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Re-visiting Quality Failure Costs in Construction

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Case Study

Abstract: Quality failure costs have been reported to range from less than 1% to over 20% of a project's original contract's value (OCV). Inconsistencies in their definition and determination have rendered such costs often being cited inappropriately to support a case for poor quality in construction. In this paper, quality failure costs, which are expressed in the form of non-conformances (NCRs) costs, are derived from 218 projects delivered by a contractor between 2006 and 2015. A total of 7082 NCRs costs are categorized and quantified and the differences between project types, procurement and contract size are statistically examined. The analysis revealed that: (1) mean NCR costs were 0.18% of OCV; (2) structural steel and concrete subcontracted works had the highest levels of NCRs; (3) differences were found in the cost of NCRs between procurement methods and contract size; and (4) NCRs had an adverse impact on profitability. The research provides the international construction community with an invaluable insight into the 'actual costs' of quality failure that have been borne by a contractor. Thus, the paper makes a call to reinvigorate the need to engage with benchmarking so as to engender process improvement throughout the international construction industry.

Keywords: Concrete, non-conformances, profitability, quality failures, structural steel

Introduction

For several decades, quality failures have been identified as a significant and recurring problem in construction projects (e.g., Carper 1987; Burati *et al.* 1992; Abdul-Rahman 1993; Abdul-Rahman 1995; Willis and Willis 1996; Barber *et al.* 2000; Hwang *et al.* 2009; Love *et al.* 1998; Love *et al.* 2016b; Teo and Love, 2017). The adverse consequences of quality failures have been widely espoused, which include damage to reputation, loss of productivity, reduced profitability, and an increase in safety incidents (Love *et al.* 2016b). According to the

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Productivity Commission (2016) in Australia, for example, productivity levels have been declining and in construction industry, a negative growth in multifactor productivity of -2.3% and labour productivity -0.8% occurred in 2014-15 (p. 8). The frequent occurrences of quality failures limit the growth in the output of goods and services of the construction sector, which has been outpaced by increases in its inputs of capital and labour (Richardson 2014).

The cost of quality failures that have been previously reported in the literature vary from less than 1% to over 20% of a project's contract value (e.g., Abdul-Rahman 1993; Willis and Willis 1996; Josephson and Hammarlund 1999; Love *et al*. 1999; Love and Li 2000a,b; Barber *et al*. 2000; Josephson *et al*. 2002). Such costs, however, have been often equivocally cited, particularly as a multitude of different terms that have been used interchangeably (e.g., deviations, defects, NCRs, and rework) to denote quality failures (Love and Edwards, 2005). The 'actual' failure costs that are borne by contractors generally have not been made explicit in the literature. It has been observed that only a fraction of the quality failure costs incurred in a project are borne by contractors and form part of its cost (Love *et al*. 1999). This observation has been reinforced by Barber *et al*. (2000) who perceptively noted that rework will be "recognized by the contractor, only if the client had itself identified the need for correction or where the contractor was in a position to make a claim for additional payment from the client related to extra work or against one of their sub-contractors or suppliers." (p.482).

Considering this observation and the disparity that exists between the approaches that have been used to calculate quality failure costs (Davis *et al*. 1989; Low and Yeo 1998; Rogge *et al*. 2001; Love and Irani 2003; Robinson-Fayek *et al*. 2004; Tang *et al*. 2004), it is suggested that the reported figures should be considered with prudence. In fact, there is a danger that they have become a factoid, as no context and caveat is provided when they are cited. But more specifically, there have been a limited number of fieldwork studies in the last ten years that have examined quality failure costs (e.g., Jaafari and Love, 2013). Nevertheless, the quality cost figures presented in studies such as Burati *et al*. (1992), Love and Li (2000a) Robinson-Fayek *et al*. (2004) and Hwang *et al*. (2009) have been consistently acknowledged to highlight quality-related problems within construction projects despite differences in calculation.

Generally, NCRs will require additional work to be undertaken to rectify the non-conforming product to ensure it complies with the required specifications, unless the NCR is classified as a deviation that is within the acceptable threshold stipulated within the specifications. The rectification process of an NCR is referred to as *rework*. Love (2002a) has defined rework as the "unnecessary effort of redoing a process or activity that was incorrectly implemented the first time" (p.19). This definition is all-encompassing and includes design changes and errors that result in the rectification of works during construction. In this instance, costs arising from rework may be claimed by a contractor from a client, subcontractor or designer, according to the explicit contractual terms and conditions, depending on who is responsible for the rework. Contrastingly, Robinson-Fayek *et al*. (2004) refer to rework as the 'total direct cost of re-doing work in the field regardless of initiating cause' and specifically exclude change orders and errors due to off-site manufacture (p.1078).

It is widely accepted by contractors that quality failures are a ubiquitous problem, but they have been reluctant to publicize the 'actual' costs they incur due to commercial and legal reasons as well as the potential adverse impact on their reputation (Teo and Love 2017). If, however, headway is to be made toward mitigating quality failures and for organizational learning to effectively occur, then there is a need to better understand their nature so as to initiate a process of industry-wide benchmarking. The Egan Report (1998), in the UK, for example, which became a beacon for worldwide reform for the construction industry, highlighted the problems of quality and subsequently called for a 20% reduction in rework. But, almost 20 years on, and with the benefit of hindsight, there has been a lack of benchmarking data made available to contractors, which has resulted in many being faced with a quandary about 'what' and 'how' to go about improving their operations to achieve such a set target.

This paper utilizes an exploratory case study to present the 'actual' quality failure costs that were incurred in 218 construction projects, with particular emphasis being placed on a contractor's operations. The quality failure costs are quantified from NCRs that were formally raised and the differences between various project types are examined. In this research, NCRs that result in rework do not include: (1) approved project scope changes initiated by or errors in information supplied by the client; (2) design changes or errors that do not affect field construction activities; and (3) off-site supplier/subcontractor errors that are corrected off-site and do not affect field construction. Contributory factors identified within the contractor's quality management system (QMS) are also analysed.

At this juncture, it is important to note that Love *et al*. (2016b) have been particularly critical of analysing singular causal factors. However, in this case the authors present what was actually logged in the contractor's QMS as a cause. The case study findings saliently demonstrate that there is a need to revisit and clarify the reporting of quality failure costs within construction. While the results presented are limited to a homogenous dataset, the authors' preliminary investigations with other Australian contractors, indicate that they are comparable. Consequently, the findings provide an invaluable platform to begin to initiate a process of benchmarking, which can be undertaken nationally and internationally and therefore stimulate the much-needed process improvement within the construction industry.

Quality Costs

Quality refers to conformance to requirements or specifications (Juran 1974; Crosby 1979). Quality is defined by ISO 9001:2015(E), 3.6.2 as the "degree to which a set of inherent characteristics of an object fulfils requirements". The cost of quality comprises of both the cost of conformance (i.e. prevention and appraisal costs), and NCR (i.e. internal and external failure cost) (Feigenbaum 1991). Examples of prevention costs include the cost of implementation of a quality system and process control, quality planning, and quality training (Ittner 1996). Appraisal costs involve costs related to the testing, verification, validation, audits and inspection of materials and products. Failure costs are classified as internal when rectification is required on an error or defect before the product is handed over to the client, and external failure when the product has left the organization and is no longer under its control (Love and Li 2000b). Quality performance can only be improved if costs of failure or NCRs are measured and managed. The identification of costs and causes of quality failure can provide the management with information about process failures so as to prevent their future occurrences. For a detailed review of the process associated with quality costing refer to Campanella (1999), Tang *et al*. (2004) and Rosenfeld (2009). A summary of reported quality failure costs, or variants thereof that have emerged in the literature, are provided in Love *et al*. (2016b).

Quality failures, in this paper are aligned with NCRs which are a non-fulfilment of, or deviation from the agreed specifications or requirements. Love and Edwards (2005) have identified that NCRs arise due to failure, errors, deviations, defects, omissions, and damage. Failure represents an unacceptable difference between expected and observed performance (Leonards 1982) such as a structural failure of a beam or column or a critical defect (Drdácký 2001, p.181). An error refers to the incorrect execution of an activity resulting in non-conformances with specification (Burati *et al*. 1992). A deviation refers to a product that does not fully conform to the specified design requirements (Davis *et al*. 1989), whereas a defect is a deviation of a severity sufficient to require corrective action (Burati *et al*. 1992). Defects can be considered as flaws that are introduced through lack of quality workmanship, poor design, manufacturing, fabrication, or construction, which may not be apparent during the construction stage and surface during operations and maintenance (Nicastro 2010).

Case Study

Exploratory research is undertaken to examine a problem that has not been clearly defined and invariably relies upon secondary data (Shields and Rangarjan 2013). When the purpose of research is to gain familiarity with a phenomenon or acquire new insight to formulate a more precise problem, exploratory studies are a justifiable approach to adopt (Babbie 2007). Recognizing the need to better understand the quality failure costs, the researchers approached a contracting organization that had been involved with various others studies to participate in the research. The contractor acknowledge that quality failures were a problem within the industry and also observed that their occurrence resulted in safety being compromised. In addition, participation in the research was conditional on commercial confidentiality and anonymity being given. On agreement, the contractor provided the researchers with access to a dataset of 218 projects that had incurred NCRs from 2006 to 2015. The dataset contained a vast array of rich information such as direct NCR costs, type and description, the reported cause, type of project, contract value and change-orders. However, the dataset contained no information regarding indirect costs and liquidated damages associated with NCRs. A total of 16,811 NCRs from the 218 projects were recorded. The analyses were categorized according to the following project types: (1) building, (2) infrastructure, and (3) rail.

Research Findings and Analysis

An NCR can be attributed to a contractor, subcontractor, designer or client, or a combination of different parties depending on the source of the non-compliance. The cost associated with rectifying an NCR includes: (1) materials, plant and equipment, labour, supplier/subcontractor; (2) administration; (3) re-design; (4) procurement of rectification works; (5) demolition, waste disposal, and transport costs; (6) time delays; and (7) supervision, inspection and re-testing. The cost of NCRs was broken down and apportioned to each of the respective parties. This enabled the contractor's cost of rectification to be determined. The total NCR costs recorded were AU$76,233,999. Fig. 1 identifies that the contractor was responsible for 50% of the costs to rectify NCRs that occurred, which amounted to a total of AU$38,047,786 (n=7,082). Not all

NCR or deviations from specified requirements will necessarily result in rework. The analysis revealed that 3,142 (44%) of the NCRs were assessed as 'used-as-is', which were found to be approximately AU$5.08 million. If concessions for the 'used-as-is' had not been granted, then the cost of NCRs to the contractor may have been significantly greater.

Subcontractors were found to be responsible for 43% of rectification costs, which totalled AU$32,985,079. Designers and clients were only responsible for 7% of the overall costs of rectification. In a commercial high-rise building project for example, a distortion occurred in its structure due to a misalignment of a diagonal truss member. During the review of the shop drawings, the engineer failed to recognise the excessive load that had been transferred to the trusses bottom chord. The affected components of the steel structure were removed and replaced. This oversight resulted in a rework cost of approximately AU$1 million being borne equally between the engineer and subcontractor.

Analysis of NCR Cost Categories

NCR costs varied significantly, from '< AU$10' to '> AU$100,000'. The NCRs were categorised into nine cost categories to enable a more detailed level of exploration and analysis. The severity of NCRs was determined by the cost of rectification and categorized as follows:

- Type 0: < AU$10
- Type 1: AU$11 - AU$100
- Type 2: AU$101 - AU$2,000
- Type 3: AU$2,001 - AU$5,000
- Type 4: AU$5,001 - AU$10,000
- Type 5: AU$10,001 - AU$20,000
- Type 6: AU$20,001 - AU$50,000
- Type 7: AU$50,001 - AU$100,000
- Type 8: > AU$100,000

Fig. 2 illustrates the number of NCRs in each cost category. Those '> AU$100,000' comprised of the lowest number (0.67%), but accounted for 34% of the total costs incurred. This is in stark contrast to the NCRs that occurred in the 'AU$101 to AU$2000' category, which comprised of the largest proportion (54%), yet only 7% of the total cost. Table 1 identifies a significant proportion of the costs of rectification experienced by the contractor were attributed to NCRs '> AU$100,000' (39.43%), which consisted only 0.64% of their total number. Pareto analysis illustrates that 83% of NCR costs contributed to only 17% of the total number that occurred (Fig. 3). The contractor's NCR dataset was not categorized by subcontract trades. This hindered the researchers' ability to individually categorize each NCR. Since NCRs '> AU$100,000' accounted for the largest proportion of their total cost (34%); 77 NCRs in this category totalled AU$26 million, NCRs in this cost category were examined in greater detail.

Interestingly, subcontractors were responsible for a greater share of the rectification costs (i.e., 56% of the total cost of NCRs '> AU$100,000'), as compared to the contractor who incurred 40%, whilst the client and designer incurred a total of 4%. NCRs '> AU$100,000' were categorized into the respective subcontract trades to provide an understanding the trades likely to result in costly NCRs. Fig. 4 provides the percentage of 'Type 8' NCRs based on their subcontract trade and the total costs incurred. Structural steelwork (34%) and concrete (21%) were identified as subcontract trades where significant rectification costs arise. The mean and total cost of 'Type 8' NCRs by subcontract trade is presented in Fig. 5. Structural steelwork incurred the highest NCR costs (AU$8.84 million), followed by concrete (AU$5.45 million) and pipework (AU$2.62 million). Pipework had the highest mean NCR cost, followed by formwork, and structural steelwork.

Contributory Factors

From 2013, projects began to record contributory factors that resulted in an NCR having to be issued as part of a process to understand why margins in their projects were being adversely impacted. A total of 31 types of contributory factors were recorded for 2,249 NCRs totalling AU$16,318,560. Pareto analysis was undertaken to determine key contributory factors that require greater attention and priority. From the dataset, contributory factors were ranked in descending order in terms of their NCR cost and frequency. In Fig. 6 it can be seen that 80% of NCR occurrences were attributed to nine contributory factors: (1) Inspection and Test Plans (ITP)/process control (19.7%); (2) procedural compliance (15.4%); (3) subcontractor management (9.1%); (4) work method error or violation (8.9%); (5) design (8.6%); (6) incorrect methodology (7.8%); (7) materials availability and suitability (5.5%); (8) equipment/material handling error or violation (2.3%); and (9) experience/knowledge/skill for task (2.2%). In addition, six factors were revealed to have contributed to 82% of the total cost of NCRs: (1) subcontractor management (34.4%); (2) ITP/process control (18.8%); (3) design (13.9%); (4) incorrect methodology (6.1%); (5) work method error or violation (4.7%); and (6) supervisory error or violation (4.6%) (Fig. 7).

The Safety, Quality and Environment risk management process of the contractor required an Activity method statement (AMS) to be developed for medium and high risk activities, to ensure that the correct methodology, equipment and resources were in place prior to the commencement of works. Based on the AMS methodology, Safe Work Method Statements and Standard Operating Procedures provide logical step-by-step procedures that need to be undertaken by work crews, if they are to successfully execute processes ‘right the first time’ and assign responsibilities for tasks.

While adhering to such procedures and supervision can provide assurance that work is undertaken correctly, the contractor has minimal control over an individual’s actions or inactions within a work crew. To ensure that work and processes were carried out in accordance with requirements and standards ITPs were developed (e.g., compaction and bolt assembly testing). An ITP is a single document that identifies the materials and work to be inspected or tested at specified witness and hold points. They act as checkpoints to verify the quality of completed work. Further work cannot proceed without the approval or release of the hold point. For example, steel reinforcement is required to be inspected and certified by an engineer prior to concrete being poured. In the next section of this paper, subcontract trades that were issued the most NCRs in the 218 projects sampled are examined.

Subcontract Trades

Structural steelwork and concrete were identified as the main trades that contributed to a significant proportion of the total cost of ‘Type 8’ NCRs. Within this ‘> AU$100,000’ category, the cost of a concrete NCR ranged between AU$120,000 and AU$875,000. A total of AU$4.5 million ‘Type 8 NCRs’ and AU$4 million for structural steelwork and concrete, respectively, were directly borne by the contractor. Given the frequent occurrences and significant cost impact to the contractor, a focus on improving concrete and structural steelwork construction processes will enable an improvement to the overall quality performance and productivity of the contractor. NCRs were examined further to identify common underlying contributory factors for concrete and structural steel.

Structural Steelwork

Structural steelwork incurred the highest mean and total cost of rectification. From the influence diagram in Fig. 8, three major issues can be identified from the NCRs: (1) defective quality of the fabricated structural steelwork; (2) misalignment of components; and (3) welding defects and non-compliances. In addition, the key contributory factors causing these defects were: (1) subcontractor management; (2) incorrect fabrication; (3) design error; and (4) ITP/ process control. If a project consists of large proportion of structural steelwork and given the costliness of these NCRs, then it is important to implement processes to reduce the impact of rework caused by these contributory factors. For example, in a new port facility project, there were approximately AU$3.6 million structural steelwork NCRs, attributed to the subcontractor. Contrastingly, in another marine works project that involved the expansion of an existing wharf terminal, the contractor bore the cost of AU$3.5 million to attend to structural steelwork NCRs.

Poor workmanship was identified as a recurring issue with subcontractors, which included: poor finish quality, insufficient coating thickness and coverage, non-conforming welds, and corroded steelwork. There were also numerous cases where fabricated steelwork procured from overseas, were delivered defective and thus did not conform to the specified quality. For example, several shipments of roadway frames and trusses were delivered with defective structural welds and coating defects. This defective work initially cost the contractor approximately AU$68,536 to handle the damage and coating defects for the conveyor trusses shipment that was later charged to the subcontractor.

Another major cause of NCRs was the incorrect fabrication of steelwork, which was not in accordance to the design requirements (e.g., incorrect hole size, wrong dimensions, and misalignment of cleats, bolts and plates). This was observed on several occasions to be the responsibility of subcontractors who committed errors during the fabrication process or had referred to superseded revisions of construction drawings.

Design errors were also a contributory factor to NCRs as demonstrated in the case of the commercial building described above. An error in the alignment of a diagonal truss member was not identified and caused structural distortion to the permanent steel structure. This resulted in a major rework cost of AU$1 million to replace the structural members, and was claimed against the subcontractor and designer. It was observed from the NCR descriptions that failures to comply with ITPs/ process control were common and in many cases, incorrect installation and welding defects were reported. In addition, welding defects such as the use of non-compliant materials and their failure were also a frequent occurrence.

In terms of structural steelwork, there needs to be greater focus on ensuring the accuracy of detailing, and fabrication is according to the latest revision. Common issues leading to NCRs being raised for structural steelwork were associated with: (a) truss fabrication; (b) bolts and cleats position, orientation, centres, hole centres and size errors; (c) paint damage and defects; and (d) welding failure and defects.

Concrete

The common types of concrete NCRs were identified and are presented in Fig. 9. There were four main factors contributing to NCRs: (1) failure to comply with ITP/ process control; (2) incorrect methodology/materials; (3) work method error or violation; and (4) lack of procedural compliance. Failure to follow ITPs/ process controls can lead to incorrect finished levels (or out of tolerance) for various structures, such as, piles, slabs, walls and invert levels. For instance, in a slab pour, concrete was not placed in accordance to the levels detailed in design drawings, resulting in a shortfall of 17mm in the 'as-built' reduced level, and causing delay to subsequent works. Adhering to process control is critical to reduce problems during concrete placement, such as blockage of tremie pipe, insufficient vibration and compaction, and concrete contamination.

In the case of materials and methodology, there were instances where subcontractors used unapproved and incorrect concrete pre-mixes, and incorrect methodology which resulted in NCRs being raised due to insufficient concrete cover, inadequate grouting and non-complying strength. There were also several occurrences of errors that led to set-outs being incorrect. Even when subcontractors followed the required work method, errors and/or violations can affect the quality of casted in-situ concrete, which resulted in voids and honeycombing, crack lines, and uneven surface of finished concrete being experienced. In particular, key issues related to the raising of a NCR for concrete included:

- poor finish quality (e.g., cracks, honeycombs, roughness, voids and cavities);
- failure of slump test;
- issues during concrete pour and placement;
- finished concrete levels out of tolerance or misalignment (e.g. slab);
- the required compressive and flexural strength were not achieved; and
- usage of incorrect concrete mix.

Quality Failure Costs

To assess the impact that quality failures had on a project's cost performance, the proportion of NCRs as a percentage of their original contract value was calculated. This cost excluded NCRs due to client's change orders and subcontractor's defects. The percentage of NCR cost could only be calculated for 68 of the 218 projects as only their contract values were made available for analysis. However, the statistical analysis of this sample is considered robust with ±10% margin of error at 95% confidence level (Hulley *et al.* 2001).

The mean percentage of contractor's NCR cost was 0.18% of their original contract value. Majority of the contractor's NCR costs were less than 1% of contract value. Only 4 out of the 68 projects were over 1%. It is noted that the NCR costs quantified did not include indirect costs and liquidated damages. Research undertaken by Love and Li (2000a) found that in a project that experienced a total of 3.15% rework costs, those that were actually attributable to the contractor was 0.14%. In another study, Love and Li (2000b) found that actual cost of rework to a contractor for nine out of a sample of 14 projects to be less than 0.4% of contract value (civil, building, rail and marine projects). Fig. 10 represents the range of percentages (minimum and maximum) for civil, building, rail and marine projects from the case study and those presented in Love and Li (2000b). It can be seen that the contractor performed better in building projects with the percentages of between 0% and 0.06% of contract value, but marginally poorer in the other areas. While the sample sizes are significantly different, as are the contractual and business environments, this comparative analysis enables a provisional form of benchmarking to be undertaken.

Statistical analysis was undertaken to determine if there was a significant difference between the mean percentage NCR costs across different project types using a Kruskal-Wallis test. The sample of 68 projects comprised of seven types of project: (1) civil; (2) building; (3) power; (4) rail; (5) heavy industry; (6) water; and (7) telecommunications. Fig. 11 illustrates the range of percentage of NCRs cost for each project type. Heavy industry (comprised of marine and mining projects) had a higher percentage of NCR costs with a mean of 0.6% of the contract value. Building and water projects incurred the lowest percentage of NCR cost. The two civil project outliers were the construction of an elevated crossing (AU$170 million) and supply base facility (AU$110 million), with NCR costs of 1.16% and 1.01% of their original contract value, respectively. The majority of civil projects experienced NCR costs of less than 0.50% of their original contract value. For building projects, the construction of a hospital (>AU$1 billion) and information technology centre (AU$60 million) were the two outliers with 0.04% and 0.06% respectively. The percentage of NCR costs as a percentage of their original contract value for rail projects were generally less than 0.30%, except for a rail revitalization project, which was 1.44%. Notably, in the heavy industry projects, the design and construct of a new loading facility comprising (AU$140 million) had incurred the highest NCR cost as a percentage of its contract value at 2.22%.

Statistical analysis revealed that there is a significant difference in the mean percentage of NCR cost between different project types. The Kruskal-Wallis test results yielded a value of 0.00, ($\chi^2(6)=25.159$, $p=0.00$) and demonstrated a statistically significant difference in the mean percentage of NCR cost between the different project types. Fig. 12 and 13 identify the mean and range of percentage of NCR cost for each type of project, respectively. Fig. 12 identifies that heavy industry has the highest mean of 0.60%, followed by civil 0.26%, then rail 0.16%, power 0.14%, telecommunications 0.10%, building 0.02% and lastly water 0.01%.

A Kruskal-Wallis test revealed that there is a significant difference in the mean total NCR cost between different procurement methods ($\chi^2(7)=18.669$, $p=0.009$). In particular, higher NCR costs were found to have been incurred in PPP projects, as noted in Fig. 14. The projects were categorized according to their contract value; (1) 'small' (< AU$20 million) (2) 'medium' (AU$20 million to AU$100 million); (3) 'large' (>AU$100 million). In Fig. 15, the mean NCR cost for 'large' projects were substantially higher in comparison with the other categories. A Kruskal-Wallis test indicated that a significant difference existed in the mean total NCR cost between project size categories ($\chi^2(2)=35.519$, $p=0.00$).

Impact of Quality Failures

The direct costs of NCRs attributed to the contractor for 38% of the projects amounted to AU$38 million over the period. However, these direct costs did not account for cost related to costs that are indirect in nature; supervision, planning, resourcing, risk mitigations, administration, rescheduling, investigations, procurement of materials/equipment, delays and program disruption leading to liquidated damages. There has been a paucity of research that has sought to determine the indirect costs of rework in construction. According to Love (2000b) their determination is an arduous task, but nevertheless it was observed during the rectification of an event that costs were six times greater than their initial installation. Hypothetically, if this figure is applied to the contractor's 218 projects in this study, then the 'estimated' indirect cost of the NCRs incurred, *ceteris paribus*, would have been in the region of AU$228 million. If the estimated actual costs are taken into account as well, then the total NCR cost per annum could have been AU$26.6 million. Notably, this excludes costs and time due to safety incidents/accidents that can arise when attending to an NCR event (Teo and Love, 2017).

The contractor's pre-tax profit for the financial period of analysis was approximately AU$437 million, which equates to a mean of AU$51.4 million per annum. Taking into account both the direct and indirect cost of NCRs, the mean yearly profit of AU$51.4 million could have potentially increased by AU$26.6 million. In this instance, the potential pre-tax profit could have been AU$663 million. The purpose of the aforementioned exercise is to simply demonstrate that NCR costs of less than 1% can have a significant impact on a contractor's medium to long-term profitability.

As previously mentioned, prior quality failure studies have tended not to differentiate between those parties responsible for costs that are incurred. Clients or their representatives are generally responsible for initiating change-orders and thus responsible for such costs. Changes in scope, errors and omissions in documentation have been identified as the main contributors rework costs that arise. Emphasis, therefore, needs to be placed on reducing such change orders arising from the design process. This, however, has been and remains a perennial problem, despite the emergence of Building Information Modelling (BIM), which has been advocated as a solution for reducing design changes and errors and reducing rework (Sacks *et al* 2010a,b). Observations from the dataset of projects provided indicated that change-orders during construction significantly contributed to cost increases being incurred in projects that been delivered using BIM to Levels of Development 300 to 500. In the projects that were utilizing BIM, the changes-orders that materialized were predominately due to scope changes, and in many instances resulted in rework being undertaken during construction; these costs were excluded from the analysis and their responsibility lay with the client and/or design team.

Conclusions

Quality failures can significantly impact the profitability of contractors. While there has been a considerable amount of research that sought to quantify such costs, differences in their determination and definition have resulted in report figures being used out of context. This has hindered the ability for effective benchmarking, and which has been exacerbated by contractors being reluctant to share quality failure cost due to issues of commercial confidentiality and the potential impact on their reputation. However, if the construction industry is to improve its quality performance, it is imperative that contractors share their experiences so that a process of external benchmarking can be engendered and industry-wide process improvement initiated.

In this paper, the cost of 7,082 non-conformances from 218 projects were analysed and quantified. The analysis revealed that the contractor (50%) and subcontractor (43%) were required to bear the rectification cost of NCRs. In addition, NCRs '> AU$100,000' only comprised 0.67% of the total number, but accounted for 34% of the total costs incurred. Structural steel and concrete were identified as being main subcontracted works that were prone to increased non-conformance levels.

The mean NCR cost as a proportion of a project's original contract value was calculated to be 0.18%. Differences between NCR costs between project types, procurement methods and project size were examined. In contrast to previously reported research, it was revealed that differences in NCR costs exist between procurement methods and project size. NCR costs were found to be higher in projects procured using Public Private Partnerships and greater in those with a contract value in excess of AU$100 million. Public Private Partnerships are typically used to deliver large capital works and are prone to having larger quantities of steel and concrete, where the subcontract trades are susceptible to non-conformances.

The research has also unearthed the financial impact of non-conformances on the contractor's pre-tax profitability over the period of analysis, which was estimated to be in the region of AU$226 million. It would be unreasonable to assume that all NCRs can be prevented, but even if NCR costs were reduced by 50%, the future additional profit would be significant. Future research is required to examine in greater detail the circumstances that contribute to steel and concrete works being issued with non-conformances. Indeed, these are labour intensive activities and supervision is paramount, but perhaps with the increasing shift toward prefabrication and mechanization, alternative forms of materials and construction methods can be considered. Needless to say, the analysis presented provide the international construction community with an invaluable insight into the 'actual costs' of quality failure that have been borne a contractor. With this in mind, a call is made for similar studies to be undertaken so as to stimulate the process of benchmarking.

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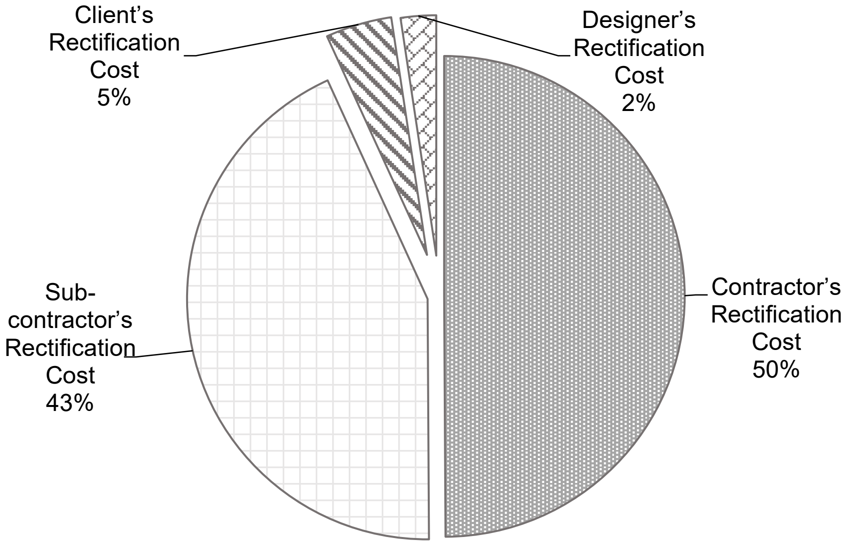

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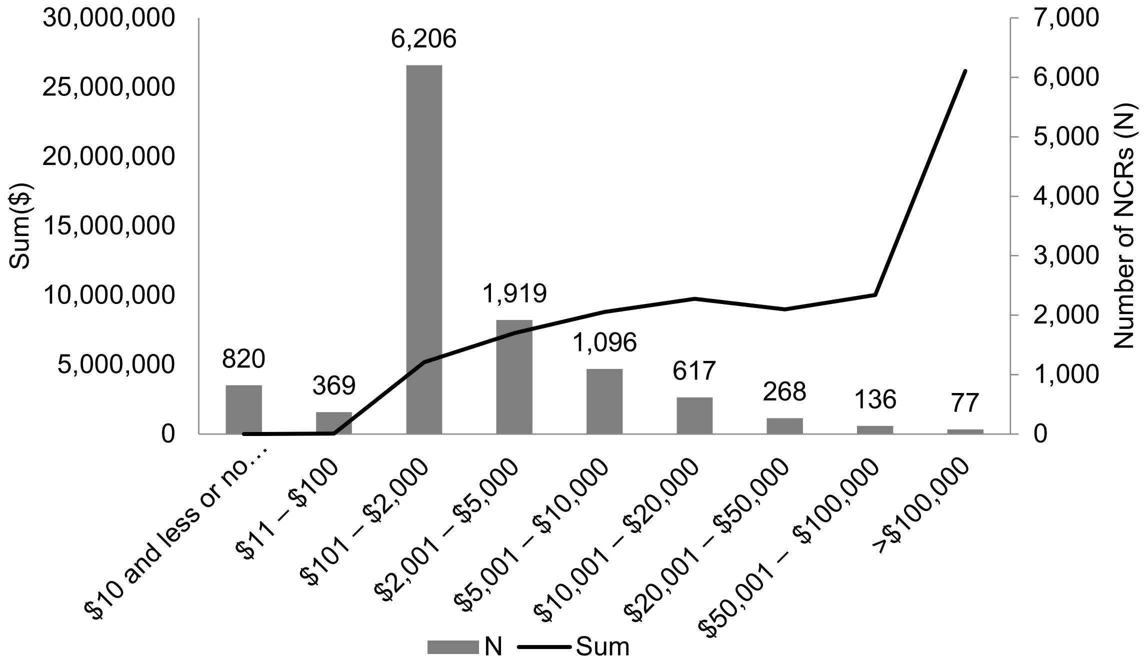

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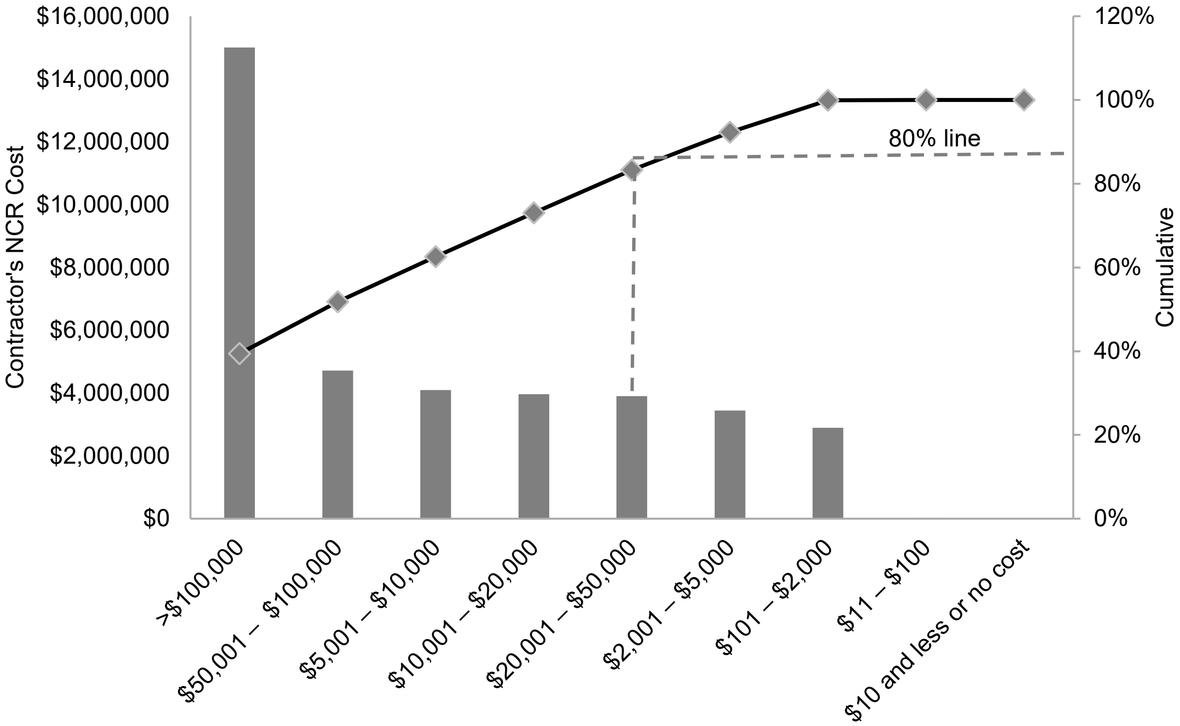

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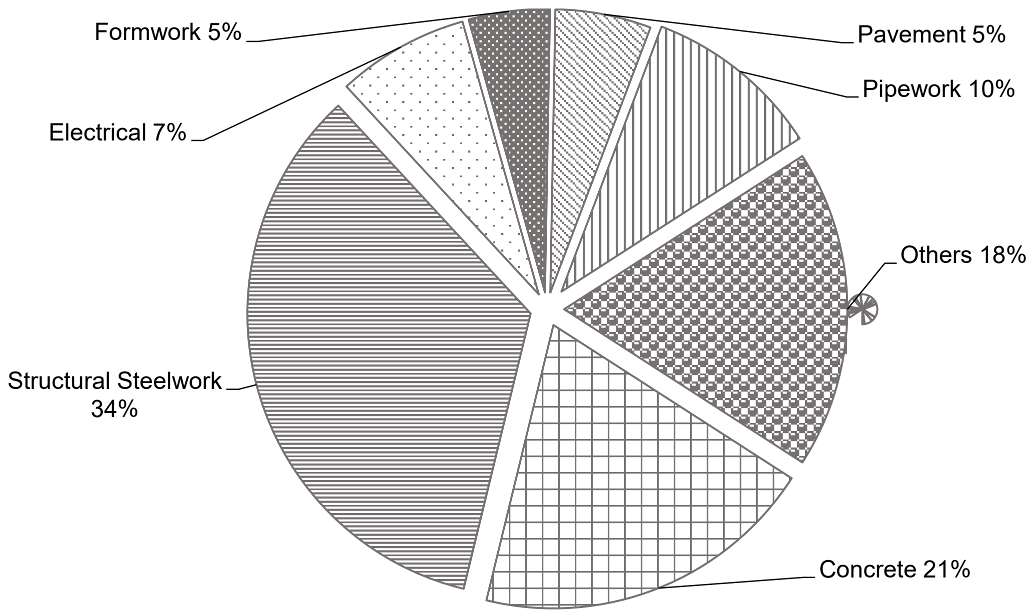

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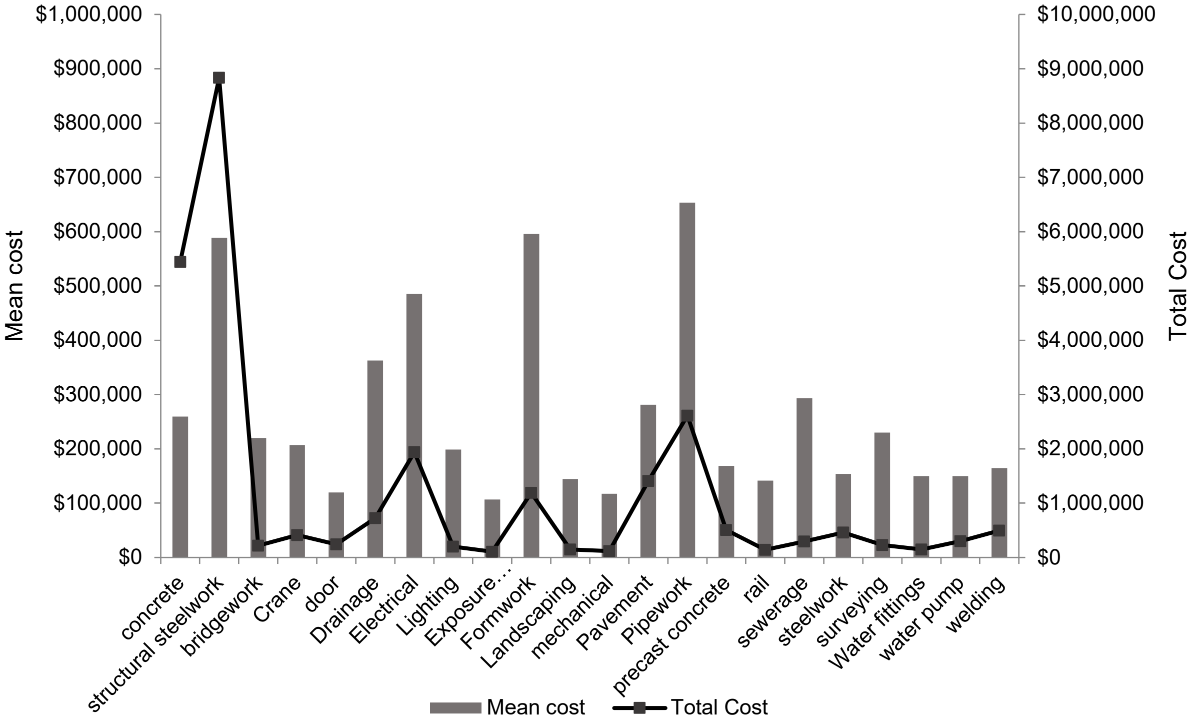

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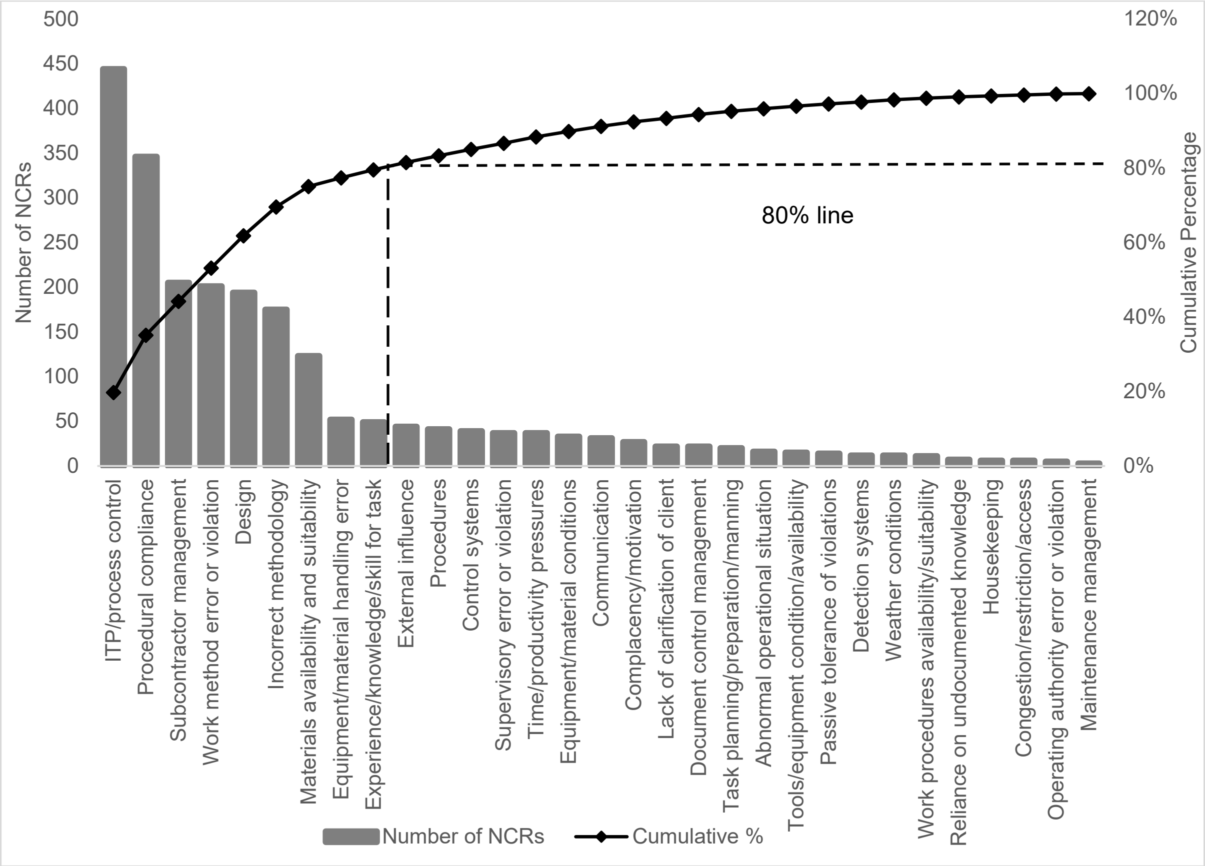

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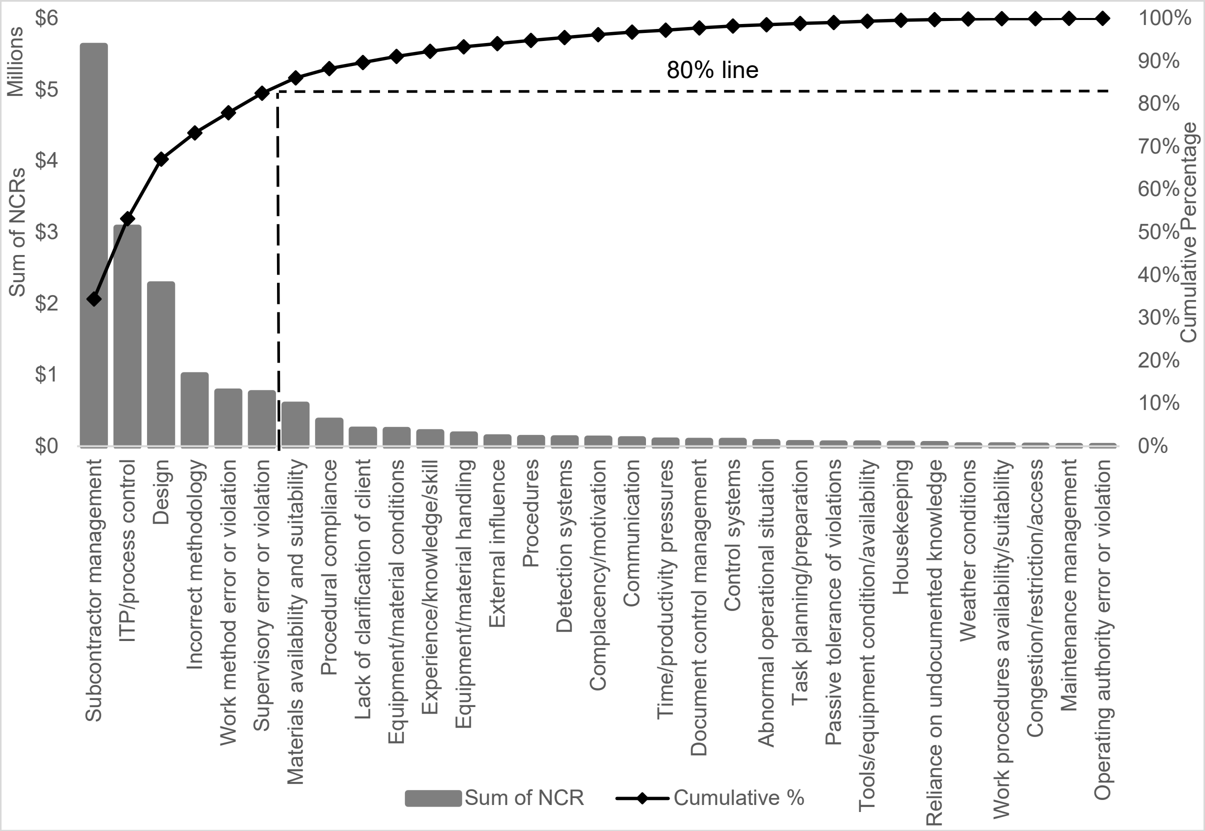

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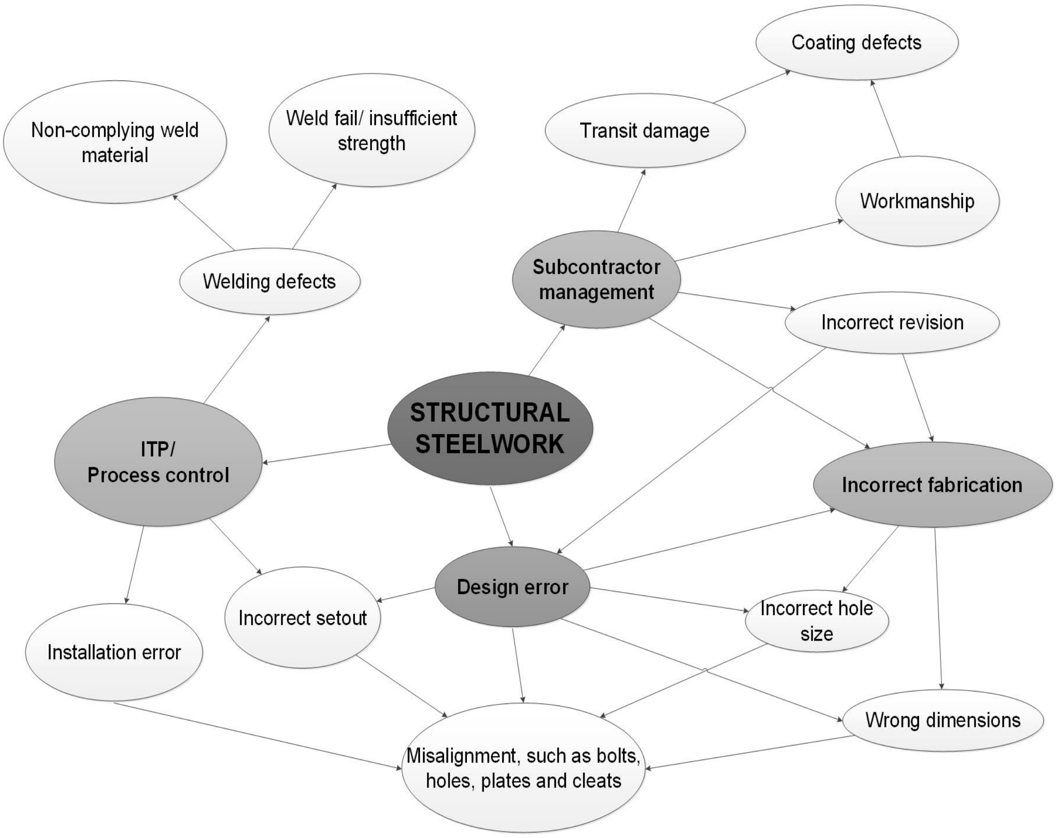

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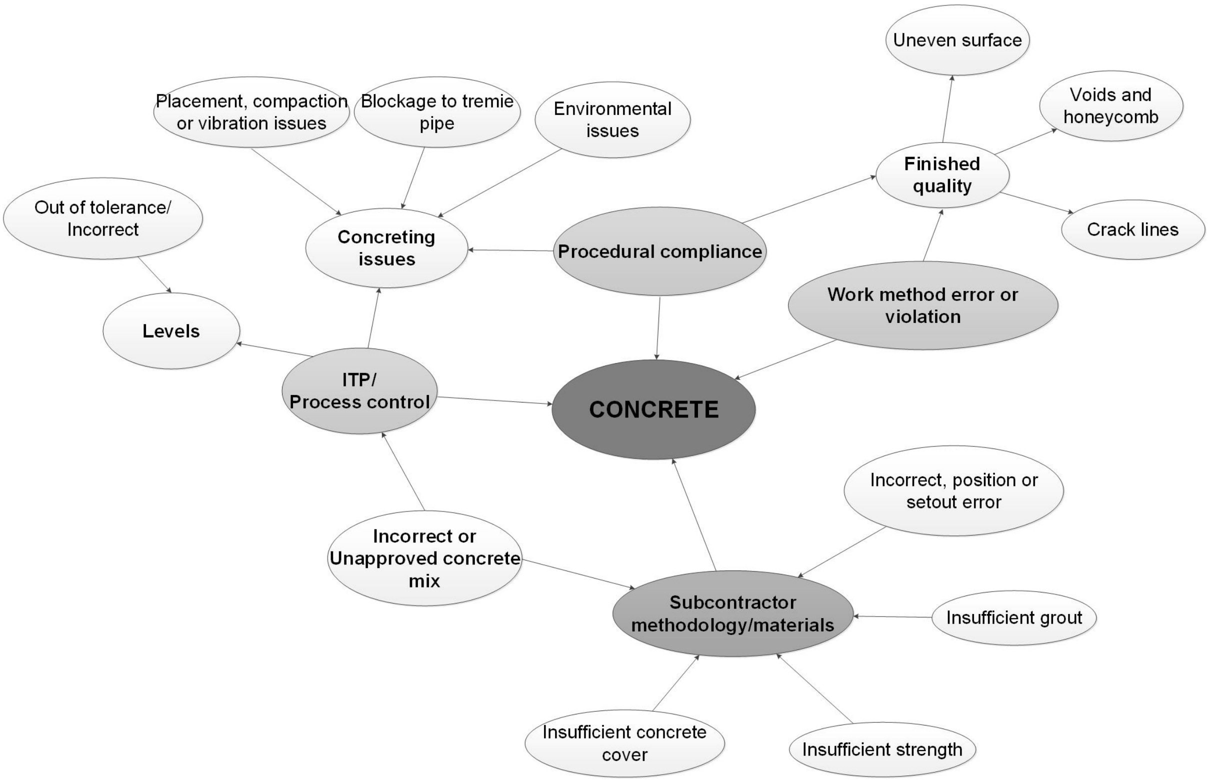

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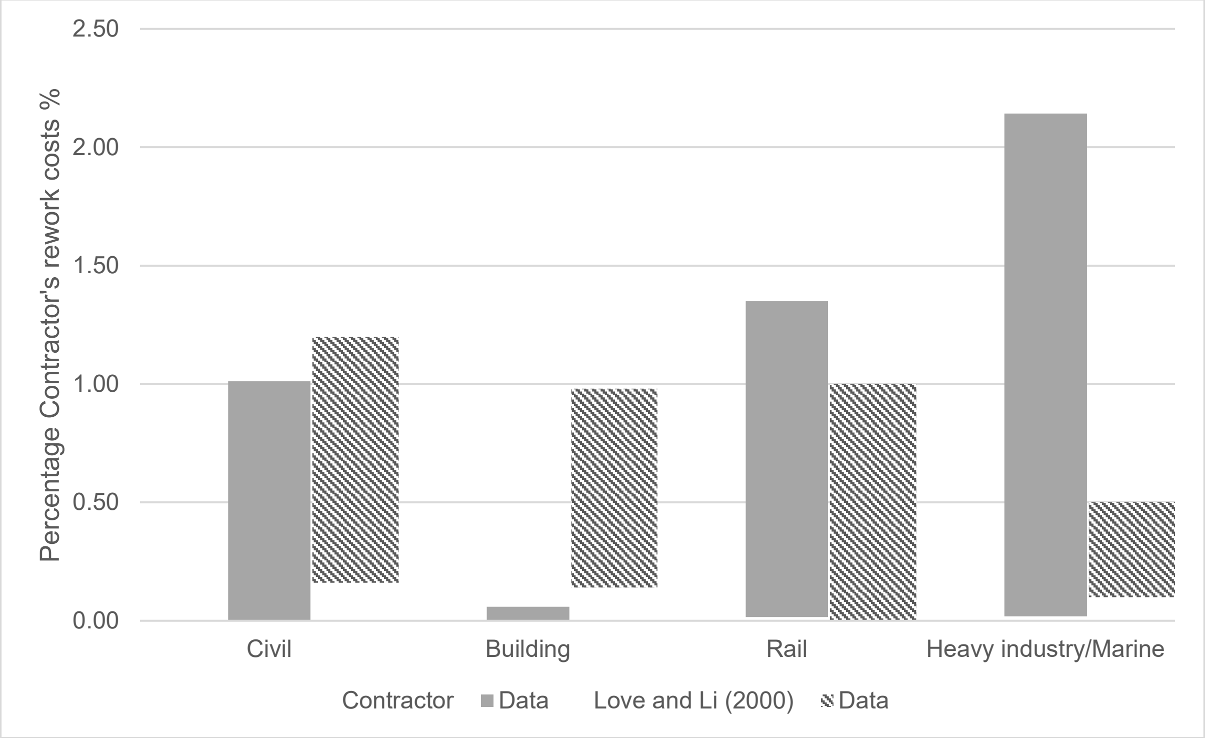

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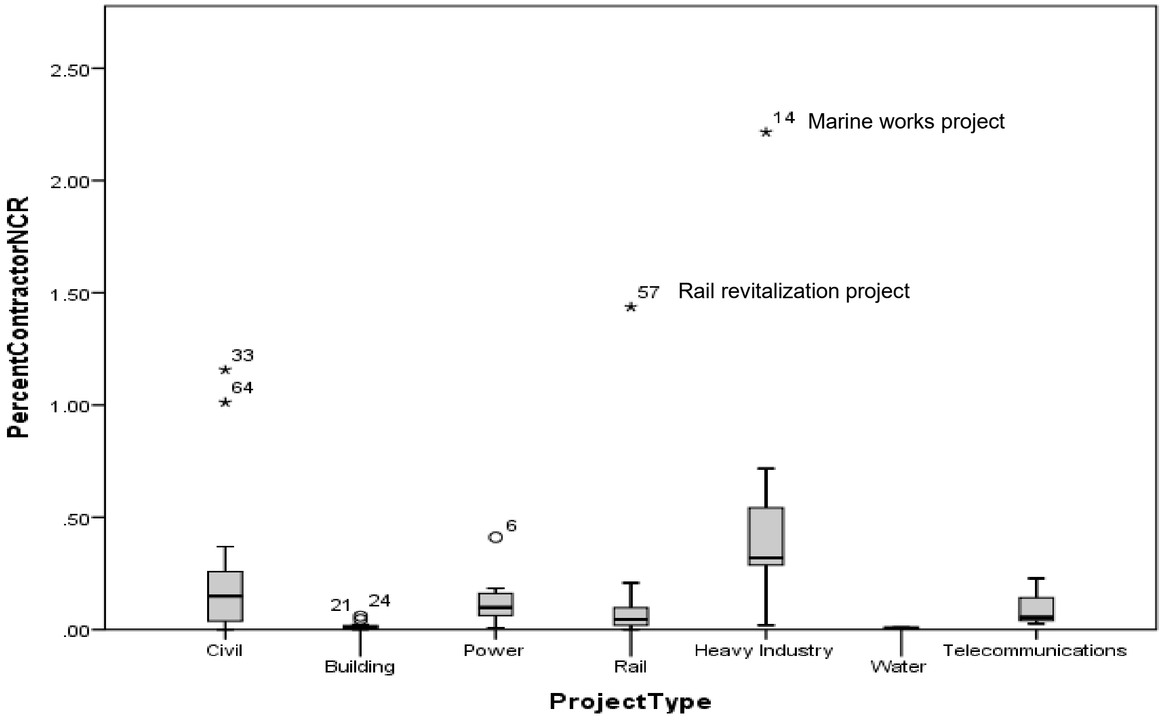

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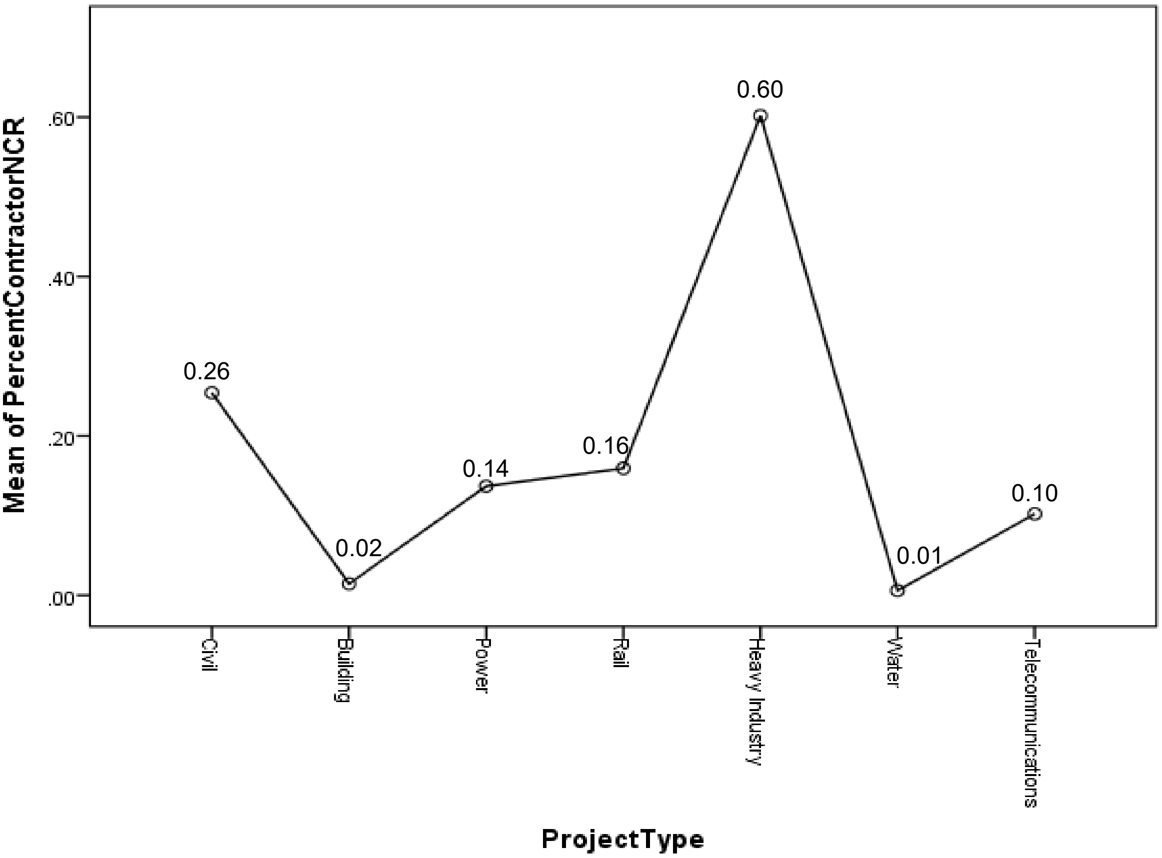

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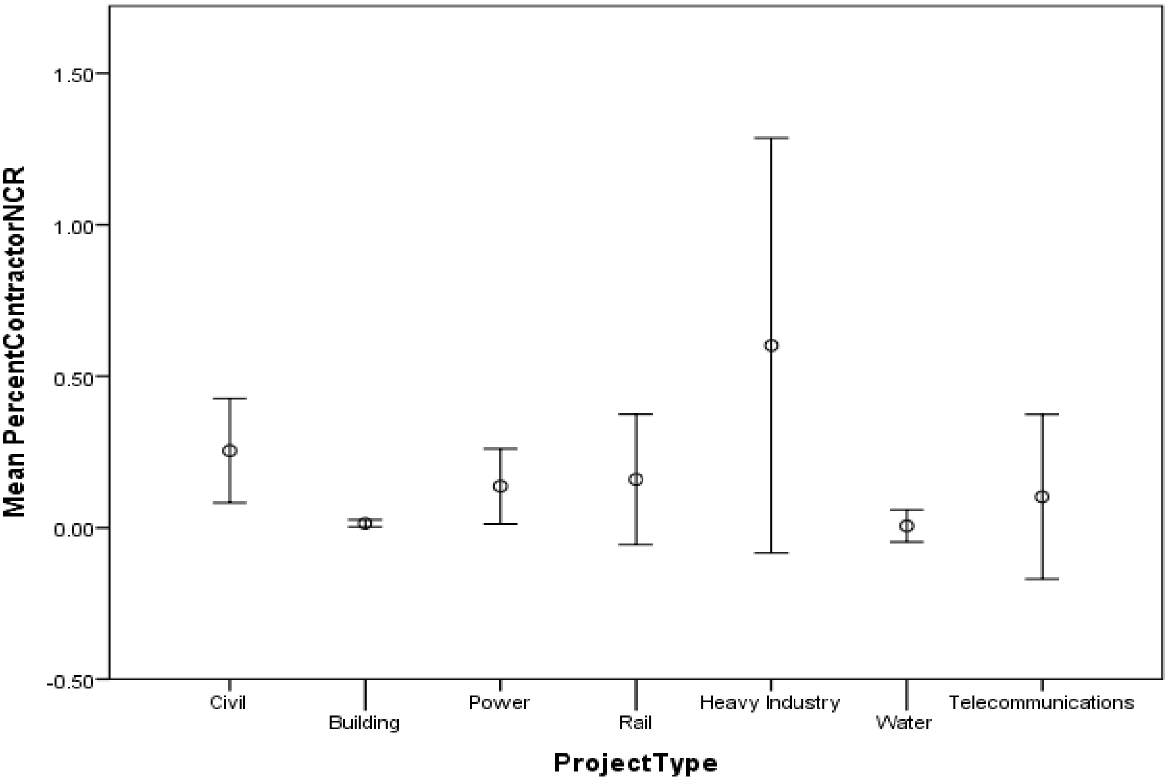

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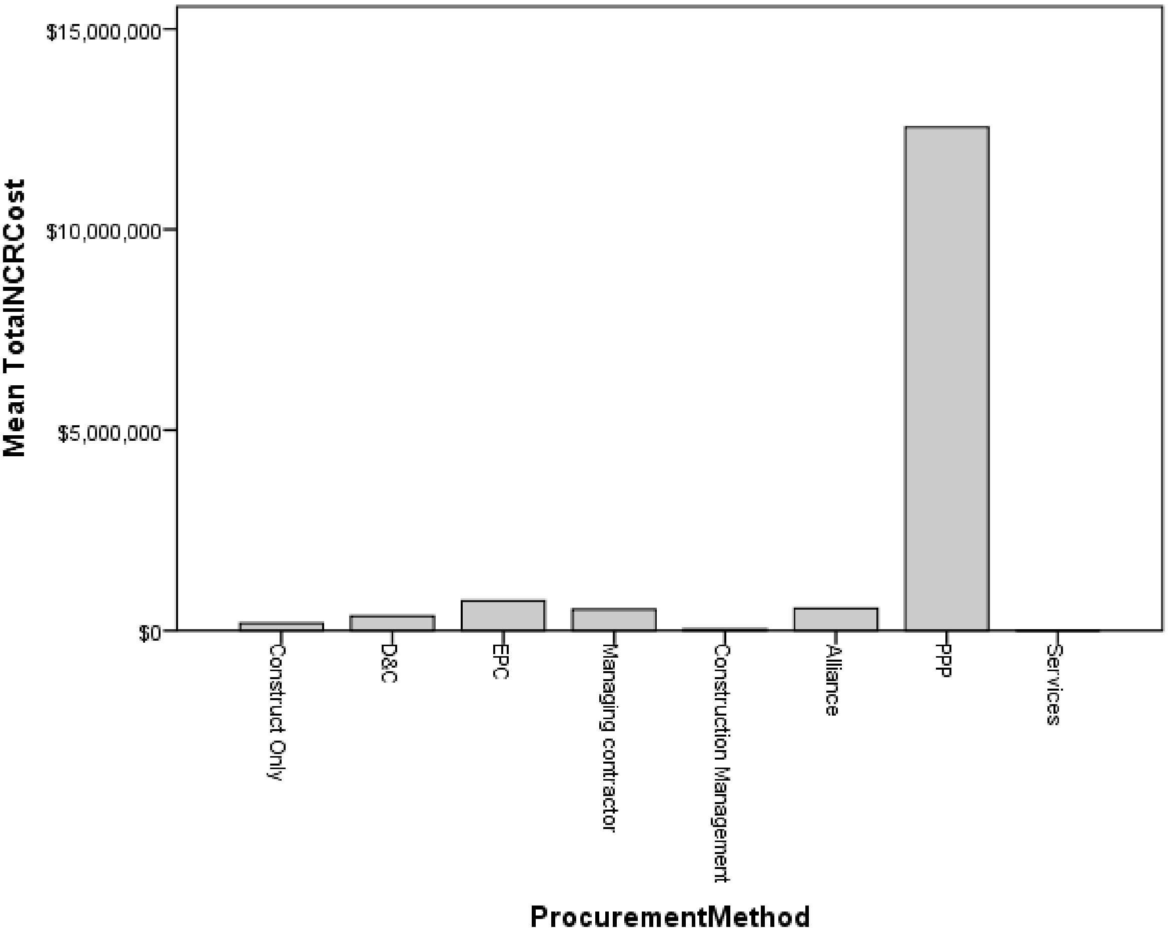

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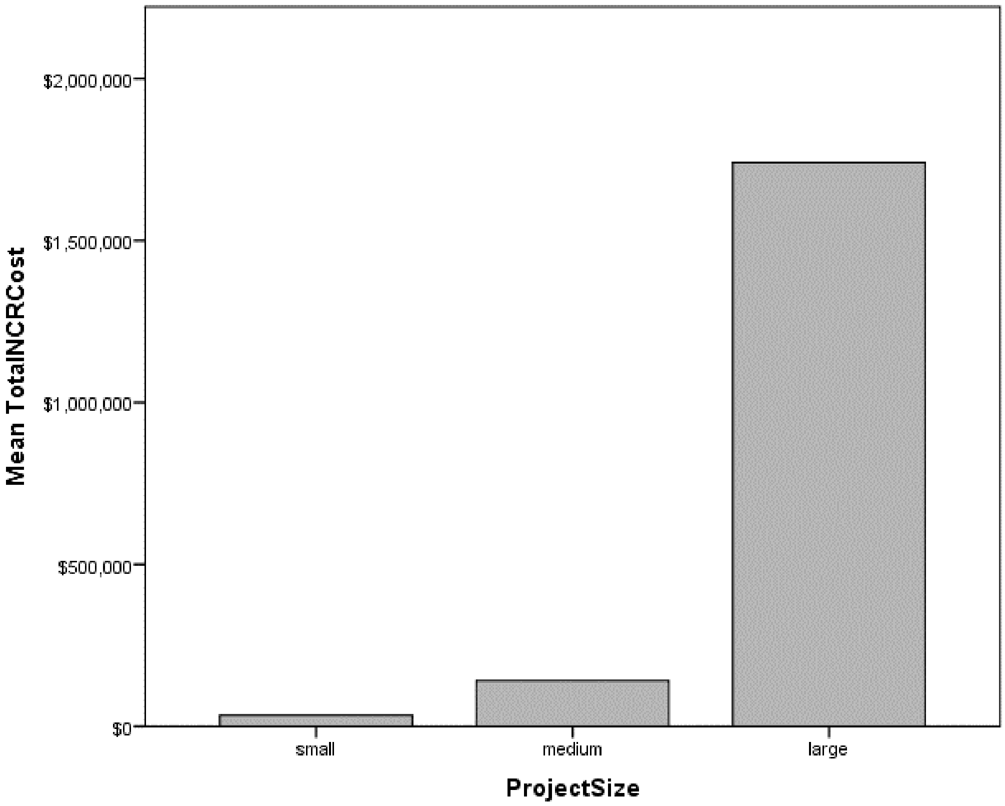

Fig. 15. Mean total NCR cost by project size

Table 1. Cost of NCR borne by the contractor by cost category

Cost Category	**N**	**%**	**Total (AU$)**	**%**	**Mean (AU$)**
< AU$10	574	8.11	468	-	1
AU$11 – AU$100	274	3.87	24,204	0.06	88
AU$101 – AU$2,000	4,067	57.43	2,899,328	7.62	713
AU$2,001 – AU$5,000	987	13.94	3,443,544	9.05	3,489
AU$5,001 – AU$10,000	614	8.67	4,092,254	10.76	6,665
AU$10,001 – AU$20,000	312	4.41	3,968,895	10.43	12,721
AU$20,001 – AU$50,000	132	1.86	3,903,737	10.26	29,574
AU$50,001 – AU$100,000	77	1.09	4,713,652	12.39	61,216
>AU$100,000	45	0.64	15,001,706	39.43	333,371
Total	7,082	100	38,047,786	100	5,372