent project knowledge held by each staff member cannot be seamlessly passed directly from one individual to the next, even if a hand-over ‘transient’ period (and/or de-briefing) occurs. Even staff recruited from the same organization cannot acquire sufficiently detailed project knowledge immediately after commencing work on site. There is an initial project absorption period needed for all staff. In practice, activities are executed at varying levels, depending upon the individuals’ skill and competence, and as a result, quality can be compromised. Cooper (1993) suggests that the quality and the error discovery rate are the most important factors that should be considered. Therefore, bolstering a project with additional resources does not automatically resolve fundamental problems; a more pre-emptive approach should be utilized to reduce the number of errors, or at least to reduce the time taken over their detection.

3. RESEARCH APPROACH

The conceptual model provides insights about the inter-dependencies and behavior between key variables that may contribute to design errors. A case study approach based upon analytic induction is used to further examine the underlying dynamics that may contribute to the production of design errors. A case study is exploratory in nature, based on interviews and relies heavily on verbal reports and unobtrusive observation as data sources. This methodology should be used to investigate the technical aspects of a contemporary phenomenon within a real life context, particularly in critical and unique circumstances (Flyvbjerg, 2006). It is particularly useful when the boundaries between phenomenon and context are difficult to ascertain and when multiple sources of evidence are used. A case study can provide analytical rather than pure statistical generalizations and can capture the complexity and dynamism of organizational settings in projects (Flyvbjerg, 2006). Analytic induction refers to a systematic examination of similarities between various social phenomena to develop generic concepts or ideas. It also allows for modification of social concepts and their relationships throughout the research process, with the goal of most accurately representing the reality of the situation (Ragin, 1994). No analysis, however, can be considered final as reality is inexhaustible and dynamic. The determination of causal mechanisms that lead to design errors can provide an understanding of the interaction that can exist between variables. The conjunction of events can result in orthodoxies being established and through the process of observation, generalizations can be made. If such generalisations can be repeatedly tested and confirmed they can lead to the discovery of a lawful relationship.

3.1. Data collection

An Australian public sector client was invited (and subsequently accepted) to participate in the research during 2009. The client identified two projects where cost overruns were forecasted to occur due to significant design problems that were being experienced. Specifically, the problems pertained to design errors that occurred in the contract documents that were produced by the design consultants. With the unequivocal support and permission of the client, the researchers approached both design consultants and contractors involved with the identified projects and explained the nature of the research. All agreed to actively participate in the research. A series of in-depth interviews were conducted over a four month period with participants who had been involved with the delivery of a school. A total of 24 in-depth interviews were undertaken, which ranged between 60 to 90 minutes in duration with architect, engineers,

project managers, contract administrators, contractor's project managers and client. The interviews were digitally recorded using a recording device, and then transcribed and distributed to each interviewee for comment and approval. Data collected during and after each project's completion enabled the researchers to develop a richer understanding of the key issues and errors that emerged during each project's procurement. A variety of methods were used to obtain data, which included interviews and documentary sources (e.g. variation lists, site instructions, architect's instructions, drawings and specifications, and non-conformances).

4. SCHOOL CASE STUDY PROJECT

This case involved an upgrade to an existing school. The project was procured using a Traditional Lump Sum procurement method (with an AS 2124 standard form of contract), had a contract value of A\$25 million and a contract period of 68 weeks. The project experienced a cost growth and schedule overrun of A\$1.1 million (4.4%) and 4 months (25.5%) respectively. The cost growth in this project was entirely due to errors contained within the contract documentation. Interestingly, contracts were awarded to lowest tenders for design and construction services that were provided to the client. While the client has a policy of obtaining 'value for money' (VfM), it would appear from the issues that arose that this was overlooked in this project. The school upgrade comprised of the construction of five phases: playing courts, car park, fire tank pump housing, bin store, paving and landscaping, as well as upgrades to the school's entire electrical power infrastructure (including a substation and irrigation system). New buildings, which included a library, canteen area and lecture theatre, were required in the first phase. In the second phase, a performing arts building was constructed. In the third phase, manual arts workshop with a garden store and bore water treatment plant. In the fourth a home economics and textiles teaching block and in the final phase, a new administration building.

4.1. *Quality management policies and procedures*

The engineering design for the school was subjected to a number of multiple reviews, checks and sign-offs. While such policies and procedures are a vital part of the design process, they can also be detrimental and a waste of time if design consultants do not coordinate and integrate their work. In this case, a clear misunderstanding of expectations and requirements of the client and project team members occurred. It was revealed that structural engineer and architect worked independently with limited design coordination. Consequently, design omissions, errors and changes occurred. Despite the occurrence of omissions and errors, the structural engineer was adamant that they had acted professionally and diligently. A focus on simply 'doing things right, rather than doing the right things' appeared to subconsciously reverberate from the structural engineer during the interview. The undertone from the structural engineer was that the engineering design was correct; it was not their fault that errors occurred. The engineer was however very cognizant not to blame upon anyone, but implied that the architect may not have provided them with all the information they required. Recognizing the potential for errors in calculations and loading assumptions that could be made, the structural engineer organized for their work to be checked by a third party, specifically to ensure compliance to Australian standards. The structural engineer adopted a risk mitigation strategy to prevent errors from occurring. Risks were identified and prioritized. More time was then allocated to checking the critical designed components and structure. This process was deemed to be an essential part of the verification process; if it was not undertaken the potential for an engineering failure and accident was considered to significantly increase.

4.2. *Design coordination*

Audits, reviews and verifications are only useful if design documentation is coordinated systematically between design consultants. Despite the structural engineers' rigorous reviews, they omitted to design the storm water drainage. In fact, the architect, who was acting as the project's superintendent, overlooked this issue as well. As a result, the contractor did not include the storm water drainage in their tender submission. An independent hydraulics engineer was employed to attend to this oversight. The cost of this omission error was A\$100,000. In another related example, the structural engineer omitted to 'design ferrule connections' which were required to be cast into the sixty precast reinforced concrete columns. Such connections would serve to accommodate the tensile forces that would be imposed on the columns from the floor above. Again, this omission occurred due to inadequate information flow between the architect and engineer.

4.3. *Project governance*

Like the hospital upgrade case, the contractor in this project observed that the contract documentation produced by design consultants contradictory. According to the contractor all design consultants needed to do to resolve this issue was "communicate with each other". It appeared the procurement method and contractual obligations of parties' hindered 'effective' communication from taking place. Different consultants had been appointed at different stages of the design process and therefore were constrained by what already had been designed, particularly by the architectural drawings. Both the architect and contractor believed that many of the errors that did arise could have been prevented if the contractor was included in the design process. The client preferred to use TLS contracts in conjunction with competitive tendering. Issues surrounding accountability, probity, and familiarity were deemed to be the drivers for their use. It was perceived that there had also been limited attention of the client to project governance. The client did not actively participate in the project, which resulted in key decisions being taken by the superintendent who also assumed the role of architect. Acceptance of the lowest bids, from design consultants and the contractor provided the impetus for firms to adopt self-serving practices to maximize their fees. The verification of the project team's performance was also left to the superintendent. In the case of such projects, taxpayers are funding them and it is therefore necessary that 'VfM' rather lowest cost is adhered too, so as to ensure they are delivered on time and within budget.

4.4. *Professional fees and margins*

The mechanical and electrical engineer suggested that a 'silo mentality' had become ingrained within the way in which projects were being procured. The engineer proceeded to state that there was no motivation or incentive in place to encourage design consultants to work together in a harmonious and collaborate way. The issue of fees then began to emerge and it was stated:

"It's cut throat out there. Fees are very tight and clients are not willing to pay us what we require. I understand that documentation is sometimes poor, but we also don't have enough time to prepare it. Client's expectations have increased, but fees have not. They think that we can design overnight sometimes".

The revisions made to documentation as a result of errors and changes were costly, particularly to the structural engineer who stated:

“We assumed that we’re going to do the design once and things were not going to keep changing. We’ve been redesigning and redesigning because of other people’s errors”.

As fees were considered to be tight and with an unrealistic schedule in place to document the design, consultants implemented ‘time-boxing’ to ensure the key areas of the design were complete. In adopting this approach however they reduced their ‘scope of work’. This resulted in aspects of their designs being incomplete. As a result, this led to inconsistencies occurring between architectural and engineering drawings as well contractual variations being raised and issued during construction.

5. TOWARD DESIGN ERROR PREVENTION

The developed conceptual model, Figure 1, was able to capture the underlying dynamics contributing to design errors. Additional variables and amendments to causal directions and influences were identified and as a result have been incorporated into a revised model which is presented below Figure 2.

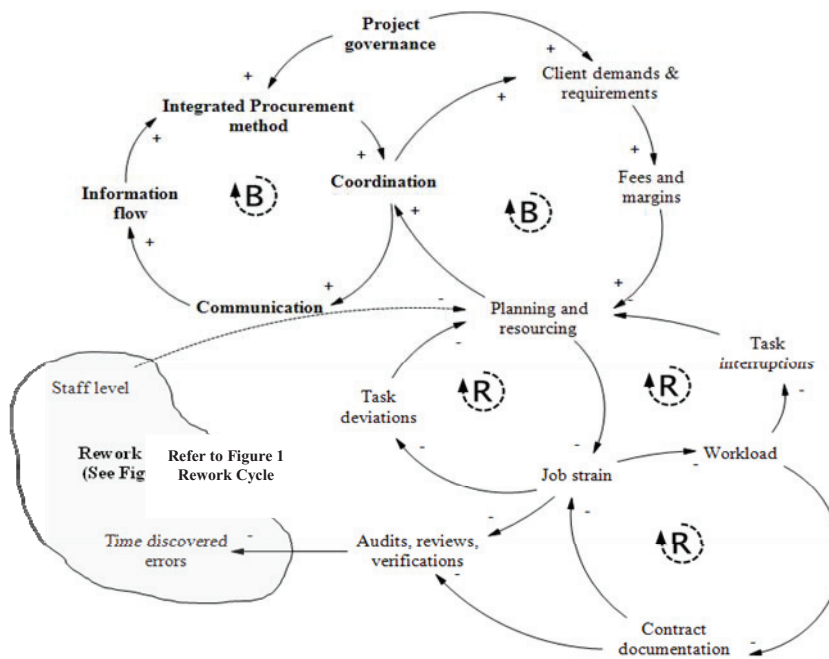


Figure 2. Systemic causal model of design errors

Differing external and internal conditions appear to work in incongruence to produce an environment for producing design errors which become visible in contract documentation. The following symbols denoted in Figure 2 represent the positive and negative polarities that were found to contribute to the conditions that generate design errors during the procurement of social infrastructure projects. The positive polarities (B) focus on the project (i.e. governance, procurement, scope, and selection) and organization (i.e. margins and fees, planning and resources). It is through changing these practices that

provide the impetus for changes within design firms and influences the cognitive capabilities of people. The organization essentially acts as the interface for the project. The negative polarities place emphasis on organizational practices and people (*R*). These reinforcing loops indicate that an action produces a result which influences more of the same action thus resulting in growth or decline in design errors. The lack of effective governance framework can provide an environment for opportunistic behavior to occur. Unrealistic client demands and expectations place considerable pressure on design consultancies particularly when competitive tendering is used as a mechanism for their selection (Love et al., 2009). The use of ‘time-boxing’ practices to meet schedule demands may contribute to audits, reviews and verifications being omitted, allowing design errors to materialize during construction. Risk assessments of design documentation should be undertaken at each stage of the design process to reduce the likelihood of changes and errors occurring during construction. Such an approach would significantly reduce the likelihood of cost and schedule overruns as well as disputes. Adopting a proactive approach to design management would enable realistic forecasts of the project’s cost and completion date to be attained. A considerable amount of public sector projects experience cost and schedule growth as the original estimates are deemed to be too optimistic (Flyvberg et al., 2009).

The procurement method adopted significantly influences the degree of coordination, communication and flow of information between project team members. Thus, an integrated procurement approach such as an alliance or design and build can provide the foundations for establishing harmonious relations between project team members to be established. In addition, a contractor can be involved in the design process. It is proffered that public sector clients should include financial ‘penalties’ or ‘incentives’ within their contracts with design consultants so as to ensure that project objectives are being achieved consistently. The design firm should ensure that they have the adequate resources to undertake the projects that they commit to undertake. Noteworthy, the construction industry in Western Australia is currently experiencing a considerable skills shortage which has resulted in staff multi-tasking and working longer hours (Love et al. 2010). Having dedicated personnel allocated to specific projects would reduce job strain, which in turn would reduce the potential to omit tasks and enable staff to better deal with interruptions. Planning and resourcing is also linked to workload. A reduction in workload or having more time to undertake required tasks can result in staff taking short-cuts and reusing details and specification that have no relevance to the project. Having time to reflect and think about the problem at hand will ensure an appropriate design solution is attained. A reduction in the number and severity of errors will be identified when audits, reviews and verifications are undertaken. Some errors will be missed, but many should be discovered on-site before construction physically commences. The analysis of the conditions contributing to design error generation has enabled the following orthodoxy to be established:

“A lack of project governance juxtaposed with the use of competitive tendering provides an environment where the services offered by design consultants are reduced or omitted in order to maximize their profit. The omission of critical tasks and practices such as design audits, reviews and verifications invariably leads to contract documentation being erroneous (incomplete) and increases the propensity for cost and schedule growth to be experienced”.

6. CONCLUSION

Design errors are a symptom of dysfunctional organizational and managerial practices that prevail within the construction industry. They significantly contribute to cost and schedule growth, rework, disputes and jeopardize safety. In addressing this issue, a systemic approach to determining the underlying dynamics contributing to design errors was developed and examined using a social

infrastructure case. The analysis of the case led to the establishment of an orthodoxy, which implies that inadequate project governance and competitive tendering of design services provide an environment for opportunism whereby critical tasks and practices such as audits, reviews and verifications are omitted so that fees can be maximized. It is suggested that a multitude of strategies need to be adopted in congruence to prevent design errors from occurring.

REFERENCES

- [1] Bijen, J. (2003). *Durability of Engineering Structures: Design, Repair and Maintenance*. Woodhead Publishing, Ltd
- [2] Cooper, K.G. (1993). The rework cycle: benchmarking for the project manager. *Project Management Journal*, **24**(1), p.17-22.
- [3] Cusack, D. (1992). Implementation of ISO 9000 in construction. ISO 9000 Forum Symposium, November, Gold Coast, Australia.
- [4] Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry*, **12**(2), p.89
- [5] Flyvbjerg, B., Garbuio, M., and Lovallo, D. (2009). Delusion and deception in large infrastructure projects: two models for explaining and preventing executive disaster. *California Management Review*, **51**(2), pp.170-193.
- [6] Love, P.E.D. Edwards, D.J., Irani, Z., and Walker, D.H.T. (2009). Project pathogens: the anatomy of omission errors in construction and resource engineering projects. *IEEE Transactions on Engineering Management* **56**(3), pp.425-435.
- [7] Love, P.E.D. Edwards, D.J. and Irani, Z. (2010). Occupational stress, support and mental health in construction. *ASCE Journal of Construction, Engineering and Management* **136**(6), pp.650-658.
- [8] Matousek, M., and Schneider, J. (1976). *Untersuchgen zur Struktur des Sicherheitsproblem bei Bauwerken*. Birhäuser, Basel, Switzerland (In German)
- [9] Ragin, C.C. (1994). *Constructing Social Research: The Unity and Diversity of Method*, Pine Forge Press.
- [10] Rodrigues, A., and Williams, T.M. (1998). System dynamics in project management: assessing the impacts of client behaviour on project performance. *Journal of the Operational Research Society*, **49**, pp.2-15.
- [11] Wardhana, K., and Hadipriono, F.C. (2003a). Analysis of recent bridge failures in the United States. *ASCE Journal of Performance of Constructed Facilities*, **17**(3),
- [12] Wardhana, K., and Hadipriono, F.C. (2003b). Study of recent building failures in the United States. *ASCE Journal of Performance of Constructed Facilities*, **17**(3), pp.151-158.
- [13] Williams, T.M. (2002). *Modelling Complex Projects*. John Wiley and Sons, Chichester