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Abstract. The cost of quality while a well-established measure in the manufacturing and other industries, has shown to have limited data available within the construction industry. This case study research article seeks to establish within the construction industry the cost of quality throughout the project lifecycle. The Lean Six Sigma methodology of Design, Measure, Analyse, Improve and Control was used to develop a framework to raise awareness and track the cost of quality both good and bad. The Prevention Appraisal Failure model was used to determine the cost of quality across a portfolio of construction projects completed. The research found that cost of failure was in excess of the cost of appraisal and prevention and thus was leading to non- value add effects waste. During the internal audit process a lack of adherence to documented processes within the quality system was identified as directly contributing to the cost of poor quality in a number of projects. An improvement in the tracking of costs was delivered due to the implementation of a structured framework for data capture and a training presentation to raise awareness. The framework is to be a robust structure and framework that could be adapted in other construction companies and possibly other industries.

Keywords: Cost of quality · DMAIC (Define, Measure, Analyse, Improve, Control) · Lean six sigma systems · PAF (Prevention, Appraisal, Failure)

1 Introduction

Mahmood, et al, [1] describe a construction project as a onetime activity completed within a defined scope, schedule, and budget. Project completion within these constraints and maintaining quality can be difficult to achieve. Research has shown that the costs associated with implementing and maintaining quality can outweigh the tangible benefits [2]. The arrival of the Covid Pandemic in 2020 and the Russian invasion of Ukraine in 2022 has had a significant impact on the construction industry. A recent survey by Construction Industry Federation noted increased prices on steel and difficulties in obtaining it as with lumber and other imperative aggregate materials. Construction Europe (2022) report that the Russian invasion of Ukraine could reduce economic growth in 2022 by 2% which will have a significant impact on the construction industry growth [3]. Evidence gathered through the internal function audits in the case study organisation

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has noted estimators experiencing as much as 30% rises in the cost of project materials and services. This information further emphasises the need to ensure that cost of defects and rework are managed within the controls of a quality management system. The construction industry does not have a realistic idea of the actual cost of quality on projects in relation to how much profit is lost to attain a sufficient level of quality [4]. Only two studies [4, 5] have offered a framework for analysis of cost of quality in construction. These studies fail to provide any insight either within conformance or nonconformance costs [6].

Total Quality Management (TQM) and Lean practices such as just in time, engineering and reengineering are being adapted by the construction industry to some extent [7]. Most recently, due to the case study organisations exponential growth, the development of a Lean Framework for Offsite Manufacturing is in development. Projects are becoming more complex and onerous which is exposing the company to greater risk which must be managed. The high cost of quality is one of these risks. Off Site Manufacture (OSM) encompasses the design, construction, validation, verification and transportation of building elements. The Construction industry has been referred to as a unique industry that faces challenges that other industries such as Manufacturing, and Healthcare do not.

Construction projects are capital intensive and characterized by long, complex and interconnected processes of planning, design and execution [8]. There are limited publications on the Cost of Quality in construction projects in particular according to Rosenfeld [8] but some studies within construction industries have set out ot study or quantify the costs of quality [9] and the costs of reworks [10]. However despite Irish Construction companies striving to remain competitive in the market; most of the research on the costs of quality in construction has been outside of Ireland [8–10]. The case study organisation in this study is an example of one Irish company that is expanding geographically over the last number of years. This growth creates great risk for the company and it is imperative that there is awareness on where costs are being lost. The lack of research literature around the cost of quality in construction is indicative of the need for further research for construction companies to leverage from.

Thus the research questions for this study is:

1. Establish the cost of quality in the construction industry utilising Lean Six Sigma methods
2. Create a robust framework for projects costs to include process updates, training programmes and a COQ tracking mechanism.

By meeting RQ's 1 and 2 the expected results were to build a base for lessons learned, an ability to develop data driven decisions, an ability to attract future efficiencies through prevention initiatives and right first time. Finally by tracking costs establish a potential for data driven predictive project decision making.

Section 2 outlines the Literature Review, Sect. 3 the methodology followed by the results and discussion in Sects. 4 and 5. Finally the conclusion is outlined in Sect. 6.

2 Literature Review

Quality standards can increase the cost of production of products and services which may translate into higher prices. This is a point of concern especially in the construction industry where competition is fierce, and margins are tight [11]. In order to maintain quality, companies must allow for the associated costs of achieving quality as improvement is not only about customer satisfaction, but also about sustainability and delivering projects on time and within budget [12]. Joseph Juran developed the concept of the cost of poor quality in 1951 and sought to recognize the economic impact of poor quality as the total costs that could be saved if there were no quality issues [13]. It was Juran's belief that it was imperative to link the cost of quality to the bottom line. He believed that creating this measure was the only way to change the mindset and drive change [14]. English estimated the costs of poor-quality data accounts to 10 to 25% of revenue.

According to Escobar et al. [15] traditionally quality control was about looking for defects and fixing them to prevent reoccurrence. In today's market, it is about customer requirements and starting upstream to build quality at the design concept stage. In-order to comply with the project scope, schedule and quality, right first time must be achievable. Haupt and Whitman [16] report that the construction industry has been unaccepting of the concept of TQM and unlearn the traditional practices. Change is notably difficult in the competitive environment in which construction operates and where making margin is the primary motivation. One of the main factors to be considered by construction companies in such a competitive environment is to endeavour to find a balance between the product or service quality and concomitant expenses [5]. Waste in the construction industry is due to process variation and non-value adding activities [17]. According to Aziz and Hafez [18] up to 30% of construction work is rework and at least 10% of materials are wasted. Waste in the construction industry has contributed to the low performance over a number of decades [7].

The key to success of any improvement initiative is leadership and management commitment. Leaders should lead by example and adapt a situational style of leadership that inspires employees to deliver value for the company [19]. Very little research has been done in the construction industry alone in relation to the cost of waste and rework [3]. The statistics for waste are much lower in the manufacturing industry which has seen the construction industry look to the practices of the manufacturing industry as suggested by [7].

3 Methodology

The objective of this research is to determine the cost of quality and the level of knowledge and awareness relative to the cost of quality in construction projects. The approach used for this research was inductive [20] with data collection from literature and empirical data was gathered through the internal audit process carried out with Project and Operations Managers [21]. The objective is to determine the true cost of quality through analysis of good and bad quality.

There is significant amount of waste in the construction industry due to nonconformance or bad quality. Rework is a large part of that and is not being quantified in

relation to its impact on the overall project margins. The cost of good quality will also be looked at in terms of appraisal and preventative activities. It will be determined if there is more value in building quality into processes to reduce dependence on appraisal and preventative activities and therefore reduce the cost of good and bad quality.
Internal Function Audit
An internal function audit was conducted to examine the current cost of quality across projects completed in the year 2021. The criteria for the audit was based on the Prevention, Performance, and Appraisal (PAF) Model using the Internal Function Audit Checklist. For ease of understanding, the checklist was designed to ensure the audit criteria of the prevention appraisal and failure was aligned with the practical project delivery requirements. The audit was carried out over a number of weeks. Project Managers were notified of the audit as is a requirement of stage 1 audits in line with the requirements of ISO 9001:2015 and the associated audit guideline of ISO 19001 [22]. The concept of Six Sigma follows a defined structured approach to completing an improvement project namely, Define, Measure, Analyse, Improve, and Control, known as DMAIC [23]. DMAIC methodology together with Lean tools will be used to deliver this research objectives. De Mast et al., [24] suggest that a Lean Six Sigma (LSS) approach may be more appropriate to the construction industry as Lean encourages a decrease in process instability by reducing process waste (Muda) and Six Sigma supports a decrease in process variability (Mura).

4 Results

4.1 Define

The first step of the project was to define the cost of quality and measure it. Figure 1 demonstrates the breakdown of the types of COQ issues that may arise and from then the COQ could be measured.

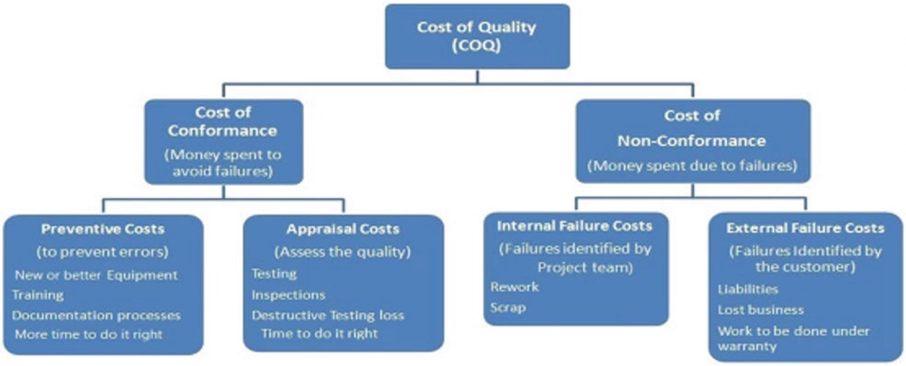


Fig. 1. Defining the costs of quality and types of costs and measures

The Cost of Quality for projects opened and closed over a 12 month was analysed based on the PAF model resulting in costs of €659,844. The approximate collective value of 33 projects over the 12 month period was €325m. This shows the cost of quality was operating at 0.20% of the gross value of the projects. There were limitations on the results as due to the confidential nature of the company finances, the net values were not made available. Recording of non-conformances increased from 3 in the year prior to the project to 13 in the year of the project aided by the development and roll out of a cost of quality training programme to create an awareness of the Cost of Quality.

Improved collection capability of operational data was realised due to the development of a database to facilitate the collection of key data in relation to impact, contributing factors and cost both estimated and actual.

4.2 Measure

The audit checklist was based on the methodology of establishing a consistent measuring system by asking the following questions:-

1. What is to be measured?
2. What are the criteria for measurement?
3. What is the scope of measurement?

For this audit preventative costs were measured in-terms of what were the critical to quality measures i.e., time taken by the Project Manager to review the contract and a % of salary was assigned over the 33 projects under review. The appraisal section considered the cost of time applied to checking key operational activities throughout the project life cycle through the quality assurance and quality control audits. Failure costs considered the cost of internal failure or non-conformance and external failure (Table 1). When analysed by project specific criteria it revealed that the majority of internal failures were due to subcontractor issues. This is not surprising as the case study organisation is highly reliant on outsourced activities for project delivery.

4.3 Analyse and Improve

A fishbone diagram and 5 Whys exercise were used to ascertain the root cause of the problem using the 6M methodology. During a brainstorming session with the quality team and operations the existing company culture, commitment and leadership were the top 3 issues identified that need to be considered.

A framework was developed in MS Excel to facilitate the logging and tracking of key data to allow for effective data analysis on which decision could be based and actions taken. A key principle of Total Quality Management is fact-based management. Decisions have to be based on fact and not precedent or opinion [5]. The case study organisation are striving towards operational excellence. According to Mahmood [1] it is fundamental that cost information is used in decision making. A Nonconformance Master Register database was developed to capture any non-conformances that lead to quality issues and cost issues.

The process for non-conformance and corrective action was revised to reflect the updated controls as and integrated into the QMS as part of a procedure - Control of Non-conforming Outputs & Corrective Action Process. Two new forms (Fig. 2) were

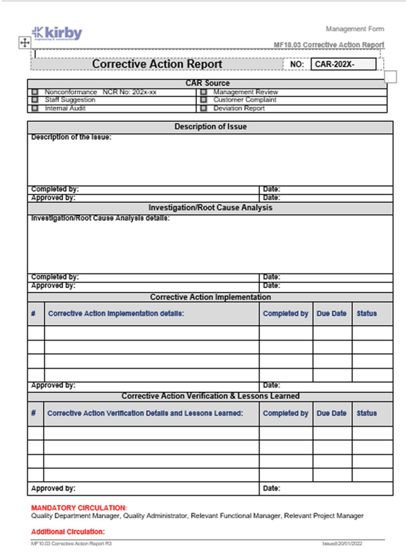
Table 1. Costs of quality derived from internal audit checklist (example)

Type of Cost	Item	Responsible	Cost	Total cost
Prevention	Contract review	PM	€ 22,000	**€ 150,000**
Prevention	CTQ Matrix	PM	€ 26,000	
Prevention	QA Plan	QC	€ 14,450	
Prevention	Internal Training Plan	QC	€ 7,300	
Prevention	Quality Management System	QA	€ 50,000	
Prevention	Internal Quality Training	QC/QA	€ 20,000	
Prevention	External Quality Training	External	€ 10,250	
Appraisal	Project Managers & Directors Inspections	PM/SS/Directors	€ 10,000	**€ 127,776**
Appraisal	Walk-downs/Snagging	PM/SS	€ 5,000	
Appraisal	Tests	QC	€ 10,000	
Appraisal	Internal Audits Projects	QC	€ 25,776	
Appraisal	Internal Audits Offices	QC/QA	€ 25,000	
Appraisal	External Audits	External	€ 32,000	
Appraisal	Internal Audits to Supplier	QC	€ 20,000	
Internal /External failure	Internal NCR	Projects	€ 382,068	**€ 382,068**

created to capture detailed operational data at project level. A summary of the details will feed into the Nonconformance Master Register to collate all internal and external failure costs. These forms were developed to ensure the impact of the issues were considered together with the contributing factors, remedial work, root cause analysis and associated costs.

4.4 Control

Roll out of the cost of quality training programme and knowledge commenced in December 2021 with invites from the inhouse training platform issued to relevant roles within site and management staff. Over 33% of staff were trained initially with a plan in place ot deploy to all employees. Due to the success on the uptake of the training, it will be rolled out to all site, engineers, and management before end of 2023. The implementation of the improvements will be monitored in line with the internal function audit


Management Form
MF10.03 Corrective Action Report

Corrective Action Report NO: CAR-202X-

CAR Source	
☐ Nonconformance NCR No: 202x-xx	☐ Management Review
☐ Staff Suggestion	☐ Customer Complaint
☐ Internal Audit	☐ Deviation Report

Description of Issue	
Description of the Issue:	
Completed by:	Date:
Approved by:	Date:

Investigation/Root Cause Analysis	
Investigation/Root Cause Analysis details:	
Completed by:	Date:
Approved by:	Date:

Corrective Action Implementation

#	Corrective Action Implementation details:	Completed by	Due Date	Status
Approved by:		Date:		

Corrective Action Verification & Lessons Learned

#	Corrective Action Verification Details and Lessons Learned:	Completed by	Due Date	Status
Approved by:		Date:		

MANDATORY CIRCULATION:
Quality Department Manager, Quality Administrator, Relevant Functional Manager, Relevant Project Manager

Additional Circulation:

MF10.03 Corrective Action Report R3 Issued:20/01/2022

Fig. 2. Corrective action report template

process as illustrated in Table 1 on the Internal Audit Process. This process is written in accordance with the requirements of the international standard ISO9001:2015 [22] for Quality management systems requirements and ISO19011, Guidelines for auditing management systems [25].

5 Discussion

This research conveys how to design and implement an integrated company-wide transformation. This research demonstrates how the DMAIC methodology was used to develop a structured framework to raise awareness and track cost of quality on construction projects. It is evident through this research that the complete cost of quality is not considered on construction projects in the case study organisation. As reported by Abdelsalam and Gad [4] the construction industry does not have a realistic view of the actual cost of quality on projects and how much profits are lost to attain a sufficient level of quality. This was evident in this research as a knowledge gap was revealed in areas that previously may have not been considered as directly impacting the cost of quality such as prevention and appraisal or conformance costs. The cost of failure is considered due to the potential negative impact it could have on project profit margins but the cost of prevention and appraisal or conformance is not fully recognised as a tangible area that can be measured or has an obvious benefit [6]. Within construction projects there is always an emphasis on maintaining the project profit margin which leads to speeding up the rate of construction at the cost of quality to maintain the schedule and subsequently the budget. This is where rework becomes an issue therefore increasing the costs [26]. Utilising the cost of quality failure analysis shows that the majority of internal failures occurred during the installation phase by a supplier/subcontractor. The installation or construction phase of projects operate under tight schedule constraints where quality may be overlooked to meet schedule constraints. The budget and schedule have to be structured to allow for the cost of quality to ensure there is continuous improvements that adds value to the company and the client [12]. The case study organisation realised that the cost of conformance should be considered during the planning phase of the project in line with Sebastian [27]. As suggested by Juran and Godfrey [14] these costs should be directly linked to the profit margin of projects and the case study organisation found this approach effective.

Due to the implementation of a structured framework for measuring the COQ and recording NC's as well as deploying and the COQ training the number of non-conformances or failures recorded on the system increased from quarter one of 2021 to quarter one in 2022. The structured framework and training presentation emphasised the process behind the failure rather than the people. This created a more blameless method of reporting where individuals felt save to report with the view that process improvement through investigation and lessons learned was possible [28]. This is supported by management as the behaviour that's required to assert a culture change. The recording of non-conformance and corrective action outcomes needs to be recognised as vital organisational knowledge that creates lessons learned to prevent reoccurrence [29]. This thinking should be considered as an aspect of the case study organisation's overall strategic direction.

For the purposes of this research the total cost of quality was determined by gathering operational data from 33 projects initiated and completed in 2021, 19 of which recorded non-conformances. It is difficult to determine if the details are completely accurate as some of the costs were hidden or estimated either over or under. The nature of the business is to subcontract work and purchase manufactured items, this creates difficulty for project manages to accurately assess the true cost of failure. It is also often the case that suppliers and subcontractors do not fully realise the implications of not protecting the supply chain. This research shows the cost of quality as operating a 0.20% of gross project value prior to the project. This figure will increase further due to the implementation of the improvements outlined in this research - until the COQ is measured it cannot be managed.

Research tells us that traditionally within the construction industry quality control was about looking for defects, fixing them and putting plans in place to prevent reoccurrence in the future [29]. Having a COQ framework ensures the industry takes a more preventive, proactive approach as much as is practicable [26]. This research has highlighted the majority of issues recorded in the case study organisation are due to subcontractor or supplier performance which aligns with Abdul-Aziz's study on quality management in Japanese construction [30]. The area of subcontractor and supplier approval and evaluation may need to be reviewed to assess if the criteria currently in place is sufficient for the growing needs of the case study organisation.

The structured framework created for the gathering of operational data in relation to non- conformance and corrective can be digitised in future to further improve its capabilities in the future.

6 Conclusion

This research fulfilled its research objectives by creating a structured framework to which vital operational data could be gathered to determine the true cost of quality and the rollout of a training program to create awareness around and measure the total cost of quality.

This research resulted in creating an understanding of all the elements of cost of quality both good and bad. A structured RCCA process to understand and record the causes of failure and the importance of root cause analysis though the corrective action process. The development of a structured framework to act as a single source of truth to record issues and where future projects can look to for lessons learned is important.

While data gathering may have had limitations initially in terms of a reluctance to disclose the costs, the implementation of the structured framework for data collection and training presentations were instrumental in changing the mindset, behaviours and project management costing in a positive way. The improvements were rolled out during a 6 month period and their success can be verified by the increase in non-conformance reporting from the year after the changes were implemented.

The results of this research illustrate how efficient and effective the LSS DMAIC methodology is at providing a framework to drive continuous improvement. Using this methodology led to the provision of a transparency around the cost of quality that had not previously existed. The success of this project demonstrates the value adding capabilities of the DMAIC methodology and how it could greatly benefit other areas of the industry. Future research can delve more into the types of improvements that can be made by measuring the COQ in the construction industry.

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