Citation
Love, P. and Smith, J. and Ackermann, F. and Irani, Z. and Teo, P. 2018. The costs of rework: insights from construction and opportunities for learning. Production Planning & Control. http://doi.org/10.1080/09537287.2018.1513177

The Costs of Rework: Insights from Construction and Opportunities for Learning

Peter E.D. Love [a], Jim Smith [b], Fran Ackermann [c] Zahir Irani [d] and Pauline Teo [e]

[a] School of Civil and Mechanical Engineering,
Curtin University, Perth, GPO Box U1987, Western Australia, 6845, Australia
Email: p.love@curtin.edu.au

[b] Jim Smith
School of Sustainable Development,
Bond University, Robina, QLD, Australia
Email: jismit@bond.edu.au

[c] Fran Ackermann
The Business School
Curtin University, GPO Box 1987, Perth, Western Australia 6845, Australia
Email: Fran.Ackermann@curtin.edu.au

[e]Zahir Irani
Faculty of Management, Law and Social Science
University of Bradford
Bradford West Yorkshire, BD7 1DP, UK
Email: z.irani@bradford.ac.uk

[e]Pauline Teo
[d] School of Property, Construction and Project Management
RMIT University, Victoria, 3000, Australia
Email: pauline.teo@rmit.edu.au

Accepted

To be published in *Production, Planning and Control*

(Taylor and Francis)

The Costs of Rework: Insights from Construction and Opportunities for Learning

Abstract

During the production of artefacts in construction there is a likelihood for errors to be committed, which may need to be rectified so that they conform to defined contractual requirements and standards. In doing so, this initiates a process of rework, which is a problem that the industry has incessantly aimed to redress for decades with limited success. Rework is a 'known-unknown', but there remains a high degree of uncertainty about its costs. Such uncertainty occurs as there is a proclivity for the costs associated with rework to be largely ignored, concealed or considered to be normal function of operations. This paper presents the results from the first longitudinal and in-depth study of rework costs in construction. Based on a sample of 19,605 rework events derived from 346 construction projects delivered by a contractor between the years 2009 and 2015, it was revealed that their mean yearly profit over the period of analysis was reduced by a staggering 28%. In addition, 88 (0.45%) of the total 19,605 rework events accounted for 34% of the total costs that were incurred. The complete cost data for 98 of the 346 projects was made available, which enabled a mean rework cost of 0.39% of contract value to be determined. The research provides construction organisations with an improved understanding of the nature and likelihood of rework costs enabling them to move from a position of being a 'known-unknown' to becoming a 'known-known'. Being able to 'anticipate what might go wrong' and ensure that risk management and controls are put in place throughout the construction process will contribute to their dynamic capability.

Keywords: Construction, costs, information, learning, quality, rework, profit,

Introduction

> "No one knows the cost of a defective product - don't tell me you do. You know the cost of replacing it, but not the cost of a dissatisfied customer". W. Edwards Deming

Rework has been identified a fundamental problem that adversely impacts the performance and productivity of Australian construction organisations (Love and Li, 2000; Love, 2002; Love *et al*., 2018a), but it is equally, *mutatis mutandis*, an issue for many countries worldwide such as Canada, China, Singapore, Spain, and the United Kingdom (UK) (Robinson-Fayek *et al*., 2004; Hwang *et al*., 2014; Taggart *et al*., 2014; Ye *et al*., 2015; Forcada *et al*., 2017). Despite a plethora of academic studies that have sought to determine the costs of rework, there remains no consensus as to what these amounts are, how they are determined and the 'actual' impact on project and organisational performance and productivity (Love *et al*., 2016; Love *et al*., 2018a).

It has been well recognised that rework can adversely impact project costs, safety, schedule, profitability, and the environment (Burati *et al*., 1992; Willis and Willis, 1996; Ford and Sterman, 2003; Hwang *et al*., 2009). Research that has examined the costs, causes and impacts of rework has tended to: (1) utilise questionnaire surveys that seek the perceptions of varying types of respondents from heterogeneous populations (or specific data from companies)(e.g., Love, 2002; Hwang *et al*., 2009; Hwang *et al*., 2014; Ye *et al*., 2015): (2) limited numbers of case studies where generalisations are unable to be made (e.g., Barber *et al*., 2000; Love and Li, 2002; Josephson *et al*., 2002 Robinson-Fayek *et al*. 2004); and (3) simulation modelling using techniques such as System Dynamics that are based on assumptions that are aimed to mimic reality (e.g., Han *et al*., 2013; Parvan *et al*., 2015). Moreover, the lack of a standard definition of rework and method to determine its costs can result in factoids being propagated within the literature about how it impacts project performance (Love *et al*., 2018a).

In fact, rework figures of '5% of project costs' or '10% of construction costs' have been used to support lines of inquiry and to endorse tools that claim to potentially reduce its occurrence (e.g., COAA, 2006). The evidence supporting such claims and the general rework figures reported in the literature (e.g., Love *et al*., 2004; Robinson-Fayek *et al*., 2008; Hwang *et al*., 2009) should be treated with caution and with *caveats* being used when justifying their use so as not to take them out of context. If headway is to be made to better understand the 'real' costs of rework that actually materialises at the frontline of construction, then access to contractors' financial and cost data is required.

Understandably, there has been typically a reluctance by contractors to make their data available to due to reasons of commercial sensitivity and a fear that their reputation could be tarnished. The unavailability of actual rework costs has stymied the Australian construction industry's ability to progress toward effectively enacting continuous improvement initiatives to reduce its occurrence (Love *et al.*, 2018a).

Recognising the need for the construction industry to improve its performance, a leading contractor made available their rework costs so that a process of benchmarking could be initiated. The cost of 19,605 rework events derived from 346 projects constructed over a six-year period (2009 to 2015) were provided and analysed. The research presents invaluable insights into costs of rework that arise during construction and their impact on an organisation's profitability. In doing so, moving rework costs from a position of being an 'known-unknown'. (i.e., expected or foreseeable conditions) that can be anticipated but not quantified based on past experience, to being a 'known-known'. Rework can derail projects and therefore its costs should be illuminated rather being hidden. The insights into rework costs presented in this paper provides construction organisations and their managers with much-needed knowledge to stress the limits what can be known about a project prior to its commencement. Moreover, this can invoke learning as well as the cultivation of healthy foundation for risk assessment and a pre-occupation with 'anticipating what might go wrong', which are innate features of error management.

The paper commences with a review of rework costs that have been reported in the normative literature to provide a context for the analysis that is presented and discussed. Then, the costs of rework that occurred in 346 construction projects delivered by an Australian contractor between the years 2009 and 2015 are examined. In particular, the research identifies those specific high cost rework events that had a significant impact on the contractor's profitability. The research provides construction organisations with an improved understanding of the nature and likelihood of rework costs enabling them to move from a position of being a 'known-unknown' to becoming a 'known-known' The research does not, however aim to examine the nature of rework causation, as this has been addressed in numerous studies (e.g., Willis and Willis, 1996; Robinson-Fayek *et al*., 2004; Hwang *et al*., 2014; Pervan *et al*., 2015; Love *et al*. 2018b).

Rework Costs

Definitions of rework abound the literature. Terms such as quality deviations, quality failures, non-conformances (NCRs) and defects have been used interchangeably to denote rework (e.g., Burati *et al*., 1992; Barber *et al*., 2000; Josephson *et al*., 2002). Love (2000) examined rework from a project perspective and defined rework as the "unnecessary effort of re-doing a process or activity that was incorrectly implemented the first time" (p.19). This definition is all encompassing as it includes design changes and errors that require rectification during construction. As a matter of fact, design changes and errors often result in a contractor undertaking additional work over and above that originally stipulated in a contract resulting as a change order which is invariably issued entitling the contractor to payment (Love *et al*., 1999). While design changes after an item has been constructed or installed have been known to occur in projects, they are rare events and thus should not be considered as a normal function of construction practice. The inclusion of design changes and errors therefore naturally inflates the costs of rework that are experienced.

Arguably, the most widely used definition for examining rework from a construction perspective is the one provided by Robinson-Fayek *et al*. (2004) "the total direct cost of re-doing work in the field regardless of the initiating cause", which specifically excluded change orders and errors caused by off-site manufacture (p.1078). In this instance, rework costs that arise become the direct responsibility of the contractor and their subcontractors. As mentioned above, reported costs of rework have been found to significantly vary in the extant literature not only due the methodological approaches used to calculate them, but also whether a project or construction perspective is taken. The upshot of varying rework costs lays with the definition that is adopted and its scope. Two views of rework dominate the literature:

- *project rework*, which includes scope changes and manufacturing errors off-site. In this case, rework is presented as a cost to the 'project' and no distinction is made to who actually pays for the repeated works.

- *construction rework,* which excludes scope changes and manufacturing errors that arise off-site and focuses on the costs to the contractor.

Each of these forms of rework are discussed hereinafter.

Project Rework

Examining NCRs that required rework Cnudde (1991) found that they contributed to between 10% to 20% of total project costs. In particular, Cnudde (1991) noted that 46% of rework costs were attributable to design deviations and 22% due to the poor execution of work during construction. A considerable amount of design deviations often arise due to errors and omissions contained in contract documentation (Crawshaw, 1976). Poor quality documentation produced by design consultants has been consistently identified as a problem within construction literature (e.g., Crawshaw, 1976). The estimated costs related to rework resulting from design deviations can be as high as 20% of a design consultant's fee for a given project (Gardiner, 1994).

Using data from nine fast-track industrial construction projects Burati *et al.* (1992) identified the average direct costs associated with rework (including redesign), repair, and replacement to be 12.4% of the total project costs. Design changes, errors and omissions were found to be, on average, 78% of the total deviations incurred and 79% of total costs. Notably, Burati *et al.* (1992) stated that the reported figure of 12.4% was conservative, as it only focused on those direct costs that had an impact on total project costs. Indeed, this reported figure would have been significantly greater if the indirect costs that materialise from rework such as delays, disruption, claims, litigation were also included (. But such costs are difficult, if not impossible, to quantify in monetary terms (Love and Edwards, 2005). Within the logistics literature, for example, Bowersox *et al.* (1985) estimated the cost of rectifying a poor-quality product or service can be more than eight times its original cost. Likewise, Sörqvist (1998) revealed that a multiplier effect of at least three to five times was directly related to the indirect effects of a quality failure.

Nylén's (1996) examination of four rail projects revealed mean rework costs to be 10% of construction costs, with clients being responsible for 72% of their occurrence. Focusing on seven building projects constructed from 1994 to 1996, Josephson and Hammarlund (1999) acted as non-participant observers, calculating rework costs to range from 2.3% to 9.3% of construction costs. In a similar vein, Barber *et al.* (2000) used a work shadow technique in two projects that were procured using a Design-Build-Finance-Operate procurement method and unearthed rework costs to be 16% and 20% of their original contract value (OCV).

A procurement method is an "organisational system that assigns specific responsibilities and authorities to people and organisations and defines relationships of various elements in a construction project" (Love *et al.*, 1998: p.222). A procurement method implicitly allocates risk between parties. Consequently, this has led CIDA (1995) to suggest that rework costs would vary with those procurement methods adopted to deliver a construction project. Such risks are exacerbated by poor communication practices, which has often been identified as a product of using traditional lump sum (TLS) procurement methods due to the separation of design and construction processes (Banwell, 1964). Accordingly, CIDA (1995) found that when TLS are used to deliver projects the innate poor communication practices that prevail juxtaposed with the absence of a quality management system may result in rework costs exceeding 15% of their OCV. In stark contrast to CIDA (1995), Love's (2002) examination of 161 construction projects found there to be no significant difference between procurement methods and project types for rework costs. Total mean project rework costs were revealed to be 12% of OCV, but this figure comprised of 6.4% for those that were direct and 5.6% for indirect costs.

Using data obtained from 359 projects from the Construction Industry Institute's database in the United States Hwang *et al.* (2009) calculated the direct rework costs to be as high as 5% of construction costs. Here Hwang *et al.* (2009) included owner changes, design errors/omissions, vendor omissions, vendor changes, construction errors/omissions, construction changes, and transportation errors. Noticeably, it was reported that rework costs differed between: (1) heavy industrial and buildings; (2) projects of US$50 to US$100m and >US$100m; and domestic and international projects. Yet, despite these differences no explanation as to why they occurred was provided by Hwang *et al.* (2009).

Clearly, rework can negatively impact project cost and time performance. In fact, Love (2002) has shown that rework contributed approximately 52% of the cost growth experienced in 161 projects of the projects sampled. As research has repeatedly demonstrated cost growth does not vary as a result of a project's characteristics (e.g., size, project type, procurement method), (e.g., Ireland, 1985; Naoum, 1994; Walker, 1995; Love *et al.*, 2002), what then contributes to rework? Evidence explicitly indicates that organisational and managerial decisions and actions are the underlying mechanisms that provide an explanation for the occurrence of rework and its negative impact on project costs (Barber *et al*., 2000; Robinson-Fayek *et al*., 2004; Love *et al*., 2004; Taggart *et al*., 2014; Love *et al*., 2018b).

Construction Rework

When considering rework from a purely construction perspective (i.e. excluding design/change orders) it will be seen that reported costs are significantly lower than those that have been identified above. Noticeably, there has been a paucity of studies that have focused on construction rework (e.g., Love and Li, 2000; Robinson-Fayek *et al*., 2004; Jaafari and Love, 2013; Forcada *et al*., 2017). Burroughs (1993), for example, observed that a contractor had experienced rework costs of 5% of their contract value due to poor quality drawings that had been issued 'for construction'. Using project-specific data provided by a contractor Love and Li (2000) ascertained that the rework cost for 14 projects as a percentage of OCV to be for: (1) eight civil and rail engineering, ranging 0.15 to 1%; (2) three marine engineering, ranging 0.10 to 0.5%; and (3) three building ranging, from 0.14 to 0.98%. A similar magnitude for rework costs have been reported in Jaafari and Love (2013) where a value of 0.05% of OCV was reported for a mono-rail project that had an estimated contract value of US$120 million.

In contrast to the aforementioned findings, Forcada *et al.*'s (2017) analysis of 788 rework incidents in 40 construction projects produced a mean cost 2.75% of OCV. While Forcada *et al*. (2017) adopt a construction rework perspective, there is absence of an operational definition, and therefore the figure being reported should be treated with a degree of caution as it is not clear if design changes have been incorporated into their analysis. Moreover, Forcarda *et al*. (2017) fail to explain why different project types are a causal factor that contributes to rework. It is suggested that Forcarda *et al*. (2017) may have fallen to the folly of issues surrounding the use of *P*-value of 0.05 and accepted the results on-face value and thus strived to justify them. Indeed, Forcada *et al.*'s (2017) results should be treated cautiously as there is an over-reliance on a *P*-value of 0.05, which cannot determine whether a hypothesis is true or if the results are important (Baker, 2016). Put simply, a *P*-value signifies that if the null hypothesis is true, and all other assumptions made are valid, there is a

5% chance of obtaining a result at least as extreme as the one observed. Hence, a *P*-value cannot indicate the importance of a finding.

Forcada *et al.* (2017) identified a significant difference between building projects and civil engineering projects based on a *t*-test. The explanation put forward was that building projects are more complex than civil engineering. But, the study did not measure complexity and provide a context of the scope and nature of works that were constructed; the data used in the study was derived from technical datasheets and NCR reports. Again, Forcada *et al*. (2017) suggests that there is a difference between rework costs in projects procured by private and public sector and those delivered by a joint venture or sole contractor. However, no practical rationale as to why this would be the case is provided. Moreover, Forcada *et al*. (2017) do not define a 'joint venture' and 'sole contractor' within the context of a procurement method? So, conclusions of this nature that are reliant on spurious statistics and ill-defined project characteristics are unable to provide a valid and reliable explanation can be considered to be merely methodological artefacts that do not stand up to close scrutiny. They may be informative, but they are certainly not definitive.

Acquiring quality and productivity-related data from projects in real-time can provide contractors with an ability to manage and control errors that materialise and mitigate the negative consequences that may arise from rework that they may perform (Ding *et al*., 2017). For this to occur, contractors will be required to develop an information architecture that integrates its scope, cost, time and quality management systems. Several attempts have been developed to enable the classification and determination of reworks costs, but these have been generally manual and time consuming to implement in the field (e.g. Davis *et al*., 1989; Burati *et al*., 1992; Willis and Willis, 1996; Low and Yeo, 1998; Love and Irani, 2003; Tang *et al*., 2004).

Robinson-Fayek *et al*. (2004) developed a robust classification system to capture the costs of rework, which was piloted over a nine-month period during the construction of an iron-ore expansion project with a contract value of approximately CDN$599 million, though it was unable to provide a definitive or even *ball-park* figure. Instead it focused on determining the major cost contributor of rework for 108 incidents totalling $582,703, these being: (1) engineering and reviews (61.65%); (2) human resource capability (20.49%); (3) materials and equipment supply (14.81%); (4) construction planning and scheduling (2.61%); and (5) leadership and communication (0.45%). Since the development of Robinson-Fayek *et al.*'s (2004) system there has been minimal, if any headway made, to developing a system to capture and provide realistic rework costs in projects. The upshot is that there remains a void in the literature about the real costs of rework, particularly from a construction standpoint and how they actually impact a contractor's bottom-line.

Research Approach

Many research studies that have examined rework costs have tended to rely upon heterogeneous data-sets (e.g. Burati *et al*., 1992; Josephson and Hammarlund, 1999; Love, 2002; Hwang *et al*., 2009; Hwang *et al.* Ye *et al*., 2015). Such data-sets are loosely connected and thus there is a propensity for them to possess a considerable amount of 'noise' due to inconsistencies in the processes and standards applied to determine rework costs. Moreover, many contractors ignore rework as they are deemed to be a normal function of operations (Moore, 2012) and in some instances costs and incidents may be deliberately concealed (Ford and Sterman, 2003; Love *et al*., 2018b).

There have been only a limited number of studies that have had direct access to rework cost data from a specific project or from a contracting organisation's portfolio (e.g. Barber *et al.* 2000; Love and Li 2000; Robinson-Fayek *et al*., 2004; Forcada *et al*., 2017; Love *et al*., 2018a). The problem associated with determining rework costs has been well-documented (e.g., Love *et al*., 2108a), but their extent of occurrence remains a mystery to both the academic community and industry. In seeking to clarify this issue and bring to the fore the actual costs of rework that materialise in practice, an illustrative case study approach is adopted for this research (Fry *et al*., 2009).

Typically, an illustrative case study is used to describe an event in its natural real-life context; they utilise one or two instances (variables) to demonstrate the reality of a situation (e.g. rework and margin). In this instance, the case study sheds light on the actual rework costs and how they can adversely impact the profitability. The case study serves to make the 'unfamiliar, familiar', and provide a common language to begin to understand the nature of rework costs in construction. With this in mind, the research presented aims to capture those rework costs experienced by contracting organisation over a prolonged period whereby standard procedures, processes and policies were consistently implemented under the auspices of a homogenous organisational quality culture.

Case Selection

The case study organisation selected for this study is a tier-one contractor that recognized that rework was a problem and had initiated several internal studies to examine its causes and impacts. Several projects that the construction organisation had been contracted to deliver had received national awards for both their quality and safety programs as a result of continuous improvement initiatives that had been implemented. The researchers had previously collaborated with the chosen organisation on a number of earlier studies and therefore were familiar with their processes, procedures and staff. As a consequence, access to cost and quality data was freely provided to the researchers for analysis as commercial confidentiality was ensured. The operational definition of rework adopted by the contracting organisation and used in this study was "an action on a non-conforming product to make it conform to requirements". This definition only includes the direct cost borne by the contractor to remedy works.

Dataset

Access to the construction organisation's quality data from 2009 to 2015 that covered 346 completed construction projects was made available to the researchers. Prior to 2009 quality records were not available in a digital format and in some instances were deemed to be incomplete and inaccurate for the study. Projects that were under construction were excluded from the analysis. The quality data used to determine rework costs were derived from the NCRs, which were categorised according to their monetary value: (1) <AU$2000; (2) AU$2,001 to AU$100,000; and (3) >AU$100,000. Qualitative descriptions of rework events were provided by site staff and the parties deemed to be responsible and their corresponding cost liability were also included in the quality data.

Complete cost data that included the OCV (i.e. project size), final contract value, expected margin, final margin, client approved variations, and rework costs directly borne by the contractor were provided for only 98 (28%) out of 346 projects; issues of commercial sensitivity prevailed in this instance and therefore not all project information was not made available. This research is focused on construction rework costs and they are represented as a percentage of the OCV. So, client approved variations (e.g. scope changes) that may have resulted in rework were outside the remit of the research and thus excluded from the analysis. Supplementary reports such as ‘financial assurance reviews’, and ‘project reviews’ were made available to provide a context for rework events in excess of AU$100,000.

Analysis

Descriptive statistics are used to provide an overview of the costs for the rework events that arose in the 346 construction projects. In addition, a one-way analysis of the variance (ANOVA) was undertaken with the sample of 98 construction projects to determine whether there were any statistically significant differences between their mean cost of rework for different projects and procurement methods. In essence, an ANOVA was used so that findings could be compared with previous studies (e.g., Hwang *et al*., 2009; Forcada *et al*., 2017). Pearson’s correlation coefficients were computed to determine the strength of linear association between the following project characteristics: (1) project type; (2) procurement method; (3) rework costs; (4) OCV; (5) final contract value; and (6) margin. To determine if these characteristics are predictors of the contractor’s rework costs, a *forward* stepwise regression was performed. In this case, no preconceived predictors were considered.

A probability density function (PDF) and cumulative density function (CDF) were then computed and the likelihood of rework costs exceeding their mean and median were determined to provide a basis for conducting risk analysis. Such established probabilities could be incorporated into future estimates of construction costs. A PDF for a continuous distribution can be expressed in terms of an integral between two points:

[Eq.1]

A CDF was also produced. For theoretical continuous distributions the CDF is expressed as a curve and denoted by:

[Eq.2]

The empirical CDF, which is displayed as a stepped discontinuous line and dependent on the number of bins, is represented by:

[Number of observations] [Eq.3]

The PDF, CDF and distribution parameters such as () were examined for continuous distributions such as *Beta*, *Burr*, *Cauchy*, *Error, Gumbel Max/Min*, *Johnson SB*, *Normal* and *Wakeby* using their respective estimation methods of Maximum Likelihood Estimates. The 'best fit' distribution was then determined using the following 'Goodness of Fit' tests, which measures the compatibility of a random sample with the following theoretical probability distributions: (1) *Anderson-Darling statistic* (A^2): and (2) *Kolmogorov-Smirnov statistic (D).* The above 'Goodness of Fit' tests were used to test the null (H_o) and alternative hypotheses (H_1) that the datasets: H_0 - follow the specified distribution; and H_1 - do not follow the specified distribution. The hypothesis regarding the distributional form is rejected at the chosen significance level (α) if the statistic A^2, χ^2 and D, are greater than the critical value. For the purposes of this research, a 0.05 significance level was used to evaluate the null hypothesis.

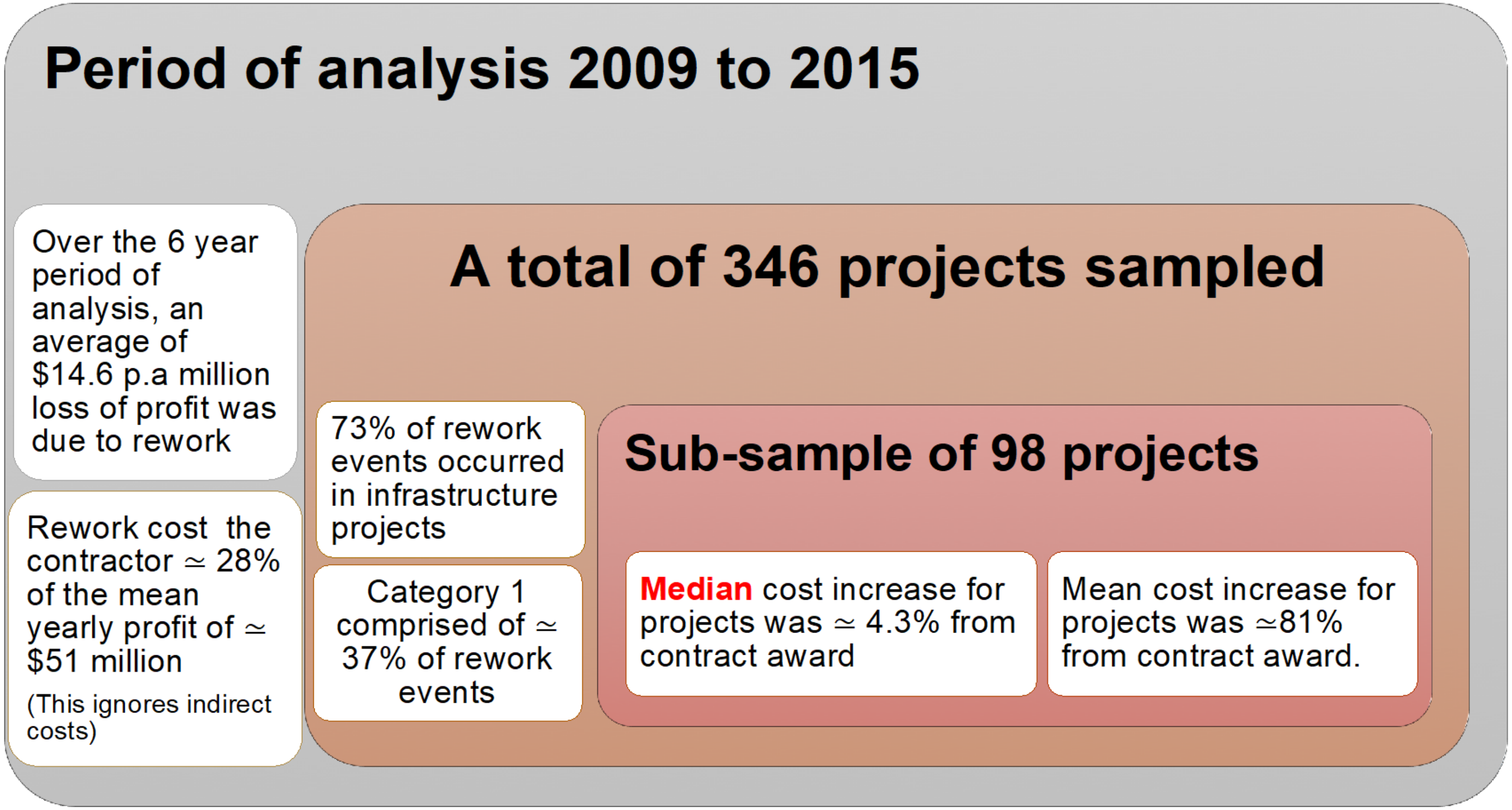
The p-value, in contrast to fixed α values is calculated based on the test statistic and denotes the threshold value of significance level in the sense that H_o will be accepted for all values of α less than the p-value. Once the 'best fit' distribution was identified the probabilities for determining rework costs were calculated using the CDF. To simulate the samples' randomness and derive rework cost probabilities, a *Mersenne Twister*, which is a pseudorandom number generating algorithm, was used to generate a sequence of numbers that approximated the sample to 5000 (Love and Sing, 2013).

Research Findings

Sample Characteristics

The analysis of the NCR data revealed that a total of 19,605 rework incidents occurred in a total of 346 construction projects. This equates to a mean of approximately 57 rework incidents per project. Table 1 presents a summary and categorisation of the rework costs that were incurred by the contractor. The NCR costs presented are based on the contractor's categorisation of severity with those over $100,000 being of immediate to senior management. Over the six-year period of analysis a total of AU$88.5 million worth of rework was undertaken, which had a negative impact on the contractor's margin as a mean of AU$14.6 million per annum was forgone due to rework, which had not been anticipated to occur (Figure 1). Moreover, the contractor's profitability over the period of the analysis was reduced by a staggering 28% (Figure 1). Markedly, a significant proportion of rework events (37.45%, n=7,305) were found to not have any monetary value apportioned to them (Table 1). These costs were generally due minor defects such as the requirement for patching, painting and the like. Such costs were generally borne by the subcontractor.

Surprisingly, however, 'Category 3', which only accounted for 0.45% (n=88) of rework that was incurred, contributed to 34% of the total cost incurred. Furthermore, the 88 rework events were attributable to only 36 projects (Figure 3).



Period of analysis 2009 to 2015

Over the 6 year period of analysis, an average of $14.6 p.a million loss of profit was due to rework

Rework cost the contractor ≃ 28% of the mean yearly profit of ≃ $51 million

(This ignores indirect costs)

A total of 346 projects sampled

73% of rework events occurred in infrastructure projects

Category 1 comprised of ≃ 37% of rework events

Sub-sample of 98 projects

Median cost increase for projects was ≃ 4.3% from contract award

Mean cost increase for projects was ≃81% from contract award.

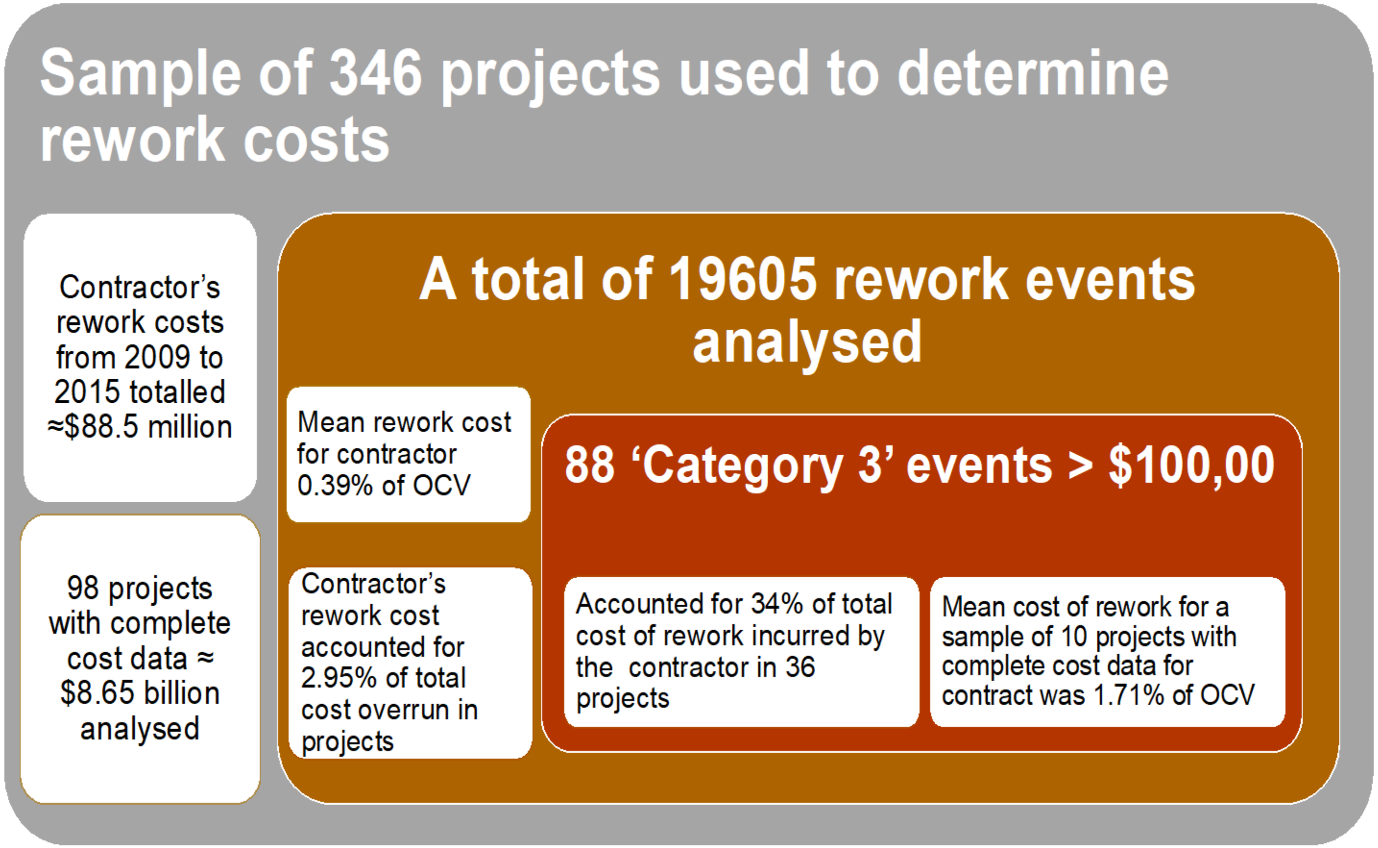
Figure 1. Dataset characteristics

Table 1. Number of rework incidents and costs for projects constructed

Categorisation	Type	Total	%	Sum ($)*	Mean $	Max. ($)	Median ($)	Min. ($)
Category 1	Negligible cost	7,305	37.45	824†	-	-	-	-
	10 to 100	421	2.16	36,541	87	100	100	15
	101 to 2,000	6,968	35.72	5,858,311	841	2,000	600	110
Category 2	2,001 to 5,000	2,231	11.44	8,476,222	3,799	5,000	3,800	2,001
	5,001 to 10,000	1,284	6.58	10,317,538	8,035	10,000	8,203	5,001
	10,001 to 20,000	728	3.73	11,502,559	15,800	20,000	15,000	10,001
	20,001 to 50,000	326	1.67	10,830,331	33,222	50,000	30,000	20,001
	50,001 to 100,000	155	0.79	11,386,169	73,459	100,000	70,182	50,500
Category 3	> 100,000	88	0.45	30,085,281	341,878	3,500,000	180,000	100,350
	Total	**19,605**	**100**	**88,493,777**				

*Australian Dollars

† While there was no cost, some items were provided with a monetary value but they were insignificant and less than $10



Sample of 346 projects used to determine rework costs

Contractor's rework costs from 2009 to 2015 totalled ≈$88.5 million

98 projects with complete cost data ≈ $8.65 billion analysed

A total of 19605 rework events analysed

Mean rework cost for contractor 0.39% of OCV

Contractor's rework cost accounted for 2.95% of total cost overrun in projects

88 'Category 3' events > $100,00

Accounted for 34% of total cost of rework incurred by the contractor in 36 projects

Mean cost of rework for a sample of 10 projects with complete cost data for contract was 1.71% of OCV

Figure 2. Rework descriptive

Sub-sample Analysis

The total of value of the work for the 98 construction projects where complete cost data was provided was approximately AU$8.65 billion. The mean OCV was $240,292,245 and the standard deviation was AU$112,211,435. In addition, the mean and the median margin were 17.89% and 8.05%, respectively. The mean cost difference between the OCV and final contract value was 81.2%, but there were number of outliers (Figure 3). A *Grubbs* test was used to detect the outliers from a Normal Distribution with the tested data being the minimum and maximum values (Grubbs, 1950).

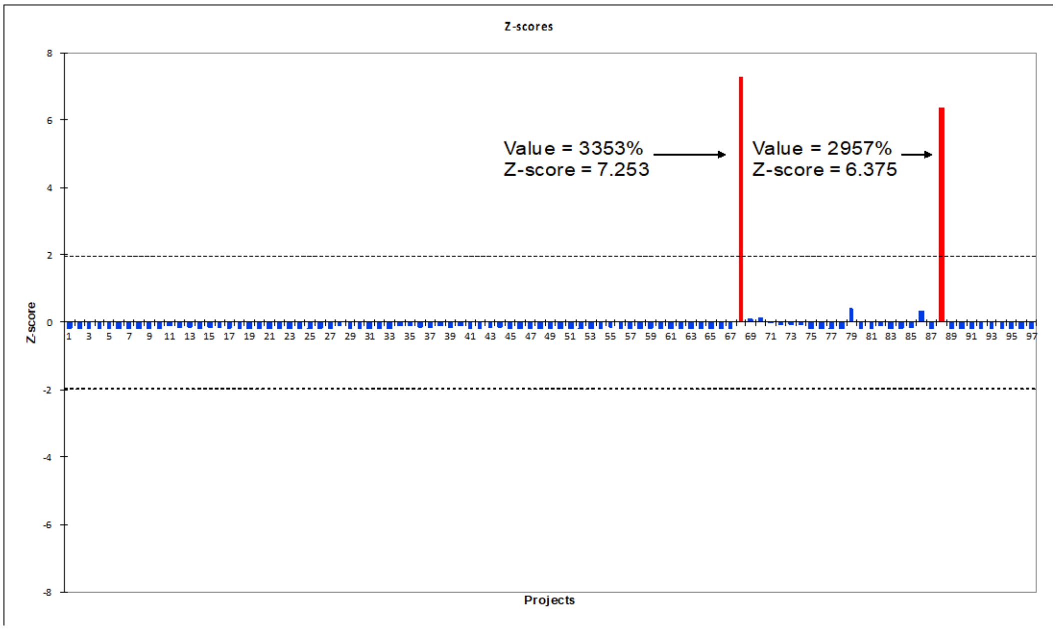


Figure 3. Determination of outliers for cost difference

The result is a probability that belongs to the core population being examined. So, if the data are approximately normally distributed, then outliers are required to have Z-scores ± 3. As denoted in Figure 3 two projects had extremely high Z-scores and were outright outliers. Considering these Z-scores the 'best-fit' distribution was determined and presented below. Importantly, the mean is not an appropriate analysis to use in this instance and therefore emphasis should be placed on the median cost difference, which was 4.3% of OCV.

A summary of the types of procurement methods used to deliver the 98 projects is provided in Table 2. Here it can be seen the most common project types were rail (n=32) and civil (n=20) and in the case of procurement methods design and construct (D&C) and construct only. A one-way Analysis of the Variance (ANOVA) was computed to determine if rework costs varied by project type and procurement method. Levene's test for homogeneity of variances was not found to be violated ($p < 0.05$), which indicates the population variances for project type and procurement methods for rework costs were equal. Thus, there were no significant differences between project types and procurement methods for reworks costs, F (42,55) = 0.208, $p < 0.05$ and F (42,55) = 1.486, $p < 0.05$, respectively. Procurement methods were categorised as 'Traditional' or 'Non-Traditional' and the ANOVA test was then repeated. It was found that Levene's test for homogeneity of variances was not found to be violated ($p < 0.05$), which indicated the population variances for the categorised procurement methods for rework costs were equal. Again, there were no significant differences found between procurement methods and rework costs F (42,55) = 1.398, $p < 0.05$.

Pearson's correlation was undertaken to determine the linear association with between project characteristics with the only significant association being identified between OCV and rework costs ($p < 0.01$). Considering this correlation, OCV was grouped as follows: (1) < AU$50m; (2) AU$50-AU$101m; (3) AU$101-AU$150m; (4) AU$151-AU$200m; and (5) >AU$200m. An ANOVA was undertaken to determine if there were significant differences between the size of the project and total rework costs. It was found that Levene's test for homogeneity of variances was violated ($p < 0.05$), which indicated that the population variances were not equal and there were significant differences between the size of a project and total rework costs. The results of a Tukey's HSD (honest significance difference) post-doc test identified that the differences were found for mean rework costs for projects over AU$200 million. Figure 4 presents a mean-plot of rework costs incurred by contract value.

Then, stepwise regression was performed to determine if project characteristics were predictors of rework costs that were experienced. The regression confirmed the correlation analysis, as OCV was identified as a predictor of the rework costs that may materialise; that is, larger projects experienced higher levels of rework costs. The regression model $R^2 = 0.96$ F (1,96) = 2566.73, $p < 0.01$. As a result of the OCV being a significant predictor of rework costs, determining the likelihood of their occurrence prior to commencement of construction can provide a contractor with additional information that is needed to be able to 'anticipate what might go wrong' and therefore put in place mechanisms to control and manage potential risks. In doing so, distribution fitting provides an ability to derive the probability that rework, *ceteris paribus*, may arise and negatively impact a profit margin.

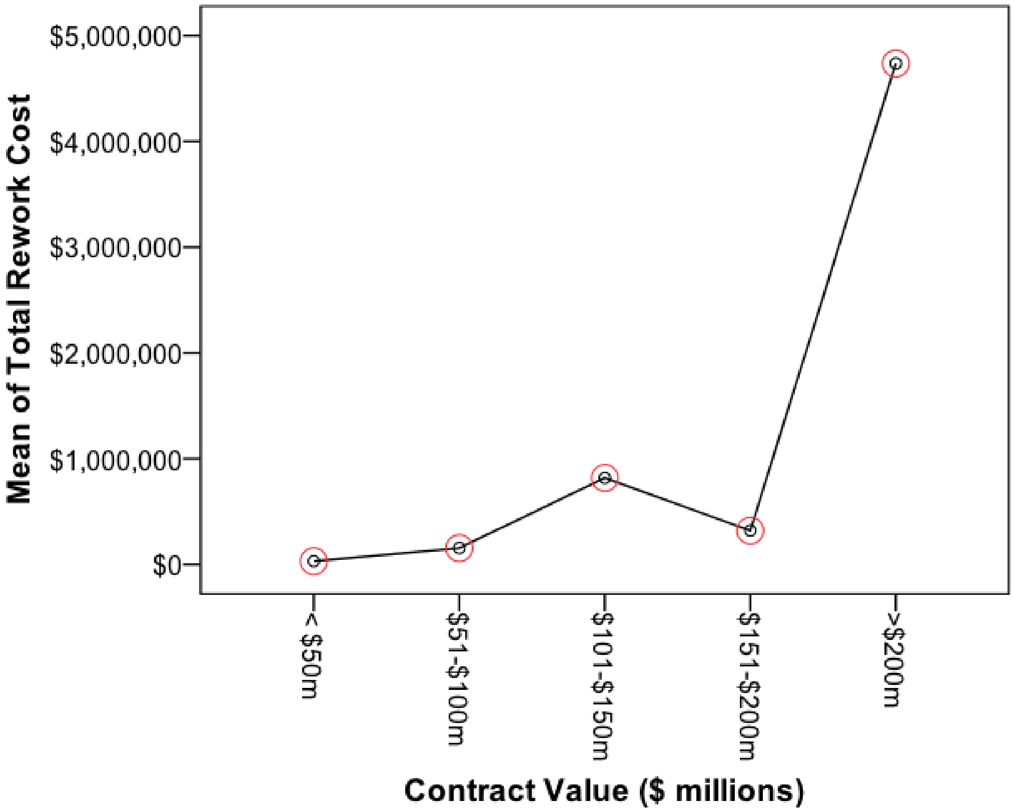


Figure 4. Mean-plot of rework costs by contract size

While rework has a negative impact on margin, it was not possible to determine the actual reduction that was incurred in a project. A considerable number of projects were issued with change orders, where an additional margin would have been included for performing this extra work.

Table 2. Types of project and procurement method used

	Procurement Method**						
Project Type	Design and Construct	Construct Only*	Construction Management	Services	EPC[#]	Management Contracting	Total
Building	4	10	1	1	-	2	**18**
Civil†	7	11	-	-	-	2	**20**
Rail	15	14	-	1	-	2	**32**
Power	1	4	-	-	-	-	**5**
Heavy Industry	3	1	-	-	3	-	**7**
Water	1	7	-	-	-	-	**8**
Tunneling	0	2	-	-	-	-	**2**
Telecommunications	2	3	-	-	-	-	**5**
Services	-	-	-	-	-	1	**1**
Total	**33**	**52**	**1**	**2**	**3**	**7**	**98**

*This term was used by the contractor, but is equivalent to TLS, ** Traditional (n=45) and Non-Traditional (n=53), #Engineering, Procurement and Construction.

†Here civil refers to roads, earthworks, drainage. Notably rail, water and tunnelling form part of civil works but have been separated in this instance

Distribution Fitting

A *Beta* was found to be the 'best-fit' distribution for rework costs incurred by the contractor. Previous research has shown that beta distribution is suitable for modelling cost uncertainty in construction projects (e.g., Riggs, 1989; Abou-Rikz *et al.*,1993). It can be used to model events that are constrained to take place within an interval defined by a minimum and maximum value and therefore is often used in scheduling to describe the time of completion and the cost of a task. Here, only costs are modelled as no scheduling information from the projects used in the study were provided. In fact, rework is akin to being 'unplanned' work, but when identified the schedule will need to be revised, particularly if it is major incident and the critical path is impacted.

The Anderson-Darling statistic A^2 was revealed to be 108.77. The Kolmogorov-Smirnov test revealed a D statistic of 0.11676 with a P-value of 0.0271 for the sample of 98 projects. Both the 'Goodness of Fit' tests accepted the H_0 for the distribution of rework costs. The domain of a Beta distribution can be viewed as a probability and can be used to describe the distribution of an 'unknown' probability. The Beta distribution is defined by the following parameters, which are all continuous: α_1, α_2 and a, b. The shape parameters are α_1 ($\alpha_1 > 0$) and α_2, ($\alpha_2 > 0$), with a, b the boundary parameters ($a < b$). The domain for this distribution is expressed as $a \leq x \leq b$. The PDF for a Beta distribution is defined as:

$$f(x) = \frac{1}{B(\alpha_1, \alpha_2)} \frac{(x-a)^{\alpha_1 - 1}(b-x)^{\alpha_2 - 1}}{(b-a)^{\alpha_1 + \alpha_2 - 1}} \qquad \text{[Eq.4]}$$

The CDF is expressed as:

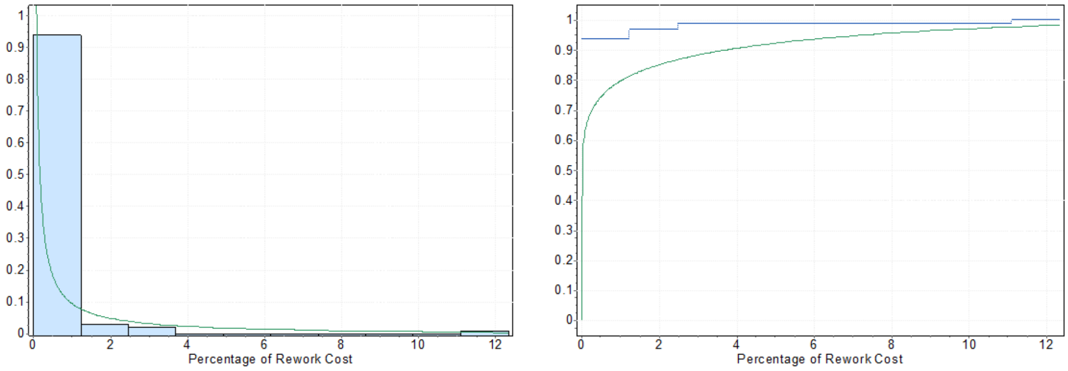
$$F(x) = I_Z(\alpha_1, \alpha_2) \qquad \text{[Eq.5]}$$

where,

$$z \equiv \frac{x-a}{b-a} \qquad \text{[Eq.6]}$$

B is the Beta Function, and I_z is the Regularised Incomplete Beta Function.

The PDF and CDF are presented in Figure 5. In this case, the parameters of the distribution are α_1=0.10064, α_2=1.8815, a=6.3264E-15, b=22.008. Using the Beta PDF, the mean and median rework costs probabilities are calculated. As the mean and median rework cost are 0.39% and 0.05% of OCV, the probability of occurrence is $\leq$ 90% and $\leq$ 59%, respectively. As the extent of rework costs occurring in construction have been indeterminate, the results presented here provide a basis for defining these parameters and engendering benchmarking. Furthermore, the Beta distribution can be extended to form a Pert-Beta, which is akin to a four parameter Beta, which is useful when considerable historical datasets exist that can be used to incorporate estimates of the minimum and maximum values.



Probability Density Function

Cumulative Density Function

Figure 5. Rework cost distributions

High Cost Rework Events

'Category 3' rework events were identified as being high cost by the contractor. As identified in Table 1 a significant proportion of the total costs that were in occurred were due to 'Category 3' events. A detail analysis of these costs is undertaken to acquire an understanding about how they had a negative impact on the contractor's profit margin. In Table 3 a summary of parties financially accountable for 'Category 3' rework events are presented. For these specific 88 events, it can be seen that the contractor was responsible for 44 of these totalling approximately AU$18.8 million (56%). While the research presented in this paper focuses on the costs borne by the contractor, it is interesting to note that subcontractors, design consultants and clients had also been responsible for rework that occurred during construction.

Seldom are designers called upon to be financially responsible for rework. Design consultants are expected to use reasonable and ordinary care in the practice of their profession and responsibilities are in part defined by *social ascription* (Grunwald, 2001). Design consultants cannot always guarantee the results of their service, their liability for errors and omissions can be determined by whether they have performed their services with the standard of care consistent with other professional designers within the community (Guckert and King, 2002). But, even when a pre-contract standard of care is agreed upon, any financial recovery may hinge on whether the error (by the designer) or an omission (not in accordance with the contract) can be proved.

The rework events that the design consultants were financially held accountable occurred under a D&C contract. In this instance, the design consultants had been contracted by the contractor for their services. In one rework incident, an engineering consultant was charged $500,000 as the structural steel frame of a building was subjected to distortion. A steel truss member had been diagonally misaligned, which had not been identified by the engineer during their shop drawing review. An investigation by an independent structural engineer revealed that this misalignment resulted in an excessive load being transferred to the truss's bottom chord.

A major road development project with a contract value of AU$480 million and delivered using a D&C procurement method experienced 13 of the 88 'Category 3' rework events. A summary of the events, denoted causes, and costs that materialised are reported in Table 4. In Table 5, ten projects with a combined total value of AU$1.3 billion that experienced 'Category 3' rework, and where complete cost data was made available, are presented.

The projects identified in Table 4 accounted for 48% of the total rework costs that were incurred over the period of analysis and 33% of the 'Category 3' events that occurred. The mean total rework cost for this sample of projects was 1.17% of OCV. It can be seen that a significant proportion of the rework costs of this major road development project accounted for 80% of the total reported in Table 4.

Table 3. A summary of parties financially accountable for ‘Category 3’ rework events

Cost	**Sub/c**	**Contractor**	**Client**	**Design Consultant**	**Total Rework Cost**
Cost ($)	10,179,237 (40%)	18,823,544 (56%)	515,000 (2%)	567,500 (2%)	30,085,281 (100%)
Number of events	38	44	2	4	88
Mean ($)	267,874	427,807	257,500	141,875.00	341,878

Table 4. Example of ‘Category 3’ type rework events for a major road development project

Event Description	**Causal Factor**	**Problem**	**Trade/ Package**	**Sub/c ($)**	**Contractor ($)**	**Total Rework ($)**
A number of bolts from different batches throughout the bridge snapped whilst being tensioned. This is against XX 78 Clause 6.4.1.3	Defective items installed	Bolts snapping	Bridgework	220,000	-	220,000
Damage to Soldier Piles (Critical Damage) against XX403 Clause 3.8.3	Inadequate supervision	Damage to new works	Piling	-	150,000	150,000
Beams produced by XX using Mix-13-Super-Workable concrete, had not been approved for use by [the contractor]. Upon inspection of the beams, pronounced lines were visible between the layers of concrete. Further investigation showed some cracking.	Unapproved concrete mix	Lines in precast concrete	Precast beams	106,683	-	106,683
In CC210 North – Area 2 twenty-six soldier piles had been cast on different dates. Once concreting was finished a 21m long liner was extracted. The concrete level then dropped down below the required cut-off level stated on the drawings.	Inadequate supervision	Concreting issues	Piling	-	304,534	304,534
Culvert - Incorrect Exposure Classification	Incorrect exposure classification	Incorrect exposure	-	-	107,000	107,000
Five girders were cast with a super workable concrete mix. Pour lines were visible on the surface which required repair to prevent moisture ingress in accordance with the precast manufacturer's approved proposal.	Unapproved concrete mix	Lines in precast concrete	Precast beams	150,000	-	150,000
Contractor noted on the [*date removed*] a number of	Equipment	Sagging	Formwork	-	999,000	999,000

deck units on the western side of BR401 appeared to have a greater than expected sag prior to the pouring of the deck slab.	failure	deck units				
Piles XXX can't achieve the set values according to the engineer's drawing and requirement.	Inadequate supervision	Insufficient strength	Piling	-	120,000	120,000
During XX construction works the following defects were observed within the cable pit drainage system. Drains collapsed or blocked - Drains not installed. Refer to attached report.	Inadequate supervision (ITP)	Drains collapse or blocked	Drainage	-	500,000	500,000
XX not compliant to XX Ch2 600 to 2 710 Lane 1:- - Level: Compliant (+-10mm PSTS40 Cl 6.4.2.) - Thickness: Non-Compliant (Exceeds upper-limit of 280mm RFI:03273 mm; Average thickness 269mm > 240mm min PSTS40 Cl 6.4.4) - 3m Straight Edge.	Non-compliance with specification	Non-compliance	Concrete	130,000	-	130,000
Procurement Package #0745 Emergency & Miscellaneous Lighting (Emergency Exit lights) supplied by XX. 1100 incorrectly specified non-maintained emergency luminaires have been purchased and supplied.	Incorrect procurement	Incorrect items specified	Emergency lighting	-	199,000	199,000
Concrete cover for steel reinforcement block pour N213 (KEC04-profile reinforced collar XP30 / Substation 06) was not compliant with the tolerances mandated as per specification and general notes.	Non-compliance with Australian Standards	Insufficient concrete cover	Concrete	-	105,000	105,000
Concrete Flexural Strength Test P630 sampled on XX did not achieve required Characteristic Flexural Strength of 4.6MPa as detailed in Section 6.3.6 of BC-PBA-GLTSP109-SPC-0001-1-02. Flexural Strength achieved was 3.9 MPa please find attached Test.	Inadequate supervision	Insufficient strength	Concrete	-	160,000	160,000
Total				**606,683**	**2,644,534**	**2,705,217**

Table 5. ‘Category 3’ events with complete cost data

				‘Category 3 costs				
Project Type	**Procurement Method**	**Contract Value ($)**	**Contractor's Total Cost of Rework ($)**	**'Cat. 3' (N)**	**Sub/c**	**Contractor**	**Design Consultant**	**Total**
Tunnelling	Design and Construct	56,964,494	286,570	1	-	120,000	-	120,000
Civil	Design and Construct	183,256,377	272,143	1	150,000	-	-	150,000
Industrial	Design and Construct	101,075,754	228,017	6	682,000	1,774,597	-	2,456,597
Industrial	Design and Construct	102,400,000	624,262	2	126,395	136233	-	262,628
Industrial	EPC	44,081,686	182109	1	20,000	80,000	-	100,000
Rail	Construct Only†	107,366,624	75,142	1	595,309	-	-	595,309
Building	Design and Construct	180,049,561	475,525	2	446,253	-	10,500	456,753
Rail	Design and Construct	15,037,635	250,160	1	-	15,000	-	15,000
Civil	Design and Construct	64,277,438	650,000	1	-	650,000	-	650,000
Civil	Design and Construct	480,000,000	12,561,056	13	60,683	2,644,534	-	2.705,217
	Total	**1,334,509,569**	**15,604,984**	**29**	**2,080,640**	**5,420,364**	**10,500**	**7,511,504****
	Mean	**133,450, 956**	**1,560,498***	**2.9**	**200,604**	**542,036**	**1,050**	**751,150**

*Mean rework cost as % contract value is 1.17%, ** Mean ‘Category 3’ as a % of total rework costs is 48.13%,

†Akin to ‘Traditional lump sum (i.e. Design-bid-construct)

Of the 88 ‘Category 3’ events, inadequate supervision was identified by the contractor as being a major contributor of rework (Table 4). Moreover, it was reported that items had been installed incorrectly on different and sometimes repeatedly on the same project. In these cases, perhaps the supervisors had failed to carry out an inspection or check items prior to their installation? This situation can arise due to insufficient resourcing. An examination of several ‘project review’ reports revealed requests for additional staff had been sought by project managers. For example, it was stated in one report that the project had been under-staffed and that there was an urgent need “to appoint a welding supervisor, three package supervisors and two more engineers to manage the […]”. The project had not been budgeted for these additional personnel. But, without them the project’s performance had the potential to be severely jeopardised as noted in the ‘project review’s’ interim risk assessment.

Table 6. A summary of contributing factors for ‘Category 3’ rework events

Casual Factor	No.
Concrete quality	3
Defective installation and/or fabrication of items	23
Design error	4
Equipment failure	2
Incorrect exposure classification	2
Lack of clarification of client/end user expectations	3
Non-compliance with Australian Standards and specifications	9
Inadequate supervision (including Inspection and Test Plan)	42
Total	**88**

Notably, three subcontract trades packages accounted for 56% of the ‘Category 3’ rework costs that were borne by the contractor. These were: (1) steelwork including structural components (n=20,23%); (2) concrete (n=17,19%); and (3) piling (n=12,14%). These subcontract trades tend to occur during the formative stages of construction, yet the use of skeleton on-site management teams during a project’s start-up was often identified as recurrent problem by staff of the contracting organisation.

Causal factors, such as those identified in Table 5, however should *not* be considered to be independent, but rather interdependently. For example, a rework event can arise due to installing a defective item, which may have occurred due to there being a design error that may have gone unnoticed as a result of inadequate supervision. As mentioned at the commencement of this paper, it is outside of its scope to examine the issue of causation, but strategies put in place to manage and control the risk of rework will need to take a systemic perspective with particularly attention being given to a project's constraints (Williams *et al*., 1997; Ackermann *et al*., 2007; Rahmandad and Hu, 2010; Parvan *et al*., 2015).

6.0 Discussion

Rework is a significant factor that adversely impacts the productivity and performance of construction organisations and their projects. Rework is a 'known-unknown' during the production process of construction but is often ignored as a risk prior to the commencement of construction. It can, however, be anticipated but has not been able to be accurately quantified as construction organisations have not been able to capture information about its causes and costs in a systematic manner. The upshot being construction organisations are unaware of the full impact that rework is having on their bottom-line. In striving to be able to quantify rework costs the research presented in this paper has undertook the first longitudinal and in-depth study of direct rework costs that arose at the frontline of construction.

Admitting that rework is a problem, is the first step a construction organisation needs to take to address this issue. Denial and concealment of rework has been the weapon of first choice for many managers for fear of being personally blamed or incurring company reputational damage, with the second providing excuses for its occurrence. But, denial and excuses bring managers no closer to solving the problem. A lack of knowledge, is however, the biggest barrier to change. So, as a starting point, the research presented in this paper can provide construction organisations with an insight into the real rework costs borne by a contractor and provide the impetus for them to actively confront the problem that prevails practice. The rework costs presented can be used for the purposes of operational benchmarking and engendering a continuous improvement strategy to reduce rework while concurrently improving safety and minimise environmental impacts of construction.

The emergence of digitisation has rapidly introduced different ways wherein construction organisations can add-value to their business proposition by enabling the collation of data in real-time. But, the biggest opportunity for construction organisations lies in their ability to become the custodians of information derived from the accumulated number of projects that they deliver. Being in a position to better understand the nature and likelihood of varying types of risks that threaten project performance, such as rework, can enable construction organisations to move them from a position of being a 'known-unknown' to become a 'known-known'. Enabling managers to be able to 'anticipate what might go wrong' and ensure that risk management and controls are being put in place throughout the construction process that will contribute to their dynamic capability. Embracing digitisation can enable contractors to better manage their information management landscape so that they are able to prioritise risks to mitigate rework. The emergent knowledge can therefore be used to engender reflective practice and learning, which is core to improving productivity and performance of construction organisations and their projects.

The key to reducing the effects of the rework problem is the establishment of datasets that can be drawn upon from numerous projects to effectively utilise the computed Beta-distribution (or Pert-Beta) so as to make rational decisions at the commencement and during the execution of a project about the probability of rework and its impact on cost and schedule. In addition, by simultaneously reviewing data from multiple projects, data mining can be enacted enabling project managers to be able to identify precursors of rework (Browning and Ramaesh, 2015). By having access to data, 'known-unknowns' such as rework costs can be converted through a process, which Browning and Ramaesh, (2015) refer to as *directed recognition,* to being a 'known-known'.

7.0 Conclusions

Rework is a 'known-unknown', but there has been a high degree of uncertainty surrounding its costs. Such uncertainty occurs as there has been a proclivity for the costs associated with rework to be largely ignored, concealed or considered to be normal function of operations by construction organisations.

To address this issue, the research presented in this paper sought to shed light on the direct costs of rework that occur in construction projects and determine how they can negatively impact an organisations profitability. Relying on sample of 19,605 rework events derived from 346 construction projects delivered by a contractor between 2009 and 2015, it was revealed that their mean yearly profit over the period of analysis was reduced by a staggering 28%. In addition, 88 (0.45%) rework events accounted for 34% of the total costs that were incurred. Complete cost data for 98 projects with a combined value of AU$8.65 billion, which included their original and final contract value, and margin and rework costs were made available for further analysis. The mean rework cost for the contractor was found to be 0.39% of contract value. The 88 high cost rework events, which all exceeded AU$100,00, are analysed and a context of the costs that were incurred is provided.

The research provides invaluable insights into the actual direct costs that have been borne by a contractor. Previous studies have been unable to provide such an in-depth analysis of direct costs as data has been often difficult to obtain due to issues of commercial confidentiality. However, the contractor that participated in this research was motivated to address a problem that has gone unaddressed and share their data to initiate benchmarking and enable dialogue and stimulate further research in this fertile area of inquiry. Not only should future research seek to enact a process of benchmarking of direct rework costs but also those of an indirect nature. Understanding the nature of rework costs will provide a platform for the establishment of strategies to reduce and contain rework during construction.

References

Abou-Rikz, S.M., Halpin, D. and Wilson, J. (1993) Fitting beta distribution based simple data. *ASCE Journal of Construction Engineering and Management*, **120**(2), pp.288-305

Ackermann, F., Eden, C., Williams, T. and Howick, S. (2007). Systemic research assessment: A case study. *Journal of the Operational Research Society*, **58**(1), pp. 39-51.

Banwell, H. (1964). *The Placing and Management of Contracts for Building and Civil Engineering Works*. The Banwell Report, HMSO, London, UK

Barber, P., Sheath, D., Tomkins, C., and Graves, A. (2000). The cost of quality failures in major civil engineering projects. *International Journal of Quality and Reliability and Management*, **17**(4/5), pp.479–492

Barker, M. (2016). Statisticians issue warning over misuse of P values. *Nature*, **531**(7593)

Bowersox, D.J. Carter, P.L., and Monckza, R.M. (1985). Materials logistics management. *International Journal of Physical Distribution and Logistics Management*, **23**(5), pp.46-51.

BRE (1981). *Quality Control on Building Sites*. Paper 7/81, Building Research Establishment, Garston, UK

Browning, T.R. and Ramasesh, R.V. (2015).Reducing unwelcome surprises in project management. *MIT Sloan Management Review*, Spring,pp.53-62

Burati, J.L., Farrington, J.J., and Ledbetter, W.B. (1992). Causes of quality deviations in design and construction. *ASCE Journal of Construction Engineering and Management*, **118**(1), pp.34–49.

Burroughs, G. (1993). *Concrete Quality Assurance: The Contractor's Role*. Quality Assurance in the Construction Industry, Concrete Institute of Australia, September, Melbourne, Australia

CIDA (1995). *Measuring Up or Muddling Through: Best Practice in the Australian Non-Residential Sector Construction Industry*. Construction Industry Development Agency (CIDA) and the Master Builders Association, Sydney, Australia

COAA (2006). *Project Reduction Rework Tool*. Canadian Owners Association of Alberta (COAA), Retrieved from: https://www.coaa.ab.ca/library/project-rework-reduction-tool/, Accessed 11th February 2018.

Crawshaw, D.T. (1976). Co-ordinating Working Drawings. Building Research Establishment, Current Paper (CP)60/76, Watford, UK

Cnudde, M. (1991). *Lack of quality in construction – economic losses*. Proceedings of the European Symposium on Management, Quality and Economics in Housing and other Building Sectors. 30th September – 4th October, Lisbon, Portugal, pp.508-515.

Davis, K., Ledbetter, W.D., and Burati, J.L. (1989). Measuring design and quality costs. *ASCE Journal of Construction Engineering and Management*, **115**(3), pp.385-400.

Ding, L-Y., Li, K., Zhou, Y. and Love, P.E.D. (2017). An IFC-inspection process model for infrastructure projects: Enabling real-time quality monitoring and control. *Automation in Construction*, **84**, pp.96-110.

Forcada, N., Gangolells, M., Casals, M. and Macarulla, M. (2017). Factors affecting rework costs in construction. *ASCE Journal of Construction, Engineering and Management*, **143**(8), 04017032

Ford, D. and Sterman, J. (2003). The lairs club: Concealing rework in concurrent development. *Concurrent Engineering: Research and Applications*, **11**(3), pp.167-182.

Fry, H, S., Ketteridge, and S. Marshall. (1999). *A Handbook for Teaching and Learning in Higher Education*, Glasgow: Kogan Page.

Gardiner, J. (1994). Management of design documentation: Where do we go from here? In Wakefield, R. and Carmichael, D.G.(Eds.) *Construction and Management: Recent Advances*, pp.113-118

Grubbs, F.E. (1950). Sample criteria for testing outlying observations. *Annals of Mathematical Statistics*, **21**(1), pp.27-58.

Grunwald, A. (2001). The application of ethics to engineering and the engineer's moral responsibility: perspectives for a research agenda. *Science and Engineering Ethics*, **7,** pp.415-428.

Guckert, D., and King, P. (2002). Who pays for architect's mistakes. *Facilities Manager*, Retrieved from: https://www.facilities.uiowa.edu/infolibrary/WhoPaysForArchitectsMistakes(APPASepOct02).pdf, 21st February, 2018

Han, S., Love, P.E.D., Pena-Mora, F. (2013). A system dynamics model for assessing the impacts of design errors in construction projects. *Mathematical and Computer Modelling,* **57**(9/10), pp. 2044-2053

Hwang, B-G., Thomas, S.R, Haas, C.T. and Caldas, C.H. (2009). Measuring the impact of rework on construction performance. *ASCE Journal of Construction Engineering and Management*, **135**(3), pp.187-198.

Hwang, B-G., Hao, X., and Goh, K. J. (2014). Investigating the client-related rework in building projects: The case of Singapore. *International Journal of Project Management*, **32**(4), pp.698–708.

Ireland, V. (1985). The role of managerial actions in the cost, time and quality performance of high rise commercial buildings. *Construction Management and Economics*, **3**(1), pp.59-87.

Jaafari, H., and Love, P.E.D. (2013). Quality costs in construction: The Case of the Qom Monorail project in Iran. *ASCE Journal of Construction Engineering and Management*, **139**(9), pp.1244-1249.

Josephson, P-E., and Hammarlund, Y. (1999). The causes and costs of defects in construction: A study of seven building projects. *Automation in Construction*, **8**(6), pp.681-642.

Josephson, P.-E., Larson, B., and Li, H. (2002). Illustrative benchmarking rework and rework costs in the Swedish construction industry. *ASCE Journal of Management in Engineering*, **18**(2), pp. 76–83.

Love, P.E.D. (2002). Influence of project type and procurement method rework costs in building construction projects. *ASCE Journal of Construction Engineering and Management*,**128**(1), pp.18-29.

Love, P. E. D., and Li, H. (2000a). Quantifying the causes and costs of rework in construction. *Construction Management and Economics*, **18**(4), pp.479–490.

Love, P.E.D., and Li, H. (2000b). Overcoming the problem associated with quality certification. *Construction Management and Economics*, **18**, pp.139-149.

Love, P.E.D., and Irani, Z. (2003). A project management quality information system for the construction industry. *Information and Management*, **40**(7), pp.649-661.

Love. P.E.D. and Edwards, D.J. (2005). Calculating total rework costs in Australian construction projects. *Civil Engineering and Environmental Systems*, **22**(1), pp.11-27.

Love, P.E.D., and Sing, C-P. (2013). Determining the probability of rework costs in construction and engineering projects. *Structure and Infrastructure Engineering*, **9**(11), pp.1136-1148.

Love, P.E.D., Skitmore, R.M., and Earl, G. (1998). Selecting a suitable building procurement method. *Construction Management and Economics*, **16**(2), pp.221-233.

Love, P.E.D., Smith, J., and Li, H. (1999). The propagation of rework benchmark metrics for construction. *International Journal of Quality and Reliability Management*, **16**(7), pp.638-658.

Love, P.E.D., Irani, Z., and Edwards, D.J. (2004). A rework reduction model for construction projects. *IEEE Transactions on Engineering Management* **51**(4), pp.426-440.

Love, P.E.D., Edwards, D.J., and Smith, J. (2016). Rework causation: Emergent insights and implications for research. *ASCE Journal of Construction Engineering and Management* **142**(6) 10.1061/(ASCE)CO.1943-7862.0001114

Love, P.E.D., Teo, P. and Morrison, J. (2018a). Re-visiting quality failures in construction. *ASCE Journal of Construction and Engineering Management,* **144**(2), (ASCE)CO.1943-7862.000142

Love, P.E.D., Teo. P., Ackermann, F., Smith, J., Alexander, J. and Palaneeswaran, E. (2018b). Reduce rework, improve safety: An empirical inquiry into the precursors of error in construction. *Production Planning and Control*, **29**(4), pp.

Low, S.P., and Yeo H.K.C. (2004). A construction quality costs quantifying system for the building industry. *International Journal of Quality and Reliability Management*, **15**(3), pp. 329-349.

Moore, P. (2012). Contractors confront the growing costs of rework. *Engineering News Record.* Retrieved from: https://www.enr.com/articles/2338-contractors-confront-the-growing-costs-of-rework?v=preview, accessed 15th February 2018

Naoum, S.G. (1994). Critical analysis of time and cost management and traditional contracts. *ASCE Journal of Construction Engineering and Management*, **120**(4), pp.

Nylén, K.G. (1996). *Costs of Failure in a Major Civil Engineering Project.* Licentiate Thesis, Division of Construction Management and Economics, Department of Real Estate and Construction, Royal Institute of Technology, Stockholm, Sweden.

O'Connor, J.T. (1985). Impacts of constructability impact. *ASCE Journal of Construction, Engineering and Management*, **111**(4), pp.404-410

Parvan, K. Rahmandad, H., and Haghani, A. (2015). Inter-phase feedbacks in construction projects. *Journal of Operations Management*, **39-40**, pp.48-62

Rahmandad, H. and Hu, K. (2010). Modelling the rework cycle: Capturing multiple defects per Task. *System Dynamics Review*, **26**(4).pp.291-315.

Riemer, J.W. (1979). *Hard Hats*. Sage Publications, Beverly Hills, CA.

Riggs, L.S. (1989). Numerical approach for generating beta random variables. *ASCE Journal of Computing in Civil Engineering*, **3**(2), pp.183-91.

Robinson-Fayek, A., Dissanayake, M., and Campero, O. (2004). Developing a standard methodology for measuring and classifying construction fieldwork. *Canadian Journal of Civil Engineering* **31**(6), pp.1077–1089

Sörqvist, L. (1998). *Poor Quality Costing*. PhD Thesis, No.23., The Royal Institute of Technology, Department of Materials Processing Production Engineering, Stockholm, Sweden.

Taggart, M, Koskela, L., and O'Rourke, J. (2014). The role of the supply chain in the elimination and reduction of construction rework and defects: an action research approach. *Construction Management and Economics*, **32**(7/8), pp.829–842.

Tang, S.L., Aoieong, R.T., and Ahmed, S.M. (2004). The use of process cost model for measuring quality costs in construction projects: Model testing. *Construction Management and Economics*, **22**(3), pp.263-275.

Walker, D.H.T. (1995). An investigation into construction time performance. *Construction Management and Economics*, **13**(3), pp263-274.

Wanberg, J., Harper, C., Hallowell, M., and Rajendran, S. (2013). Relationship between construction safety and quality performance. *ASCE Journal of Construction Engineering and Management*, **139**(10), (ASCE)CO.1943-7862.0000732

William, T.M, Ackermann, F. and Eden, C. (1997). Project risk: systemicity, cause mapping and a scenario approach. In: Kahkonen K and Artto KA (Eds). *Managing Risks in Projects*. E&FN Spon, London, pp 343–352.

Willis, T.H., and Willis, W.D. (1996). A quality performance measurement system for industrial construction engineering projects. *International Journal of Quality and Reliability Management*, **13**(9), pp.38-38.

Ye, G., Jin, Xia, B. and Skitmore, R.M. (2015). Analysing the causes for reworks in construction projects in China. *ASCE Journal of Management in Engineering,* **31**(6), (ASCE)ME.1943-5479.0000347