Modeling Cost of Quality in the Construction Industry:

A closer look at the Procurement Process using System Dynamics

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The aim of this research is to develop the Cost of Quality (COQ) model for the procurement process of the construction industry and establish a general course of action for minimizing quality costs. A case study in a large Canadian construction company was conducted and the use of the Prevention-Appraisal-Failure (PAF) approach for the COQ model of the procurement process was explored. In contrast to the conventional COQ analysis we take into account not only the internal quality costs within the company, but also the costs of its suppliers. Several different policies were designed and their effects on quality costs investigated through System Dynamics (SD) simulation. The findings suggest that Prevention costs should be increased to minimize failures. It was also found that Appraisal cost is quite high in the procurement process and should be reduced in order to minimize overall COQ. However, this strategy could increase failure occurrences thereby damaging a company's reputation. The possible reductions of Appraisal cost in the construction companies should thus be carefully considered.

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LITERATURE REVIEW

Industry practices nowadays have begun to introduce the notion that achieving desired quality and customer satisfaction is no longer sufficient. This must be done at the lowest possible cost as well. In order to facilitate this, companies and business owners now consider the concept of identifying cost of quality. This is not a straightforward task as there has been some debate about what these costs include (Machowski and dale, 1998).

Generally speaking, the cost of quality can be understood as the cost of conformance as well as the cost of non-conformance. The cost of conformance would include costs incurred to prevent poor quality for example inspections and quality Appraisal whereas the cost of non-conformance would include costs incurred due to product or service failure such as recalls, returns or rework.

The widely accepted definition of the cost of quality, according to Dale and Plunkett (1995), is the costs that are incurred in the design, implementation, operation and maintenance of a quality management system, the cost of resources committed to continuous improvement, the cost of system, product and service failures, as well as any other necessary and non-value added activities required to achieve a quality product or service.

The function of COQ attempts to link the benefits of improving quality to customer satisfaction, and associate them with a corresponding cost. This is also known as the concept of coupling reduced costs and increased benefits. Using this logic we can demonstrate that the cost of quality is a tradeoff between the cost of conformance and the cost of non-conformance (Schiffauerova and Thomson, 2006).

Given the increased importance of incorporating COQ into the business practices of many organizations, more and more companies have begun to search for the theory behind many quality models used for this type of analysis. Despite the growing importance of this topic, Dale & Plunkett (1995) have suggested that there is still a lack of research and development referencing this subject, especially Japanese literature given their reputation for quality practices in various industries. Regardless of this, they further suggest that only a handful of references are required to fully capture what is required to be considered when questioning COQ models.

William *et al.* (1999) focus on the historical development of quality costing as well as the different opinions of using COQ models in business practices. Some attention is also given to the data collection methodology used in various different organizations as well as published quality costing data from several corporations with successful COQ outcomes is presented in their work. An added benefit to this research is that they list and analyze all the quality costing method shortcomings and limitations.

Tsai (1998) introduced in his article an activity based costing whereby the primary COQ model used was the Prevention, Appraisal and failure approach (PAF). This is a traditional COQ model suggested by Juran (1951) and later by Feigenbaum (1956).

Prevention costs are known as the costs incurred for preventing a non-conformity by ensuring the process is in place is capable of delivering high quality products or services. Love & Irani (2002) best described Prevention costs as all amounts spent or invested to prevent or reduce errors or defects, that is, to finance activities aimed at eliminating the causes of defects.

Appraisal costs are in association with the measurement system used to appraise the quality of a product or service. In other words it is the detection of errors or defects by measuring conformity to the required level of quality: issued architectural and structural drawings, work in progress, incoming and completed material inspection (Love & Irani, 2002).

Failure costs are the efforts in place to correct a non-conformity that has taken place before or after delivery to the customer. Failure costs are thereby classified as internal failures and external failures. Internal failures would include costs due to scrapping or reworking defective product or compensation for delays in delivery whereas external failures would include costs that are incurred once the product or service has been delivered to customer such as cost of repairs, returns, dealing with complaints and compensations.

Crosby (1979) introduced a costing method similar to that of Juran's PAF method however Crosby saw quality as a measure of conformance to requirements and therefore defined COQ as the cost of conformance, which includes the price of doing things right the first time, and the cost of non-conformance which is the money wasted when a product or service fails to deliver its intent of conforming to customer requirements.

The process cost model, which was developed by Ross (1977) and later used by Marsh (1989) represents a quality costing method that is process based rather than product or service oriented. This method, along with several others, focused on the intangible costs associated with profit not earned, reduced revenue or loss of customers due to non-conformity of products to client requirements.

Dale and Plunkett (1995) recently emphasized the importance of including intangible and opportunity costs when considering the cost of poor quality. Robison (1997) proposed another method of COQ analysis that is worth mentioning, which is the identification of the cost of everything that has gone wrong in a process. Again this method is very much later to the earlier methods that were developed.

Regardless of the various different costing methods, the concept of identifying the cost of quality encompasses one primary idea and that is to link all areas of improvement to a cost or customer expectation that is quantifiable, and thereby sufficiently actionable to reduce the overall cost of quality. Thomson and Schiffauerova (2006) provided an analysis of the quality costing practices of four successful companies.

Specifically, the way these companies collect, measure and monitor quality costs, what costing calculations were made and what COQ method was utilized. Each company considered had well established quality programs and they each belonged to different industrial sectors.

When observing these four companies we see that it is evident the business industry and size of the company has a heavy influence on the quality methods and efforts practiced.

High-tech companies such as companies A which is in the telecommunications industry, B which belongs to the electronics industry and C which belongs to the aerospace industry tend to implement more structured quality programs that in turn require a higher level of support and discipline to achieve 100% quality or zero defect.

Company D, which appears to be less high tech, manufacturing home products attempts to satisfy merely a set target and no real efforts to achieving anything more.

Company A is the only company that measures both non-conformance and conformance costs which allows company A to adequately optimize their COQ. Companies B and C however only measure their non-conformance costs. This is justified due to the importance placed on their products to perform. Company B is in the electronics industry thus must place their products functionality first and company C being in the aerospace must naturally place safety as their number one priority. This thereby causes both companies to dedicate almost 100% of their efforts on eliminating non-conformances consequently disregarding the cost of compliance.

Company D however, belonging to the manufacturing industry stands to gain a great deal by implementing efforts for measuring the cost of compliance. This allows them to optimize their costs of quality and improve their quality policies.

In 1992, Porter and Raynor (1992) further investigate this model by paying close attentions to the limitations.

COQ in Manufacturing

Productivity has been considered a primary focus in the manufacturing industry. Higher production results in more sales thereby maximizing profits. In the early days of manufacturing, productivity and quality were regarded as two separate entities. Furthermore, it was generally believed that an increase in quality meant an increase in cost. This is incorrect and since the dawn of quality improvement, it has become widely accepted, especially in the manufacturing industry that an increase in quality resulted in less expense by improving productivity through the elimination of rework and unnecessary inspections (Gunasekaran et al., 1994).

The importance of quality costing becomes more and more apparent every day. A recent study on manufacturing companies in Malaysia shows the significance of implementing quality costs. The findings had suggested that the employing quality costing methods into the daily processed improves performance and productivity and that it was an effective way for a company to impact their bottom line (Tye et al, 2011).

It can be seen that quality has surpassed the role of simple inspections by becoming an integral factor when deciding on strategic tools that play a part in increasing the efficiency of a company, or more specifically an assembly line by improving the utilization of resources and meeting the requirements that customers have requested. This, of course, is in conjunction with price and reliability considerations.

Ferdows & De Meyer (1990) attempted to explain how some manufacturers defy the commonly accepted "production logic". When compared to their competitors not only do they produce better quality products but they do so at significantly lower cost margins, with a more dependable process that responds faster to changing market requirements.

Gunasekaran et Al. (1994 suggested that nowadays the integration of quality into work processes is decentralized and that each department is responsible for its own quality standards and that their individual objectives should support the overall goal of the organization. Keeping this in mind, it is important to note that each department is constrained by the parameters of all other remaining departments under the organization and therefore an integrative approach to quality by all departments should be considered. Furthermore, it is suggested that there be a smooth flow of information concerning the company's goals and policies.

When considering productivity and quality manufacturing, one must take a look at how the dramatic increase in automation in the manufacturing industry has affected the output. Knowledge workers, maintenance staff, operators, draftsmen, etc. all play a significant role in delivering high quality and productivity. Furthermore, they are the only viable means of using an integrative approach to quality by engaging all departments in all work processes, and as mentioned earlier, the cross functional approach to quality improvement is highly recommended.

The manufacturing industry has several concepts that can be employed in order to improve productivity and quality. Just in time (JIT) manufacturing, which is used in and often referred to as the Toyota Production System, is a production strategy that aims to reduce inventory costs by having parts produced "just in time" for delivery to take place. The process relies on kanban, a term describing signals in the quality practice, to indicate when the next part should be made. Zero Inventories (ZI) is another concept similar to JIT in that it simply aims to increase profit margins by reducing inventory thereby eliminating the need for warehouses or other costly methods of storage. Total Quality Management (TQM) is another strategy employed at many manufacturers. TQM functions on the premise that a product's or service's quality is the responsibility of everyone who is involved in the processes corresponding to producing or delivering that product/service. In simpler terms, it maximizes the involvement of management, the workforce, suppliers and often even customers to achieve consumer satisfaction (Feigenbaum, 1983). All these manufacturing strategies have a great impact on productivity and quality improvement.

A large amount of research has been done on the means of improving quality and productivity in the manufacturing industry. Most of this research discusses benefits achieved by localized improvements such as batch production, setup reduction, the use of modern computers etc. Gunasekaran et al. (1994) on the other hand, offer a strategic approach on how to improve productivity and quality of the whole organization against the business strategy. The cost of quality in terms of profit and loss must be considered as the COQ is the basic measuring tool of any quality improvement efforts.

The measurement of variables at several points during a process is essential when determining what quality improvement initiatives can be taken. It is imperative to understand where a process may be broken or inefficient in order to implement meaningful improvement. These measurements, taken at various stages of the process, provide insight into where changes can be made in order to streamline or fix the process as well as provide information on the performance of a production line.

Competition in the manufacturing industry has led to several strategy changes and newer techniques of measuring performance. Measurement, planning and improvement can be integrated into a strategic process. Quality measurements are often non-financial and can be quantified using activity based costing.

Another worldwide tool for quality improvement in the manufacturing industry (among other industries) is the ISO 9000 series. It offers a guideline on establishing and maintaining a quality system, heavily involving the correct documentation. It focuses heavily on the notion that companies own personnel must realize that quality falls within their own control of their internal processes.

COQ in the Construction Industry

Implementing quality programs in the construction industry is a relatively new concept. In fact, usually only the bigger construction firms implement a detailed quality program other than the common place ISO standards and even less practice measuring cost of quality.

Love and Li (1999) studied companies and consultant firms in Australia and their practices, or lack thereof, of quality costing. Seeing that it not common to exercise quality costing methods in their day-to-day business culture, it is difficult to determine the benefits these businesses stand to gain by measuring their quality costs.

Love and Li state (1999) that although direct quality costs such as salaries, documentation and audit costs can be measured with an acceptable degree of accuracy, their associated advantages are much more difficult to quantify.

Many influential processes in the engineering, procurement, construction and management industry (EPCM) greatly impact the cost of quality failures. The procurement process, for example has become notorious for leading to cost overruns on projects. Therefore it has become apparent that in order to improve a projects performance, the causes and costs of rework must be determined.

An interesting study done on the perceptions of time, cost and quality management on building projects revealed that the perceptions of the clients, contractors and consultants involved in the same project are not uniform. Clients believe that their expectations for time, cost and quality are realistic whereas their contractors and consultants think the opposite. In the study the conclusion showed that clients had rated quality as more important than project time performance whereas the contractors and consultants believed that in order to please the client they had to invest their resources on time and cost. (Bowen et al, 2012)

As mentioned earlier, ISO 9000 standards are nowadays the most widely used quality initiatives among construction companies. It has been adopted by several countries around the world and is applied by almost all industries as well as engineering and construction.

A contractor's quality assurance program is essential for detecting and preventing recurrence of quality related problems. The internal organization for standardization (ISO) was formed in 1926 when it began to be recognized that standardizing work processes ensures minimizing variability and therefore, if all best practices are recorded as procedures, standardization would also reduce non-conformities and defects.

Bubshait and Al-Atiq (1999) discussed the use of ISO 9000 standards in construction. They mentioned that systematic quality work reduces the costs of failures in one's own work and in the final product by creating uniformity. Therefore a contractor's in-house quality assurance program is of the utmost importance to achieving customer satisfaction. By detecting and preventing failures, the client has more confidence that the project will perform as planned.

Particularly in construction, there is always a risk of not completing a project on time or within budget and to add to this, there is also always a safety aspect to consider if a project is not completed with the appropriate degree of quality in mind. Considering all these factors, it has become well known that construction and contracting companies are better off having a built-in quality assurance program to ensure immediate detection and Prevention of quality and construction related incidents.

After researching more than a dozen construction companies in Saudi Arabia, it was found that the primary reason for registering for the ISO 9001 certification are top managements interest in the standards potential to improve the quality of their projects as well as conforming to what customers expect from their services. They are looking to be one step ahead over their competitors when ISO certification becomes a mandatory requirement (Bushait & Al-Atiq, 1998).

Research by Bushait & Al-atiq was also done on the value that ISO certification adds to a contractor or organization working within the construction industry. A majority of these companies acknowledged the benefits they stand to gain from being certified however a few of the interviewed contractors had made a few reservations about whether or not certification added value to construction related processes.

ISO certification assesses a process rather than a product or a service and its important to note that there may be several processes in the construction industry that although required by contract to fulfill, do not necessarily add any value or improve a projects quality. Non-value added activities such as these include processing delays, temporary or permanent storage, inspections and any rework required to meet customer satisfaction or engineering specifications. Generally speaking there are a few factors that need to be involved for a process to be value added; first there must be a noticeable change that is desired by the customer, second the customer must be willing to pay for the results that a certain process will deliver, third and possibly more importantly the process must be done right the first time.

Half the contractors that were interviewed reported that there are few difficulties with implementing an ISO quality program whereas the other half had a few concerns; ISO 9001 is very document intensive in that it requires that thorough and correct documentation is kept for every critical process performed. For some contractors, especially the smaller ones that may have limited staff and many quick simple work processes, maintaining documentation as required by ISO can serve to be a very tedious and unnecessary task. Since being ISO certified also means that subcontractors should either be ISO certified themselves or at the very least comply with ISO standards, bigger firms often have a problem controlling their sub-contractors. For these reasons it is found that the full implementation of an ISO program is difficult making deviations from the program a likely possibility.

Similarly to legal documents, ISO clauses can contain jargon that may not be always clearly interpreted by all companies. There is also a need for the availability of resources to comply to all ISO requirements, and often these resources do not exist and it becomes an added workload to employees whose primary job duties lie elsewhere. Furthermore, there seems to be a general shortage of quality personnel in the engineering industry making it difficult to hire employees with such experience. (Bubshait & Al-Atiq, 1999)

In addition to the difficulties with conforming to ISO, there are also some reasons that were identified as to why some companies are discouraged from implementing ISO certification within their work processes. First, because of the added expenses that would be incurred and second because there is always a certain resistance to change when implementing a new program that isn't familiar to existing personnel including management. There is also a risk of losing productivity due to the efforts exerted in implementing a new system from employees that have other duties. Once again, this ties into limited personnel.

Often in construction projects, there is a likelihood of a project operating from several offices including a remote job-site that makes coordination and communication difficult, specifically when different time zones, languages and cultures are present.

Bubshait and Al-Atiq (1999) offer some remarks about ISO 9001 by adding that there seems to be a misconception of the standards. Through their research they have found that some of the contractors that were interviewed believe that ISO requirements merely require a documented "consistent" level of quality rather than a document best practice process. The correct concept that needs to be instilled with these contractors is Deming's plan, do, check, act cycle that requires a firm to first document their best practices before standardizing any of their work processes. This is then followed by continuous monitoring and updating of their work processes to ensure that any "better" practices are captured as soon as they are discovered.

One last remark made by their research is that many companies are lacking in terms of prioritizing improvements within their work processes and that this is an important attitude for a company to have when implementing a quality program successfully.

A common quality practice in the construction industry is Total Quality Management (TQM). It was described by Burati and Oswald (1993) as a journey rather than a destination. The benefits of implementing TQM are among higher customer satisfaction, better quality products and services and a higher market share. Like many Quality programs, implementing TQM requires that the entire company's business culture is turned around to accommodate for a new philosophy, one where the entire body of employees working for a company is involved in taking the matter of quality into their own hands. TQM calls for all personnel to engage in sculpting goals, processes, organizations and people to ensure that things are done right the first time.

In more specific terms, each employee must consider both the input and output of their own process. They must be aware of how their involvement in a process chain will affect the people in the next stage of production and to further control and assess this, it is imperative that measurements are taken along the way.

TQM also entails that rather than focusing on the 80% that is doing well, a company must primarily pay attention to the 20% that is either failing or needs immediate improvement. (Pheng & Teo, 2009)

Strange and Vaughn (1993) added to this notion by claiming that constantly monitoring, measuring and analyzing factors that have significant effect on performance will drive an automatic improvement. To effectively use the information processes from these measurements, estimating a cost of quality is the logical path forward.

Baden-Hallard (1993) associated the cost of quality in construction as the cost of conformance to requirements including costs incurred due to Prevention and Appraisal as well as the cost of non-conformance to requirements. Similarly Ferdows & De Meyer's theory (1990), research done by Culp (1993) also suggests that there is a common misconception by contractors (as well as manufacturers) that implementing TQM is an expensive process. This is a misconception and should be replaced by the understanding that it is not the successful implementation of a quality program that is expensive but rather the costs incurred when non-conformance to quality is corrected. These costs include the cost of rework, correcting errors, reacting to customer complaints, having deficient project budgets due to poor planning and coordination as well as missing deadlines.

A study done by Biggar (1990) indicated that projects can run up to 12% of their total costs spent on correcting their non-compliances to quality or customer requirements further emphasizing the need for proactively implementing a quality program such as TQM.

Very few construction companies have a quality costing method in place to measure their quality level. In fact, construction companies have only truly embraced quality in the form of quality assurance as it is mandated for all government related contracts (Love & Li, 1999). Quality assurance however, does not improve an organization's competitiveness and performance (Terziovski et al., 1997). In order to adequately measure performance, identify and implement improvements companies must have an effective quality costing system. Without a thorough quality cost analysis of companies' spending habits, it is very challenging to determine where costs can be cut or where spending must increase in order to facilitate for a quality performance at optimum cost.(Terziovski et al., 1997).

Unfortunately, this lack of quality costing commitment has resulted in quality failures becoming an endemic element in the construction industry (Love & Li, 2010). Identifying quality costs are a means of providing management information about process failures and the tasks that need to be carried out to prevent recurrence of failures.

In manufacturing, quality costing is a more common culture however this is not the case in construction and the possible reasons for this are numerous. Firstly the construction industry has a very dynamic nature. It is project based and every project is different making a generic quality costing system nearly impossible to implement. To add to this projects have different phases where every phase consists of new work processes, specialized staff and different outcome expectations. In order to develop an effective quality costing system, companies have to take it upon themselves to develop one that works for them (Hall & Tomkins, 2000).

With that said however, there are certain generic construction elements that could be identified and quantified for nearly all construction organizations and a general outline of a costing system can be designed.

Feigenbaum (1991) defined quality costing in the construction field as either the cost of control or the cost of failure to control. The cost of control comprised of Prevention and Appraisal costs whilst failure to control consisted of internal failure and external failure, much like Juran's quality cost definition. Internal failure costs were costs associated with rework, material waste and other unavoidable losses that cause an increase in operations. External failure costs were failures that resulted in a loss of profit for instance, contractual claims, defect rectification and loss of reputation and future work.

Appraisal costs include all costs incurred to the detection of defects by measuring all expected processes against a required level of quality or conformity. Specifically to construction, these items include issued architectural and structural drawings, work in progress, incoming materials and finished products.(Love & Li, 2010).

Prevention costs are considered as all costs incurred to prevent or reduce errors or defects and such costs comprise of mainly the financing of activities that aim to eliminate or reduce errors (Love & Li, 2010).

Another definition to quality costs explored earlier is the cost of conformance as opposed to the cost of non-conformance. Cost of conformance being Prevention and Appraisal costs such as training, indoctrination, verification, validation, testing, inspection, maintenance and audits. Non-conformance costs were rework, material waste and warranty repairs.(Love & Li, 2010).

Banks (1992) suggested that if companies were to adequately maintain their quality costing system and implement identified improvements, their Prevention costs should increase thereby reducing their Appraisal, internal failure and external failure costs by a significant margin earning them a significant amount of savings; the greatest savings opportunity to be expected in internal failures.

However, without an adequate quality costing system in place however, quality deviations would be un-identifiable and therefore these improvements cannot be ascertained resulting in a large opportunity cost.

Organizations in Construction

The customary structure of an organization or project in the construction industry consists of a client, a general contractor and subsequent subcontractors and suppliers. Christopher (1992) defined a supply chain as a network of entities with upstream and downstream linkages of processes and activities that provide value in the form of either a product or service to the corresponding consumer. The general contractor is the entity in this network that is responsible for meeting the demands of the client. General contractors are however, dependent on subcontractors and suppliers to facilitate meeting the client's expectations.

The construction industry is often criticized of delivering their contractual needs in poor performance (Wong & Fung, 1997). It, more often than not, undergoes budget overruns and schedule delays before completing a project and there are numerous reasons for this, several of which are attributed to the extensive supply chain network involved. The industry comprises of a multitude of different professions, job descriptions and organizations all mandated together to deliver a finished project. The client will hire the general contractor who then hires subcontractors and suppliers who, in turn, also hire their own suppliers. The general contractor will ensure all the needs of the client are met by being responsible of all contracts and the subcontractors and suppliers will be party to their own contracts with the general contractor. Furthermore, the general contractor will focus on profit generation which means higher revenue from the client and lower cost contracts with subcontractors who also focus on profit generation, while clients maintaining their own goal of minimizing costs. This network of organizations can become extensive resulting in many conflicting goals thereby making quality management significantly more complicated and decentralized (Wong & Fung, 1997). Berry et al. (1994) suggested that the aim of supply chain management is to build trust, exchange information, develop new products and reduce the pool of suppliers so as to allow management resources to build long term relationships. With regards to construction, supply chain management would have a primary focus on the general contractor and how it can optimally manage and leverage the resources of its subcontractors by effective and cooperative interaction (Wonf & Fung, 1997).

O'brien (1991) pointed out that today's general contractors have the most challenging and important function of satisfactorily executing all accepted contracts. They must take their clients ideas and turn them into a tangible reality. The finished product is usually a set of drawings and specifications.

The reasons general contractors habitually choose to hire subcontractors are because they possess the specialized expertise of technical engineering or construction skills that a general contractor would otherwise lack, or because the subcontractor can increase the labor force at a lower cost thereby increasing the general contractor's in-house capability.

Another important advantage to subcontracting is the increased flexibility and reduced long term commitment to resources required for the job. For instance, in the event that there is a lot of work to be done, a subcontractor can offer the use of extra stuff or an operating plant to aid in delivering the required work on time, and similarly in periods of low work, there is no redundant or extra resources that are not required on payroll. Therefore a significant amount of capital stands to be saved when general contractors outsource their work to subcontractors (Wong & Fung, 1997).

With these significant benefits come great risks and concerns. Subcontractors by nature are often small and not very strong financially making their work practices more random and less standardized providing minimal guarantee that the required quality standard will be delivered (Ganesan et al., 1996). They often deal with labor intensive on site work making them particularly challenging to control from the general contractors perspective. Liability for poor performance or unsatisfactory work can seldom be put in the hands of subcontractors therefore general contractors must often assume great risk in entrusting subcontractors to successfully complete the work with acceptable quality. This leads to an essential need for subcontractor supervision by the general contractor which naturally is an added cost (Wong & Fung, 1997).

Procurement Process in Construction

The procurement process is arguably the most important function in the construction industry. It can comprise between 50-70% of the total value of the project and therefore there is a great pressure placed on this process to perform adequately and efficiently (Alarcon et al., 1999).

Schedule constraints are among the largest pressures that the procurement department faces. The acquisition of materials in a timely manner usually determines the critical path of a project and therefore completing a project on schedule falls heavily on the shoulders of the procurement function.

The need to deal with several different entities can also be challenging. The procurement department in a general contracting company regularly deals with all the suppliers, the engineering department, the construction department, the contracts department as well as hired contractors. Being the centralized organization for so many of these parties can make coordination very time consuming and difficult. (Alarcon et al., 1999).

The impact of the purchased commodities on the general quality of the performance and finished product of the project is extremely significant causing great pressure on the procurement function have impeccable performance.

Lastly, the procurement department is more often than not accountable for the necessary supplies to be present on site at the exact specified times for construction. This is an imperative factor since, in construction, almost all elements are interrelated and have precedence relationships (Alarcon et al, 1999).

Salford (2005) concludes in a study done on the procurement process of the public sector construction industry, that some of the procurement problems were stimulated by an inefficient tendering process. The lowest price bidder is usually always chosen which often compromised the quality of the entire supply chain as costs were always driven down. This further caused a strain on the relationships of suppliers and contractors potentially causing more performance problems during the life cycle of the project.

Salford (2005) mentioned how for companies that always tendered their new projects, there was a lack of incentives for the hired (sub) contractors and suppliers to perform well as new job opportunities were not reliant on past performances.

Due to theses high pressures, it is very likely that procurement professionals tend to employ a fast track approach in order to serve all the needs of the project at the lowest possible cost without impacting schedule. They aim to carry out their functions in an expedited and fluid manner at all times.

For this reason it is important to assess quality down the supply chain. An article written in the applied mathematical modelling journal developed a model for supply chain design and stressed on the importance of computing COQ for the entire supply chain rather than separate discreet entities. It suggests that computing COQ in the supply chain is the first steo to integrating COQ in the decision making process as it allows the exploration of interrelationships between different business components. (Castillo-Villar et al, 2012)

System Dynamics

System dynamics is an approach to describe the structure of a complex system and provide an opportunity to study the feedback behaviourof each component of that system. Clark in his article from 1990 wrote that complex systems in their transient state are virtually impossible to solve mathematically and therefore must be simulated in order to understand. System dynamics studies processes through simulated models and allows for observation of feedback variables in closed systems. The procurement process in the construction industry is therefore an ideal complex process whereby the system dynamics approach can be taken to understand the behavior of each componenet and therefore establish a way of optimizing the parameters to reach minimal COQ.

RESEARCH GAPS

Hall & Tomins (2000) conducted a thorough cost of quality analysis of a building project in the UK and have suggested that although quality costing analysis on a project from the general contractors perspective is effectively the most useful focus to improve a projects COQ standing, it would be even more helpful to consider the supply chain involved with such a project. They recommended that future studies observe how quality costs are manifested down the supply chain and how this information could be useful to minimize the cost of quality holistically.

This study will aim to consider this view and carry out an analysis down the supply chain. In construction, it is the procurement function that is centralized between the general contractor and the subsequent supply chain therefore suggesting that a closer look should be taken on the detailed functioning and budgeting of the procurement process in order to determine improvements that can be made to minimize COQ.

RESEARCH OBJECTIVES & METHODOLOGY

This study has two primary objectives. The first is to propose a cost of quality based model for the procurement process in the construction industry. This model should aim to investigate which variables in the procurement process of the construction industry can be manipulated in order to have a significant effect on the projects total cost of quality.

The second objective in this study is to observe the effect of various proposed policies on the behavior of these variables in order to determine the expected or desired outcome. Companies can therefore apply this model to their own projects and optimize their variable values thereby minimizing their total quality costs.

These objectives will be achieved by observing and analyzing data from an engineering, procurement and construction management company whereby data specific to the procurement function on a large project has been collected.

This data has been collected through access to procurement data management systems and several interviews with procurement personnel working on the project in question. This data will then be analyzed and mined in order to create a model that will fit not only to the project but to other similar projects in the construction industry. The resulting model will then be studied in order to establish sustainable guidleines for construction companies to utilize in order to optimize their quality costs without compromising their final product or reputation.

The System Dynamics approach is also be incorporated in order to fully investigate the effects of the parameters in each other as well as the overall result.

CASE STUDY DESCRIPTION

Project X[1] is a $4 billion aluminum smelter construction project. Company A has been hired by the client to oversee the engineering, procurement and construction management of the project. Company A is a well-known global EPCM company and has been operating for over a century. It has an established quality assurance and control system and employs professionals that take care of the quality aspects in each department. Since its foundation, it has frequently updated its procedures to include a thorough quality measurement system that allows the approximate quantification of quality costs for Prevention, Appraisal and failure. Company A deals with several suppliers to purchase and install several construction commodities required for Project X. The main cost in a construction company aside from material costs is the cost of labor both on and off the field. For this reason, it is imperative to collect the salaries and wage system of Company A in order to accurately estimate the cost of many functions in the procurement department. Company A uses a grading system to establish the annual salaries of all its employees depending on their department and position in the company. Access to this information will allow accurate quality costs to be determined. The following Table is an index for dollar Figures associated with each grade:

Grade	$ Amount	Grade	$ Amount
20	$30,000	27	$100,000
21	$40,000	28	$110,000
22	$50,000	29	$120,000
23	$60,000	30	$130,000
24	$70,000	31	$140,000
25	$80,000	32	$150,000
26	$90,000	32	$150,000 +

Table 1 – Index of $ amount corresponding to each pay grade

Prevention Costs in Construction

A company in the engineering, procurement and construction industry will tend to spend the following costs that pertain to Prevention. Most companies will spend a significant portion of capita investing in written procedures to ensure that all involved departments take precautionary measures that guarantees a

[1] In order to abide by the companies confidentiality policies, it will be referred to as Company A and Project X.

certain level of quality is achieved. These procedures are written up per department and often consist of a variety of procedures ranging from 3 to 60 procedures depending on the size of the company and the project. There are often companywide procedures that span across all the projects that are taken on, and project specific procedures that are written up on a case by case basis for unique projects.

For the purposes of this study, the time spent preparing a procedure is averaged to approximately 10 hours with an hourly rate of $75/hr for technical procedures that require being written up by a certified engineer and $30/hr for non-technical procedures.

Below are the numbers of procedures per department:

Department	No. of Procedures	Technical/Non-technical
Engineering	57	Technical
Procurement	6	Technical
Project Controls	14	Technical
Construction	33	Technical
Contracts	2	Non-technical
Project Management	6	Technical
Quality Assurance	17	Technical
Environmental, Health & Safety	35	Non-technical
Finance & Accounting	12	Non-technical
Office & Administrative Services	38	Non-technical
Information Systems & Technology	3	Non-technical

Table 2 - Number of Procedures per department in Company A

Considering there are 133 technical procedures being produces at an hourly rate of $75/hr and 90 non-technical procedures produced at $30/hr it can be approximated that $126,750.00 are spent on procedural development for Project X.

A few important notes to consider are that these hourly rates are approximated to Canadian wages and considering the global nature of Company A, these procedures could've been written in countries where the hourly rates can differ greatly.

Another pertinent preventive cost in the construction industry is the wages of the employees that belong to departments whose primary focus is failure Prevention. Such departments include a subset of the procurement department often known as Supplier Quality as well as the Quality Assurance department. The Supplier Quality department ensures that all commodities that are purchased for the project are in good condition and that the necessary measures are taken to guarantee proper and immediate correction of all failures. In Company A, the supplier quality department consisted of two employees; the SQ manager (Grade 28 with an annual salary of $110,000/yr) and the SQ assistant representative (Grade 23 with an annual salary of $60,000/yr). Project X is over the span of 4 years so the total cost of the Supplier Quality department is calculated at $680,000.00 for the whole project.

The Quality Assurance department's primary focus is to pledge the correct functioning of all departments and proper application of all procedures assigned to the project. It is not always the case that EPCM companies hire a QA team but this is an asset that adds to preventive and Appraisal costs which has been proven to cause positive results in minimizing failure costs. When examining the QA procedures at Company A, it is found that roughly 1/3 of the focus of the QA department is focused on Prevention whereas the other 2/3 are allocated towards Appraisal. The department also consisted of two employees; the QA manager (Grade 28 with an annual salary of $110,000/yr) and the QA Engineer (Grade 23 with an annual salary of $60,000/yr). In the span of 4 years (noting that only 1/3 of the focus is preventive) it can be calculated that $306,000.00 is spent on preventive costs in the QA department. When combined with the procedure development preventive costs, it is found that the total Prevention costs incurred by Company A in the lifespan of Project X (4 years) is $1,113,417.00.

This study aims to also include the supplier's quality costs. This information can be quite sensitive and difficult to come across but there is a general rule in the construction industry that states that at least 2% of all contract costs of construction commodities should be spent on failure Prevention. Given the total purchase order values for project X is $ 218,147,371.00, 2% of this would mean that $4,362,947.43 is the total Prevention costs incurred by all suppliers combined.

Finally, this results in $5,476,364.10 incurred in Prevention costs for the Project X, including both company and supplier costs.

Appraisal Costs in Construction

There are three obvious and measurable Appraisal costs incurred by the EPCM company in the construction industry; functional reviews, annual audits and supplier quality budgeted hours.

Functional reviews are done on a quarterly basis and assess the functionality of the Engineering and construction department. Usually they are carried out in the form of a full day meeting (8 hours) and involve upper management communication with their direct reports.

The following positions and their respective grade salaries are present during these meetings:

Position	Salary Grades
Regional Engineering Manager	32
Project Director	32
Project Engineering Manager	30
Deputy Project Engineering Manager	30
Carbon Area Specialist	29
Power Area Specialist	29
Reduction Area Specialist	29
Automation Area Specialist	29
Infrastructure Area Specialist	29
Mechanical Engineering Group Supervisor	28
Civil, Structural & Architechtural Engineering Group Supervisor	28
Plant Design & Piping Engineering Group Supervisor	27
Control Systems Engineering Group Supervisor	27
Electrical Engineering Group Supervisor	28
Chief Engineer	29

Table 3 - Functional Review employee participation and respective pay grade

Given the attendees and their corresponding salary grades, to have them all working together for one hour would cost $953. Functional reviews take 8 hours and are conducted four times a year therefore the total cost incurred for carrying out functional reviews on a project spanning four years is $122,000.00. Audits are similar yet also different to functional reviews in that they inspect the functionality of all departments and often lower tier employees are also participants.

Company A is ISO 9001 certified and therefore is obliged to carry out clause 8.2.2 which specifies that a company abiding by ISO regulations must perform at least one internal audit of all its functions annually and take immediate action to correct non-conforming products or services. Therefore during the four years span of project X, company A must perform four audits on each of its departments.

Department	Hours typically spent on	Cost of carrying out 4

	an audit per year	audits
Engineering	3 days = 24 hours	$5747
Procurement	1 day = 8 hours	$2728
Project Controls	2 days = 16 hours	$2148
Construction	5 days = 40 hours	$11,117
Finance & Accounting	1.5 day= 4 hours	$644
Information Systems & Technology	1.5 day= 4 hours	$704
Office Services & Administration	1.5 day= 4 hours	$704
Human Resources	1.5 day= 4 hours	$353
TOTAL	104 days	$18,945

Table 4 - Annual Audit Department involvement with respective costs

The remaining Appraisal cost is that of the budgeted hours allocated to surveying suppliers and their purchased commodities. For every purchase order, a surveillance level from 1-4 is allocated that dictates the number of supplier quality hours required to ensure successful delivery of a commodity. This surveillance level will be allocated on the basis of how important the quality of a commodity is and how difficult it may be to ensure adequate quality. Other factors include the cost of a particular purchase order, for example the higher the cost the higher the surveillance level, as well as from where the commodity is being exported. For instance supplies coming from Europe or North America, where quality is a high priority, may get a lower surveillance level than those coming China, where many suppliers tend to focus on high production rates rather than high standards of quality.

There are 33,975 SQR hours on Project X. These surveillance hours are conducted usually by the Supplier Quality manager himself or by a commodity expert therefore the hourly rate for these specialist can be averaged to $56/hr. This results in approximately $1,902,600 worth of SQ Appraisal costs. Adding all these Appraisal expenses together and it is found that a total of $2,043,545.00 of company Appraisal costs is incurred.

Supplier Appraisal costs consist mostly of inspection test plans. These are reports that are required to be filled out on average every week by all suppliers and contractors on a project. Although the hours spent writing such a report is not recorded officially, it is assumed that each report takes nearly an hour to fill out and is usually taken care of by one of the field engineers for said supplier therefore costing approximately $25/hr. For the same purchase orders mentioned for the SQR hours, there are 25,875 inspection test plans required for the commodities purchased for Project X therefore the Appraisal costs incurred by the suppliers of Project X is nearly $646,875.00.

Therefore total Appraisal costs incurred by Project X is $2,690,420.00.

Failure Costs in Construction

Failures in the construction industry can be very difficult to identify much less measure. In manufacturing it is simply a matter of whether or not the product is found to be defective or however in construction the project is usually the handover of engineering drawings from the company or the delivery of a functioning facility from a contractor. For this reason, estimating failure costs for project X is an approximation based on rework hours for Company A and unsatisfactory deliveries of commodities from its suppliers.

Reworked man-hours are not conventionally recorded at Company A as this would rely on employees admitting that a process or function has failed to complete an assignment during the allocated time. This type of honesty is difficult to guarantee. Despite this however, studies have been performed on company A that has estimated a rework rate for engineering hours loosely based on project hours earned versus project hours completed. Each department had developed a metric that would roughly estimate the amount of rework done with every job-hour. The engineering department's rework rate was calculated as the reworked job-hours divided by earned job-hours. After having implemented this measuring system to nine different projects that Company A has previously worked on, an average of the rework rate was found to be 2.33% of engineering man-hours. To apply this to Project X the total number of engineering job-hours were identified and 2.33% of those hours were considered rework. The total engineering hours for project X was calculated to be $165,480,000.00, thus making $3,855,684.00 the cost of rework. This type of failure cost is incurred by Company A. To explore failure costs incurred by suppliers, we investigate the number unacceptable, over, shortage & defective (UOSD) reports recorded. These reports are created when a commodity is found to be unacceptable after having been delivered. This could be for various different reasons, among them the commodity is damaged, defective, of poor quality or even when there exists a shortage in quantity. This type of failure is considered to be an external failure on the supplier's part and can therefore be added to the total failure costs for Project X. There currently exists 16 different UOSD reports on Project X. Estimating the cost of correcting these failures is extremely difficult as the costs can be incurred by several different entities and their costs can even vary tremendously however the average cost of correcting a UOSD failure is roughly assumed to be $1000. This adds an extra $16,000.00 to the total failure costs of project X, thus the total value of $3,871,684.00.

Type of Cost	Value	% of COQ
Prevention	$5,526,484.00	46%
Appraisal	$2,690,420.00	22%
Failure	$3,871,684.00	32%
Total COQ	**$12,022,468.00**	**100%**

Table 5 - Total amounts for each PAF category

Looking at the overall results, Project X has incurred a total cost of quality of approximately $12,022,468.00. To compare these results to models that have developed for the manufacturing industry, Juran's quality model is considered.

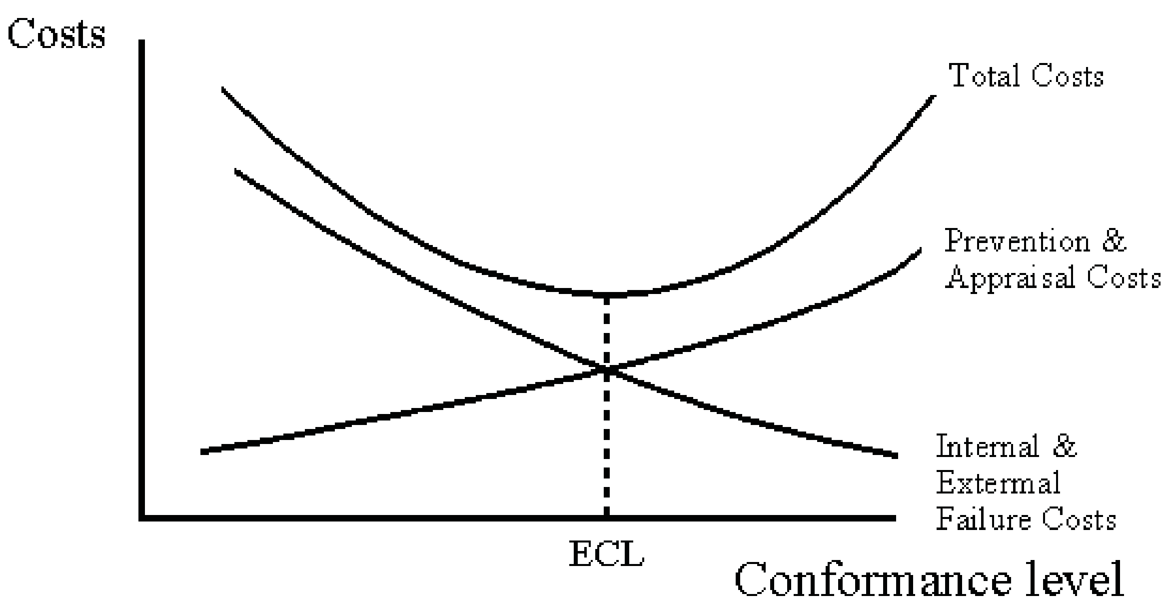


Figure 1 - Juran's Cost of Quality model for Manufacturing

According to Juran's quality model, the lowest quality cost possible of being incurred is when the cost of Prevention and Appraisal is equal to the costs incurred for correcting failures. In the case of project X, the cost of Prevention and Appraisal are $8,166,784.00, which translates to approximately 68% of total COQ costs. The cost of failure is only about 32%. This suggests that in order to lower the COQ cost of Project X, the Prevention and Appraisal costs must be re-evaluated. Juran specifies that the wisest course of action in this scenario is to decrease the Appraisal costs to an absolute minimum rather than attempting to adjust Prevention costs.

In manufacturing, reducing the Appraisal costs would usually imply reducing the size of the sample of the finished product that is selected for inspection and testing however in construction, because of varying nature of the “products and services” that are involved to deliver the final product (which often is a set of drawings or a finished facility), reducing Appraisal costs can prove to be a risky endeavor. If for example, functional reviews and audits were eliminated or involved a smaller workforce to reduce cost, Project X runs the risk of not catching flaws or gaps in a process, and of course losing ISO certification which mandates that a full audit is conducted on every department at least yearly. This implies that in order to be able to meaningfully and without great risk make plausible decisions about reducing quality costs, there must be a more specific and detailed analysis of where the quality costs are being incurred.

Due to the dynamic nature of construction projects, it is hard to compare costs and phases of several projects in order to draw meaningful conclusions about COQ costs in construction therefore it is simpler to look at particular functions in a construction project and conduct an in-depth analysis on the PAF costs.

For instance, procurement process can be studied and a comparison between the different POs can be considered in order to come up with conclusions about the different kinds of COQ costs incurred for different commodities in construction.

Given certain specific costs of every PO we may categorize these incurred costs into Prevention, Appraisal and failure in the following fashion.

MODELING COQ IN THE PROCUREMENT PROCESS

PAF categorization for the Procurement Process

After conducting several interviews with a supplier quality engineer with over 20 years of experience and currently working on Project X, several assumptions were found to be useable yet not necessarily proven. These will be pointed out in the reasoning of every approximated cost incurred. It was necessary to use these assumptions due to the lack of an existing robust quality measurement system at Company A (much like most other companies in the construction industry).

It is common knowledge amongst many quality engineers that an approximate 2% of all purchase order values are spent on preventing poor quality. This is a Prevention cost incurred by the suppliers. Company A incurs a Prevention cost of roughly the number of man-hours spent producing a Material Requisition report for every PO. A quick survey was taken of all the responsible engineers (RE's) that take care of engineering packages and they were asked on average how long it takes them to prepare the Quality section of their MR reports. This was averaged at 10 hours and considering an RE's pay grade of usually between 24 and 25, the hourly rate is taken at $36/hr. These two factors together make the cost categories associated with Prevention costs incurred for every PO.

Appraisal costs incurred for every PO is calculated by supplier quality budgeted hours allocated for every PO. There are 4 different surveillance levels that a PO can be assigned. Important POs that require frequent surveillances will be assigned a level 3 or 4 as well as POs where the commodity tends to have high failure rates. Less important POs or commodities that have a higher tolerance for variance are usually assigned surveillance levels 1 or 2. Depending on these surveillance levels and the type of commodity in question, supplier quality inspection hours are budgeted and distributed to all the different purchase orders. A supplier quality engineer, usually with a grade level of 27-28 tends to these surveillances therefore the Appraisal cost of purchase orders are calculated by a $56/hr multiplied by the number of assigned supplier quality hours. This is an Appraisal costs incurred by Company A. Another Appraisal cost category, this time incurred by the suppliers for POs, is the number of inspection test plans that are required to be completed for every PO. These are reports that are required to be filled out on average every week by all suppliers and contractors on a project and take nearly an hour to fill out. They are usually taken care of by a field engineer therefore costing approximately $25/hr. These two components comprise of the Appraisal costs calculated for each purchase order.

There are two main forms of failures that can occur during the procurement process for Company A, and its suppliers working on Project X; internal to supplier failures that consist of supplier quality issues and external to supplier failures that comprise of errors found after the delivery of the commodity to Company A. Supplier Quality issues can take the form of minor issues such as administrative errors that can usually be corrected immediately or within 24 hours or more serious errors such as dimensional or performance errors whereby correction may often mean that the manufacturing process must be restarted. For the purpose of this study, only the more serious issues recorded are taken into consideration as the smaller issues may have almost negligible correction costs.

After conducting interviews with the Supplier Quality engineers working on Project X, it was decided that the most effective way to properly estimate the impact of SQ issues on COQ is to assume that for every severe SQ issue, 1% of the corresponding PO value is used to correct it. This is a rough assumption but after applying it to a few case studies where the correctional costs of the issues were recorded, it was found to render a value that is within 4% of the real value. These failures were corrected depending on their source either by Company A or by the corresponding supplier. When a commodity has been delivered and is found to be unacceptable by any means, a UOSD report is written up. This report states whether the product is unsatisfactory, there is a miscalculation of the quantity or the product is damaged or defective. This is considered a supplier's external failure and is, therefore a cost incurred by the supplier. The cost for this type of failure can differs tremendously, for example if there is a shortage in quantity, the supplier would have to cover the cost of shipping more and any inconvenience fees that company A may have stipulated in the agreement. This cost when compared to the cost of a product being defective or damaged is insignificant as in this scenario, a supplier will have to ship back the defective product, and re-ship the correct product as well incur any inconvenience fee. This potentially renders the initial batch of products wasted and may even imply that the suppliers manufacturing process has to be reassessed. An exception is in the event the product was damaged during shipment (which happens often) in which case there is usually insurance to cover any associated fees. Unfortunately, very few records that list the costs associated with UOSD are kept. The reasons are that this information can be very sensitive for the suppliers, who often protect their reputation by keeping this information confidential, and also there lie many difficulties in collecting all this information in one place as the costs can often come from a combination of different sources. For this reason, a rough estimate of $10000 is assumed for UOSD related failures.

Thus we find that there are two main visible failure costs in procurement process of construction; supplier quality related failures, and failures appearing after the delivery of a commodity from a supplier.

General COQ model

Looking at all these different parameters, the general model for COQ costs in the procurement process in construction is as follows:

$\mathbf{P= P_{supplier}+P_{company} = 0.02a+360}$

$P_{supplier}$ =2% of all purchase order values spent on Prevention costs

$P_{company}$=10 hours spent producing a material requisition quality report at a cost of $36/hr (this is fixed)

$\mathbf{A = A_{company} + A_{supplier} = 56b+25c}$

$A_{company}$= budgeted supplier quality hours (paid by company) at a cost of \$56/hr

$A_{supplier}$= inspection test plans produced for purchase order at a cost of \$25/hr

$\mathbf{F = F_{internal} + F_{external} = 0.01ad+10000e}$

$F_{internal}$= 1% of purchase order value assumed to correct a supplier quality issue

$F_{external}$= \$10000 average to correct a UOSD report

Note that company external failures are not tolerated. Documents are inspected before being sent out to the suppliers for purchase.

where:

a= Purchase order value ($)

b= Budgeted supplier quality hours per purchase order

c= number of inspection test plans per purchase order

d= number of supplier quality issues per purchase order

e= number of UOSD (supplier defects) per purchase order

It is important to mention that for every purchase order on the critical path, a failure can cause many weeks delay in first hot metal (start of production of the plant under construction, therefore resulting in a cost of a full week of production). This is not considered in the analysis as this type of failure is not tolerated. The client would soon rather employ extra employees overtime in order to meet critical path deadlines, therefore this type of failure has not been recorded on this project.

Once all the Prevention, Appraisal and failure costs were calculated for all purchase orders, a visual analysis was done to determine whether any patterns existed between the percentage of quality costs and their distrubition amongst preventive, Appraisal and failure costs. The total costs of each purchase order are listed in the Table below as well as the estimated value of how much was spent on preventive, Appraisal and failure corrective measures. Based on these numbers, the percentage ot the total PO cost spent on COQ was found, as the percentage of how much was spent on preventive & Appraisal, and failure correction.

Commodity	Total $PO	COQ	% Total for P+A	% Total for F	%COQ for P+A	%COQ for F
Lifting Equipment	225000	19%	5%	14%	24%	76%
Lifting Equipment	113325	7%	5%	2%	71%	29%
HVAC Equipment	149529	3%	3%	0%	100%	0%
Steel	24207	86%	73%	12%	86%	14%
Induction Furnace	422400	5%	3%	2%	61%	39%
Steam Plant	3505698	6%	2%	4%	37%	63%
Rferactories for AB furnace	165000	9%	9%	0%	100%	0%
Anode stacking Cranes	1522656	4%	4%	0%	100%	0%
Furnaces and Launder System	2054400	11%	4%	7%	35%	65%
Precast Concrete	5604900	24%	3%	21%	13%	87%
Steel	124539	203 %	170%	33%	84%	16%
Roofing and Sding material	118560	17%	15%	2%	91%	9%
Air Compressor System	5987549	7%	2%	5%	30%	70%
Aluminum	475000	15%	5%	10%	34%	66%
Pot Superstructures components	40679	85%	85%	0%	100%	0%
Cathode blocks	2817232	4%	2%	2%	52%	48%
Gas Treatment Centre (GTC)	12077974	20%	2%	18%	11%	89%
Aluminum	6263033	2%	2%	0%	100%	0%
Cathode Sealing Equipment	340036	20%	4%	16%	21%	79%
Cathode Sealing induction Furnace	375643	13%	3%	10%	25%	75%
Anode Clads & Cathode Clads	14186	38%	38%	0%	100%	0%
Refractory, Super Insulating	28800	19%	16%	3%	86%	14%

Refractory Concrete	26491	12%	12%	0%	100%	0%
Prefabricated electrical Rooms	897873	26%	5%	21%	20%	80%
Medium Voltage Distribution Transformers	500350	6%	5%	1%	83%	17%
LV Switchgear (600V)	84437	21%	20%	1%	94%	6%
Bricks Jointing Cement	29850	14%	9%	5%	66%	34%

Table 6 - Breakdown of COQ costs for each PO

Since the aim of this exercise is to determine patterns indicating optimum PAF distribution, the POs with the highest COQs are dicussed first. Out of 27 purchase orders, 17 of them were found to have a total percentage spent on COQ of greater than 10%.

%COQ	%P+A	%F	Δ(PA-F)
86	86	14	72
24	13	87	74
203	84	16	68
85	100	0	100
38	100	0	100
26	20	80	60
21	94	6	88
19	24	76	52
11	35	65	30
17	91	9	82
15	34	66	32
20	11	89	78
20	21	79	58
13	25	75	50
19	86	14	72

12	100	0	100
14	66	34	32
Average of %P+A	58.2%	Average of Δ(PA-F)	67.5%

Table 7 - Breakdown of COQ costs for POs with COQ>10%

The difference between the percentage spent on Prevention and Appraisal and the percentage spent on failure correction was investigated and the average difference was calculated as 67.5%. This is quite high suggesting that a large difference might be detrimental to the overall percentage spent on COQ. To investigate this hypthesis further, the purchase orders with the a % COQ of less than 10% was also studied in the same manner and yielded the following results.

%COQ	%P+A	%F	Δ(PA-F)
7	71	29	42
3	100	0	100
5	61	39	22
6	37	63	26
9	100	0	100
4	100	0	100
7	30	70	40
4	52	48	4
2	100	0	100
6	83	17	66
Average of %P+A	73.4	Average of Δ(PA-F)	60

Table 8 - Breakdown of COQ costs for POs with COQ<10%

After studying the remaining POs with %COQs between 0-10%, we find that the aforementioned hypothesis may have some limitations as there seems to be only a slight pattern in P-A-F distribution once the %COQ reaches 10% and lower. This can possibly suggest that smaller differences between the percentage spent on Prevention & Appraisal and failure correction can lead to smaller COQ or could simply be a fluke in the data. There also seems to exist a pattern between percentage of COQ and amount spent on Prevention and Appraisal as opposed to failure correction.

A further investigation is done, this time involving Juran's model which states that in order to lower total quality costs, more should be spent on preventive and Appraisal rather than correcting failure. This

model is based mainly on the manufacturing industry but may yield similar results when applied in construction since construction failures, similar to manufacturing failures can be quite costly.
The Table below represents the purchase orders where more has been spent on Prevention and Appraisal than correcting failure:

%COQ	%P+A	%F
7	71	29
3	100	0
86	86	14
5	61	39
9	100	0
4	100	0
203	84	16
17	91	9
85	100	0
4	52	48
2	100	0
38	100	0
19	86	14
12	100	0
6	83	17
21	94	6
14	66	4
31	← Average %COQ	

Table 9 - Breakdown of COQ costs for POs where P&A costs > F costs

%COQ	%P+A	%F

19	24	76
6	37	63
11	35	65
24	13	87
7	30	70
15	34	66
20	11	89
20	21	79
13	25	75
26	20	80
16	Average %COQ	

Table 10 - Breakdown of COQ costs for POs where F costs > P&A costs

The average %COQ that was found is 31% which is considered to be the on the high end suggesting that perhaps Juran's model doesn't work for the construction industry.
In order to confirm this, the purchase orders with high failure correction costs than Prevention and Appraisal costs were also considered:

Contrary to Juran's model, it appears that purchase orders where less was spent on Prevention and Appraisal than failure correction yield an average %COQ of 16% which is much smaller than that of the purchase orders where more were spent on Prevention and Appraisal. This suggests that perhaps minor failures in construction (the ones considered in this study are only minor since the major ones are not tolerated) do not cost much to repair and therefore a trial and error approach to certain commodities can be taken instead of spending a great deal preventing and inspecting failures. Since this is an unconventional conclusion, one last exercise is done to determine whether there exists an optimum percentage to spend on Prevention and Appraisal in order to minimize overall expenditure on quality. Commodities purchased for the construction of an aluminum smelter can be roughly categorized into two main streams; building equipment purchased for the construction and physical functionality of an aluminum smelter and building material purchased for the structure itself. When dividing these two components and repeating the same exercise conducted before we get the following results.

Building Equipment	Commodity Description	%COQ	%P+A	%F
COQ>10%	Lifting equipment	19	24	76
	Furnaces and launder system	11	35	65
	Gas treatment center (GTC)	20	11	89
	Cathode sealing equipment	20	21	79
	Cathode sealing induction furnace	13	25	75
	Prefabricated electrical rooms	26	20	80
	LV Switchgear (600V)	21	94	6
	Average	18.6%	32.9%	67.1%
COQ<10%	Lifting equipment	7	71	29
	HVAC equipment	3	100	0
	Induction furnace	5	61	39
	Steam plant	6	37	63
	Anode stacking cranes	4	100	0
	Air compressor system	7	30	70
	Medium voltage distribution transformers	6	83	17
	Average	5.4%	68.9%	31.1%

Table 11 - Breakdown of COQ costs for Building Equipment Commodities

After observing the results of this exercise, a pattern can be safely extracted and suggest that Juran's model can in fact be applied to construction commodities that pertain building equipment. Purchase orders whereby the %COQ is greater 10% show that failure costs exceed Prevention and Appraisal costs by approximately 40% whereas purchase orders with %COQ less than 10% prove the exact opposite; Prevention and Appraisal costs exceed those of failure corrections by 40%. The exercise is now repeated for purchase orders pertaining to building materials.

Building Materials	Commodity Description	%COQ	%P+A	%F
COQ>10%	Steel	86	86	14
	Precast concrete	24	13	87
	Steel	203	84	16
	Roofing and siding material	17	91	9
	Aluminum	15	34	66
	Pot superstructure components	85	100	0
	Anode clads & cathode clads	38	100	0
	Refractory, super insulating	19	86	14
	Refractory concrete	12	100	0
	Brick jointing cement	14	66	34
	Average	51.3%	76.0%	24%
COQ<10%	Refractories for anode baking furnace	9	100	0
	Cathode blocks	4	52	48
	Aluminum	2	100	0
	Average	5%	84%	16%

Table 12 - Breakdown of COQ costs for Building Material Commodities

For building materials the relationship between COQ and PA appears to be very strong, increasing P+A by only 8% helps lower COQ by almost 45%. For Building equipment, the relationship is less sensitive or weaker because reducing the COQ cost by only 12% requires an increase of about 36% of P+A. This suggests that when applying Juran's model to the construction industry, it is important to consider the type of commodity in question. For instance some of the Building material commodities with % COQs greater than 10% also show that have 0% failures. This result may be a necessary and important outcome therefore a significant portion of the purchase orders value is spent on Prevention and Appraisal.

SYSTEM DYNAMICS APPROACH

Although the visual analysis conducted allows some observations to be made, a more systematic and accurate approach is taken to observe the relationships between Prevention, Appraisal and failure costs. Using System Dynamics, not only can a more precise conclusion be made but all affecting factors in our PAF model can be analyzed to show interconnecting relationships as well.

Simulation Model

Therefore the System Dynamics approach has been used to describe the structure of this complex system. As there are complicated relationships between variables of this system, using this approach can help to study the feedback behavior of each variable and its effect on other variables and the system as a whole (Sterman, 2000).

Since there is a great difference between using the SD approach in COQ for manufacturing and COQ for construction project, the following model has been defined specifically for the cost of quality for the function of procurement. The most important difference to mention is that construction projects are extremely dynamic and are executed in phases, therefore there cannot be an accurate comparison between one phase and another as they differ in value, activities and final result. Another important difference to note is defining the time horizon in this type of project. Project performance is constantly changing and therefore the model should reflect this. The duration of this function within the project is 444 days, which has been considered as the time horizon of this study in the model. There are 12 purchase orders relating to building material in this project and since building materials was the category the correlated most closely to Juran's manufacturing model, these were the purchase orders used for the analysis.

The main purpose of this simulation is to verify the predicted behavior of COQ models in construction environment and study the feedback behavior of each variable and its effect on other variables and the system as a whole.

Sub systems of the model include the following:

Prevention costs consist of percentage spent by supplier on Prevention as an auxiliary variable, which is 2% of the related purchase order (PO). PO value is imported to the model for each day and hours spent by company on quality assurance and quality control (QA+QC) is 10 hours.

Appraisal Costs are made up of company and supplier inspection hours. Each of these are determined by observing the number of hours used for inspection multiplied by the number of records obtained documenting each inspection. The company has budgeted supplier quality (SQ) hours for inspection and suppliers are mandated to produce inspection test plans (ITP).

Failure costs are categorized as an external failure costs and internal failures. These costs have been calculated based on number of internal and external issues. There is a relation between internal failure, Prevention costs and Appraisal costs with external failure costs and Prevention costs and Appraisal costs with internal failure costs which are generated based on the raw data of the project.

Rate of COQ change is the rate variable of the model and cost of quality is the level variable in this model.

The constant data has been imported to this model from excel sheet and they are updated daily due to the nature of data obtained in construction.

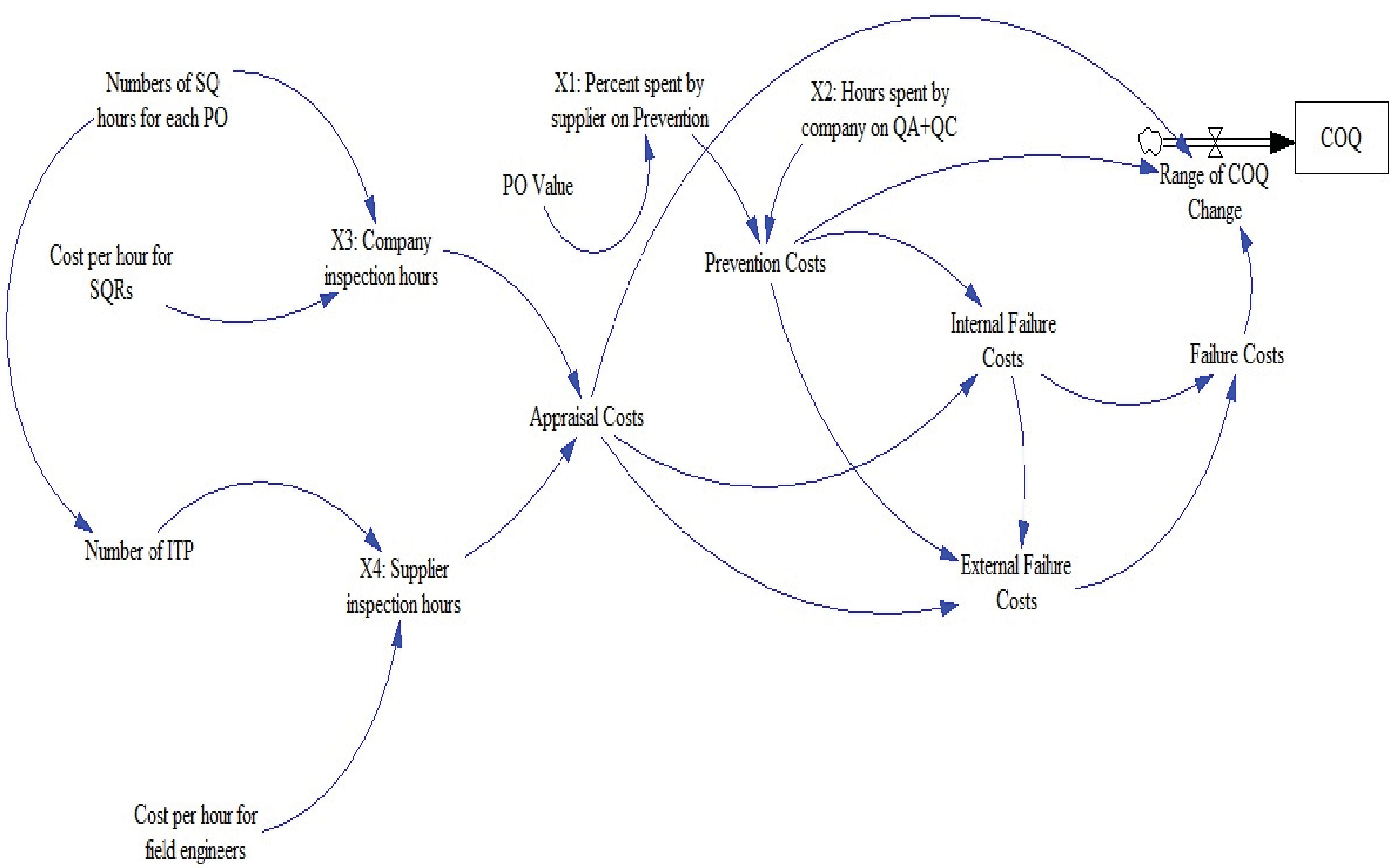


Figure 2 - Systems Dynamics representation of the COQ model

Validation of the Model

In order to validate a model, one must verify the assumption, the structure of the model and it's behavior. This assumptions in the model were verified through literature review as well as conducting interviews with seasoned supplier quality engineers whose experience in the field qualify them to make valid assumptions. The structure of the model is largely based on Juran's COQ model for manufacturing as well as Kiani's COQ model using the system dynamics approach. The behavior of the model was verified in two different ways, first by testing the extremes, both the highest and lowest levels of our input variables were used to assess the outcome and secondly the existing conditions were simulated and in both cases, the results proved to be consistent.

Policy Design

The motivation for this particular analysis is to prevent the rework that is often incurred in the construction industry. Love and Li (2010) concluded in their research on causes and costs of rework in construction, that quality failure in the procurement process of construction projects have become the leading cause of cost overruns in construction. By determining which activities benefit the overall project as opposed to which activities are wasteful, construction companies can begin to streamline their processes much like the manufacturing industry and eliminate any unnecessary expense as well as add worthwhile expenses that would reduce cost of quality overall.

In this analysis, the effect of different Prevention costs was observed to determine the relationship between Prevention, COQ and failure costs.

First, the existing conditions were simulated in Vensim using the model to ensure the proper functionality of the model. Then four different Prevention scenarios were simulated and compared to the existing conditions to observe the relationship between changing Prevention and other factors.

The policies were designed to determine the trend in which the model would react to the increase and decrease of Prevention and Appraisal. Prevention currently amounts to 2% of the PO value and this is what is generally accepted as an appropriate amount to spend on Prevention in the procurement function of a construction project. The policies were therefore designed to determine the results in the event Prevention was halved (1%) or doubled (4%) and middle milestone for the sake of a continuous curve. Similarly, policies for Appraisal, which are currently being determined on a case by case basis depending on the nature of the PO and budgeted Appraisal activity hours are assigned, are being designed in order to assess the trending result of doubling (200% of existing Appraisal) and halved (-50% of existing Appraisal) with milestones in the middle as well.

According to Juran's model there is an ideal level of both Prevention and Appraisal to achieve minimum amount of COQ. When applied to the manufacturing field, this balance is 50% Appraisal and 50% Prevention. This may either differ significantly or be very similar in the construction industry. This model and these policies were designed to determine this and we would expect to conclude that there also exists an ideal balance between Appraisal and Prevention to minimize COQ in construction procurement.

We would expect that these policies would be similar to Juran's model in that Prevention and Appraisal would both help minimize COQ by significantly decreasing the amount of both external and internal failure. We would also expect to have some specific differences most probably attributed to the difference between manufacturing commodities as opposed to the processes of purchasing, inspecting and installing. It's also worth noting that another difference would be how each purchase order will go through the stages of the project differently and this may also have some effect on our results.

RESULTS

Prevention and Appraisal Analysis

The first policy we explore is that of the effect of COQ as Prevention changes and Appraisal remains the same. According to Juran and other COQ policies, we would expect that increasing Prevention should lead to a decrease in COQ until of course Prevention costs reach a redundant stage where increasing this value beyond its effect on failure costs, will simply add to the COQ costs.

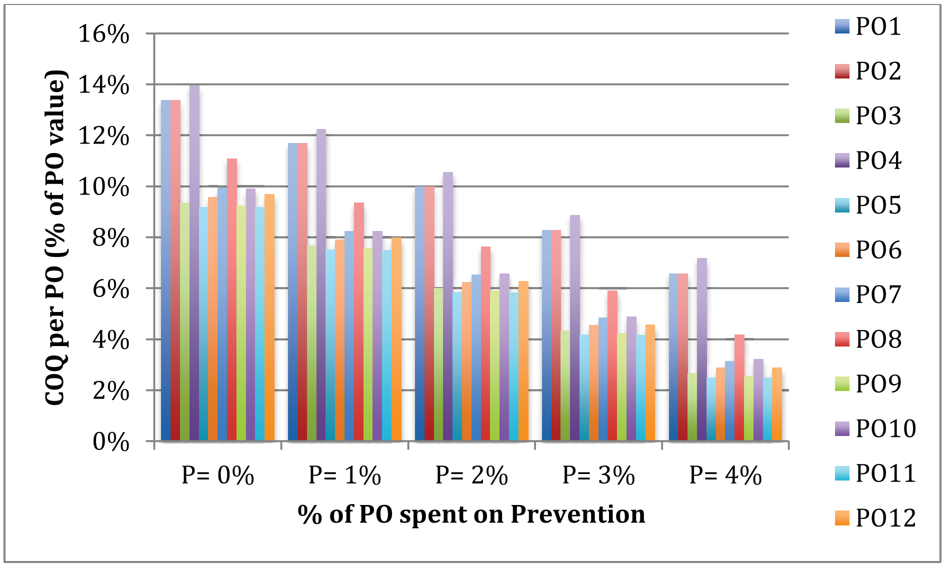


Figure 3 - % of PO spent on Prevention vs. COQ per PO

Figure 3 shows the relationship between Prevention and COQ. From this Figure it can be observed that although increasing Prevention is likely to add to COQ costs, it actually decreases total COQ. The more that is spent on Prevention, the lower COQ gets. This is a similar result to what you would expect in manufacturing and complies with Juran's model for cost of quality. This is likely explained by the decrease in total failure being larger than the increase in Prevention causing the overall COQ to decrease. Figure 4 further confirms this expected result. In this Figure it can be seen that as Prevention is increased, failure is decreased with the lowest failure rate seen at 4% of PO spent on Prevention.

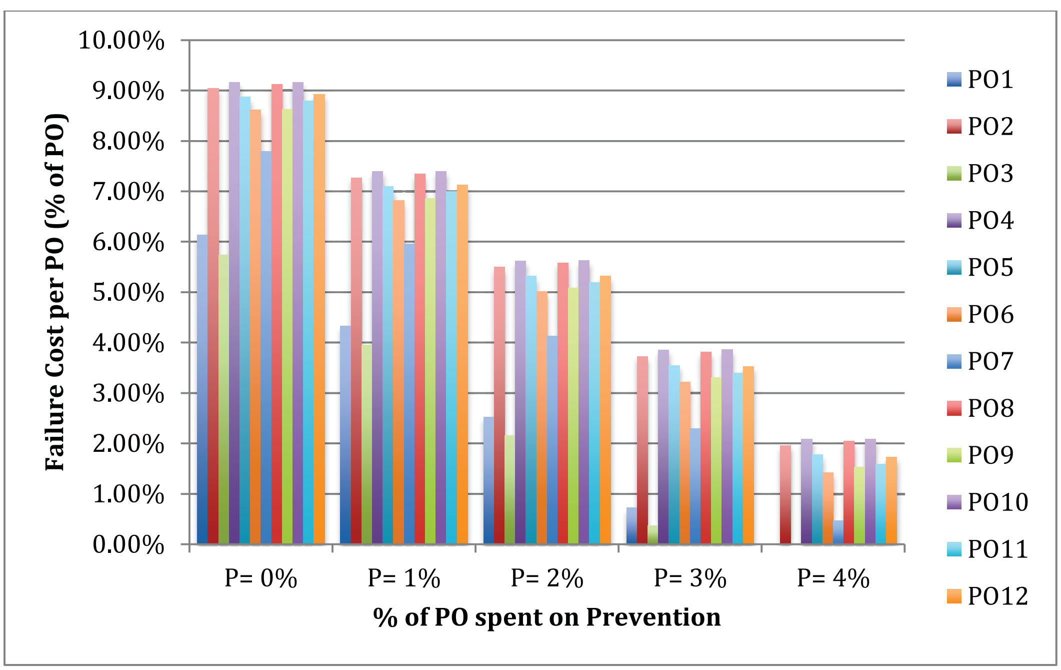


Figure 4 - % of PO spent on Prevention vs. Failure Cost per PO

It is clear from these results that an increase in Prevention can lead to a significant decrease in failure costs. This suggests that in the construction industry, the process of purchasing material can be streamlined by determining cost of quality using Juran's model for Prevention. However, the effect of Appraisal cost in construction still needs to be examined.

A similar analysis was done on Appraisal costs. This time simulations were performed for 0% analysis, 50% less Appraisal than the existing condition, 25% less Appraisal than the existing condition and 100% more than the existing condition. We would expect to find that Appraisal should behave similarly to Prevention in that its increase should lead to a decrease in failure costs and therefore an overall decrease in COQ. The results can be seen in Figure 5.

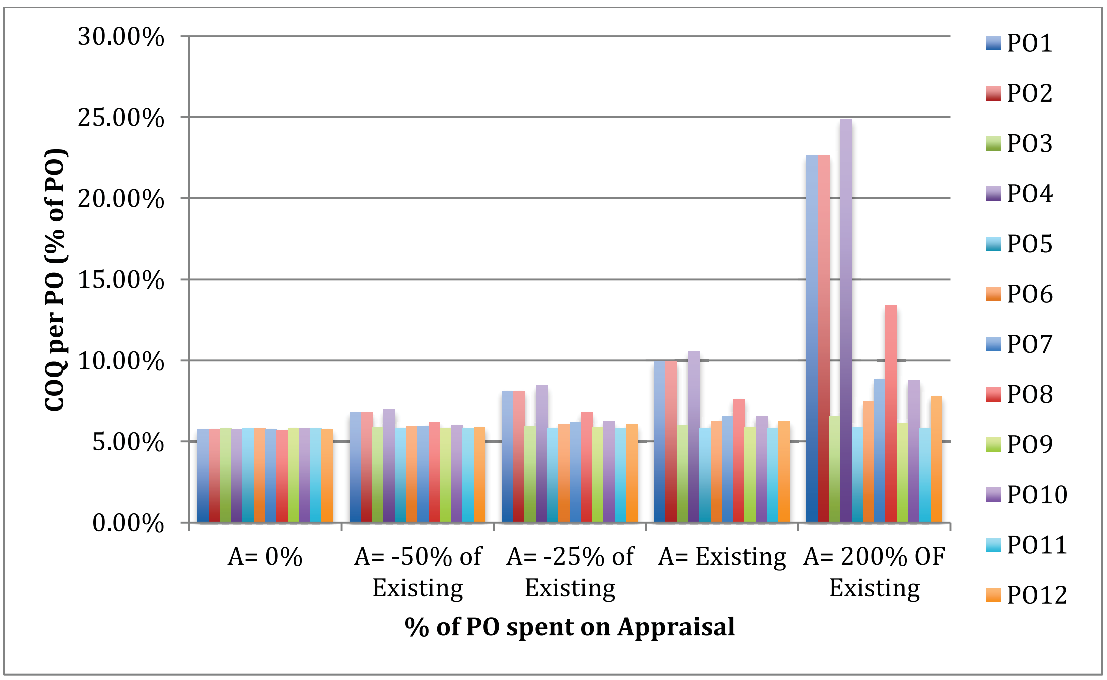


Figure 5 - % of PO spent on Appraisal vs. COQ per PO

From this graph it can be observed that COQ is a lot less sensitive to changes in Appraisal. In fact in the case of some POs, COQ increases with increasing Appraisal costs. This is an unexpected result and the relationship between failure and Appraisal needs to be established before any conclusions can be made.

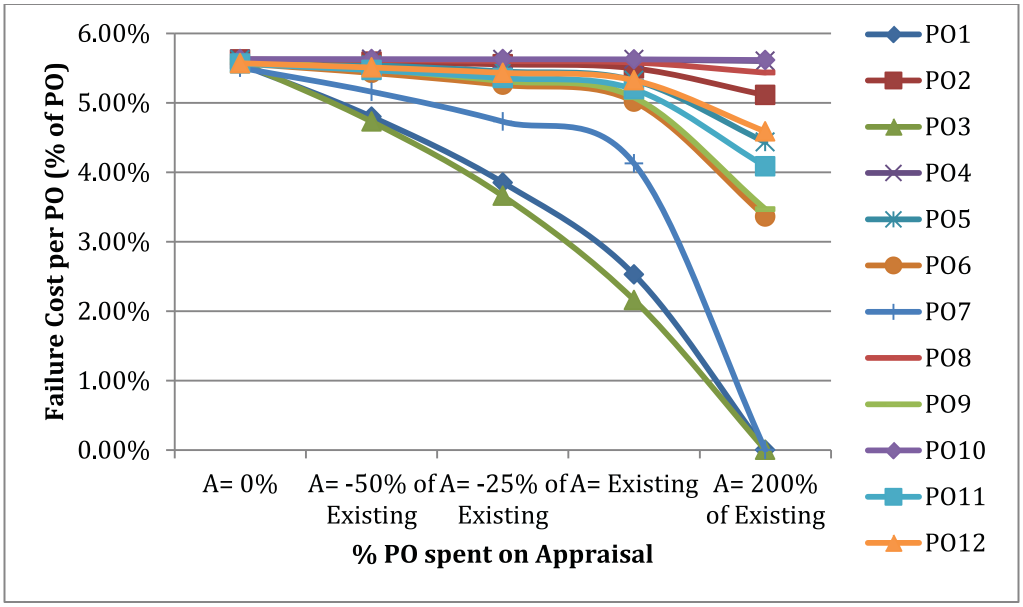


Figure 6 - Increasing Appraisal vs. Failure Cost per PO

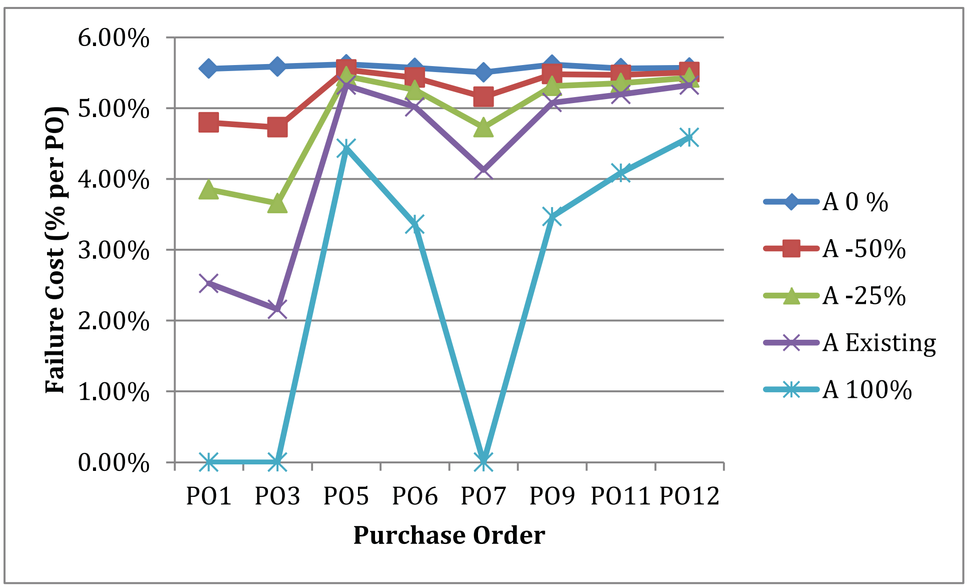


Figure 7 - % of PO spent on Appraisal cost vs. Failure costs

Figures 6 and 7 show the relationship between failure cost and Appraisal cost to be negative which is what is expected when considering Juran's model. This observation leads to the conclusion that increasing Appraisal cost does in fact decrease failure. However, these results suggest that the lowest COQ occurs when Appraisal costs are 0 despite the decrease in failure costs. This leads to the conclusion that too much of the PO value is spent on Appraisal and that perhaps Appraisal is generally more expensive than failure costs in the procurement of construction materials.

Analysis of Combination Policies

An analysis was done to show all the combination policies and an attempt to determine optimal Prevention and Appraisal was done.

Figure 8 shows the effect of Prevention on COQ if nothing was spent on Appraisal. This policy was designed to determine if there existed a different trend for increasing/decreasing Prevention when nothing is spent on Appraisal. We would expect the trend to remain similar to the previous results in that increasing Prevention would decrease COQ. If our previous results are accurate, we would also assume that no expense incurred on Appraisal may decrease the overall COQ for each category of Prevention.

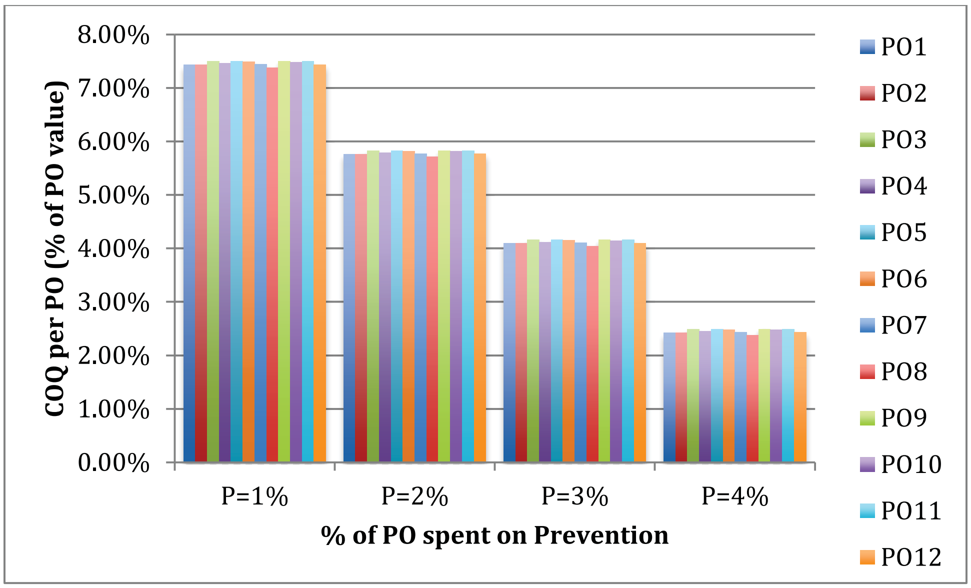


Figure 8 - % of PO spent on Prevention vs. COQ per PO (Appraisal = 0%)

Figure 8 confirms the expected results. The increase of Prevention does in fact decrease COQ and generally, due to 0% of expenditure utilized on Appraisal, the overall COQ is less. Although this disagrees with Juran's model, it supports our previous policy. Similarly, this policy is used to examine failure cost in the absence of Appraisal cost. We would expect a decrease in failure cost as Prevention increases however we would also expect a visible difference between our previous analysis of failure cost. With non-existent Appraisal costs, there would typically be a greater amount of failure cost.

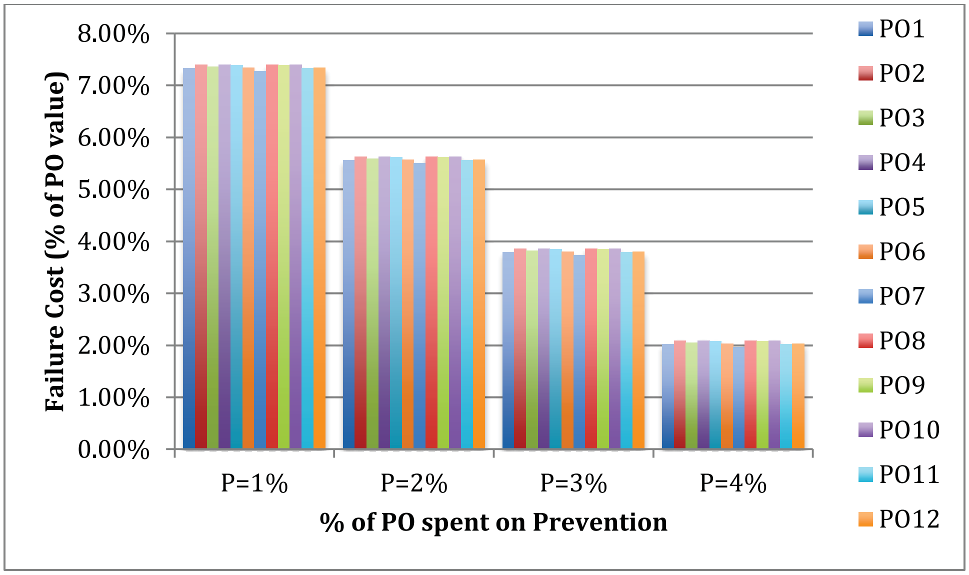


Figure 9 - % of PO spent on Prevention vs. Failure Cost per PO (Appraisal = 0%)

The results were as expected, Prevention decreases failure cost however the lack of Appraisal has shown a visible increase in failure when comparing to previous analysis (Figure 4).

The next policy is for 50% less than what is currently being spent on Appraisal as well as an analysis of how changing Prevention affects COQ. The purpose of this is to identify if spending 50% less on Appraisal than what is currently being spent would constitute an optimum amount of Appraisal. The expected result is to once again show a decrease in overall COQ due to increasing Prevention but less of a decrease than the previous analysis (Figure 8) due to incurring some Appraisal cost which according to previous analyses has an increasing effect on COQ.

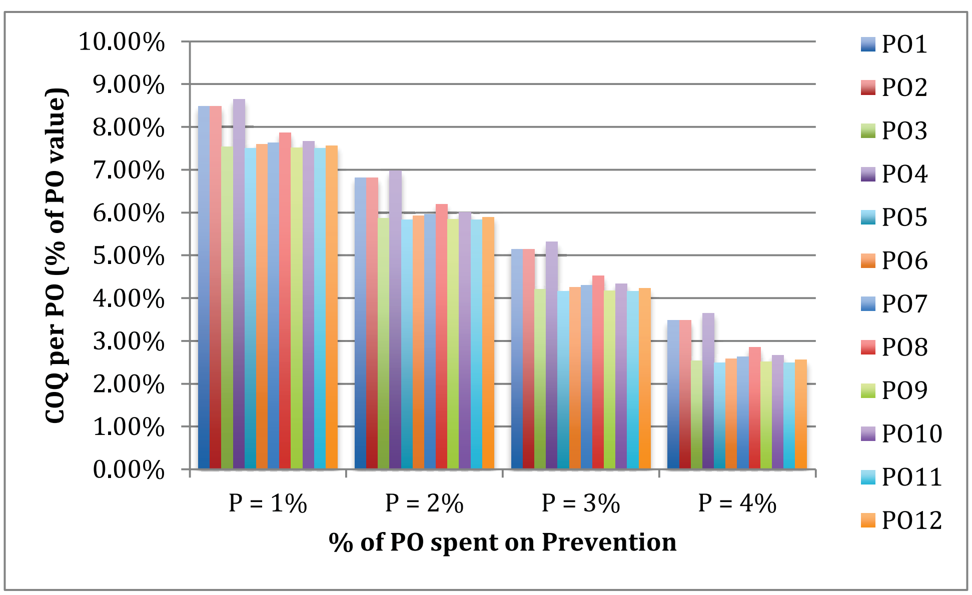


Figure 10- % of PO spent on Prevention vs. COQ per PO (Appraisal = -50% of existing Appraisal value)

Figure 10 shows the results that were expected. Increasing Prevention once again decreases COQ but when compared to Figure 8, it is clear that COQ is higher when there is expenditure on Appraisal. When doing an analysis to observe failure cost, we would expect less failure as Prevention increases but when compared to Figure 9 we would expect to see less failure costs.

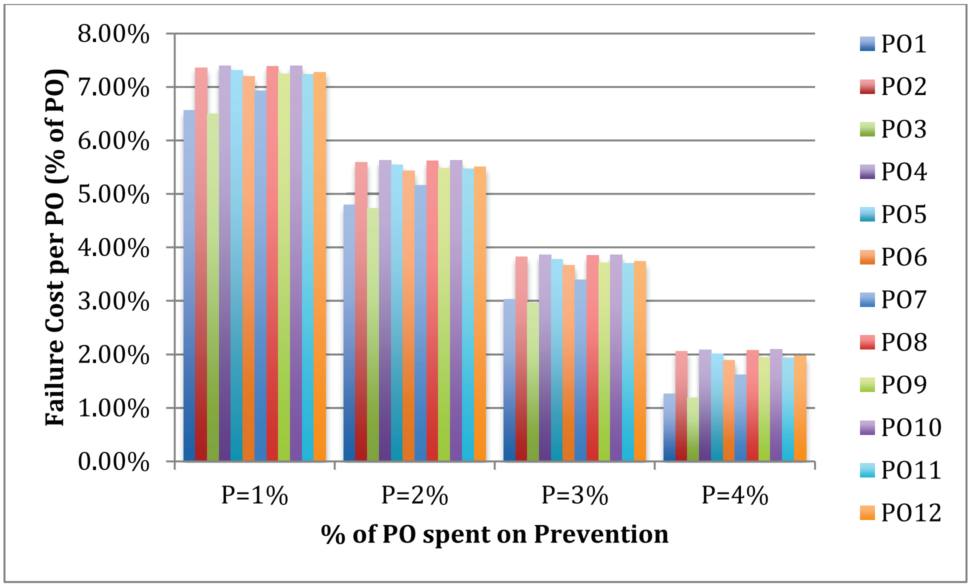


Figure 11- % of PO spent on Prevention vs. Failure Cost per PO (Appraisal = -50% of existing Appraisal value)

Figure 11 shows the expected results. Increasing Prevention decreases failure costs however when compared to Figure 9, there is a visible decrease in failure costs. It is worth mentioning that this decrease is more visible in some POs more than others. The next policy is designed for 25% less Appraisal than the existing amount with the different Prevention scenarios to determine if an optimum balance of Prevention and Appraisal exists with these combinations. The expected result is similar to the one seen in the previous policy. Increasing Prevention is expected to decrease COQ and the added expenditure on Appraisal should lessen this decrease by contributing to COQ despite Juran's theory of the relationship between increasing Appraisal and decreasing COQ.

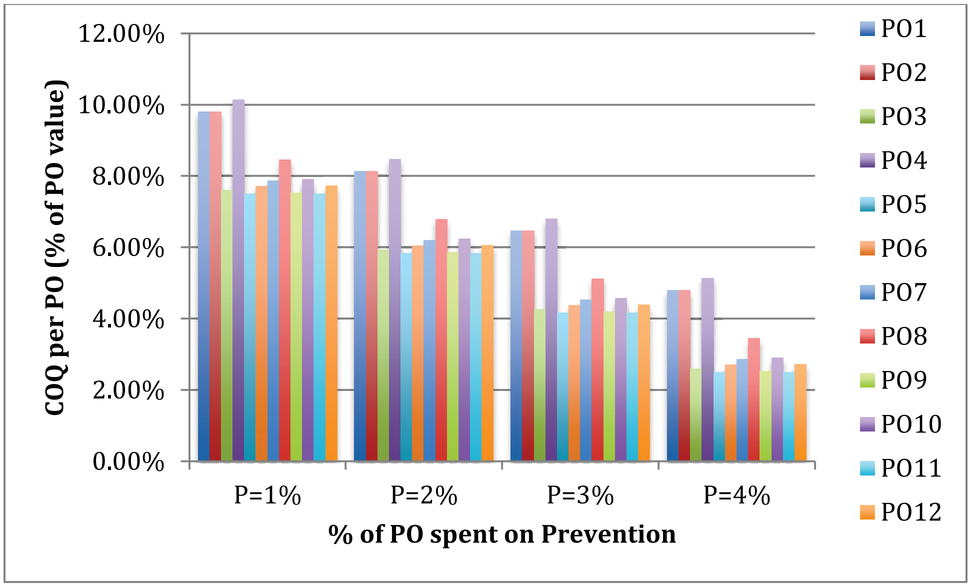


Figure 12- % of PO spent on Prevention vs. COQ per PO (Appraisal = -25% of existing Appraisal value)

Figure 12 shows the results that were expected. COQ decreases with increasing Prevention and the added expenditure on Appraisal creates a slightly higher overall value of COQ when compared with previous Figures 8 and 10. When assessing the failure costs with this policy we would expect a decreasing failure costs with increasing Prevention yet with the added expense on Appraisal, there should be the payoff of less failure costs.

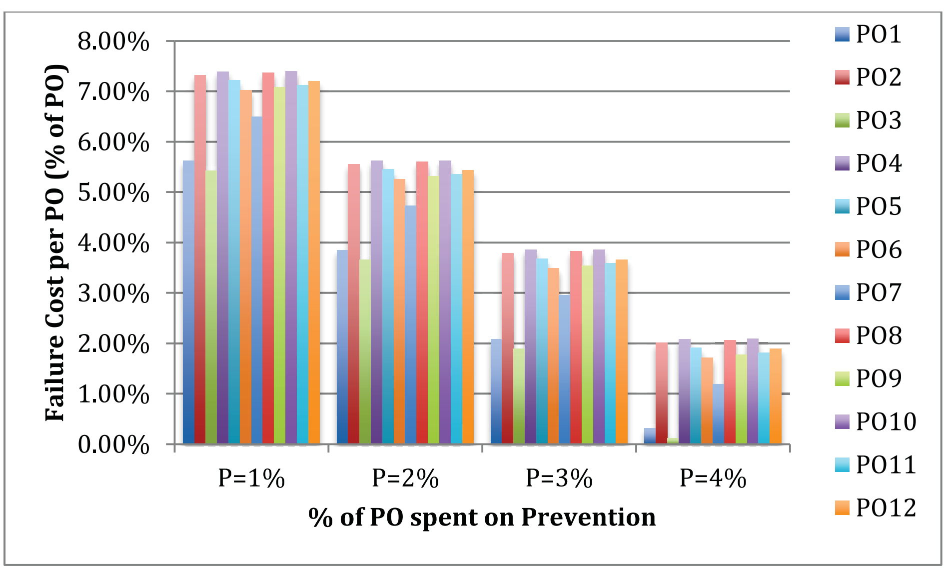


Figure 13 - % of PO spent on Prevention vs. Failure Cost per PO (Appraisal = -25% of existing Appraisal value)

Once again, Figure 13 shows the expected results showing the same trend of Prevention as previous charts as well as a reduction in failure costs due to the added capital spent on Appraisal.
The next policy is doubling the existing amount spent on Appraisal. This policy was designed to determine if there exists an optimum combination of both Prevention and Appraisal to minimize COQ. The expected results would be that COQ is at the highest level due to the dramatic increase in Appraisal. The changing Prevention scenarios should behave similarly to the previous policies.

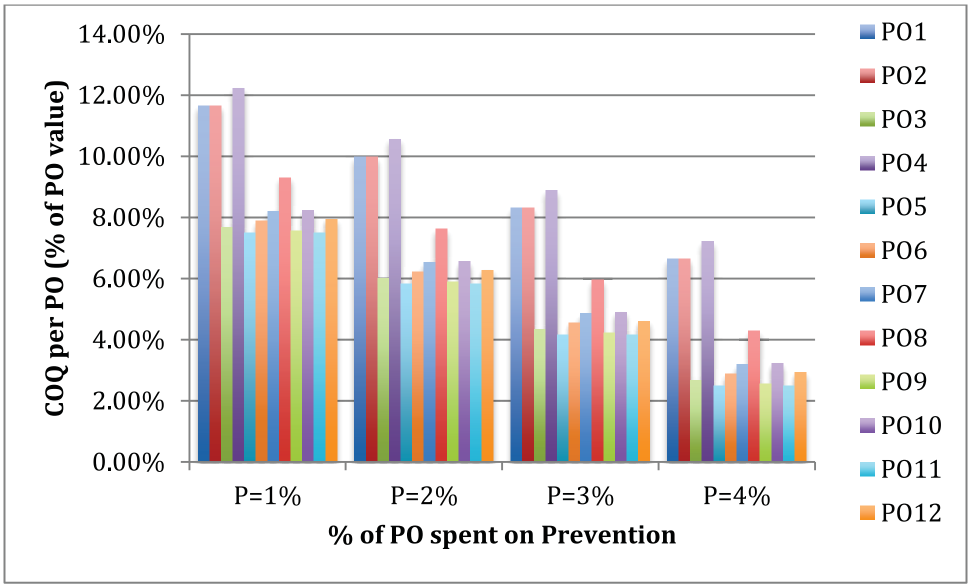


Figure 14- % of PO spent on Prevention vs. COQ per PO (Appraisal = 100% increase of existing Appraisal value)

The results are as expected shown in Figure 14. Increasing Prevention decreases COQ but as predicted, COQ is extremely high with the doubled amount of Appraisal cost. When examining the effect on failure costs we would expect a substantial reduction in failure with both the increase in Prevention as well as in comparison to other charts where much less was spent on Appraisal.

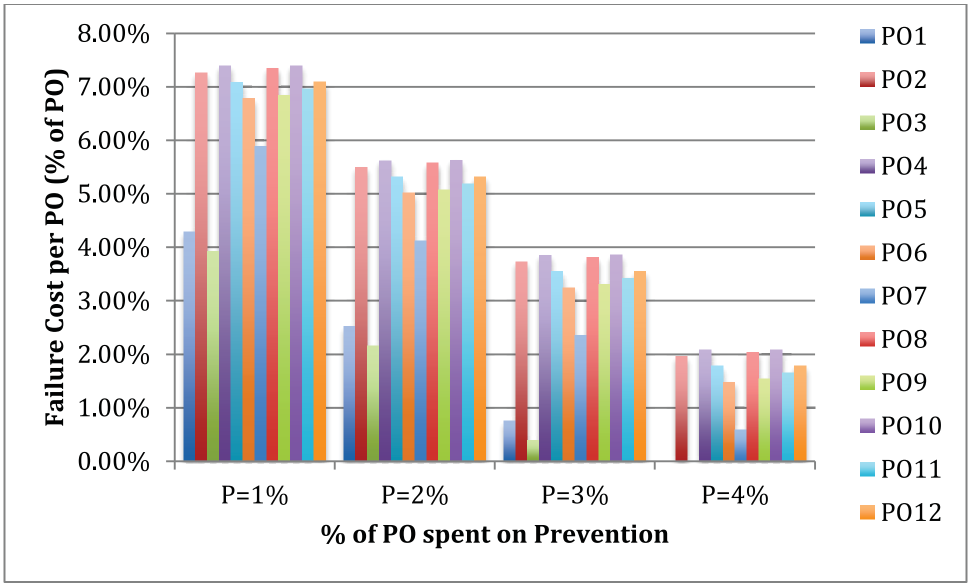


Figure 15- % of PO spent on Prevention vs. Failure Cost per PO (Appraisal = 100% of existing Appraisal value)

Figure 15 shows the final result of our analysis comparing Prevention scenarios with different Appraisal costs. Like all other results, they are as expected and from this analysis we can safely conclude that Prevention substantially decreases COQ as it increases and unlike the behavior of Appraisal costs in manufacturing, in construction it proves to have a negative overall effect on COQ.

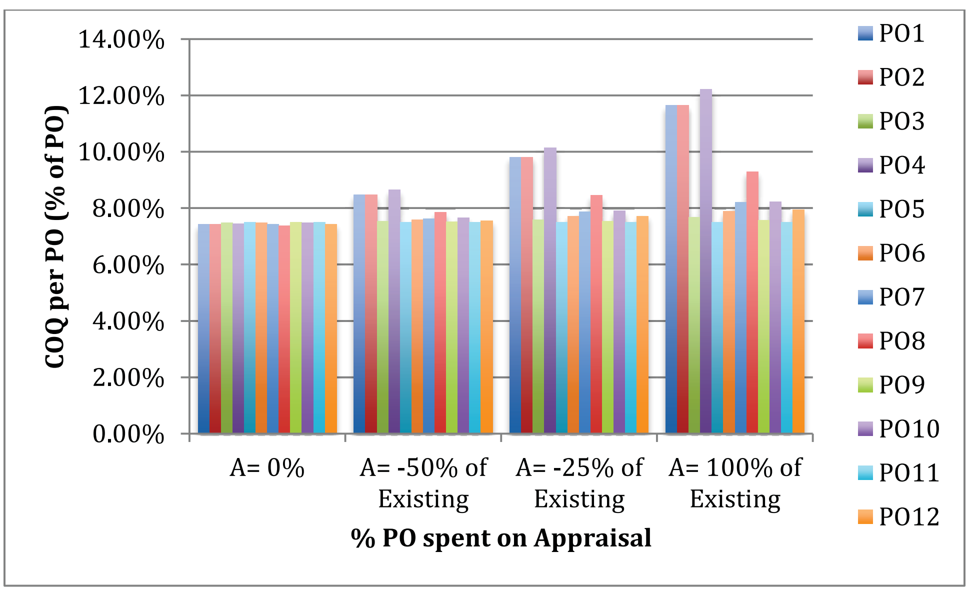


Figure 16– %PO spent on Appraisal vs. COQ per PO (Prevention = 1% of PO value)

Our analysis now shifts towards scenarios in which Prevention is constant and Appraisal is changing. Figure 16 shows the results of different Appraisal costs and only 1% of POs spent on Appraisal. It is clear from this chart that increasing Appraisal actually has an adverse effect on COQ, especially in POs 1, 2 and 4. When observing the effect Appraisal has on failure cost, it is clear that although Appraisal raises COQ, it decreases failure costs substantially in some POs whereas others show little change. This is clear in Figure 17, especially for POs 1,3 and 5.

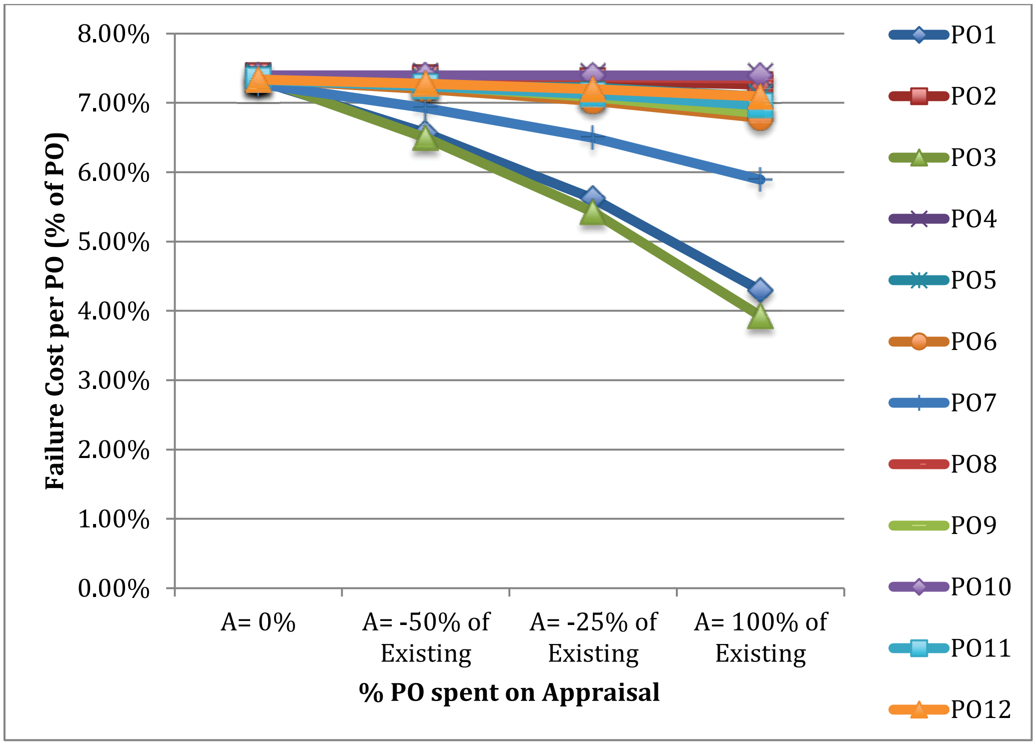


Figure 17– Increasing Appraisal vs. Failure Cost per PO (Prevention = 1% of PO value)

When observing the effect Appraisal has on failure cost, it is clear that although Appraisal raises COQ, it decreases failure costs substantially in some POs whereas others show little change. This is clear in Figure 17, especially for POs 1,3 and 7.

Figure 18 - % of PO spent on Appraisal cost vs. Failure cost (Prevention = 1% of PO value)

Figure 18 verifies this result as it clearly displays that the maximum amount of Appraisal yields the lowest failure costs.

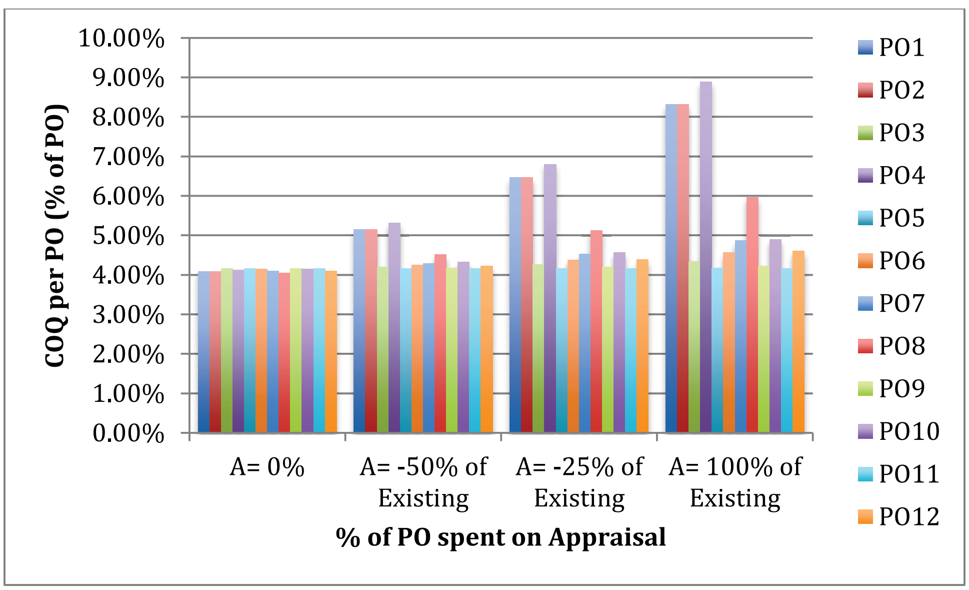


Figure 19- %PO spent on Appraisal vs. COQ per PO (Prevention = 3% of PO value)

The same analysis is conducted this time with 3% of the PO cost spent on Prevention. If we compare Figure 19 to Figure 16 we can clearly identify that increasing Prevention decreases overall COQ significantly, much like our observations in the previous analysis for Prevention. Yet again, increasing the amount spent on Appraisal increases overall COQ value. Once again this is mostly apparent in POs 1, 2 and 4.

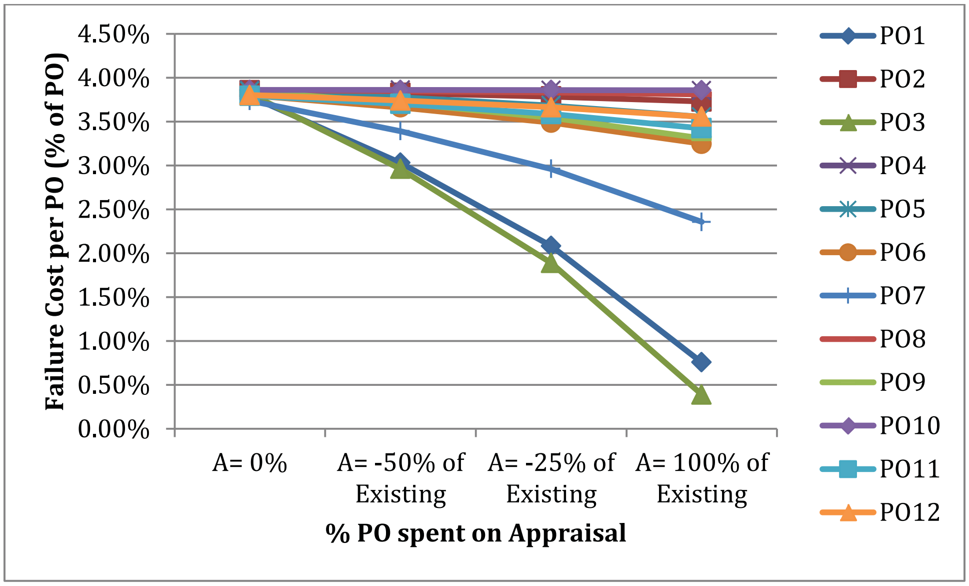


Figure 20 – Increasing Appraisal vs. Failure Cost per PO (Prevention = 3% of PO value)

When observing the effect on failure cost, we can see from Figure 20 that increasing Appraisal has a great impact on reducing failures, especially for POs 1,3 and 7. When compared to Figure 17, we see a reduction from greater than 7% failure down to less than 4% in Figure 20, which emphasizes the reducing effect of Prevention on failure cost.

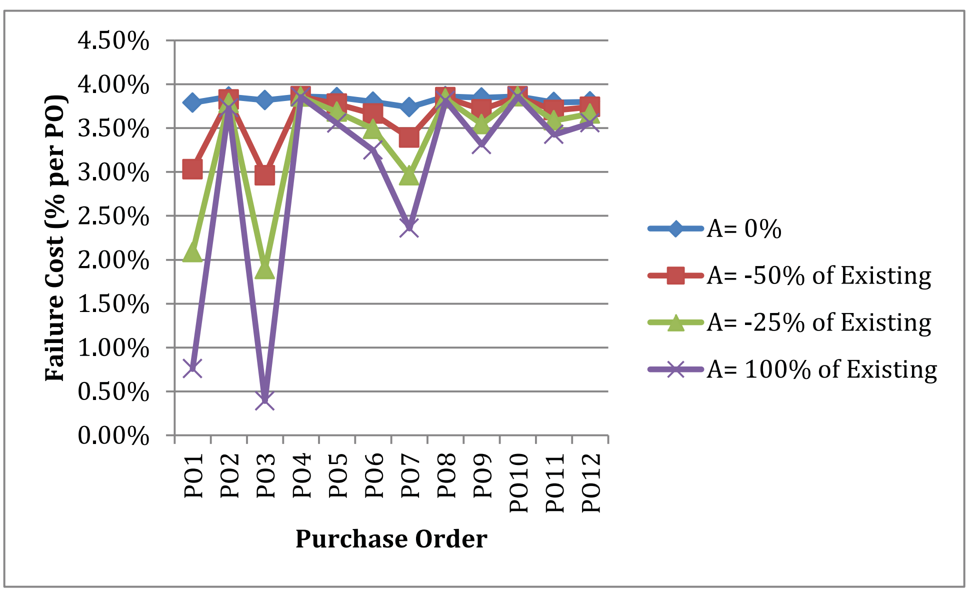


Figure 21 - % of PO spent on Appraisal cost vs. Failure cost (Prevention = 3% of PO value)

Figure 21 once again highlights that Appraisal costs do in fact alleviate failure costs. This is more apparent in some POs, such as 1,3 and 7 rather than others such as POs 4, 5 and 12. There can be many reasons for this and will be discussed in the discussions section.

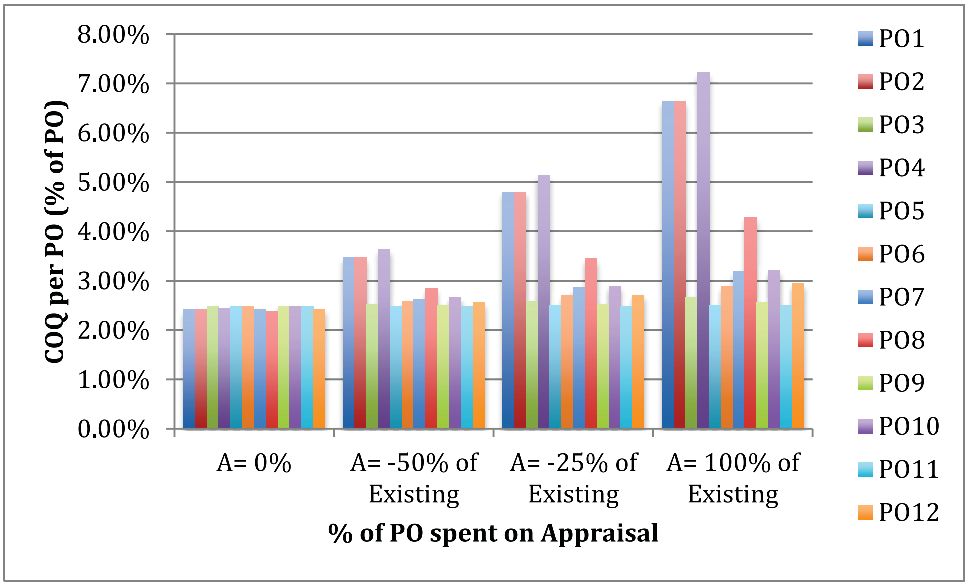


Figure 22 - %PO spent on Appraisal vs. COQ per PO (Prevention = 4% of PO value)

Figure 22 shows the final scenario for this analysis and maximum Prevention costs. Once again the same pattern is observed. Appraisal increases COQ in some POs more significantly than others and when compared to Figure 19, an overall decrease of the COQ per PO is seen. These are the expected results. POs 1,2 and 4 are once again those most sensitive to changes in Appraisal.

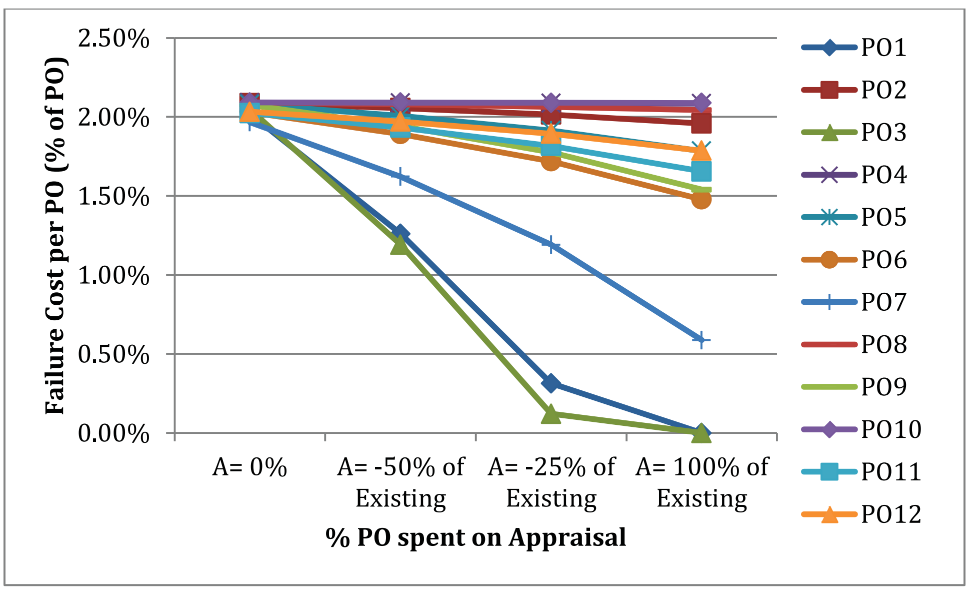


Figure 23 – Increasing Appraisal vs. Failure Cost per PO (Prevention = 4% of PO value)

Figure 23 shows Appraisal costs effect on failure cost and coupled with 4% Prevention we can see that failure is almost eliminated as a possibility in certain POs (1,3 and 7) while just reduced in others.

Figure 24 - % of PO spent on Appraisal cost vs. Failure cost (Prevention = 4% of PO value)

Figure 24 echoes the same results as previous charts, the higher the Appraisal costs the lower the failure costs and when compared to previous charts with lesser Prevention, shows a much more significant decrease in failure.

From these results it is clear that the more you increase Prevention the lower COQ becomes however there must be a point at which either COQ or failure costs will theoretically reach 0% at which point increasing Prevention any more will only serve to be redundant and begin to increase COQ.

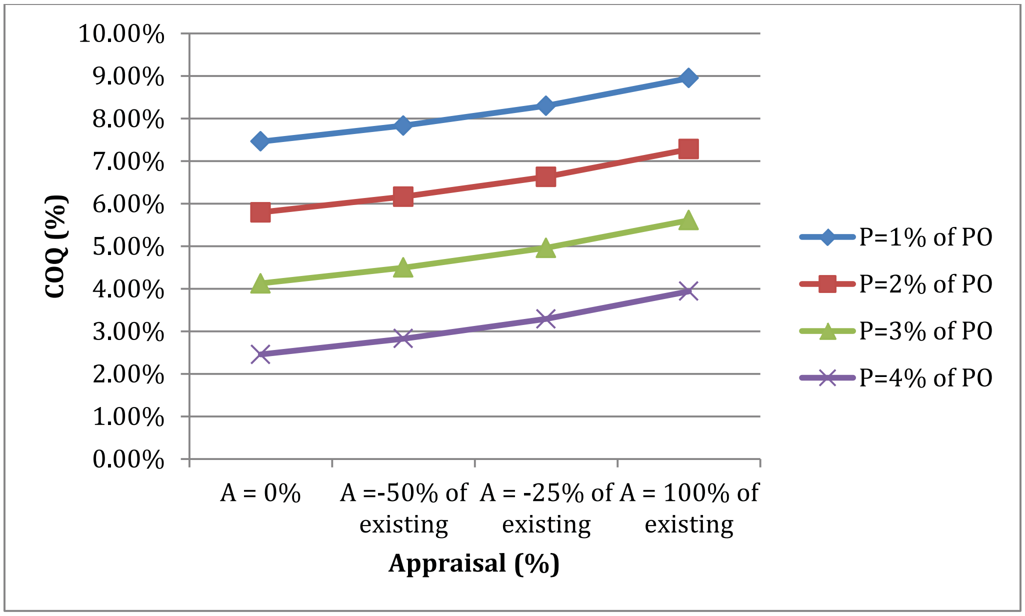


Figure 25 – Combination Policies for P and A vs COQ

Figure 25 is a graph that allows for simple comparison between the 16 different scenarios. It is clear that the scenario that reduces COQ the greatest is that in which Appraisal is 0% and Prevention is 4%. The scenario in which COQ is the highest is that in which Appraisal is 100% and Prevention is 1%. From these charts we assume that construction companies should therefore increase Prevention to the maximum and pay nothing on Appraisal however they must be wary of the amount of failures that could arise using this strategy. It is important to note that this analysis does not consider opportunity cost for developing a negative reputation that could lead to loss of work.

Figure 26 proves this notion. The scenarios in which 0% Appraisal was spent and only 1% Prevention was expended shows the highest amount failure incurred. On the other hand, the scenario in which 100% Appraisal and 4% Prevention was expended, we see the lowest rate of failure.

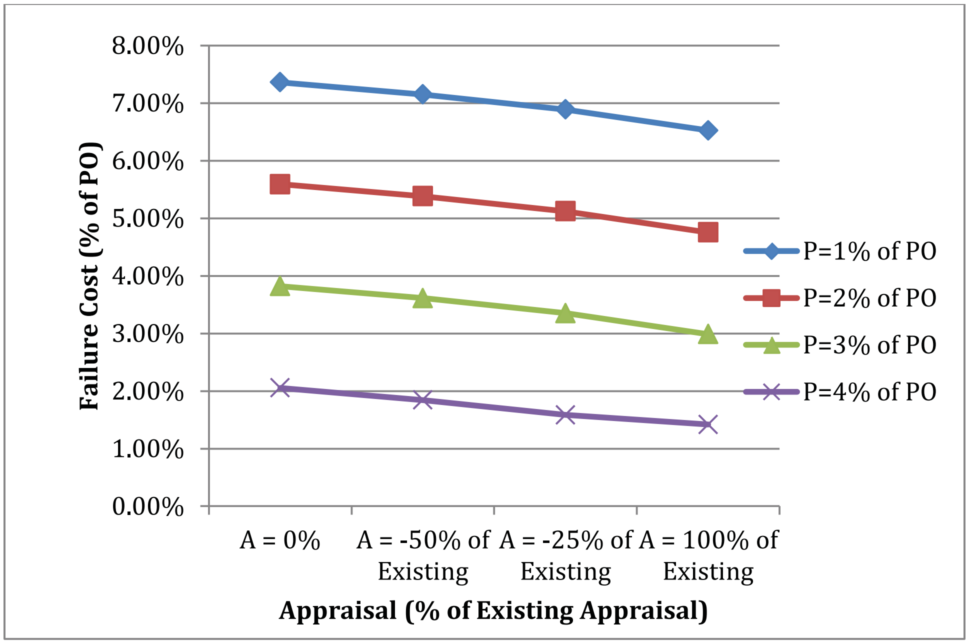
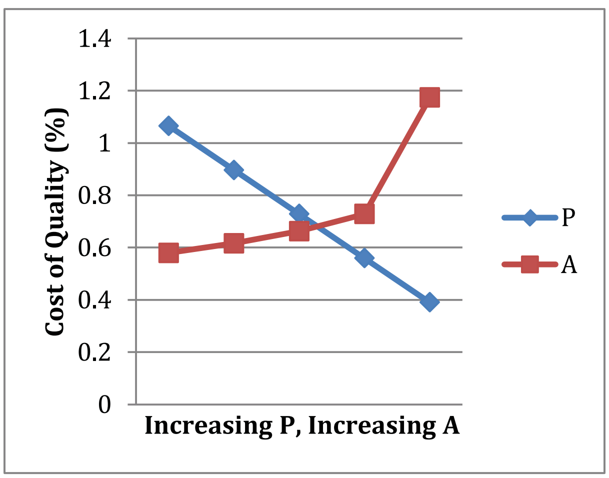


Figure 26 - Combination Policies for P and A vs Failure Cost

Furthermore, from Figures 27 and 28 we can see that although Appraisal cost seems to increase COQ it serves a great purpose of lowering failure costs significantly.



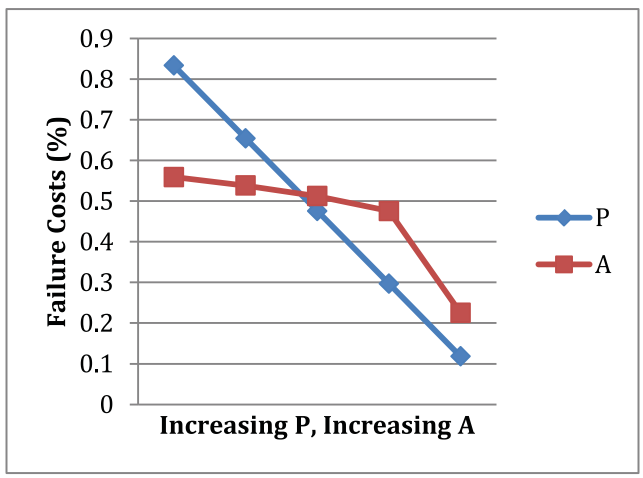


Figure 27 &28 – Trend of P and A vs. COQ & Trend of P and A vs. Failure Cost

DISCUSSIONS

The question that arises from these results is firstly, what are the reasons for Appraisal increasing overall COQ and secondly what is the reason for certain POs being affected differently by Appraisal. To understand the reason why Appraisal may cause COQ to increase so significantly we must first understand what the nature of these Appraisal activities are. In construction, Appraisal costs consist mainly of supplier quality hours spent on inspecting received materials. These job hours are attributed to supplier quality professionals completing these tasks and often throughout the course of a project may need to inspect the same materials/equipment several times at different stages of execution (i.e receipt of materials, installation of materials, functionality of equipment). This could result in hundreds of hours spent on this and therefore when employing professionals who make up to $50/hr this could get very costly. It is important to note that these SQ professionals often have to travel on site which would cause the number of budgeted hours to increase if considering travel time. When compared to manufacturing, Appraisal activities in construction are a lot more time consuming as it does not have the efficiency of an assembly line and therefore serve to be much more expensive despite still being important to minimizing failure rate. Research done by Hall & Tomkins (2000) revealed similar results in that they found that construction quality failures are small compared to the cost Prevention and Appraisal therefore providing the greatest scope of for reducing non value added expense. They suggest that finding ways to reduce failures while ensuring that the "related Prevention and Appraisal costs do not escalate beyond the return of failure reduction" (Hall & Tomkins, 2000, Page 15). This agrees with the findings in this study but only in terms of Appraisal. Prevention has a significant part in reducing expensive failures whereas Appraisal has proven to be more expensive without providing a worthwhile return on reducing failure. Hall & Tomkins (2000) do note however that over time, as focus on quality costs increase, these cost reducing methodologies would become embedded into company policy as well as streamlined and made more efficient thereby further reducing Prevention and Appraisal costs.

The second question of why some POs react differently to fluctuations in Appraisal cost could be attributed to the nature of the commodities corresponding to these POs. In our results there is a recurring pattern in which POs 1, 2 and 4 increase significantly when Appraisal is increased and POs 1, 3 and 7 incur the largest decrease in failure in comparison to other POs. These POs are probably commodities that have a high rate of failure/defects that could be easily corrected given proper inspections. The POs that are less affected could be commodities in which failure is either not as common or are not easily corrected with inspections. Another possible reason is that these POs are in stages of the project in which Appraisal activities can be extremely effective for example inspections of bulk material done right before installation whereas other POs can consist of simply 3 or 4 expensive items in which Prevention is key and Appraisal could only uncover mistakes that are too late to correct without incurring costly expenses. In this case failure is not an option and Prevention is imperative. Alarcon et al. (1999) conducted a research on improvement in the procurement process in construction projects in which they found that main problem with procurement in construction lay with schedule delays as well as lack of specified quality for the project. This conclusion could potentially explain the reason why different POs responded differently to changes in Appraisal. Some POs may have been scheduled accurately whereas other POs may have experienced delays in which added expenditure was incurred to simply address these delays rather than correct failures.

CONCLUSION

In construction, it is difficult to establish a generic cost of quality model due to the limited data collection that occurs on a project. In order to be able to properly conduct COQ analyses in construction, there must be accurate dollar values collected yet this does not occur for a number of reason; firstly, due to the sensitive nature of this type of data and secondly, because in certain cases these values are intrinsic and therefore difficult to translate in terms of capital. It was found that the procurement process is the function that allows for the most accurate COQ analysis and therefore was chosen as a focus in this study.

In terms of the procurement department's supply chain, it is important to assess the type of commodity or product in question. For building material related commodities, there seems to be a strong positive relationship between increasing preventive and Appraisal cost and decreasing COQ. This pattern also exists for building equipment however the relationship is not as strong.

In order to minimize COQ, the results of this research suggest that Prevention should be increased to 4% and Appraisal to be decreased to 0%. However, a company in the construction industry must consider the factor of reputation. Construction companies are awarded contracts after an extensive bidding process that usually considers previous projects and reputation for success. Although in this case incurring some failures may prove to be less expensive than Appraisal costs, there is the matter of opportunity cost that needs to be considered for contracts lost due to the reputation of incurring too many failures. Therefore decreasing Appraisal to a point where failure costs are too high is unwise, despite minimizing COQ. For this reason, a limitation of this study is the inability to determine the opportunity cost of decreased Appraisal at the expense of increasing failures and potentially losing future contracts. Despite this limitation, there is value in understanding that there seems to be a general excess in expenditure on Appraisal costs in the construction industry and that it would be worthwhile to investigate why this is the case. Perhaps there are too many personnel devoted to the same function therefore an assessment of division of responsibility may help determine this, or perhaps there is too much emphasis on Appraisal when there should be more efforts towards Prevention which would indicate that it would be worthwhile to focus more on preventive exercises and ensure they do not overlap with Appraisal functions.

OPPORTUNITY FOR FUTURE STUDIES

The contribution of this work is unique in that it is the first time the SD approach has been used to model cost of quality in the construction industry, and specifically in the procurement function. To advance this study, one could develop a benefit cost analysis or an opportunity cost analysis to further determine the threshold at which decreasing Appraisal cost will begin to affect the overall reputation of an EPCM company.

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